

LASER ISOTOPE SEPARATION FOR URANIUM ENRICHMENT:
A TECHNOLOGY ASSESSMENT

by

RICHARD KEITH LESTER ©

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Richard K. Lester

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ABSTRACT

An assessment of the technical, economic, and political implications of the continued development of laser isotope separation (LIS) processes for uranium enrichment has been carried out.

After almost a decade of development, there are increasingly reliable indications that laser isotope separation technologies will be capable of enriching uranium at costs substantially less than those of existing alternatives; moreover, these technologies will probably be able to recover a larger fraction of the fissile isotope U-235 from natural uranium than is economically feasible in existing enrichment plants. Like all uranium enrichment methods, however, LIS technologies are potentially capable of producing highly-enriched uranium suitable for use in nuclear weapons. A systematic, sustained, public assessment of these and related issues is necessary. This study provides a framework for a more comprehensive public policy debate than has occurred to date.

The principal technological features and problems of the two main approaches to laser enrichment - the atomic process (AVLIS) and the molecular process (MLIS) - are reviewed. Important design parameters of commercial-scale laser enrichment plants of both types are estimated, including energy requirements and dimensions of key process components.

The economic prospects for laser enrichment technologies are analyzed. Some preliminary laser enrichment cost estimates are presented. It is shown that, for a range of plausible scenarios of U.S. nuclear power development, the uranium savings achievable with low tails-assay laser enrichment plants in combination with other resource conservation measures can substantially extend the life of the present once-through fuel cycle in light water power plants, and consequently delay the need for the large-scale introduction of spent fuel reprocessing and breeder reactors. With or without the breeder, laser enrichment techniques can play an important role in easing the pressure on U.S. and world uranium supplies over the next few decades.

The proliferation risks posed by laser enrichment technologies are assessed for a variety of scenarios. The available evidence

suggests that the task of converting a commercial laser enrichment plant of either the atomic or molecular kind to the production of highly enriched uranium will be more difficult technically than the equivalent conversion of a commercial gas centrifuge plant. Moreover, to any nation contemplating the construction of facilities solely for the purposes of producing nuclear weapons material, a dedicated laser enrichment facility of either kind will be less attractive than any of several alternatives presently available, for at least the near-term future. The same conclusion will almost certainly hold in the long run for AVLIS plants. In the MLIS case, however, future advances in laser technology or the development of new uranium material/laser system combinations could substantially increase the relative attractiveness of MLIS facilities to potential proliferators.

Integration of the various elements of the present assessment leads to the following policy-oriented conclusions:

1. Existing LIS development programs in the United States should be pursued vigorously. U.S. non-proliferation goals would not now be served by a decision to halt development. The successful commercialization of LIS technologies could result in significant new benefits for U.S. non-proliferation policies. In addition, there are presently strong economic incentives for proceeding with development.
2. There is a growing possibility of direct economic competition between the later modules of the Portsmouth gas centrifuge enrichment plant, which is currently intended to provide the next increment of commercial enrichment capacity in the U.S., and the advanced enrichment technologies now under development. The government's advanced isotope separation (AIS) program should be reoriented to reflect this possibility. In general, AIS program planning should be more closely integrated with other aspects of U.S. enrichment policy. A premature commitment to the Portsmouth centrifuge plant should be avoided.
3. Private ownership of laser enrichment technology and facilities is not fundamentally incompatible with U.S. national security and non-proliferation policy goals.

Thesis Supervisor: David J. Rose,
Professor of Nuclear Engineering

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CHAPTER I

INTRODUCTION

A little under ten years ago, groups of scientists in the United States and overseas began to investigate a new method for the separation of isotopes of uranium. The method was based on a phenomenon well-known to scientists: different isotopes of the same element absorb light at slightly different frequencies. The same is true for molecules containing different isotopic species. By irradiating an isotopic mixture with light of a frequency chosen to coincide with an absorption frequency of one of the isotopes but not the others, internal energy levels of the desired isotope are selectively excited. Through further manipulations, the excited species may then be made to enter readily into chemical reactions, or to respond readily to physical stimuli, while the unexcited species remains comparatively inert. The light effectively magnifies minute differences between the photoabsorption properties of different isotopes into much more dramatic differences in physical or chemical behavior, thus allowing subsequent macroscopic isotope separations.

The possibility that isotope separation could be achieved by such 'photophysical' or 'photochemical' means was recognized many years ago, and from the 1930s on such separations were routinely performed in laboratories for several isotopic species. It was not, however, until the invention of the laser, some twenty years ago, that the industrial application of this technique began to show promise. Because of their ability to provide very high intensity, short bursts of highly monochromatic light, whose frequen-

cy can be tuned with great accuracy over a wide range, lasers are particularly well suited to function as the light source for photophysical and photochemical isotope separation processes.

Today, by far the largest demand for isotope separation services is generated in the nuclear energy sector, where for several applications, peaceful and military, it is necessary to increase the concentration of the fissile isotope U-235 in uranium isotopic mixtures. In naturally occurring uranium, the concentration, or 'assay', of U-235 is about 0.7%. The remainder consists of the non-fissile isotope U-238.

In the United States, an experimental program to investigate laser isotope separation methods for uranium enrichment was launched jointly by Exxon Nuclear Company and the Avco Corporation in 1971. Shortly afterwards, similar work began at two of the government's national laboratories, Los Alamos Scientific Laboratory (LASL), New Mexico, and Lawrence Livermore Laboratory, California. In both the Exxon-Avco program, which was conducted under the auspices of a joint subsidiary, Jersey Nuclear Avco Isotopes, Inc. (JNAI), and the program at Livermore, the emphasis was on the selective laser excitation of atomic uranium vapour. At Los Alamos, the work concentrated on laser isotope separation of uranium-bearing molecules, especially uranium hexafluoride, UF_6 .

Both the atomic and molecular laser isotope separation (LIS) schemes offer one very important advantage over most other uranium isotope separation methods now known -- the possibility of a high degree of enrichment in a single step.

Since the end of World War II, the gaseous diffusion process has been the dominant method for uranium enrichment. This process is based

on the preferential passage through a porous membrane of $U^{235}F_6$ molecules, which are slightly lighter and more mobile than molecules of $U^{238}F_6$. The mass difference between the two molecular species is less than 1%, however, and the degree of separation that can be obtained in a single pass through the membrane is very small; the U-235 assay is increased by a factor of about 1.0043. Consequently, many hundreds of steps, or 'stages,' must be combined in series in order to achieve a significant degree of enrichment in U-235. The gaseous diffusion process is very energy intensive per unit of output. Moreover, the economies of scale are such that very large facilities requiring enormous amounts of electric power are necessary if enriched uranium is to be produced by this means on a commercial basis.

In recent years, the gas centrifuge process has emerged as an economically attractive alternative to gaseous diffusion. In this case, separation is achieved by the creation of very large pseudo-gravitational fields in a rotor spinning at ultrahigh speeds. The rotor is filled with uranium hexafluoride gas, and the heavier $U^{238}F_6$ molecules drift preferentially to the walls of the centrifuge. The gas centrifuge process is much less energy-intensive than gaseous diffusion, requiring only about one twentieth of the electric power per unit of output. Furthermore, gas centrifuge facilities can be built economically in smaller sizes. Nevertheless, each centrifuge machine is limited to a very low throughput, and commercial centrifuge enrichment plants contain many thousands of interconnected machines.

If, as is expected, laser-based processes are able to produce a high degree of separation in a single step, LIS plants may turn out to be smaller, cheaper, and generally more convenient for uranium enrichment than

either the gaseous diffusion or the gas centrifuge process.

* * *

Enrichment technology has played a pivotal role in the development of nuclear energy for both peaceful and military purposes since the last years of the second world war. Enrichment plants provided the fissile material for the first nuclear bomb, and have since figured prominently in the nuclear weapons programs of each of the five 'official' nuclear powers. At the same time, these facilities have also supplied large quantities of enriched uranium fuel, the sine qua non of the rise to dominance throughout much of the world's nuclear power industry of the light water reactor (LWR). LWRs cannot run on natural uranium, needing instead fuel enriched to 2 - 4% in the fissile isotope U^{235} ; bombs need uranium enriched to much higher levels, to 90% or more, but in principle the enrichment technology that is used to produce LWR fuel can also be used to make nuclear explosives. Enrichment plants thus demonstrate vividly the duality inherent in nuclear technology; in the anodyne terminology of the day, they are deemed 'sensitive' facilities.

For many years, the evolution of the international uranium industry was largely determined by two factors: the cumbersome, highly capital and energy intensive character of gaseous diffusion technology, and the presence in the United States of three very large gaseous diffusion plants whose military duties had declined to relatively low levels by the early 1960s. The latter factor enabled the United States Government to offer low enriched uranium supplies for nuclear power reactors in plentiful quantities and at low prices, thus reducing the incentives for other countries to acquire their own enrichment facilities; and the former provided strong disincentives for such acquisitions.

These two factors allowed the United States to retain a virtual monopoly in enrichment supplies until fairly recently; the only other enrichment plants to enter service during the first twenty-five post-war years were those constructed by the Soviet Union, France, China and the United Kingdom in connection with their military programs.

More recently, new enrichment suppliers have begun to emerge. The United States monopoly has been broken, and enrichment supplies can now be ordered from two multinational European concerns and the USSR, as well as the U.S. Other prospective suppliers plan to enter the market during the next decade. In parallel with these developments, and contributing to them in part, gas centrifuge technology is seeing commercial service for the first time. The gas centrifuge process, as already noted, is less energy-intensive and is economical in smaller sizes than gaseous diffusion. The unit costs of enrichment from gaseous diffusion plants decrease rapidly with plant scale, and the smallest feasible commercial plant would be large enough to meet the fuel needs of about 50 1000 Megawatt (MWe) light water power reactors. Such a plant would consume about 2500 MWe of power. In contrast, the capacity of commercial gas centrifuge plants need only be a fifth as large, and each such plant would consume only about 25 MWe of power. These characteristics make the gas centrifuge process well-suited to the trend towards greater diversification in the international enrichment supply industry.

But while these economic and technological trends have alleviated international concerns over the risks of relying on a single source of supply -- the United States -- for a commodity as vital as enrichment services, they have also heightened fears that enrichment technology may aid

the spread of nuclear weapons to additional countries.

LIS processes demonstrate, in microcosm, the tensions underlying the enrichment sector as a whole. Economically, laser processes show several potential advantages over existing enrichment methods. Energy consumption is likely to be low, much lower than for gaseous diffusion, and perhaps as low as, or even lower than for the gas centrifuge process. Scale economies are presently unclear, but the optimum plant size for one or other of the processes may be small enough for plants scaled to meet the enrichment needs of even a relatively small national LWR programme to be economic. Laser enrichment proponents also claim significant capital cost advantages over both centrifuge and gaseous diffusion processes. Finally, laser processes offer the prospect of more efficient utilization of natural uranium resources. Gaseous diffusion enrichment plants typically extract about 75% of the fissible isotope U^{235} from natural uranium; the remainder is discharged as waste, or 'tails,' since the effort required to increase the extraction efficiency in such plants is economically unjustifiable. Laser processes may, however, be capable of recovering a higher fraction of the U^{235} economically, thus increasing the amount of energy that can be generated by LWRs from a fixed stock of natural uranium.

On the other hand, the development of laser processes, if successful, might add to the existing array of routes to the acquisition of nuclear weapons material. Moreover, fears have been expressed that laser enrichment methods may eventually provide a route that is cheaper, technologically easier to follow, and easier to conceal than any other now known.

The Need for an Assessment

Despite the significance of these issues, remarkably few independent

assessments of laser enrichment technologies have been published during the first decade of their development. Of those that have appeared, perhaps the best-known are journal articles by Krass¹ and Casper,² both of which were published in 1977. More recently, Exxon Nuclear Company issued a report written by a group of outside experts that had been asked by the firm to assess the proliferation risks presented by the JNAI LIS process.³

The paucity of assessments is certainly not attributable to any lack of interest in the subject. References to laser enrichment technologies have been common in discussions of various aspects of nuclear policy since the early 1970s. Some have dwelt on the possibility that existing or planned enrichment facilities utilizing conventional technologies may soon become economically obsolete if recent advances in LIS technologies are continued. Others have been concerned with the security risks arising from the new developments; the fear that laser isotope separation will fundamentally alter the existing spectrum of proliferation risks has often been voiced. Yet there has been no sustained, systematic, public assessment of these technologies.

The most plausible explanation for this situation is the inaccessibility of information: whether for security or proprietary reasons, LIS development programs have been surrounded by secrecy effectively since their inception. Government assessments which have been undertaken remain classified, and those with access to the results usually confine themselves in public utterances to the vaguest of generalizations. For others without such access, any independent studies must struggle with a discouragingly high degree of uncertainty.

Secrecy notwithstanding, it is argued here that there is a clear need for a careful analysis of the issues raised by the continued development

of laser enrichment technologies, with as much of the analysis as possible conducted in the public domain. In a short time, decisions will be taken which will have profound consequences for the future course of this technological innovation. In the United States, important investment decisions are shortly to be taken in both the private and public sectors. Exxon Nuclear, which, together with Avco, has already invested \$50 million in the development of the JNAI process, is about to decide whether to commit a further \$50 million for the construction and operation of an experimental test facility. For its part, the government currently plans to decide in two years which of the two LIS processes under development at Los Alamos and Livermore and a third, laserless, advanced isotope separation process being developed under contract to DOE by TRW, Inc. will be selected for further development and possible commercialization.* By then, well over \$300 million will have been spent on the three processes. Meanwhile, other enrichment policy decisions are being taken by the government which will heavily influence the development timetable for all of the advanced isotope separation technologies.

Overseas, laser enrichment process development is moving ahead independently in several other countries, including France, West Germany, the Soviet Union, and the United Kingdom.

As will be shown subsequently, these decisions and developments may have far-reaching consequences, from military security to the balance of payments, from the price of electricity in Chicago to the cost of bombs in Brazil. In the United States, the pending decisions are on a sufficiently small scale in terms of their immediate impact, budgetary or otherwise,

* The TRW process is briefly described in Appendix 1.1 at the end of the Chapter.

that they could be taken with a minimum of public debate. In the view of this author, that would be a mistake. The history of nuclear energy development in this country is replete with examples of costly decisions taken with the best of intentions but in closed fora. Sometimes the decisions have proved to be wrong, and in retrospect would have benefited materially from a more open debate at the time. In other cases, while the substantive issues themselves have not necessarily been misjudged, the process by which the decisions were reached has led to a wider lack of confidence in the outcome and distrust of its origins; both of these reactions have had crippling effects on later efforts to implement the decisions on a large scale, efforts which, in the United States, require broad political consensus as a precondition for success.

Laser enrichment technologies may see widespread application in the United States and elsewhere, or they may not. If large facilities are indeed to be constructed in the U.S., a public discussion of the merits and disadvantages of laser enrichment technologies will be necessary. It is not too early for that debate to begin.

To be sure, not all of the issues can be discussed openly without adverse effects on security. Nevertheless, what is needed at a minimum is a framework for discussion which will enable distinctions to be made between those assumptions and conclusions whose lack of public explanation masks underlying policy deficiencies and others which genuinely cannot be justified on security grounds.

The purpose of the present work is to contribute to the development of such a framework. A fundamental question raised in the study is whether, given current information restrictions, a comprehensive public assessment

of the policy issues raised by the continued development of laser-based processes is possible. The following assessment, which has drawn exclusively on unclassified material, seeks to show that it is.

Nature of the Assessment

What kind of an assessment is needed, and how can it be carried out?

A few definitions of technology assessment provide a useful starting point for this discussion. According to one definition cited by the Congressional Office of Technology Assessment, technology assessment is defined as:

a generalized process for the generation of reliable, comprehensive information about the chain of technical, social, economic, environmental, and political consequences of the substantial use of technology to enable its effective social management by decisionmakers.⁴

The Committee on Science and Public Policy of the National Academy of Sciences has suggested that technology assessment:

may acceptably describe what occurs when the likely consequences of a technological development are explored and evaluated. The objective is to improve the quality of such efforts at exploration and evaluation and thereby to foster a more constructive evolution of our technological order.⁵

And the Science Policy Research Division of the Congressional Research Service has stated that:

[Technology] assessment includes forecasting and prediction, retroactive evaluation, and current monitoring and analysis. Measurements involve noneconomic, subjective values as well as direct, tangible quantifications.⁶

General prescriptions for technology assessment based on these and other definitions abound, but usually fail to convince, because no two technologies are identical either in themselves or in their implications; each problem tends to demand its own approach.⁷ The discussion here is there-

fore confined to a brief presentation of several methodological leitmotifs which characterize this particular study. In the next section, the organization of the remaining chapters is described.

The first priority is to establish a context for the assessment, and to make it explicit. As Henry Nau has observed in somewhat different circumstances:

Any empirical attempt to describe present events in international politics is linked with the normative desire to prescribe future events. Description is selective and what we describe depends on what we are interested in explaining. Furthermore, what we seek to explain suggests what we want to predict, and prediction is a means of influencing the future by affecting the conditions of present choices.

This linkage between description, explanation, prediction, and prescription places an obligation on every analyst to preface his investigation with a clarification of basic assumptions.⁸

Much the same reasoning applies to technology assessment. Here, the assessment is approached primarily within the context of U.S. policy, and from the perspective of U.S. policy-makers. This approach is justified on two separate grounds. First, the vast bulk of publicly available information on LIS technology describes the efforts that are underway in the United States, and even this is in short supply. Very little information on laser enrichment work in other countries is available, and what little has been accumulated is presented and analyzed here in terms of its impact on the foreign and domestic policies of the United States. To adopt any other perspective would be impractical. But in addition, given what appears to be the strong technological position held by the U.S. in the laser enrichment field, and its prominent role in the international enrichment industry more generally, the perspective chosen here is likely to be of interest not only in the U.S. but also internationally.

The perspective is also limited in another important respect: the

emphasis is on U.S. public policy, and on decision-making in the public sector. As noted previously, the JNAI group has been a pioneer in the development of laser enrichment processes, and Exxon corporate policy-makers face a difficult agenda of their own. But there is no attempt to assess the feasibility of the JNAI LIS process purely from the point of view of Exxon corporate strategy. The nature of the JNAI decision process is of interest here only insofar as it bears on public sector issues, such as the use of public funds, national security, foreign policy and national economic questions, and the public health and safety. In fact, should JNAI decide to build a production-scale laser enrichment plant, JNAI decision-making would then be linked formally to the public policy process in any case, since such a plant would have to be licensed by the Nuclear Regulatory Commission (NRC), and the NRC would have regulatory authority in at least some of the preceding areas of concern.

* * *

As the preceding definitions and the accompanying discussion clearly imply, technology assessment involves much more than just the assembly and presentation of relevant information. These tasks are always necessary, nevertheless, and are especially important for the present assessment, where reliable information is hard to find, and for which the limits of public knowledge are themselves so important to establish.

Additionally, of course, the information must also be analyzed in context, and over time. In the language of systems analysis, we seek to identify the 'perturbation' caused by the technological innovation. The 'system' is usually highly complicated, and in this case consists of an elaborate network of international political, economic, and military relationships superimposed on heterogeneous national circumstances. It is difficult

enough even to define the system, to understand the interactions between all of the various elements, and to maintain and apply that understanding throughout the analysis. The problem is made all the more difficult by the dynamic character of the system itself. The technological innovation of interest is not the only changing aspect; the lead-time required for the development and commercialization of laser enrichment technology is long enough for there to be significant change in most if not all other elements of the policy environment in the meantime.

This suggests two objectives for the assessment. First, not only must the potential characteristics of mature laser enrichment technologies be anticipated, but so too must broader economic, political and security trends. Second, the technological innovation must also be analyzed from a historical perspective. The course of an innovation is strongly influenced by the political, and institutional environment in which it takes shape, and an innovation may acquire momentum in a particular technological direction for reasons related less to its intrinsic scientific and technical 'logic' than to the nature of its institutional supporting structure. Thus the current state and direction of laser enrichment programs can only be fully understood in terms of the historical influences on their development. In turn, such an understanding is a necessary step in the planning of future strategies.

The need for a strong temporal dimension to the assessment is underscored by the probable gestation period for the laser technologies of twenty years or more, and the rapidity with which the immediate political and economic environment has evolved even during the last five years. During this latter period, the position of the U.S. as a virtual monopoly supplier of enrichment services to the rest of the world has evaporated;

an upsurge of concern over the proliferation risks of nuclear power growth has led, inter alia, to international consultations and controversies over ways to increase the security of world supplies of low-enriched uranium fuel, and to new U.S. legislation imposing nonproliferation-related conditions of an unprecedented stringency on exports of U.S.-enriched fuel; the prospects for private ownership of enrichment plants in the U.S. have swung from being generally favorable to their present, highly uncertain status; projections of enrichment demand for the remainder of the century have fallen sharply and fears of an enrichment 'gap' in the 1980s have yielded to firm expectations of a large supply surplus continuing throughout the decade; and, more generally, there has been a dramatic intensification of the political uncertainties now plaguing the nuclear power industry in the U.S. and many other countries.

All of these developments demonstrate not only the need for a dynamic analysis but also the inevitability of great uncertainty. Consequently, the assessment must also seek to identify the various sources of uncertainty explicitly, if possible to bound them, and to determine which of them may be reduced or removed, and at what cost.

* * *

Beyond analyzing the various consequences of LIS processes, there is also a need to draw the various strands together, to simulate in advance (and in part) the political and administrative processes of formulating, evaluating, and choosing the policy options that will determine the course of the innovation. The most convenient and also the most useful way to accomplish this synthesis is to construct it around concrete policy questions, real or postulated.

Some may argue that this is an unwarranted venture beyond the stated

objective of contributing to the development of a framework for a public policy debate, that it strays too far from the definitions cited previously, and clearly oversteps the fuzzy but important line between technology assessment and policy analysis on the one hand and policy prescription on the other. Yet such a step is necessary in order to breathe life into the various policy conflicts and trade-offs identified in the analysis. To be sure, the questions of technological choice can never be resolved by pure reason alone; intuitive judgements and political and moral value choices will always be involved. And in practice the different perspectives and motivations of the relevant actors will combine in the future in ways which it is neither possible nor particularly desirable to represent in assessments of this kind. But by synthesizing the analytical results in the form of answers to specific policy questions, the comprehensibility of the analysis is increased; and provided that the judgements and value preferences are made explicit, the integrity of the analysis need not be compromised, even if the policy conclusions themselves are found elsewhere to be unacceptable.

Organization of the Study

The assessment is divided into six chapters. In Chapter 2, the scientific literature on laser enrichment methods is reviewed, with the objective of providing a useful technical foundation for the subsequent economic and public policy analyses. A feature of this chapter is the attempt to develop approximate design specifications for commercial-scale laser enrichment plants.

Chapter 3 analyzes the economic prospects for laser enrichment technologies. First, recent laser enrichment cost estimates are presented; the potential long-term economic benefits of laser enrichment are then

projected for various scenarios of nuclear power development; and finally some of the external economic factors which would be expected to influence the rate of LIS commercialization are explored.

Chapter 4 assesses the proliferation risks associated with laser enrichment technologies. The chapter is divided into two parts. The first consists of a technical assessment of the proliferation 'resistance' of LIS processes compared with existing technologies. The second part examines the incentives, disincentives and constraints which have influenced the spread of enrichment technology and the evolution of the international enrichment industry in the past; in addition, the effectiveness of present policies and controls against the proliferation risks posed by laser enrichment processes is analyzed.

Chapter 5 provides a historical perspective on the development of LIS technologies in the U.S. In particular, it traces the origins and consequences of some of the principal political and institutional influences on the course of LIS development until now.

In Chapter 6, the results of the previous chapters are synthesized around three policy questions: Should LIS development programs in the U.S. be continued? If so, under what schedule, and with what objectives? And what are the appropriate roles for the private sector and the government in these developments?

In Chapter 7, general conclusions of two kinds are drawn from the preceding assessment. First, some aspects of the future U.S. role in the international nuclear order are reviewed; and in the second part some general observations on the process of technology assessment are presented.

Notes to Chapter 1

1. Allan S. Krass, "Laser Enrichment of Uranium: the Proliferation Connection", Science, 196, 13 May 1977, p. 723
2. Barry M. Casper, "Laser Enrichment: a New Path to Proliferation?" Bulletin of the Atomic Scientists, January 1977, 28-41
3. Laser Isotope Separation: Proliferation Risks and Benefits, Report of the Laser Enrichment Review Panel, (Chairman, T. Keith Glennan) to Jersey Nuclear Avco Isotopes, Inc., February 27, 1979 (2 vols.)
4. "Science Policy: A Working Glossary", prepared for the Subcommittee on Science and Astronautics, House of Representatives, U.S. Congress, July 1973
5. National Academy of Sciences, Committee on Science and Public Policy, Technology: Processes of Assessment and Choice, Report to the Committee on Science and Astronautics, House of Representatives, U.S. Congress, 3, (Washington, D.C., Government Printing Office, 1969)
6. U.S. Congress, House, Technical Information for Congress, Report to the Subcommittee on Science, Research and Development, Committee on Science and Astronautics, prepared by the Science Policy Research Division, Congressional Research Service, 91st Cong., 1st sess. (April 25, 1969), 481
7. For a discussion of the problems of searching for a general method of technology assessment, see: J. David Roessner and Jeffrey Frey,

"Methodology for Technology Assessment", Technological Forecasting and Social Change, 6, 163-169, (1974)

8. Henry Nau, National Politics and International Technology, 15, (Baltimore: Johns Hopkins University Press, 1974)

Appendix 1.1: The Plasma Separation Process for Uranium Enrichment

The United States government is presently supporting the parallel development of three advanced enrichment technologies for possible future commercial application: the molecular and atomic laser isotope separation processes, for which development work is centered at Los Alamos Scientific Laboratory and Lawrence Livermore Laboratory respectively; and a 'laserless' process being developed by TRW, Inc. under contract to the U.S. Department of Energy. Current DOE policy is to bring all three technologies to a roughly equivalent stage of development, and then to choose one of the three for commercial demonstration.

The scope of this study is confined to an assessment of the laser enrichment technologies. Nevertheless, the TRW process will receive frequent mention in subsequent chapters, both directly and indirectly (through general references to DOE's advanced enrichment program), and a brief technical statement of the process principles is appropriate at this stage.

Plasma Separation Process Principles

The process is based on the difference in ion cyclotron frequency exhibited by ions of different isotopic species. A radio-frequency (RF) electric field at the ion cyclotron frequency of one of the isotopic species is applied to a stable uranium plasma immersed in a uniform magnetic field. The ions of the desired species are resonantly excited, and experience an increase in the cyclotron radius. Separation is accomplished by the preferential condensation of the larger cyclotron radius ions on the surfaces of a collector. The degree of separation

achievable is limited by several factors, including the effect of collisions between resonant and non-resonant ions. Nevertheless, there are indications that it will be possible to enrich natural uranium to an assay of 3% U-235 in a single step by this method.¹

A conceptual schematic diagram of the process is shown in Figure 1.1.1.

Note

1. Non-Proliferation Alternatives Systems Assessment Program, Final draft report (August 1979), Table 4.3.1-2

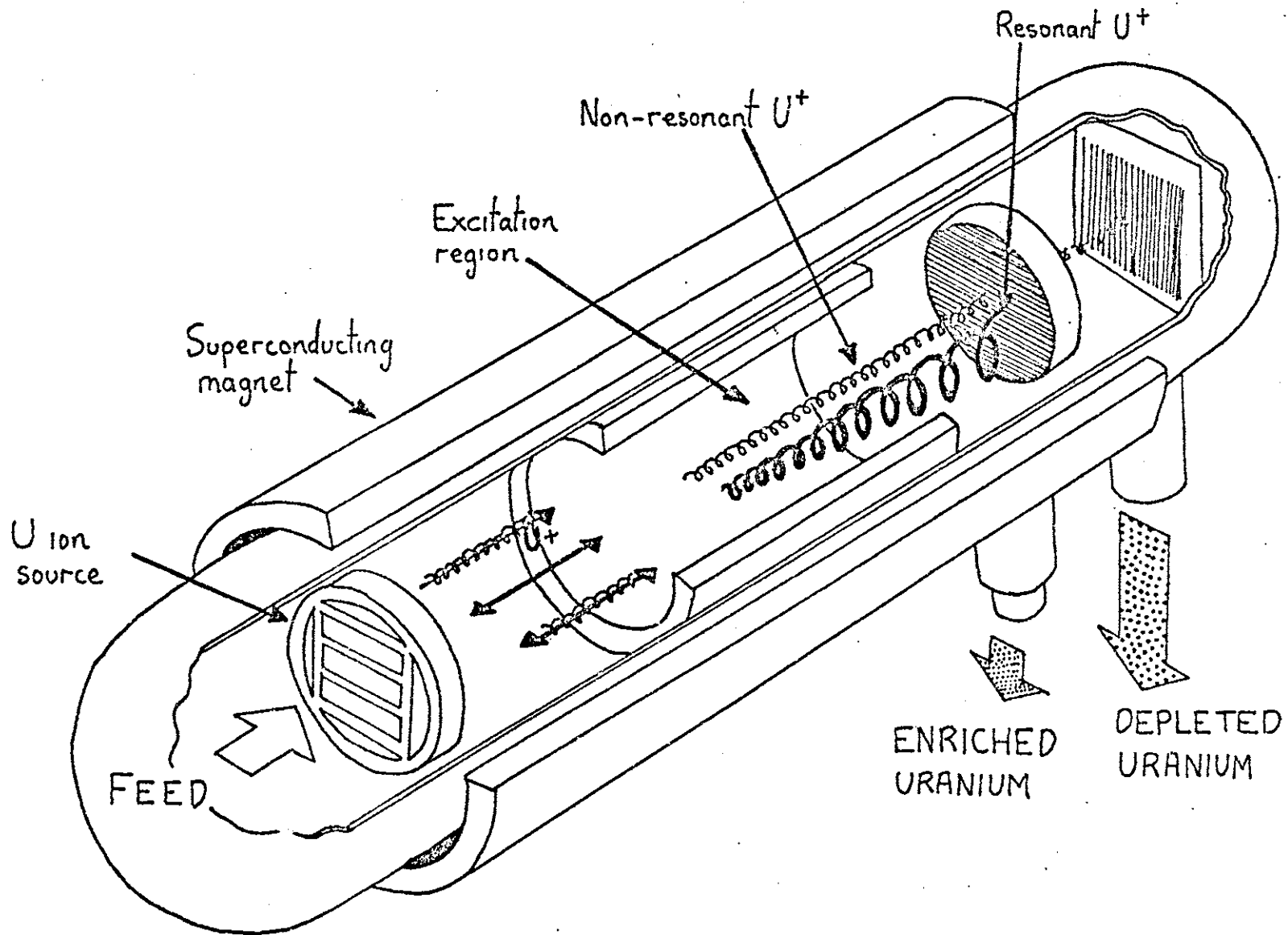


FIG. 1.1.1: PLASMA SEPARATION PROCESS SCHEMATIC DIAGRAM

CHAPTER 2

THE TECHNOLOGY OF LASER ISOTOPE SEPARATION

2.1 Introduction: General Principles of Laser Isotope Separation

The purpose of this chapter is to review the current technological status of laser isotope separation methods applied to uranium enrichment. The discussion is designed to provide the reader with a qualitative understanding of the technology, and of the technological problems associated with the development of commercial laser enrichment processes.

The review presented here provides a necessary technical foundation for the economic and public policy analyses undertaken in subsequent chapters. In general, the treatment is descriptive in character. Where possible, however, quantitative demonstrations are used to support the discussion.

In the introductory section, some general technical criteria for laser isotope separation processes are discussed, and a taxonomy of LIS schemes is presented. The second part of the chapter reviews enrichment methods based on selective laser excitation of atomic uranium vapour. Molecular LIS methods are described in the third part. In both of these sections, some potential design problems and characteristics of commercial-scale LIS plants are explored. Finally, to set the preceding discussion in perspective, some other actual or potential applications of laser photochemistry are mentioned briefly.

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Historical context:

In 1920, 6 years after the discovery of isotopes, the possibility of isotope separation by photochemical methods was first recognized.¹ Atoms and molecules absorb light only at certain, well-defined wavelengths specific to each atomic or molecular species. Absorption at a particular wavelength leads to a well-defined change in the internal state of the molecular or atomic system, i.e., the system is excited to higher vibrational, rotational, or electronic energy levels. Different isotopes of the same element absorb light at slightly different wavelengths. This "isotope shift" effect arises from the slight differences in the nuclear properties of the isotopes, including mass, shape, size, spin and nuclear magnetic or electric moments. By finely tuning the irradiating light to coincide exactly with an absorption wavelength of one of the isotopic species, thus causing it, but not the others, to undergo a change of state, the excited species may enter preferentially into chemical reactions, or respond preferentially to physical stimuli. Thus, these minute differences between the light absorption properties of the isotopic species can be greatly magnified, and macroscopic isotope separation can then be achieved.

The first successful experiment to separate isotopes photochemically was carried out in 1932, when molecules containing chlorine-35 were preferentially excited with light from an aluminium spark.² Since then, laboratory-scale photochemical separations of several other isotopes, including mercury, carbon, oxygen and hydrogen, using conventional light sources have been reported. Under the auspices of the Manhattan District during the 1940s, the photochemical separation of uranium isotopes was studied, but it was found that such methods could not compete with the gaseous diffusion process.³

In principle, the photochemical technique offered a major advantage over most other isotope separation methods - the possibility of a high degree of enrichment in a single step. It was not until the invention of the laser some twenty years ago, however, that the industrial application of this technique began to show promise.

Lasers show several advantages over conventional light sources for the purpose of isotope separation:

- (i) laser light is tunable over a wide range of frequencies, increasing the probability that the source frequency can be made to coincide with an absorption resonance frequency in the desired isotopic species;
- (ii) laser light is very highly monochromatic, facilitating the selectivity requirement that the bandwidth of the exciting source is narrower than the isotope shift;
- (iii) the very high intensity of laser light within these narrow bandwidths permits large process throughputs;
- (iv) the ability to generate laser radiation in the form of pulses, whose duration can be much shorter than the lifetime of the excited state, increases the efficiency of practical applications, wherein the excited atoms must be exposed to a second (and sometimes a third) irradiation before they decay.
- (v) the high collimation achievable with laser radiation permits long optical paths in reaction cells, increasing process throughput.

These same characteristics make lasers extremely attractive light sources for many other applications in photochemistry, and while the principal subject of this chapter is laser isotope separation, it should

be remembered that LIS is only one part of the much broader field of laser-induced and laser-enhanced chemistry. Some of these other applications are briefly reviewed in the last part of the chapter.

The potential of the laser in commercial isotope separation was recognized soon after its invention. As far back as 1963, the first known patent application for uranium laser isotope separation was filed in France.⁴ In the years since then, many applications of LIS have been proposed, including the separation of isotopes of nitrogen, sulfur, and carbon, which may be useful as non-radioactive traces in agriculture, environmental protection and production control.

Taxonomy of LIS methods

There are many possible ways to achieve isotope separation by the selective excitation of atoms and molecules. Letokhov and Moore have presented a useful classification scheme for these methods.⁵ The scheme is shown in Figures 2.1.a and 2.1.b.

Atomic Methods:

The atomic LIS classification scheme (Figure 2.1.a) shows that isotope separation may be achieved either by a one-step (i.e. one-photon) photochemical process or by a two-step (or multi-step) photophysical process. In the latter, atoms of the desired isotope are selectively excited to an intermediate electronic energy level. Then, through the subsequent absorption of one or more photons of the same or different wavelengths, the selectively excited atoms are further excited and ultimately ionized. The ions of the desired isotope are then separated from the unexcited neutral atoms of the unwanted species by the application of electric and/or magnetic fields.

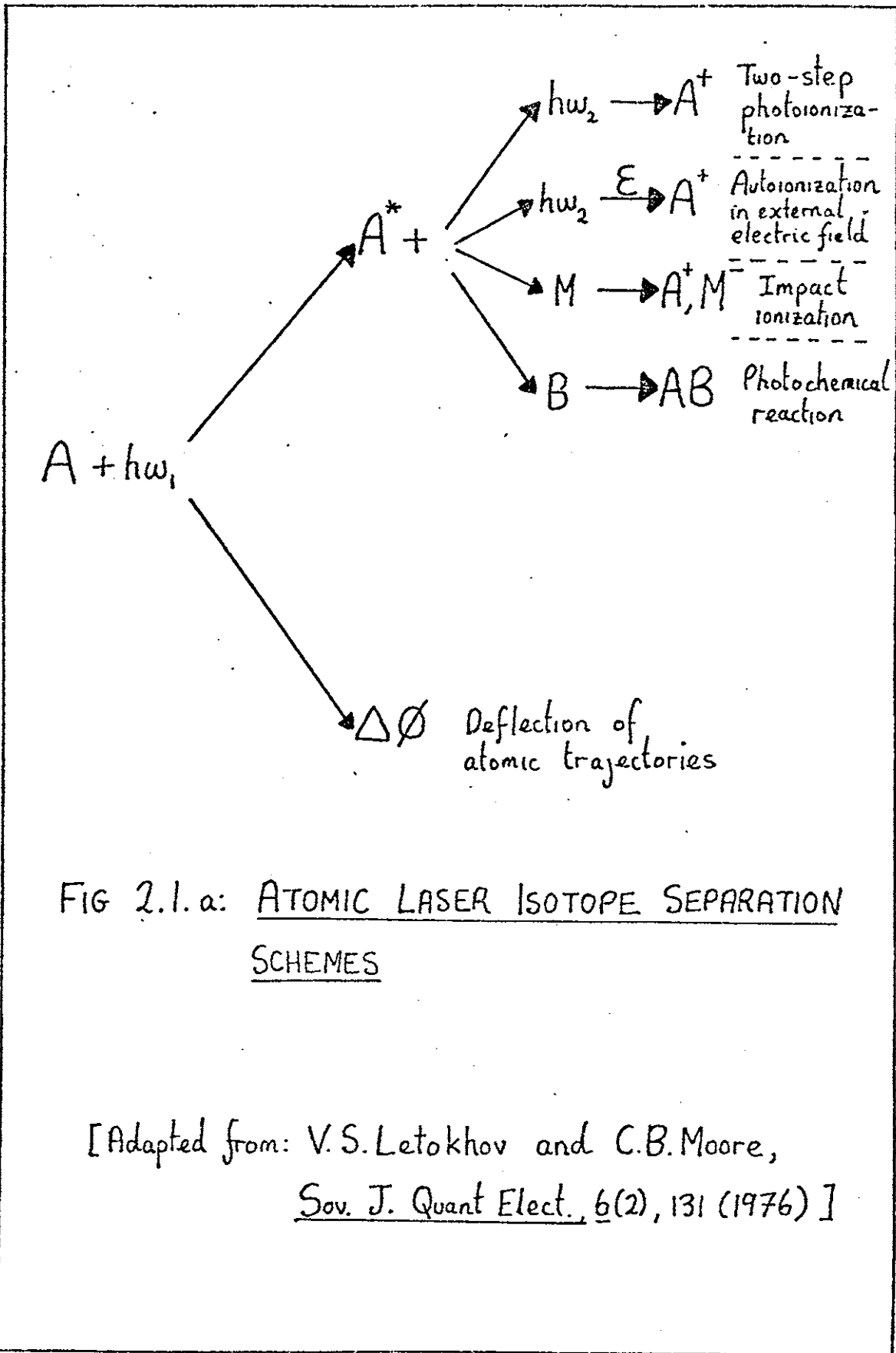


FIG 2.1. a: ATOMIC LASER ISOTOPE SEPARATION
SCHEMES

[Adapted from: V.S. Letokhov and C.B. Moore,
Sov. J. Quant Elect., 6(2), 131 (1976)]

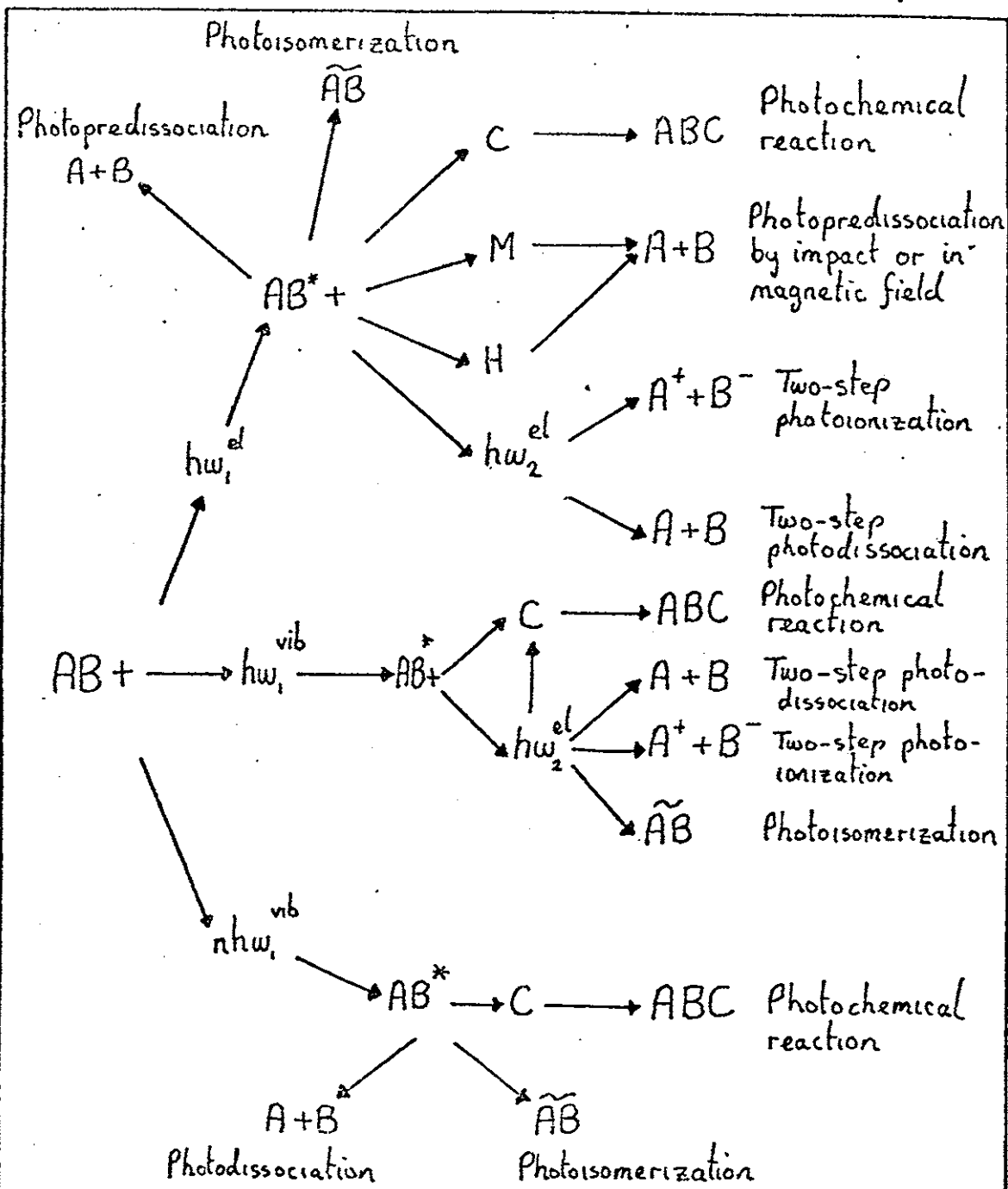


FIG. 2.1.b: MOLECULAR LASER ISOTOPE SEPARATION SCHEMES

[Adapted from: V.S. Letokhov and C.B. Moore (1976)]

When the process involves the absorption of two photons, it is commonly referred to as selective two-step (STS) photoionization.

Ionization may also occur when a selectively excited atom undergoes an internal rearrangement of excited electronic states with the release of enough energy to emit an electron - a process known as autoionization. Ionization of a highly excited state may also take place under the action of an external electric field or by collisions with electrophilic atoms or molecules.

In another photophysical scheme, based this time on the selective transfer of photon momentum, atoms of the desired isotope in a collimated beam of atomic vapour selectively absorb laser photons from a laser beam positioned perpendicular to the vapour flow, and are thus photodeflected in the direction of the light propagation.

Molecular Methods:

As shown in Figure 2.1.b laser isotope separation with molecules may be achieved by one or two-step photochemical reactions, and by selective two-step photoionization or photodissociation of the molecule. As the figure shows, the initial, selective absorption may involve the excitation of vibrational levels with infra-red photons, or of electronic levels with shorter wavelength radiation.

Figure 2.1.b also shows photopredissociation pathways, in which an internal rearrangement of selectively excited molecular electronic states leads to dissociation of the molecule. Photopredissociation is thus analogous to the autoionization process. Internal electronic rearrangement of excited molecules may also result not in dissociation but in a rearrangement of the atomic structure, a process known as photoisomerization. An additional pathway shown in Figure 2.1.b involves the

absorption of many infra-red laser photons by a single molecule, leading to selective photodissociation, photoionization or photochemical reaction.

General criteria for laser isotope separation

Six general criteria must be satisfied in any successful LIS scheme:

- (i) The initial energy level configuration (partition function) of the atomic or molecular material being irradiated must be such that selective excitation of the desired isotopic species is feasible. In general, this requires that the distribution of populated energy levels prior to irradiation is minimized.
(Ideally, all the atoms or molecules should be in a single state.)
- (ii) The absorption spectrum of the material must contain at least one well-defined shift in an absorption line due to isotopic effects, i.e., the transition linewidth must be narrow with respect to the isotope shift, and the absorption spectrum should not be so dense that the shifted line coincides with another absorption feature of the unwanted isotope.
- (iii) The exciting laser light source must be precisely tunable to the wavelength of the shifted line, be stable at that wavelength, and have a line width narrow compared to the magnitude of the isotopic shift effect.
- (iv) The laser must be efficient and powerful enough to permit a reasonably sized throughput without an excessive energy demand, and the yield of excited isotope per photon should be high.
- (v) There should be only modest energy and/or charge exchange losses between the excited component and the rest of the system.

- (vi) The physical or chemical separation process should be sufficiently selective and capable of producing a good yield of the desired isotope.

Uranium Isotope Separation

The potential application of LIS to have received most attention until now has been uranium enrichment. Several schemes have been suggested, and they may be divided, along the lines of Figure 2.1, into those using atomic uranium vapor, and those which feature uranium in molecular form (usually, but not always, as uranium hexafluoride).

All LIS schemes basically consist of four steps:

- (i) Preparation of feed for the irradiation system, with suitable geometric configuration, density, and energy level distribution.
- (ii) Laser irradiation system for selective excitation of the desired isotopic species.
- (iii) Physical or chemical separation method for collection and removal of both the isotopically enriched product and of the depleted tails.
- (iv) Final product preparation.

In the next two sections, some of the atomic and molecular methods that have been proposed until now are described in more detail. The descriptions outline the spectroscopic characteristics of these schemes and, where possible, address practical techniques for the four steps above.

2.2 Atomic LIS Methods for Uranium Enrichment

Out of the range of possible atomic LIS schemes in Fig. 2.1.a,

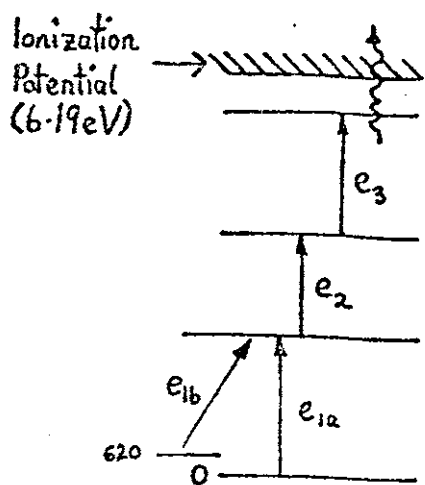
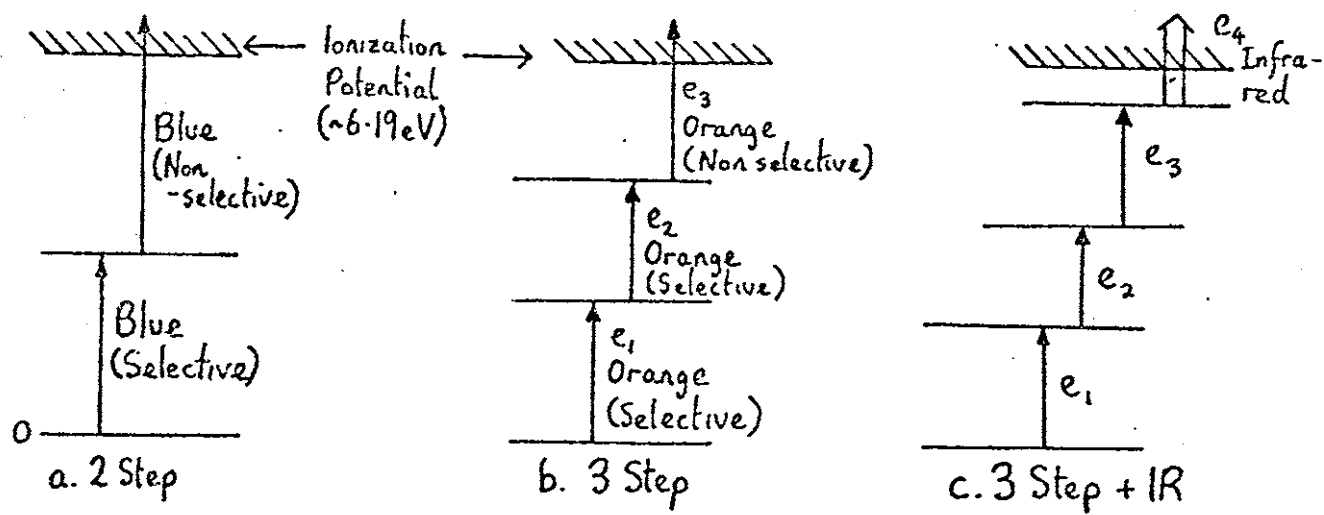
photoionization methods have received the most attention to date. Most of this section is therefore devoted to these methods; however, some alternative approaches are briefly described in the final paragraphs.

2.2.1 Laser photoionization methods: Spectroscopic considerations

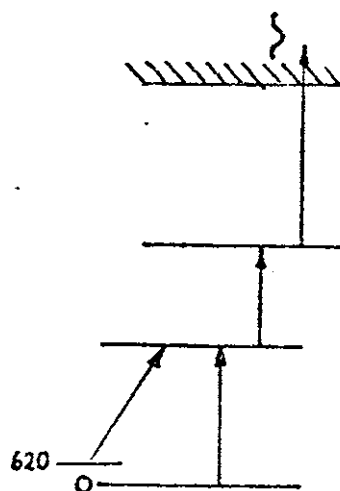
Several possible uranium photoionization schemes have been proposed. (See Figure 2.2.) In each case, the first excitation step is isotopically selective, since this minimizes the use of expensive laser photons. Selectivity may also be desirable in subsequent excitations.

The simplest scheme is selective two-step photoionization. Application of this method in at least two instances - at Avco-Everett Research Laboratory⁶ and at Lawrence Livermore Laboratory^{7,8} - has resulted in the successful separation of uranium isotopes on a laboratory scale.

Multi-step photoionization schemes have also been suggested. There are two main motivations for increasing the number of steps. First, three or more step processes permit the use of orange rather than blue dyes, and the former are more efficient in dye lasers.⁹ Second, the cross-sections for transitions to bound states are larger than for transitions to free states or states with relatively short lifetimes; for example, ionization cross-sections may be three orders of magnitude smaller than resonant excitation cross-sections.¹⁰ Under such conditions, it is more efficient to excite the selectively excited atom once or twice further with laser photons, this time to a bound state just below the ionization level, and then use another, less expensive energy source to complete the ionization. For instance, the final ionization step could be accomplished using efficient, high-power infrared CO₂ lasers, whose cost per photon is much lower than the cost of the visible or near ultra-



d. 3 Step + Electron Collisional Ionization



e. 3 Step Autoionization

FIG. 2.2: ALTERNATIVE TRANSITION SCHEMES FOR ATOMIC PHOTOIONIZATION

[Source: G.S. Janes et al, Am. Inst. Chem. Eng. Symposium Series 73(169), 1977, 62-68]

violet photons from tunable dye lasers. Alternatively, ionization can be achieved through the collisional effects of free electrons or other particles (such as other excited atoms or electrophilic molecules).

Another three-step process leads to a highly excited autoionization level in the atom, which subsequently ionizes. The autoionization level is a bound state, and therefore the cross-section for a transition to it from some intermediate excited state is larger than for direct ionization. The laser intensity requirement will thus be correspondingly reduced. (Autoionization can also be induced by the application of an external electric field.)¹¹

Figure 2.2 also shows that the first, selective transition may involve the coupling of photons to some of the thermally populated metastable states as well as the ground state. At 2500 K and thermal equilibrium, only 47% of uranium atoms are in the ground state; a further 28% are in the first excited state (620cm^{-1}), with the remainder in higher energy states.¹²

Selection criteria for photoionization schemes

Selective excitation is only possible if the line-width of the excited state is narrow with respect to the isotope shift, and if the uranium absorption spectrum in the region of the transition of interest is not such that the shifted line coincides with another absorption feature of the unwanted U-238.

Isotope shifts in the atomic uranium vapour absorption spectrum are typically in the range $0.05 - 0.1\overset{\circ}{\text{A}}$ (See Table 2.1.) Thus, to meet the linewidth criterion, the selective transition must be to a bound state, and selective photoionization will involve two or more

Table 2.1

Excited States of Atomic Uranium with Large Isotope Shifts¹

Energy (cm^{-1})	Exciting Wavelength in Air (10^{-10}m)	J	Isotope Shift ² (10^{-10}m)	Lifetime (Nanosec)
24 907	4013.8	6	-.055	
24 671	4052.1	6	-.061	
24 560	4070.4	7	-.076	
24 334	4108.4	7	-.059	
24 186	4133.5	7	-.064	
24 067	4154.0	7	-.072	
23 849	4191.9	7	-.052	
23 572	4241.1	6	-.076	60
23 543	4246.3	7	-.051	
23 534	4247.9	5	-.054	
23 487	4256.5	5	-.082	
23 433	4266.3	5	-.057	155
23 212	4306.8	5	-.080	170
22 862	4372.8	6	-.061	135
22 583	4426.9	6	-.055	130
22 056	4532.6	6	-.081	300
21 768	4592.6	7	-.073	
21 767	4592.9	6	-.090	
21 637	4620.4	5	-.075	

1. Source: G.S. Janes et al, IEEE J. Quant Electron., QE-12 (1976),
2, 111-120.

2. In other work, a typical isotope shift in the 6000\AA region has
been given as 5.7GHz (0.072\AA). (Source: "Laser Program Annual
Report - 1976", Lawrence Livermore Laboratory, UCRL-50021-76,
June 1977)

steps. Furthermore, the bound-state must be one in which line-broadening is minimized. The absorption spectrum of uranium-235 is characterized by a hyperfine structure, arising from its non-zero nuclear spin. Figure 2.3 shows the isotope shift effect and U-235 hyperfine structure for a particular transition. (U-238, with zero nuclear spin, shows no hyperfine structure.) Also shown is the Zeeman and Doppler line spreading for both U-238 and the hyperfine structure of U-235. The net effect of hyperfine Doppler and Zeeman spreading imposes a laser linewidth requirement of several gigahertz. Since lasers naturally tend to produce discrete frequencies associated with the nodes of the optical laser cavity, this requirement presents problems. In the words of Janes et al of the JNAI group, "...most of the problems associated with laser specifications are related not to the fact that the lasers must be tuned to the ultimate degree of finesse, but rather to the requirement that they contain a significant number of frequency components to excite all of the U-235 atoms."¹³

The lifetime of the excited state should be long relative to the duration of the laser pulse, so as to minimize losses due to decay or non-selective energy transfer reactions. Moreover, in general, the cross-sections should be as large as possible so as to minimize laser energy requirements. Finally, of course, the availability of tunable lasers with the appropriate frequency range, linewidth, intensity and pulse length, and with sufficient stability, will also influence the selection of the transition scheme. Table 2.1 shows that the laser involved in the selective transition must be more stable than one part in 10^5 .

The criteria which together determine the choice of the isotopic-

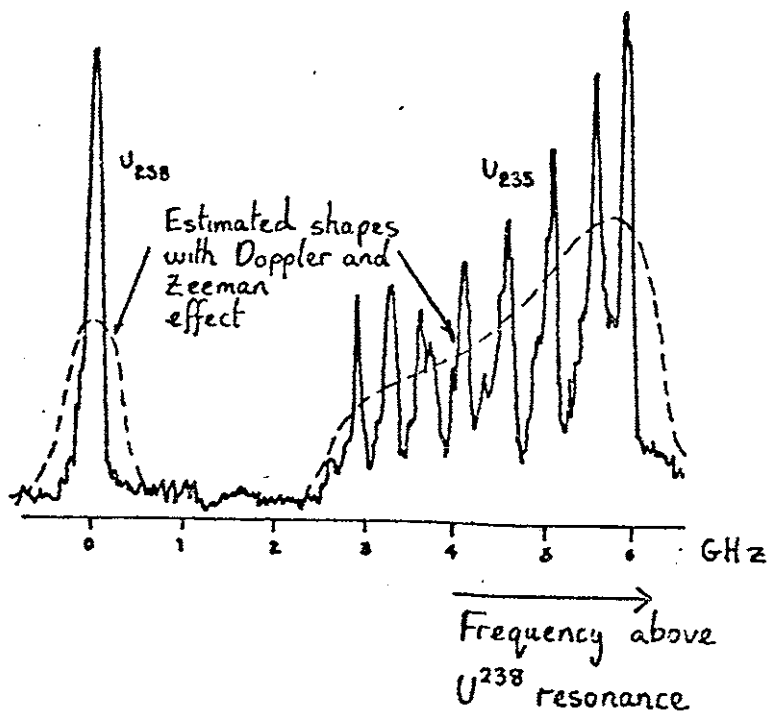


FIG. 2.3: ION YIELD FOR 3-COLOUR SELECTIVE PHOTO-
IONIZATION VERSUS SELECTIVE LASER
FREQUENCY (Feed enrichment \approx 85%)

[Source: G.S Janes et al, Am. Inst. Chem. Eng., Symposium
Series, 73 (169), 62-68, (1977)]

ally selective transition are summarized in Table 2.2. (Many of these criteria will clearly also apply in choosing the subsequent transitions.)

Table 2.2

Criteria Governing Choice of Isotopically Selective Transitions
in Photoionization Schemes

- Large isotope shift in spectral region of low energy level density.
 - Narrow linewidth of target excited state. (Hyperfine splitting, Doppler broadening, etc. minimized relative to isotope shift.)
 - Long lifetime of excited state compared with laser pulse duration.
 - Large cross-section for transition.
 - Availability of suitable lasers.
-

Spectroscopic Data Requirements

Knowledge of uranium vapour spectroscopy is essential to the success of atomic LIS schemes. The optical spectrum of uranium is one of the most complicated of all atomic spectra. Of the 92 atomic electrons, 86 occupy closed shells and are sufficiently closely bound not to be affected by optical excitation. The ground state configuration of the other six electrons is $5f^3 6d 7s^2$. An early paper in the field noted that already over 900 energy levels had been identified, 9000 transitions classified, and that there were possibly up to 300,000 visible lines.¹⁴

Most of the 900 identified energy levels were within 4eV of the ground state.¹⁵ Information on the higher levels, which is particularly

important for three and four step schemes, was in much shorter supply. However, major efforts have been devoted to the identification and spectroscopic assignment of energy levels. It is therefore certain that the data base has been improved considerably over the past few years, although the extent of progress is difficult to discern because spectroscopic information in this area is tightly held.

Other data which are important in the selection of suitable photoionization schemes are summarized in Table 2.3. Details of the techniques used to measure excited state lifetimes and photoionization cross-sections have been reported in the literature.^{16,17}

Table 2.3

Spectroscopic Data Requirements for Atomic LIS Schemes*

- Identification/assignment of energy levels (bound and non-bound).
- Excited state lifetimes and branching ratios.
- Excitations, ionization and autoionization cross-sections.
- Isotopic shifts and hyperfine splitting.
- Field-induced phenomena including effects on ionization and autoionization spectra.
- Electron-impact cross-sections (Rydberg levels)
- Excited state reaction and quenching cross-sections.
- Charge exchange and momentum transfer cross-sections.

* Source: Lawrence Livermore Laboratory, "Laser program annual report - 1976," Livermore, California, UCRL-50021-76, June 1977.

2.2.2. Design Features of an Atomic Uranium Photoionization Process

Major research and development efforts in atomic uranium LIS schemes have been undertaken in parallel by two U.S. organizations - Jersey Nuclear Avco Isotopes, Inc. (JNAI), a jointly held subsidiary of Exxon Nuclear Company and Avco, Inc., and Lawrence Livermore Laboratory in California. Neither group has published a great deal in the open literature concerning the likely characteristics of a commercial plant based on such processes. Nevertheless, on the basis of what has been published, together with certain supplementary assumptions, it is possible to speculate reasonably accurately on what a commercial plant might ultimately look like.

In the following paragraphs, some of the key design features of such a plant are either culled from the literature, or derived independently.

* * *

Figure 2.4 provides a visual guide for the subsequent discussion. The diagram indicates the likely general geometrical relationships between the laser system, irradiation chamber, atomic vapour source and collection system.

In this scheme, atomic uranium vapour flows upward from a furnace into a vacuum irradiation chamber, where it is excited and ionized by a laser beam made up of optically combined light pulses of two or more frequencies. The preferentially ionized uranium-235 is deflected from the vapour stream electromagnetically, in a direction orthogonal to the vapour flow and the laser beam, and is condensed on cooled collector plates.

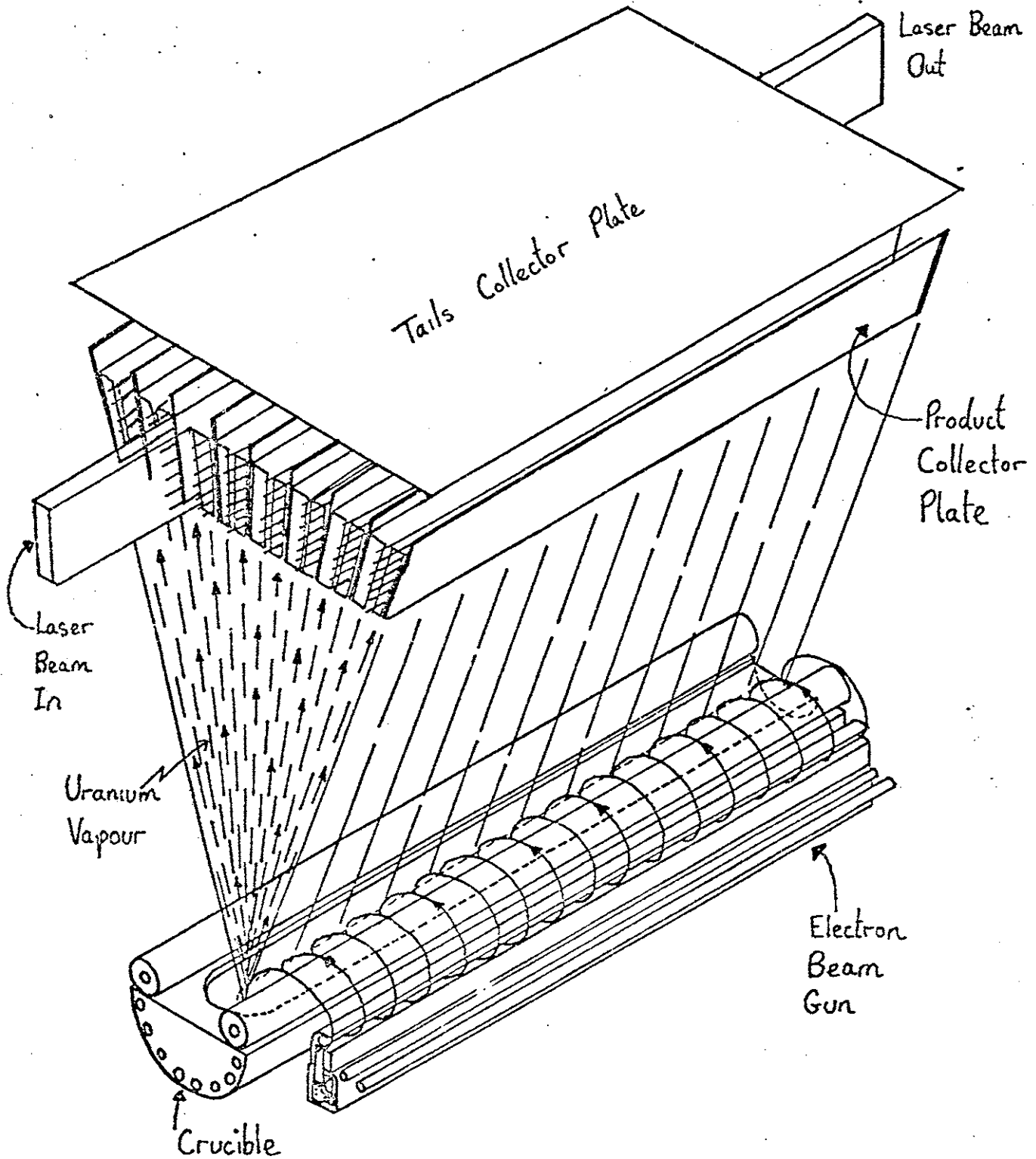


FIG. 2.4: ATOMIC VAPOUR LIS SCHEMATIC

In the next section, some general design objectives for an atomic LIS plant are introduced. Then, the design features of the irradiation chamber and laser system are discussed. Finally, the atomic vapour source and ion collection systems are described.

General Design Criteria

Terms useful for the following discussion are defined in Figure 2.5.

In a commercial LIS plant, process efficiency requirements demand that three criteria be satisfied.

- (1) The recovery of the desired U-235 isotope, r , must be maximized,

where:

$$r = \frac{Px_p}{Fx_f}$$

- (2) The separation factor, β , must be maximized (i.e., the dilution of the product with unwanted U-238 isotope must be minimized),

where:*

$$\beta = \frac{\frac{x_p}{1-x_p}}{\frac{x_f}{1-x_f}}$$

- (3) The photon utilization efficiency, ϕ , must be maximized where:

$$\phi_\nu = \frac{\text{number of photons of frequency } \nu \text{ usefully absorbed}}{\text{number of photons of frequency } \nu \text{ emitted by laser}}$$

* In practice, if β is large, there may also be a requirement to keep it below some maximum value, above which the enriched product material constitutes a security risk (i.e., it is sufficiently highly enriched for direct use in nuclear weapons). We discuss this point further in Chapter 4.

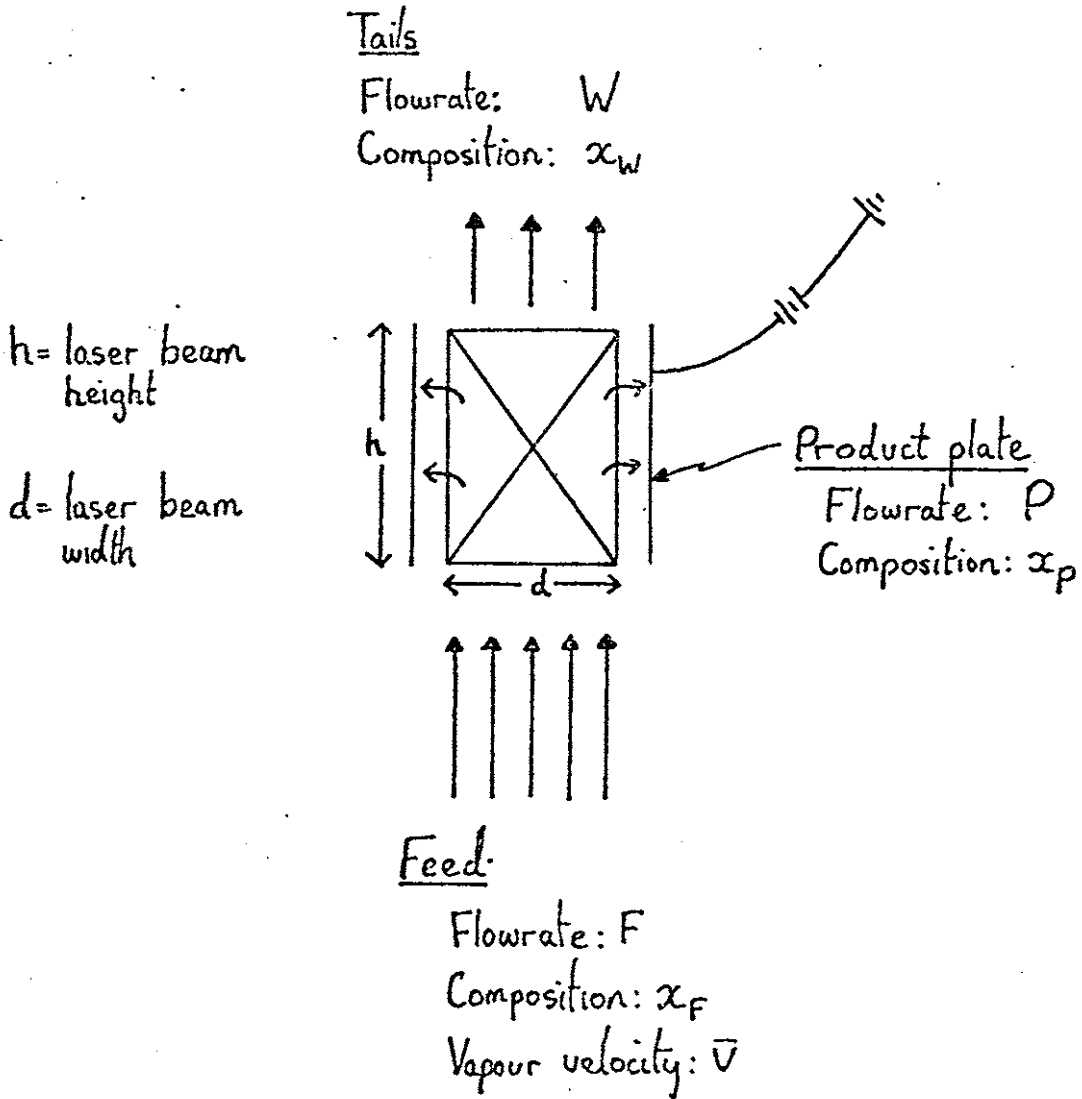


FIG. 2.5: AVLIS TERMINOLOGY

Thus, in a perfectly efficient STS photoionization system, all exciting photons would be absorbed by U-235 atoms in their ground state, all ionizing photons by excited U-235, and no photons would be absorbed in U-238. Furthermore, all U-235 atoms entering the irradiation chamber would be excited and subsequently ionized. The design task is to approach this situation as closely as possible.

Laser system requirements

The spectroscopic considerations which govern the selection of the laser "colour scheme" have been described in section 2.2.1. The efficiency criteria above determine the other characteristics of the laser system, as shown below:

(i) Laser pulse duration:

The excited atoms ultimately decay to lower energy levels or to the ground state, or alternatively transfer their internal energy non-selectively to other atoms in collisions. The efficiency of the process is therefore improved if the lasers are operated in repetitive high-powered pulses, with the duration of the laser pulses considerably shorter than the lifetime of the excited state. Furthermore, the excitation and ionization pulses should impinge on the vapour practically simultaneously. For instance, in the initial patent issued to JNAI, which suggests that the 5027.4\AA excitation level could be used as the intermediate level in a selective two-step photoionization scheme, the lifetime of this state is given as approximately 100 nanoseconds.¹⁸ The pulse length of the excitation and ionization lasers, according to the patent, should then be less than 55 nanoseconds. (The

lifetimes of some other candidate excited states are given in Table 2.1.)

(ii) Pulse repetition rate:

To maximize recovery, each U-235 atom in the vapour must "see" at least one set of exciting and ionizing photons. Thus, the required pulse repetition rate will be determined by the residence time of the vapour atoms in the irradiation volume, i.e.,

$$\text{rep. rate} \sim \frac{\bar{v}}{h}$$

where h = vertical dimension of laser beam

\bar{v} = mean atomic velocity perpendicular to the laser beam

For the atomic beam, \bar{v} is determined by the furnace emission characteristics (including the temperature, T), which in turn are influenced by the required atomic vapour density (ρ) in the irradiation volume. Typical values for ρ , T and \bar{v} have been given by Janes et al as 10^{13} cm^{-3} , 3000 K and 40,000 cm/sec.¹⁹ (We discuss the factors determining ρ shortly.) Assuming these values for the present, and assuming furthermore a typical beam dimension (h) of 1 cm, the required pulse repetition rate is 40 kilohertz.

(iii) Laser beam height (h) and laser repetition rate:

Repetition rates of 40kHz place stringent demands on laser technology. One way of reducing the required repetition rate while holding the recovery, r , constant is to increase the height of the irradiation volume (h). At the same time, however, as h is increased, the degree of collimation in the atomic beam is reduced, and non-selective thermal scattering of unionized atoms (mostly U-238) onto the collector plates reduces the separation

factor. A compromise value for h suggested by the JNAI group is 4cm^{20} which implies a pulse repetition rate of 10kHz .

Even these repetition rates represent a formidable target for laser technology. Pulsed tunable dye lasers would normally be suitable for the visible/near ultra-violet spectral range of interest in uranium photoionization schemes, but at such high repetition rates it becomes difficult to exchange the dye fast enough between pump pulses to remove the pump energy deposited in the dye and prevent thermal distortion of the beam. Thus, high repetition rates imply some limit on the pump energy deposited per pulse, and thus on the laser output power and the atomic vapour throughput rate.

The Livermore group has described 6kHz flowing dye systems (pumped by copper vapour lasers) with output powers of 0.5 watts, (equivalent to 0.1 millijoule/pulse).

On the other hand, JNAI has opted for much slower repetition rate dye lasers, in the 500 Hz range.²¹ In this case, some 20 lasers would be multiplexed to produce a 10kHz beam. Thus, for a 3-step, 4-colour scheme of the kind under consideration by JNAI, (see Fig. 2.2.e), the output of $\frac{10000}{500} \times 4 = 80$ lasers would be combined spatially and temporally to provide the irradiation source.

While the choice of a lower laser pulse rate permits a higher pump energy deposition per pulse, (in fact, unlike the Livermore scheme, JNAI uses flashtube pumping²²), and thus a higher overall output power, the slower, more energy intensive systems tend also to have longer pulse durations. In view of the requirement that

pulse length must be shorter than the intermediate excited state lifetime, the decision to opt for slower repetition rate lasers might therefore rule out some potentially attractive, high cross-section transition schemes, whose intermediate state lifetimes are short.

Irradiation chamber design

Whilst it is the atomic vapour flow velocity which primarily influences the laser repetition rate, a more fundamental process parameter is the vapour density. A key design objective is to maximize the vapour density, since this will maximize the plant throughput. Once the vapour density has been established, not only are the vapour flow velocity and pulse repetition rate determined, but so, too, is the minimum laser power requirement, as will be shown below.

The major limitations on vapour density arise from collisional processes which adversely affect both recovery of the desired isotope and selectivity (i.e. separation factor) during irradiation and subsequent collection. The key reactions include resonant charge exchange between selectively ionized U-235 atoms and neutral U-238 atoms; momentum exchange reactions between the same two species; excitation energy exchange reactions between U-235 atoms in intermediate energy states and unexcited U-238 atoms; and collective plasma phenomena.²³

The resonant charge exchange reaction cross-section has been reported to be in the range 10^{-14} - 10^{-15} cm².²⁴ Assuming that charge exchange is the dominant cause of recovery losses, it is easy to estimate the maximum allowable vapour density.

Consider a charge exchange cross-section, σ_{ce} , of 10^{-14}cm^2 . The mean free path for a uranium-235 ion is given by:

$$\lambda_{\text{mfp}} = \frac{1}{\rho \sigma_{ce}}$$

where ρ is the vapour density of all uranium atoms. In order to retain selectivity, λ_{mfp} must be significantly greater than the distance that must be travelled by the uranium-235 ion before leaving the atomic beam. The atomic beam width is, typically, on the order of 1 cm^{25} (a typical laser beam diameter). Thus, if the ions are to have, on average, a 90% chance of leaving the atomic beam without undergoing a charge exchange reaction, λ_{mfp} should equal 10 cm, and the vapour density should therefore not exceed $10^{13}/\text{cm}^3$.

In practice, a number of techniques are available for increasing the vapour density, some of which will be considered in the subsequent section on collector design, and a realistic upper limit might be as high as $10^{14}/\text{cm}^3$.

For a given process density, the maximum possible length of the irradiation chamber (and thus the maximum vapour throughput) is determined by a combination of three factors: the output power of the laser system; the attenuation of the laser radiation as a function of distance; and the minimum beam power required to ionize a suitably high fraction of U-235 atoms in the vapour stream.

Consider the last factor first. For laser pulses of energy intensity I joules/ cm^2 , with photon energy $h\nu$, and an atomic photo-absorption cross-section σ , the absorption probability for an individual

atom is given by

$$1 - e^{-I_0/h\nu}$$

Thus, the minimum laser pulse energy intensity required to sustain a high probability of uranium-235 ionization or excitation is of order:

$$I_{\min} \sim \frac{3h\nu}{\sigma}$$

and radiation of this intensity or less decays over a characteristic interaction length (the "e - folding length") given by:

$$l_e^0 \sim \frac{1}{n^{25} \sigma}$$

where n^{25} is the atomic density of uranium-235, and it is assumed that no photon absorption takes place in uranium-238.

For a three-step autoionization scheme, $h\nu$ might be $\sim 2\text{eV}$ (the ionization potential for uranium is 6.187eV),²⁶ and for typical excitation and autoionization cross sections of 10^{-14} and $10^{-16} - 10^{-17}\text{cm}^2$, respectively, the minimum pulse energy intensity would be $\sim 0.1\text{mJ/cm}^2$ for the excitation lasers, and $10\text{-}100\text{mJ/cm}^2$ for the ionization laser. The corresponding interaction lengths for uranium enriched in U-235 to 0.2% (a typical feed assay for a "tails stripping LIS plant) of overall atomic density 10^{-14}cm^{-3} would be 5 meters and 500-1000 meters, respectively.

But lasers of the type used by JNAI are capable of delivering $0.1\text{-}0.2\text{ J/cm}^2$.²⁷ In this so-called "strong saturation" case, in which the intermediate excited states are saturated over most of the irradiation length, the laser radiation penetrates much further than the characteristic interaction length, and the penetration distance for

pulse energy intensity I is given by:²⁸

$$l = \frac{I}{I_{\min}} l_e^{\circ}$$

Thus, for 0.2 J/cm^2 excitation and ionization lasers, the interaction length for each would be some 10 kilometers.*

However, there are other absorption and loss mechanisms for laser photons, at least one of which can be shown to be a greater constraint on the interaction length in some circumstances than absorption in U-235 itself.

In order to fill the angle subtended by the vapour stream from the oven/collimator source, the laser beam is folded back on itself several times, using high reflectivity mirrors, as shown in Figure 2.6.a.

Typically, 10 channels might be arranged in parallel.³² In order to ensure ease of maintenance and improved reliability, it will be convenient to construct the irradiation chamber from essentially identical, independent modules, where each module is vacuum tight and equipped with a uranium oven and product and tails collection system.³³

(See Fig. 2.4.) Each such module might be 2 meters in length and contain 10 laser beam channels; the modules might be linked as shown in Fig. 2.6.b.

Even using very high reflectivity mirrors ($\epsilon \sim 0.995$, say), mirror transmission losses would attenuate the laser radiation to 8% of its

* One potential problem arising from saturation is that the uranium vapour column is itself on the verge of self-lasing, at a frequency corresponding to the energy difference between the intermediate excited and lower states. The JNAI group has predicted that lasing difficulties may occur in vapour columns whose line-of-sight density for U-235 atoms corresponds to more than 10^{15} atoms/cm².²⁹ However, the actual value is dependent on a variety of factors, and it

over/

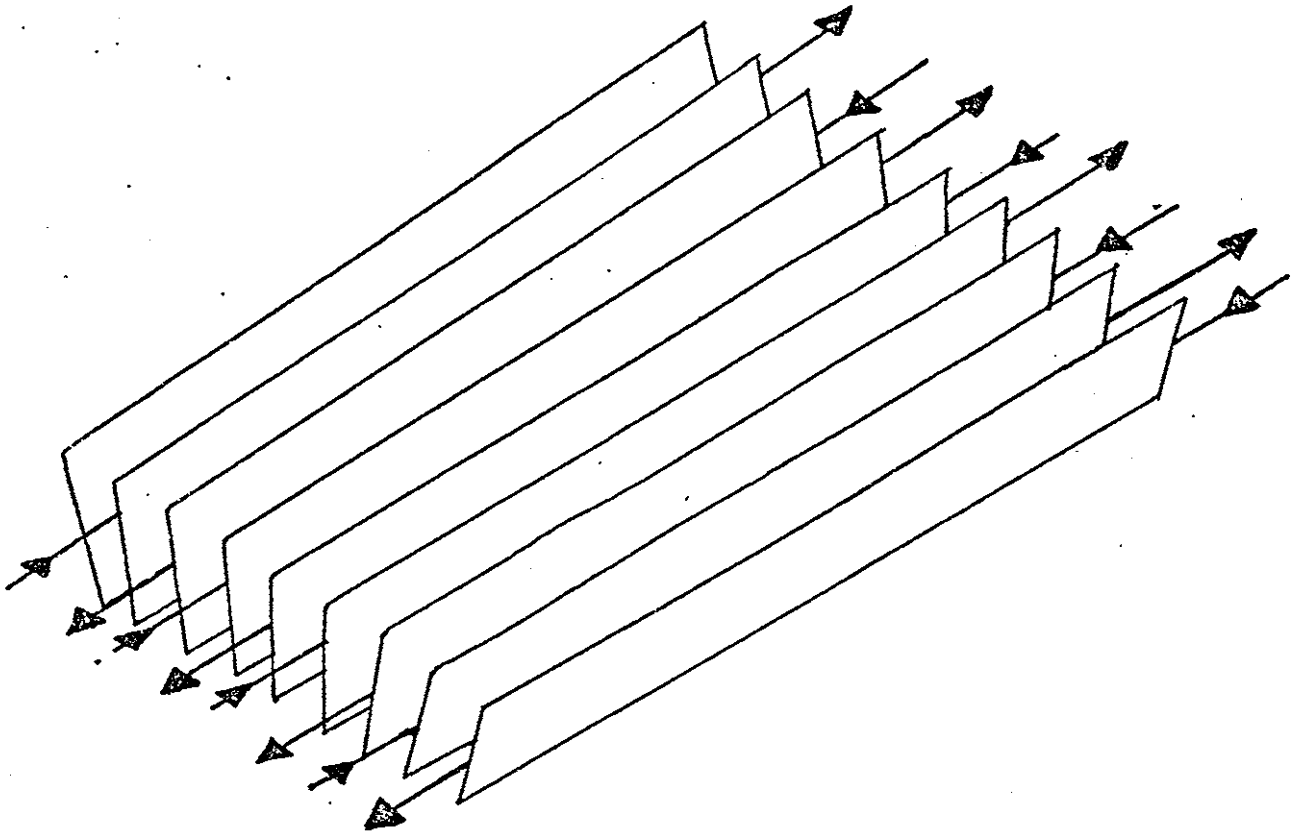


FIG. 2.6.a: LASER BEAM GEOMETRY IN AVLIS MODULE

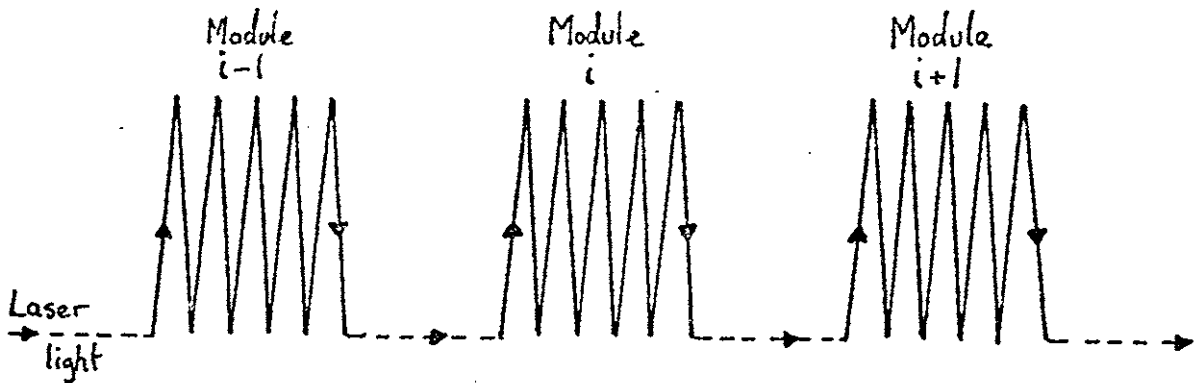


FIG. 2.6.b: POSSIBLE MODULE INTERCONNECTION SCHEME IN AVLIS PLANT

original intensity after an irradiation length of only 1 kilometer (50 such modules, 500 reflections), and for 0.2 J/cm^2 lasers and an ionization cross-section of 10^{-16} cm^2 , I_{\min} would be reached after some 1.2 kilometers (about 60 modules).

These losses, combined with optical diffraction effects and other forms of beam loss, place much lower limits on irradiation length than that suggested by the strong saturation distance.

Nevertheless, even with these limitations, an atomic LIS plant would not be small, chiefly because of the meagre concentration of the desired isotope U-235 and the prospective feed for such a plant. For instance, if it was found that the maximum irradiation length for an 0.2 J/cm^2 laser was 1500 meters, a vapour flow of 5,500 tons/year of 0.2% uranium feed would be required for optimum laser photon utilization (at a 75% capacity factor). Even so, with 0.08% U-235 in the tails, the actual U-235 content in the product is just 6.8 tons.

Collector

Two fundamental objectives must be met by the collection system: the efficiency of U-235 ion collection from the weakly ionized plasma should be maximized, and capture of unwanted U-238 on the collector plates should be minimized.

(contd.)

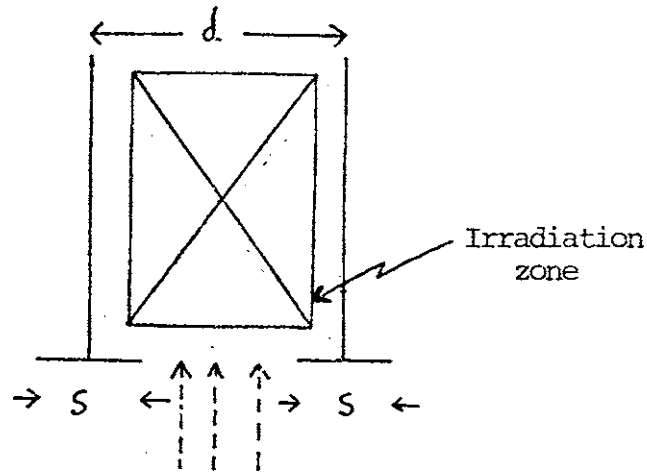
has been pointed out elsewhere that a number of ways are available to affect the system gain and configure the system so that lasing will not occur.³⁰ Recent indications from the JNAI group itself suggest that over the range of enrichment assays of interest for light-water-reactor fuel production, uranium self-lasing should not be a problem.³¹

Collection is achieved by deflection of the ions on to cooled plates by the application of electric and magnetic fields, either individually or in combination. In the JNAI patent, a low density crossed-field magnetohydrodynamic accelerator (arranged in various geometrical configurations) was the preferred means of separation. The Livermore group, the first to report uranium isotope separation in macroscopic quantities, deflected the uranium ions onto a beryllium plate electrostatically. However, several problems are encountered with extraction using electric fields alone, including space charge effects,³⁴ and the tendency for electrical breakdown to occur as higher electric fields are applied.³⁵

Some of the classes of forces that might be used in an ion extraction system have been reviewed by Hyman and Williamson,³⁶ who conclude that electromagnetic $\underline{J} \times \underline{B}$ forces will probably be capable of providing sufficient acceleration for efficient extraction without promoting unselective collisional ionization.

Some of the major sources of U-235 ion loss have already been mentioned, i.e. charge exchange interactions, momentum transfer interactions, ion - electron recombinations, etc. The causes of U-238 capture include: collection of thermal U-238 ions formed in the vapour generator and not removed before entering the irradiation region; collection of U-238 ions created in charge exchange interactions with U-235 ions; collection of U-238 ions produced by electron impact ionization; impingement of U-238 atoms given high velocity following momentum transfer interactions with accelerated U-235 ions; impingement of U-238 atoms onto the plates as vapour beam collimation breaks down (so-called "free vapour flow").

"Shadow shields" may be attached to the lower edge of the collector plates in order to reduce the effects of free vapour flow:



As the shadow shield thickness, s , is increased, the proximity of the vapour stream to the plates is reduced, thus reducing the diluting effects of free vapour flow. At the same time, however, the recovery of U-235 from the vapour stream is reduced, since a larger fraction of the vapour impinges on the shields before irradiation.

Another technique that might be used to reduce the dilution effect of thermal scattering is to orient the ion extraction system such that the ions are deflected in an upstream direction. The product collector could be shielded from particles arriving from directions other than the ion deflection direction.³⁷

Uranium vapour source

The purpose of the vapour generator is to produce uranium with a suitable density, energy level distribution function, and geometrical configuration. As we have seen, the uranium vapour density will probably be in the range $10^{13} - 10^{14}/\text{cm}^3$. Uranium is a highly refractory material (boiling point, 4135 K; vapour pressure, 1 Torr at 2729 K; melting point, 1420 K) and even to achieve such densities

requires temperatures of 3,000 K or more.³⁸ At these temperatures, there is a significant thermal population of energy levels above the ground state. For instance, at 3,000K, approximately 40% of the atoms can be expected to be in the ground state, 25% in the 620cm^{-1} level, and 35% in higher levels.³⁹ Figure 2.7 shows the equilibrium population distribution of some of the low-lying levels of uranium as a function of temperature. High recovery of U-235 will therefore require irradiation of the vapour with two or more photon frequencies at the first, selective excitation step. (See the three-step, four-photon scheme in Fig. 2.4.d and 2.4.e.) Furthermore, some non-selective thermal ionization of uranium inevitably occurs at these temperatures, thereby reducing the overall separation efficiency of the process.

Materials problems are also severe at these temperatures, in view of the highly corrosive properties of uranium liquid and vapour.

The first patent issued to the JNAI group describes an oven for the production of atomic uranium vapour which consists of a crucible of a suitable refractory material, such as graphite, containing molten uranium. Heating is with radiant heating elements.⁴⁰ At Livermore cylindrical tungsten ovens have been used, but the uranium is so corrosive at these high temperatures that the ovens reportedly must be frequently replaced.⁴¹ A uranium-rhenium alloy has been used to reduce corrosion. More recently, different approaches to the problem have been suggested, including electron-beam heating of a thin strip of the surface of the uranium.⁴² With such techniques, the high temperature required to achieve the necessary vapour pressure is highly localized, and the corrosion problems are alleviated since the hot uranium is only in contact with cold uranium, rather than the material

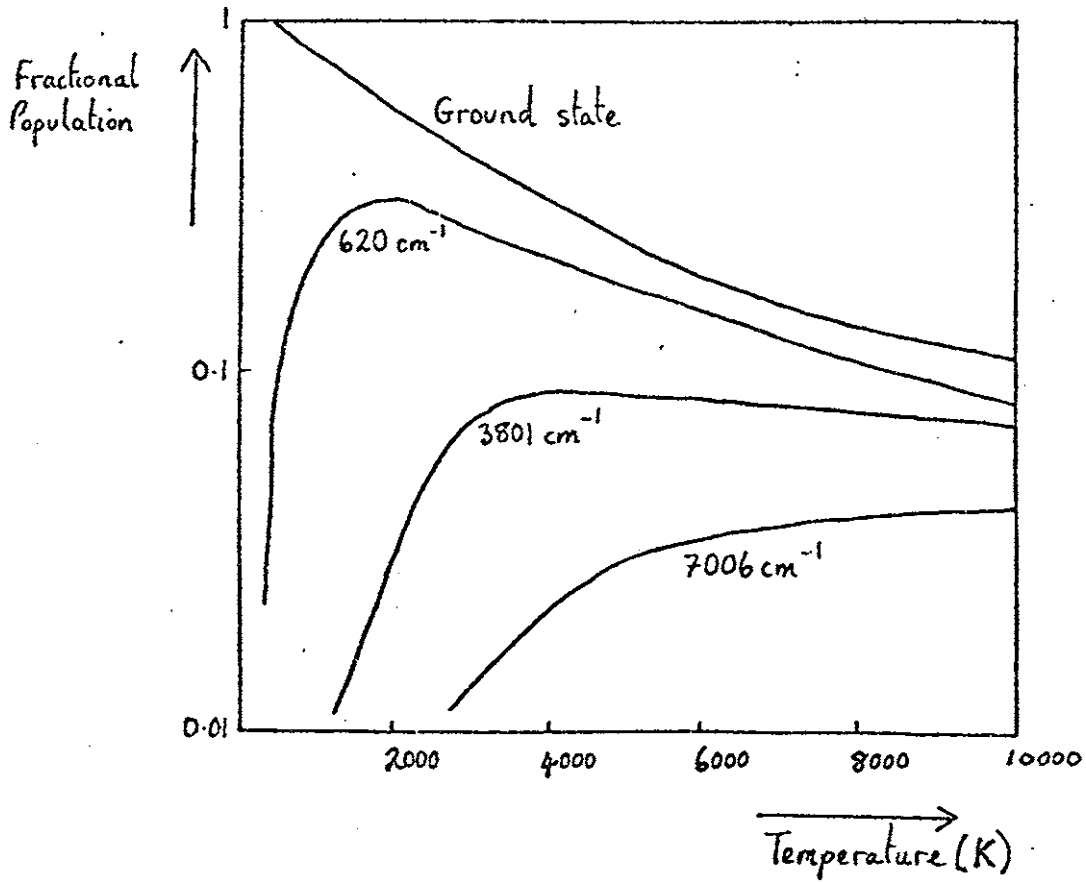


FIG. 2.7: POPULATION OF SOME LOW-LYING METASTABLE ENERGY LEVELS OF URANIUM AT THERMAL EQUILIBRIUM

[Source: G.S. Janes et al, Am. Inst. Chem. Eng., Symposium Series, 73(169), 63 (1977)]

of the crucible wall. On the other hand, e-beam heating aggravates the problem of non-selective ionization during the vapour production phase, thus reducing the separation efficiency still further.

Equally serious materials problems will be encountered in the irradiation chamber itself, where protection of the sensitive optical surfaces from the highly corrosive high-temperature uranium vapour presents a major technological difficulty. Details of one approach to this problem, developed by the Livermore group, have been given in the literature.⁴³

Since the atomic beam must be highly uni-directional in order to minimize non-selective vapour condensation on the product collector plates, the vapour source is generally coupled to a collimator. In the original JNAI patent, the collimator is made of graphite and maintained at a temperature above the melting point of uranium, so that when uranium vapour strikes it, the condensed vapour flows back into the main uranium pool.⁴⁴ The collimator is also supplemented by a magnetic field, whose purpose is to remove the thermally ionized atoms from the main atomic beam.

A more elegant technique for uranium vapour generation has been proposed at Columbia University by Lee and Zare.⁴⁵ It involves the low temperature production of free atoms of uranium in the vapour phase from a volatile uranium-bearing organic compound, uranocene. The uranocene is dissociated in gas phase collisions with metastable argon atoms. In the experiment reported by Lee and Zare, uranocene is heated in an oven to 460° K, at which temperature it has a vapour pressure of 10^{-3} torr. While there may prove to be other uranium compounds and chemical processes which are more suitable, this class

of techniques seems to hold promise for the alleviation of the severe materials problems encountered in the presence of uranium at high temperatures.

2.2.3 Other Atomic LIS Methods

Of all the possible schemes for atomic LIS, by far the largest share of effort has been directed towards the selective photoionization methods discussed in the previous section. Several other approaches have been proposed, however, including selective photodeflection of atoms or molecules by the action of light pressure.

Photodeflection by light pressure takes advantage of the momentum transfer that accompanies the absorption of a photon by an atom or molecule. The momentum transferred is:

$$p = \frac{h\nu}{c}$$

where ν is the light frequency, and the momentum is transferred in the direction of photon propagation. Re-emission of the light is accompanied by the loss of the same amount of momentum, but in a random direction. Thus, when an atom or molecule absorbs and re-emits many laser photons successively, it will gain momentum in the direction of the laser beam. If a laser beam is tuned to a frequency such that photons are absorbed selectively by the desired isotopic species in a beam of material moving perpendicularly to the laser beam, the desired isotope can be deflected out of the main beam and subsequently collected.

There are several problems with this technique. Most important is that a large number of photons must be absorbed and re-emitted before a significant amount of momentum is imparted to the atom or molecule.

Consider an atom of uranium-235 absorbing a photon of energy

3eV (roughly half the ionization potential). The velocity in the direction of light propagation is then given approximately by:

$$v = \frac{h\nu}{c \cdot m} = \frac{3 \times 1.6 \times 6.023 \times 10^{23}}{3 \times 10^{10} \times 235} \text{ cm/sec}$$
$$= 6.8 \times 10^{-2} \text{ cm/sec}$$

Compared with an average atomic velocity at 3000K of about 4×10^4 cm/sec, this velocity, and hence the angular deflection, is negligible. In order to obtain an average angular deflection of 0.001 radian, roughly 600 photons/atom would have to be absorbed. The process is thus far more energy intensive than the photoionization processes described in the previous section. Furthermore, if separation is to be based on such small deflections, the original uranium beam must be extremely highly collimated, and, at least in the case of atomic uranium beams, the difficulties of obtaining such high collimation are severe. Furthermore, the deflection rate is limited by the relaxation time of the excited species. While it is in the excited state, the atom or molecule in general cannot absorb another photon.

No successful uranium isotope separations by this method have been reported, although the enrichment of barium has been achieved with such a scheme.⁴⁶

Nebenzahl and Szöke have suggested that the photon utilization efficiency can be improved greatly by application of the so-called method of reusable photons.⁴⁷ In this method, an atomic beam is irradiated with a laser pulse which is tuned to excite the atoms selectively, imparting a momentum $h\nu/c$ to the desired isotopic species.

The laser pulse is then reflected at a mirror, and returns to the beam, at which point it stimulates a return of the excited atoms to their ground state. Exactly the same momentum is imparted in the initial direction, and the photon is re-emitted in the direction of the beam. In principle, high photon utilization efficiencies can be obtained, although limits are imposed by scattering and diffraction losses. Several other serious practical difficulties would also be encountered, and there have been no reports of any successful separations by this scheme.

Szöke has recently proposed a different photodeflection method, in which laser photons bring about the selective photodissociation of $^{235}\text{UF}_6$ molecules in a collimated beam of UF_6 . The chemical bond energy is dissipated partly in the internal excitation of the molecular fragments, and partly in their recoil motion, which causes the fragments to be deflected from the beam.⁴⁸

2.3 Molecular LIS Methods for Uranium Enrichment

2.3.1. History

The concept of molecular uranium isotope separation using lasers was first proposed in the original French LIS patent in 1963, in which the possibility of selective photoionization of UF_6 molecules was suggested.⁴⁹ Molecular-based schemes using lasers apparently received some attention in the U.S. later in the decade, for example at Lawrence Livermore Laboratory,⁵⁰ but spectroscopic problems which had dogged earlier, non-laser based efforts continued to suggest that isotope separation would be very difficult to achieve, even with the advent of laser technology.

As in all other LIS schemes, the key requirements for high selectivity and good yield are a spectrum with a well-defined isotope shift, permitting initial selectivity, and conservation of selectivity during subsequent separation stages. Separation of the selectively excited molecules might be achieved by photodissociation, photoionization, or photochemical reaction. The first two, and possibly also the last, require one or more additional photon absorptions.

For a two-step scheme, the second absorption need not be selective, i.e., both excited and unexcited species may absorb at this photon frequency; in the case of selective photodissociation, for example, overall selectivity can be conserved provided that:

$$hv_1 + hv_2 > E_d$$

but also that:

$$hv_2 < E_d$$

where hv_1 = first (selective) photon energy

hv_2 = second photon energy

and E_d = dissociation energy from ground state.

A similar condition is sufficient for selective photoionization. For a two-step photochemical isotope separation process, the corresponding requirement is for a chemical reaction with a sharply defined minimum activation energy, such that the isotopic species absorbing both photons reacts, while the species absorbing only the second photon does not.

It might be supposed that selective photoabsorption and subsequent separation could be achieved in a single absorption step. Unfortunately, in the ultraviolet region of the spectrum, where photon energies are generally sufficient to ionize or dissociate the molecules directly,

or activate them for the desired chemical reaction, the absorption line widths are so broad that the possibility of finding a suitably resolved isotopic shift is unlikely.⁵¹ Isotopically selective absorption is more feasible in the infrared region, but the energy available is inadequate for photoionization, photodissociation or photochemical activation; hence the need for schemes involving two or more photoabsorptions.

Even in the infrared region, the difficulty of finding an isotopically selective line in the spectrum of UF_6 and other molecules was well recognized.⁵² In the early seventies, however, a breakthrough was made by investigators at the Los Alamos Scientific Laboratory (LASL). The following section discusses the general characteristics of UF_6 molecular spectroscopy and describes the developments at LASL in more detail.

2.3.2. UF_6 spectroscopy and isotope shifts

Molecular absorption spectra are generally more complicated than atomic spectra, because vibrational and rotational energy level structures are superimposed on the electronic level configuration.

The isotope shifts in molecular spectra are dominated by the effect of nuclear mass differences on the vibrational energy level spacings (which are proportional to the reciprocal of the square root of the vibrational reduced mass) and the rotational energy level spacings (inversely proportional to the moments of inertia).⁵³

In molecules containing different isotopes, the classical vibration frequencies differ according to:

$$|\Delta\nu| = \frac{1}{2} \frac{\Delta\mu}{\mu}$$

where ν is the vibrational frequency and μ is the reduced mass of the

molecule. The reduced isotopic mass difference $\Delta\mu$ is non-zero only if the particular vibration mode involves the isotopic atoms.⁵⁴

Non-linear polyatomic molecules have $3N-6$ modes of vibration, where N is the number of atoms. Owing to the high symmetry of the UF_6 molecule, however, the vibrational motions can in this case be described by six normal modes of oscillation. Of these, only two, designated ν_3 and ν_4 , involve motion of the U atom. A schematic energy level diagram of the ν_3 transition from the ground state to the first vibrationally excited state is shown along with the associated absorption spectrum in Fig. 2. 8.

Room temperature measurements on separated samples of $^{238}UF_6$ and $^{235}UF_6$ have indicated a gross isotopic shift of 0.55 cm^{-1} for the 623 cm^{-1} ν_3 band, and a shift of $0.1-0.2\text{ cm}^{-1}$ for the 186 cm^{-1} ν_4 band.⁵⁵ However, the nature of the room temperature infrared absorption spectrum is such that a resolvable isotope shift that would permit practical separation is effectively impossible to find. The trouble is that the vibration-rotation states of the UF_6 molecules are so closely spaced in frequency that at room temperature many of the low-lying vibrational energy levels and rotational sub-levels are occupied. Fig. 2.9 shows the room temperature population distribution of UF_6 vibrational levels. In fact, more than half the molecules are excited to energies greater than 1200 cm^{-1} , and only 0.4% of them are in the ground vibrational state. Thus, the ν_3 transition observed at room temperature actually consists mostly of a superposition of many so-called "hot band" transitions in molecules already in excited states. Owing to anharmonic effects, the "hot bands" do not precisely coincide with the ground state bands. The consequences of this can be seen in Fig. 2.10,

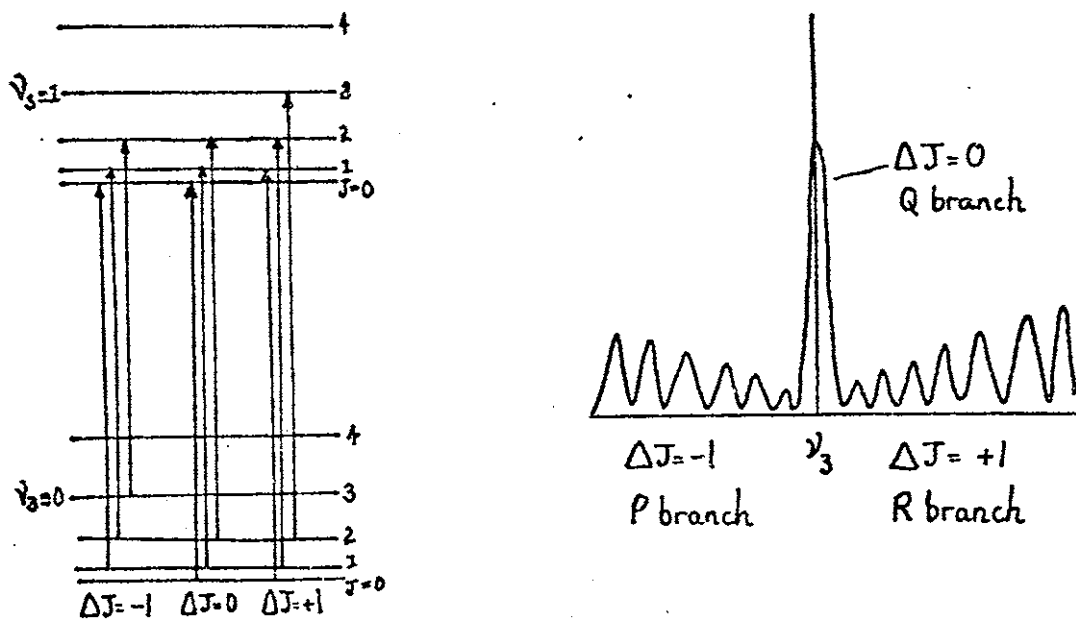


FIG 2.8: THE ν_3 ABSORPTION IN UF_6

[Source: A.S. Krass, Science 196, 13 May 1977, 723]

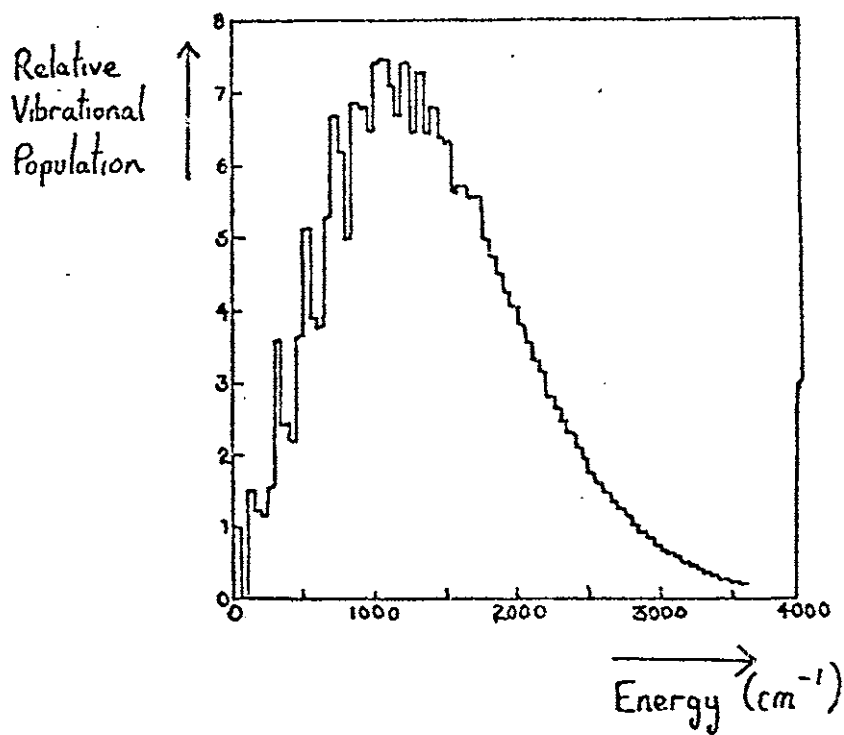


FIG. 2.9: DISTRIBUTION OF VIBRATIONAL ENERGY
AMONG UF₆ STATES AT ROOM TEMPERATURE

[Source: R.J. Jensen et al, Laser Focus, 12 May 1976, 55]

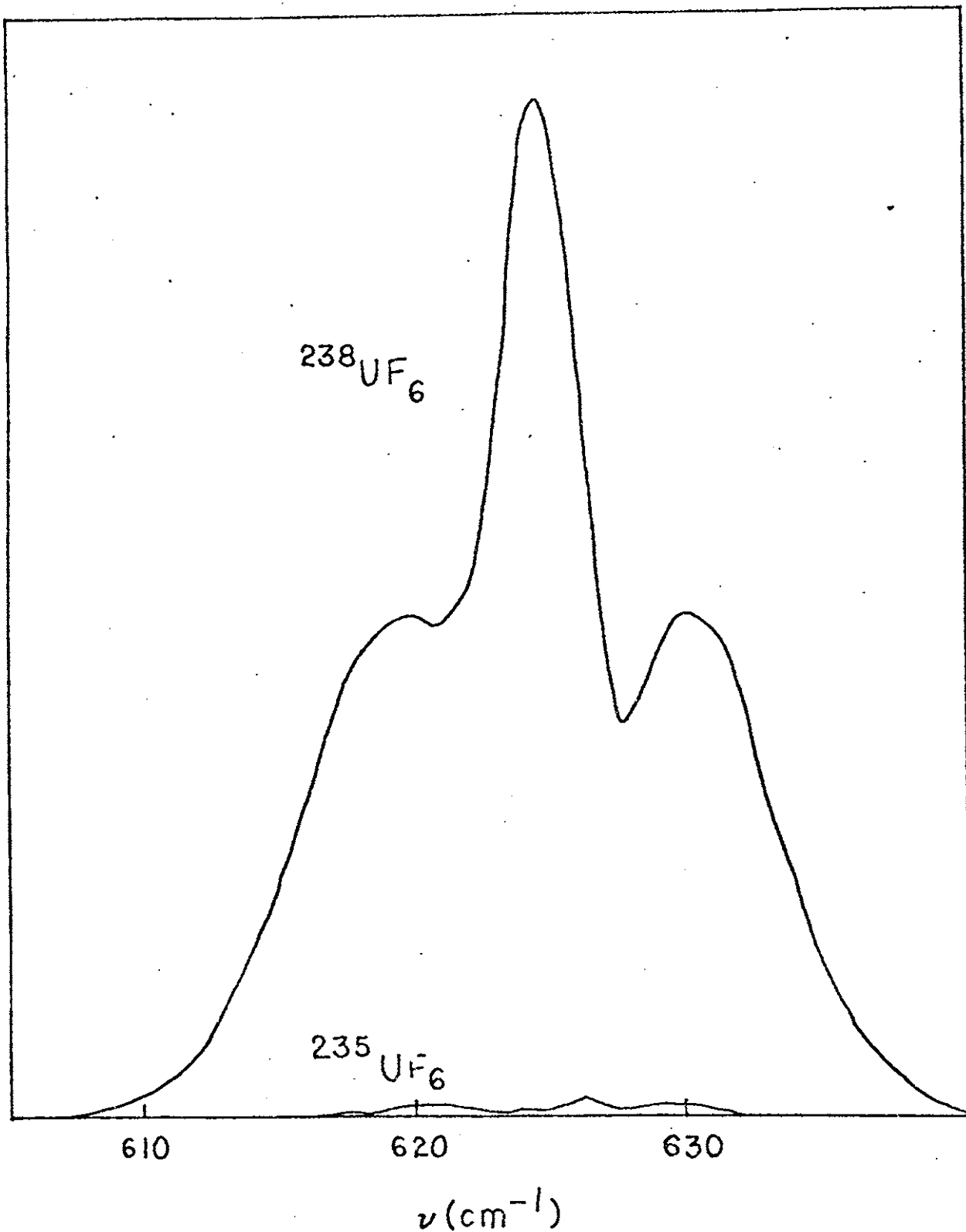


FIG. 2.10: UF_6 ABSORPTION: ν_3 AT 300K SHOWING 'HOT-BAND' EFFECT

[Source: C.P. Robinson and R.J. Jensen, Los Alamos Report LA-UR-76-191, 1976]

which shows the ν_3 absorption band for UF_6 . The width of the spectrum is due primarily to the Doppler broadened, overlapping hot bands, and the room temperature PQR feature is a combination of thousands of similar PQR structures, each arising from a different thermally populated initial state.

At lower temperatures, however, more molecules are in the vibrational ground state, and the problem presented by the hot bands is reduced. The population distribution in the ten lowest-lying vibrational states is shown as a function of temperature in Fig. 2.11. Unfortunately, very low temperatures are required if most of the UF_6 molecules are to be found in the ground state, and in practice the vapour pressure at equilibrium temperatures of this magnitude is far too low to be interesting. For instance, from Fig. 2.11, the temperature at which 90% of the UF_6 molecules are in the ground state is about 55 K - a temperature at which UF_6 has essentially no vapour pressure.

The breakthrough made by the investigators at Los Alamos was to show that this difficulty could be overcome by preparing supersaturated UF_6 at the desired low temperature by adiabatic expansion of the gas through a converging-diverging (supersonic) nozzle.⁵⁶ During the expansion, the kinetic energy of random motion and the internal vibrational and rotational energy is converted into kinetic energy of translation as the gas accelerates through the nozzle to high velocities. Large temperature reductions can be achieved by this means. The bulk fluid temperature downstream of the nozzle is given approximately by the relationship:

$$\frac{T}{T_0} = \left(\frac{P}{P_0} \right)^{\frac{\gamma-1}{\gamma}}$$

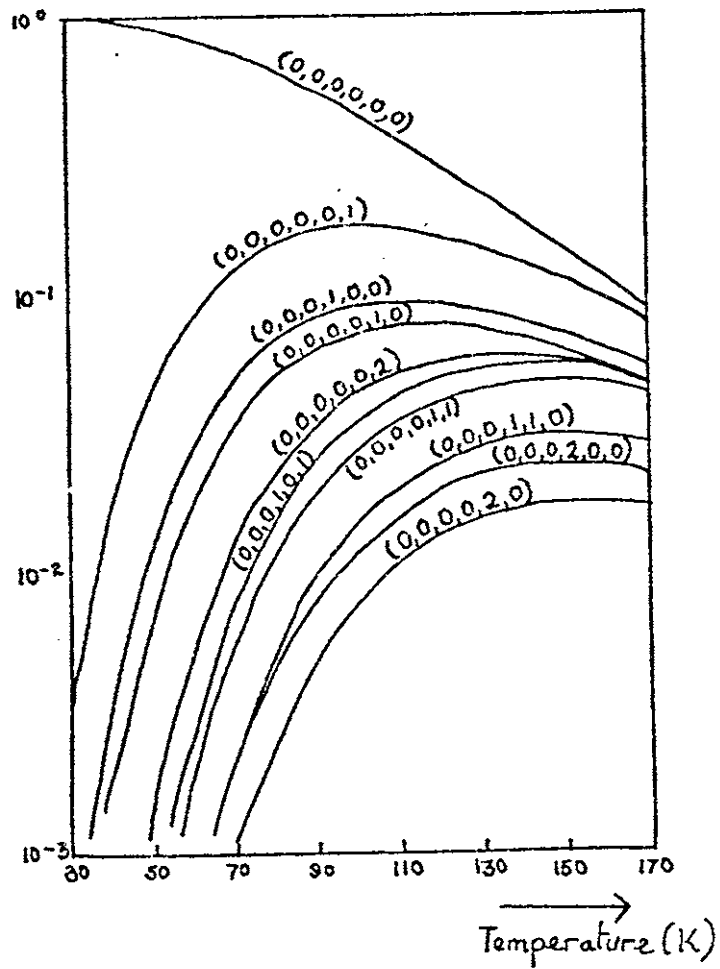


FIG. 2.11: FRACTION OF POPULATION IN 10 LOWEST-
LYING VIBRATIONAL STATES AS A FUNCTION
OF TEMPERATURE FOR UF₆

[Source: R. J. Jensen et al, Laser Focus, 12 May 1976]

where T_0 and P_0 are the temperature and pressure upstream, and γ is the specific heat ratio.)

Even for modest pressure ratios, the cooling is substantial; cooling can be increased by mixing the UF_6 , whose γ is low (~ 1.065) with a high carrier gas (e.g. helium, for which $\gamma = 1.67$). The flow-cooled, supersaturated gas exhibits a much sharper spectrum since the "hot band" population is dramatically reduced. At 50K, for example, more than 93% of the molecules are in the ground vibrational state. (See Figure 2.11.)

Fig. 2.12 shows the enhanced resolution of the absorption bands in the region of the Q-branch of the ν_3 transition for UF_6 flow cooled to 55K. Shown for comparison on the same graph is the room-temperature absorption spectrum for the same UF_6 mixture.

The flow-cooled data in Fig. 2.12 was taken in a conventional spectrometer which was unable to resolve the P and R branch lines. Recently developed tunable laser diodes provide a much higher resolution, and Fig. 2.13 shows the location of the Q branch line of the ν_3 transition for $^{235}UF_6$ relative to the R branch lines of $^{238}UF_6$, again measured in a flow-cooled gas, this time at a temperature of approximately 30.K.⁵⁷

2.3.3. LIS Schemes for UF_6

Fig. 2.14 shows some of the ways in which uranium isotope separation might be achieved following selective vibrational excitation of $U^{235}F_6$ molecules.

(1) Laser-induced Photochemistry

Enhancement of the chemical reactivity of a desired isotopic

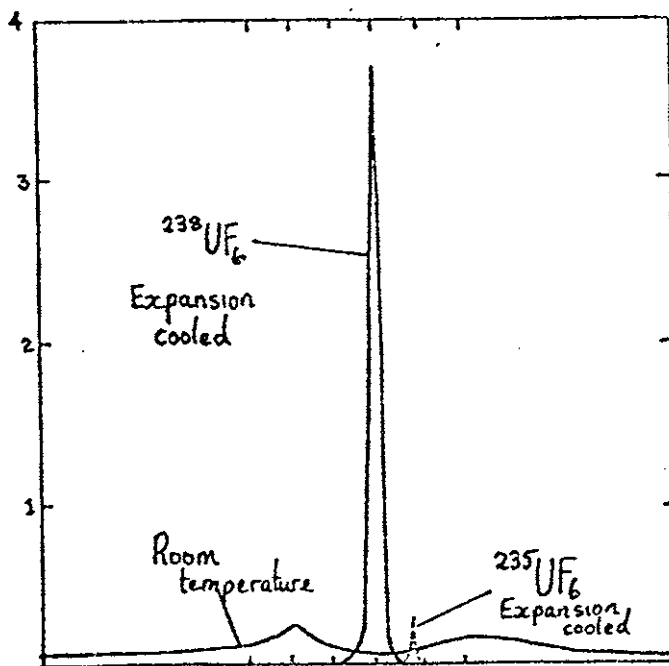


FIG 2.12 : INFRARED ABSORPTION SPECTRUM OF
EXPANSION-COOLED UF_6 COMPARED
WITH ROOM TEMPERATURE SPECTRUM

[Source: R. J. Jensen et al, Laser Focus, 12 May 1976]

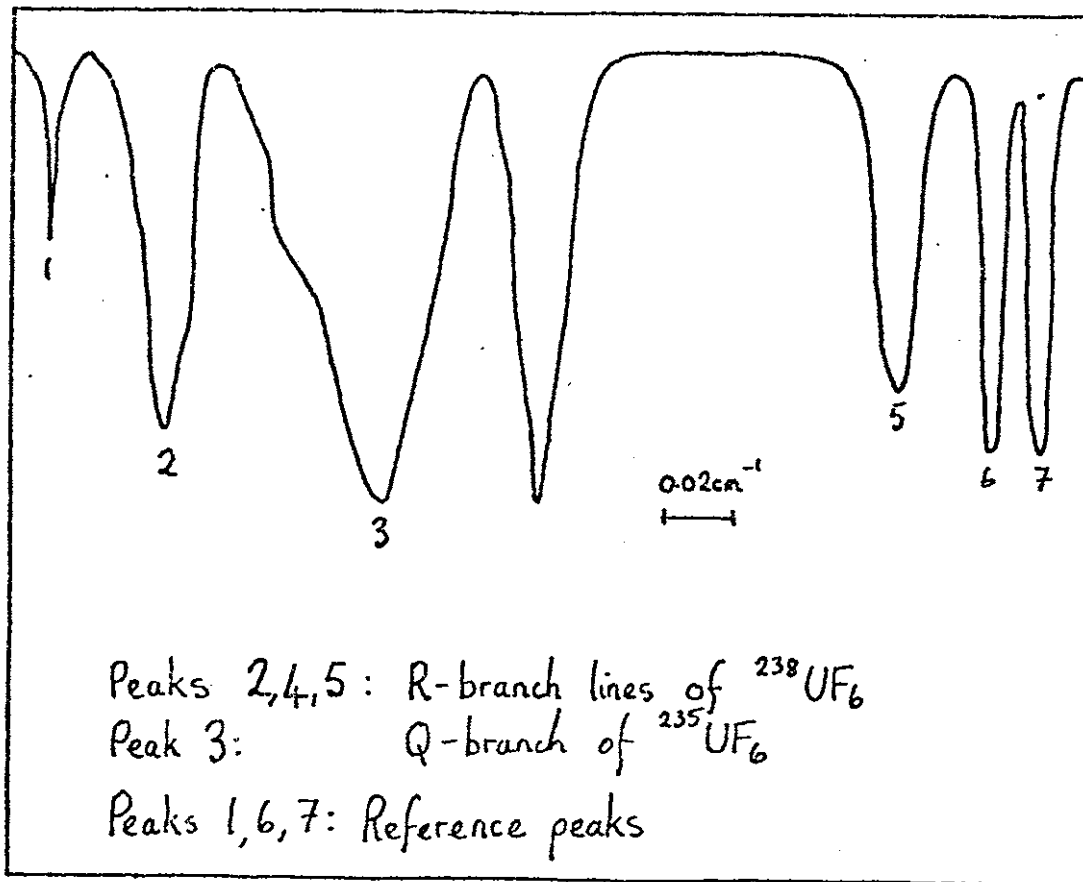


FIG. 2.13: COMPOSITE SPECTRUM OF FLOW-COOLED UF_6
TAKEN WITH TUNABLE DIODE LASERS

[Source: R.J. Jensen et al, Laser Focus, 12 May 1976]

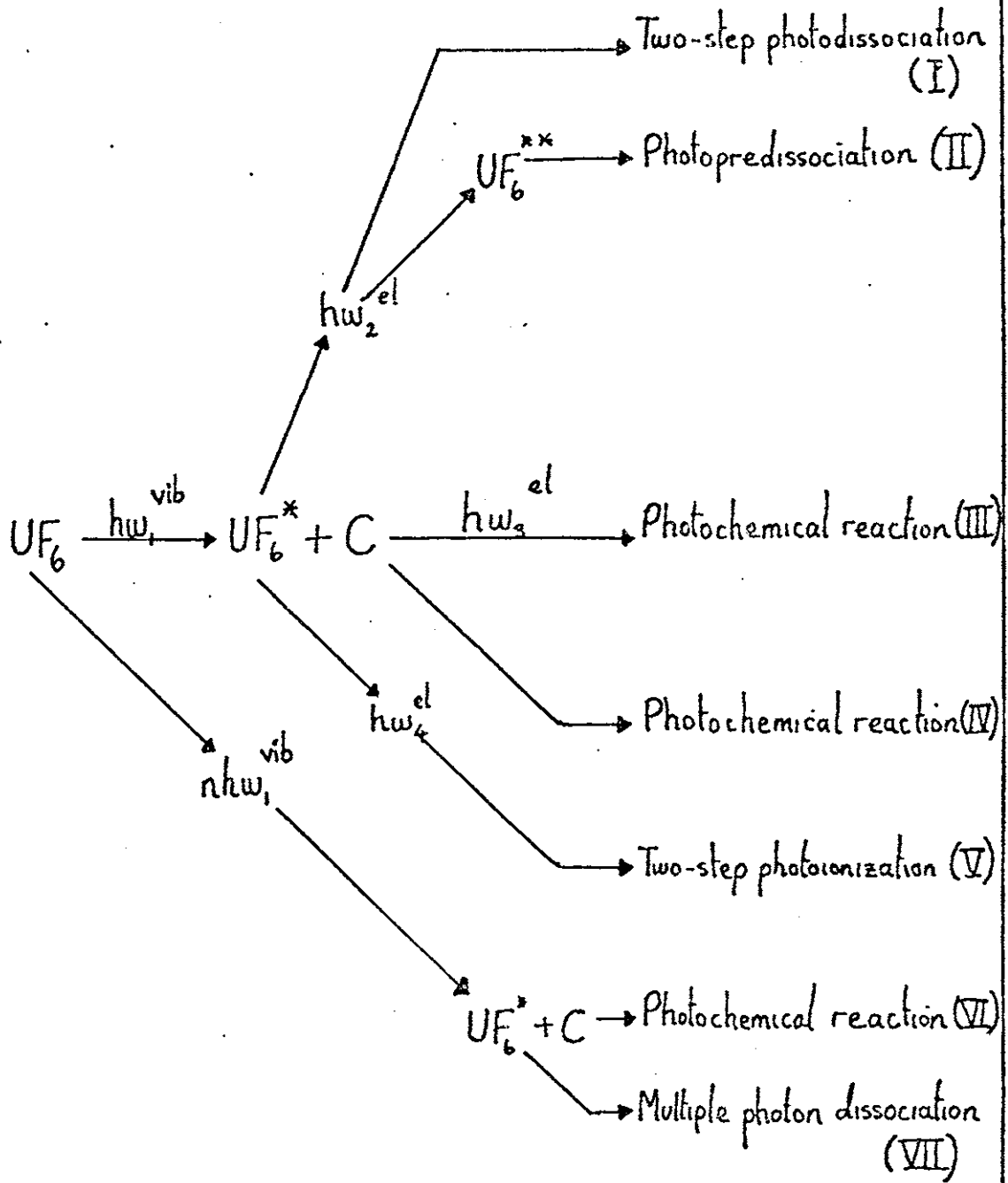


FIG. 2.14: UF_6 LASER ISOTOPE SEPARATION
SCHEMES

species by selective photoexcitation was the basis of the first successful photo-separations of isotopes in the 1930's. A laser-based extension of this technique was proposed by Robieux et al.⁵⁸

Although the systematics of the effect of internal excitation on chemical reaction rates are not yet well understood,⁵⁹ the basic principle is straightforward: the chemical reaction rate for the excited molecule is enhanced by reducing the activation energy barrier. In the simplest of terms, where the reaction rate for a first order chemical reaction is given by the Arrhenius equation: $k_1 = Ae^{-E_1/kT}$ where E_1 is the reaction activation energy, the enhanced reaction rate is given by:

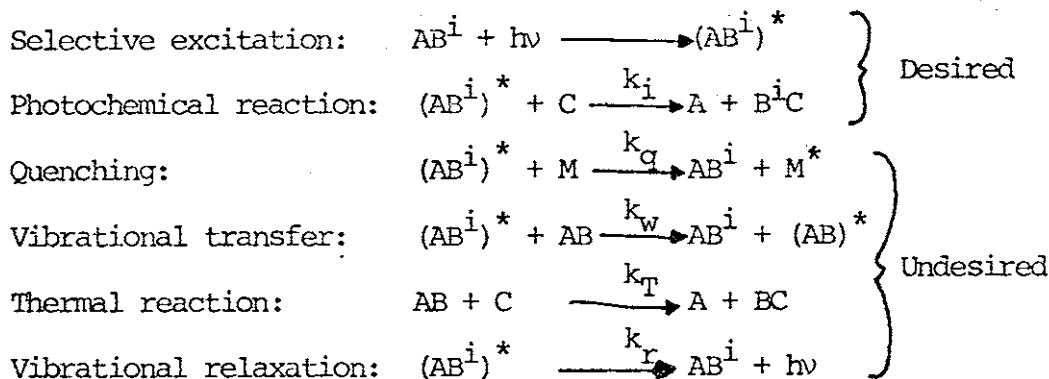
$$k_2 = Ae^{-E_1/kT} e^{\Delta E/kT}$$

where ΔE is the energy of the absorbed photon.

The molecule may be excited electronically or vibrationally. For UF_6 , most attention has been focused on vibrationally-induced photochemistry.⁶⁰ A West German patent applying to uranium isotope separation using this technique was published in 1971,⁶¹ and others have since issued. The possibility of using low-energy infrared photons from an efficient molecular laser for selective vibrational excitation offers the prospect of a very low energy isotope separation process.

Whether based on electronic or vibrational excitation, the scheme requires both a resolvable isotope shift and a co-reactant which does not react appreciably with the unexcited UF_6 either in the gas phase or on the container walls under ambient conditions. It is also necessary that the excited molecule undergoes the

desired reaction at a faster rate than it loses its energy by processes such as radiation, quenching, energy transfer to the undesired isotopic species, etc. A simplified reaction scheme for an isotopically selective photochemical process where B^i is the desired isotope of B, is shown below:



(2) Photophysical processes

Letokhov and Moore have discussed the advantages of photophysical isotope separation process based on ionization or dissociation compared with photochemical methods.⁶² In the latter case, the selectivity and efficiency of the process will depend on the rate of the desired chemical reaction relative to the rates of competing scrambling reactions and to the lifetime of the selectively excited molecule; they are thus determined by the choice of reaction scheme instead of being controlled by the laser radiation. In the case of photophysical methods, however, selectivity and efficiency of recovery will depend on whether the rate of dissociation (or ionization) exceeds the scrambling and relaxation rates. Since dissociation or ionization rates are proportional to the laser radiation intensity, good selectivity and efficiency in principle can always be achieved.

As mentioned earlier, selective photoionization of UF_6 was proposed by Robieux et al;⁶³ however, others have noted that since the ionization energy for UF_6 molecules exceeds the dissociation energy by a factor of more than three, selective photodissociation may be preferred because of its lower energy requirements.⁶⁴ In fact, the "mainline" molecular LIS process under development at Los Alamos is based on a selective two-step photodissociation (STS) scheme (see route I in Fig. 2.14). Figure 2.15 illustrates in simplified form the transition scheme for this method for a general case involving the molecular species A and B. The shift in the photoabsorption band for the dissociation step and the optimum wavelength for the dissociating photons are also shown. (It should be noted that the photodissociation band shift is not a genuine isotope shift, but rather the difference between the dissociation spectra of infrared excited and ground state molecules.) The Los Alamos STS method is discussed in more detail in the next section.

The second step in the two-step scheme can alternatively consist of an electronic excitation to a bound state, followed by spontaneous or induced molecular dissociation (see route II in Fig. 2.14). The latter may be collision-induced, or enhanced through the application of external magnetic or electric fields.

(3) Multiple-photon dissociation

In this scheme (see route VII in Fig. 2.14), an intense pulse of infrared laser light, with a wavelength at or near a resonant vibrational frequency of the desired isotopic species, excites the UF_6 molecule up through its vibrational manifold to dissociation.

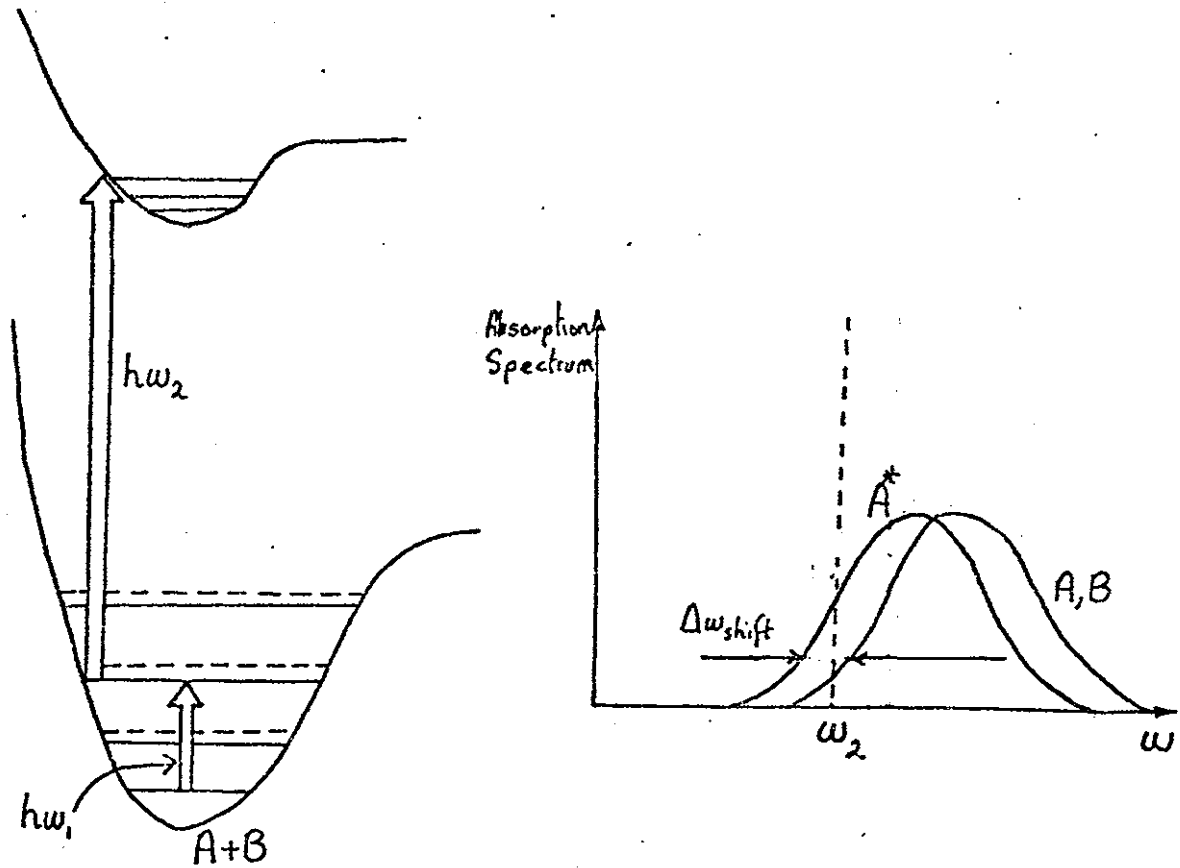
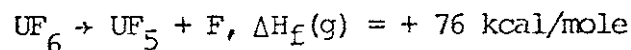


FIG.2.15: SELECTIVE TWO-STEP PHOTODISSOCIATION OF MOLECULES OF A IN A+B MIXTURE VIA INTERMEDIATE VIBRATIONAL STATE

[Source: V.S. Letokhov and C.B. Moore, Sov. J. Quant. Electron., 6(2), February 1976, 129]

Given a dissociation energy for gas phase dissociation of UF_6 of:⁶⁵



and assuming that the infrared photons are of 16 micron wavelength ($\approx 0.078\text{eV}$), at least 43 photons would, in principle, have to be absorbed by a UF_6 molecule in the ground state in order for dissociation to take place.

Although uranium isotope separation using this technique has not yet been reported in the open literature, isotopically selective experiments have been performed successfully with such structurally similar molecules as SF_6 .⁶⁶⁻⁶⁸

A modification of this method has been proposed by Wittig et al at the University of Southern California, who reported dissociation of UF_6 by a two-step method, in which 16 micron radiation from a CF_4 laser is first used for selective vibrational excitation, and the excited molecules are then dissociated by multiple absorption of 9.2 micron photons from a CO_2 laser.⁶⁹ These experiments did not achieve isotopically selective dissociation. Nevertheless, similar schemes, involving a precisely tuned low-power infrared laser for selective excitation and a second, high-power but less precise IR laser for multiple photon dissociation, have apparently been successful in isotopically selective dissociations of SF_6 and OsO_4 in the Soviet Union.^{70, 71}

Laser powers on the order of one gigawatt/cm² have been used in some of these experiments, and a potentially attractive feature of such methods, particularly the latter 2-laser scheme, is the ready availability of high-power CO_2 infrared lasers that may be suitable for such applications. At this stage, however, the

mechanism by which the photons are absorbed is not well understood. Aldridge et al have reviewed some experimental and theoretical efforts to deal with this problem, and more recent reports indicate that the question is still not resolved.⁷²⁻⁷⁵

The multiple-photon approach might also be modified so that the laser pulse drives the molecule only part of the way up the vibrational ladder to dissociation; the enhanced reactivity of the selectively excited molecules at some intermediate level would then be the basis of the subsequent separation.⁷⁶ (See route VI in Fig. 2.14.)

2.3.4. The Los Alamos STS Photodissociation Process

Although no description of a uranium enrichment plant based on the STS photodissociation process has appeared in the open literature, the principal system components can be identified with reasonable confidence. Figures 2.16 - 2.18 show how these components might be arranged in a commercial plant.

Uranium hexafluoride is mixed with a high γ carrier gas, such as helium, in a ratio typically of 1:10 or less, and expanded adiabatically through a converging-diverging nozzle. The gas mixture is accelerated to supersonic velocities and cooled to perhaps 50K or below, the exit temperature depending on the pressure ratio across the nozzle. (Table 2.4 shows how the nozzle exit temperature varies as a function of pressure ratio for adiabatic expansion and an inlet temperature of 300K.)

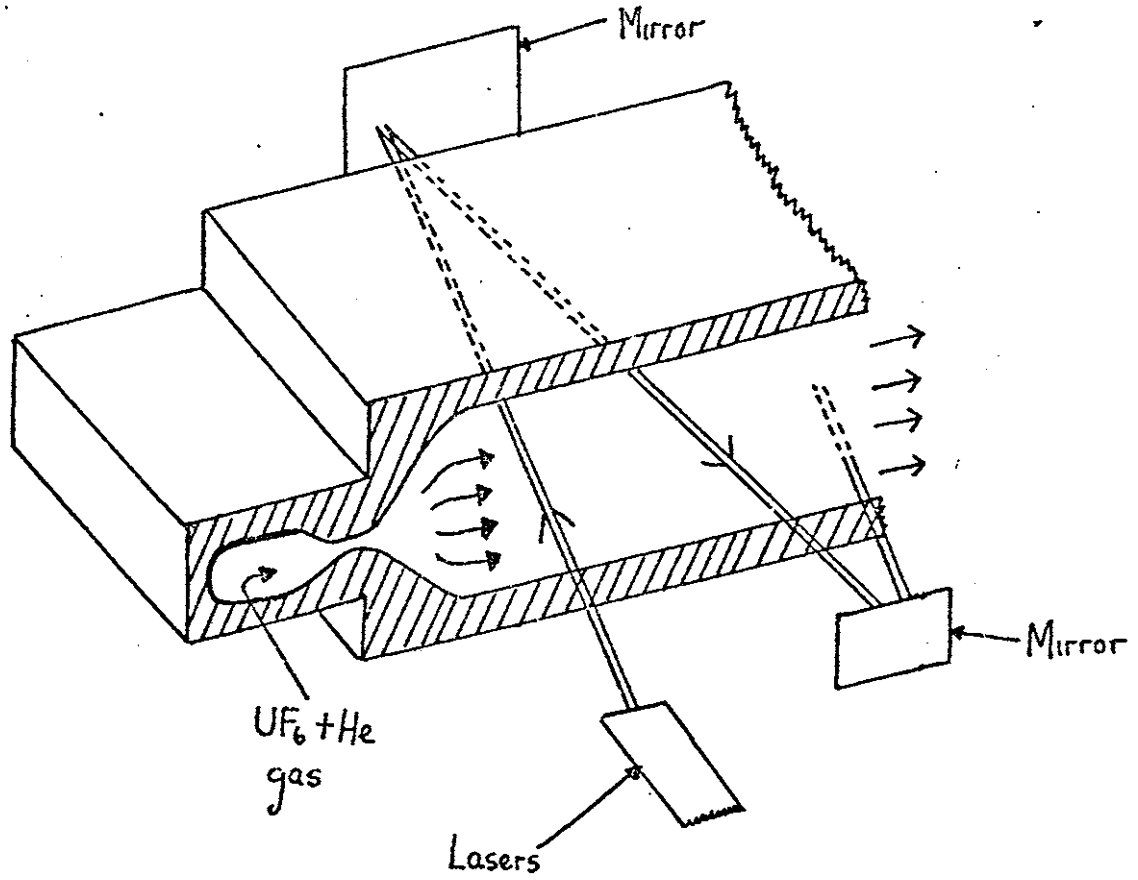


FIG 2.16: SCHEMATIC DIAGRAM OF MLIS FLOW COOLING AND IRRADIATION SECTIONS

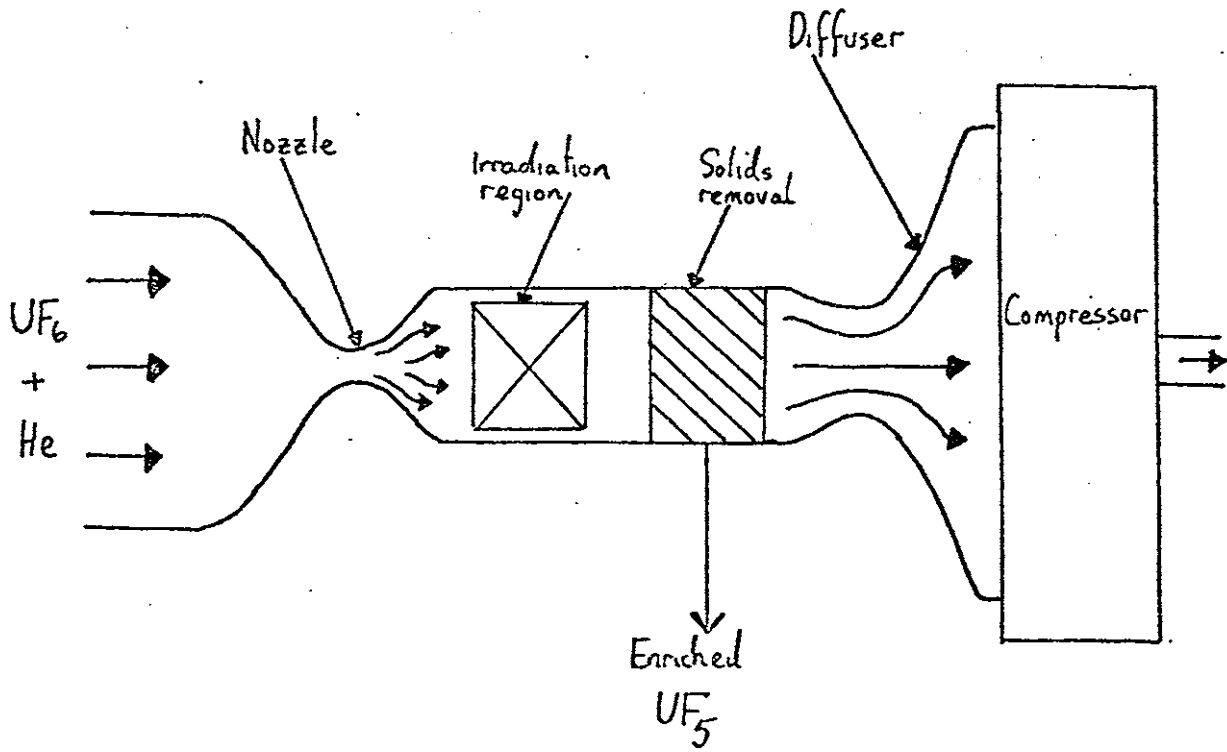


FIG. 2.17: MLIS SCHEMATIC

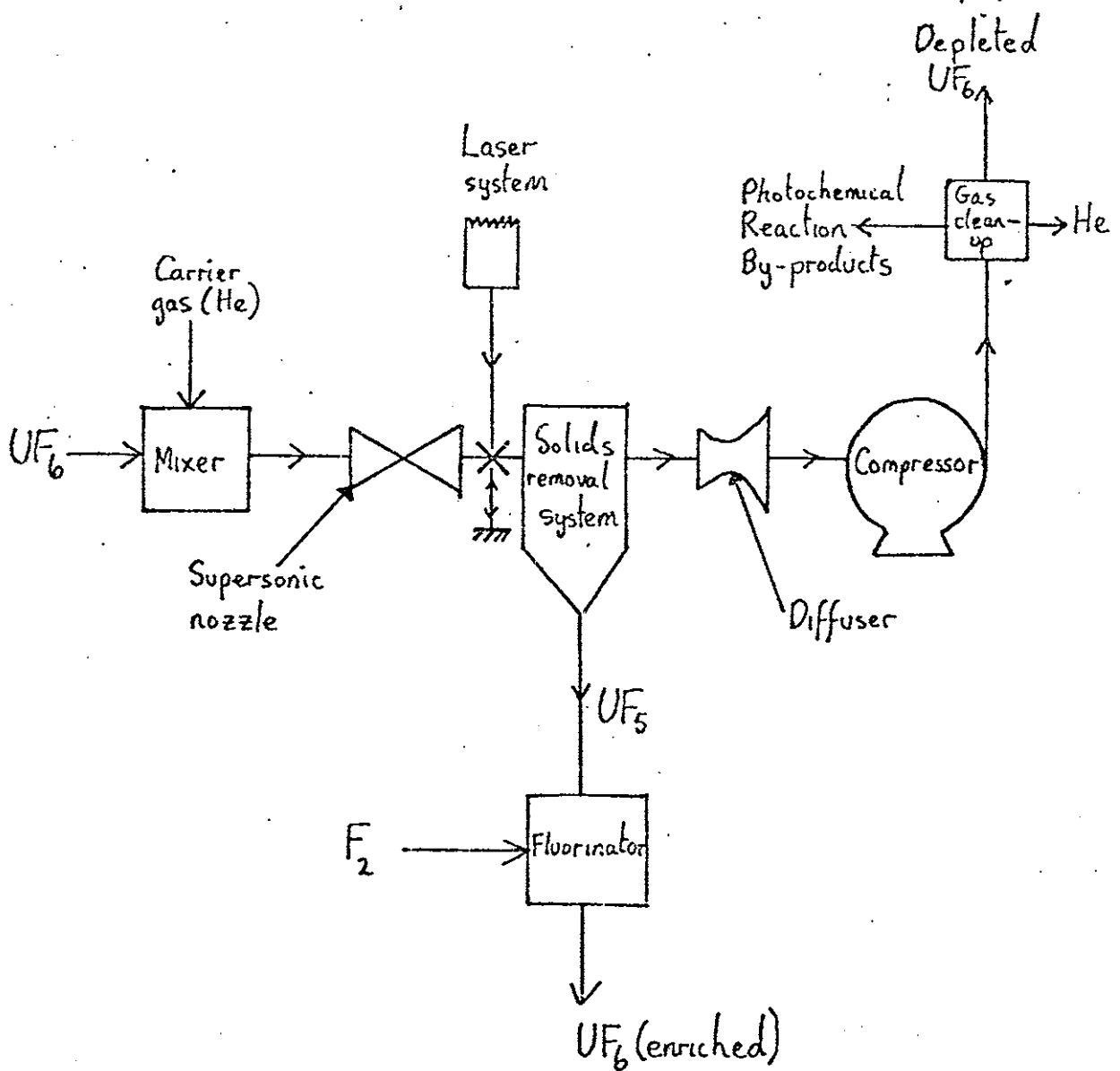


FIG. 2.18: COMPONENT CONFIGURATION FOR MLIS STAGE

Table 2.4

Nozzle exit temperature as a function of pressure ratio

Inlet temperature = 300K
 $\gamma_{\text{mixt}} = 1.64$ (95% He, 5% UF_6)

$P_{\text{inlet}}/P_{\text{exit}}$	T_e (K)
10	122.0
50	65.2
100	49.7
150	42.5
200	37.9
500	26.5
1000	20.2

The cooled gas is then irradiated transversely by infrared and ultraviolet laser photons. $^{235}\text{UF}_6$ is selectively dissociated and solid uranium pentafluoride "snow" precipitates out of the gas flow. The uranium pentafluoride is removed by filters, electrostatic precipitators, or other such means for solids removal, and after separation is refluorinated. The undissociated $^{238}\text{UF}_6$ and the carrier gas are exhausted and separated from each other and from any other photochemical reaction products, such as fluorine, produced during irradiation.*

Depending on the degree of isotopic separation obtained in a single irradiation, it may be necessary to arrange several of these photodissociation stages in series in order to produce reactor grade

* Facilities similar to those which might be required in an MLIS plant for separating UF_6 vapour from a light carrier gas are under development in West Germany in connection with the Becker separation nozzle program.⁷⁷ In fact, it is to be expected that the gas flow system technology in an enrichment plant based on the IASL "mainline" process would be similar in several respects to the separation nozzle process.

uranium from natural feed. A 'one-up, one-down' cascade arrangement, in which the heads and tails streams from any given stage are made to flow to the two adjacent stages, is shown in Figure 2.19.

Flow cooling system

As the nozzle exit temperature is reduced, the 'hot band' problem becomes less troublesome, and the photon absorption selectivity is improved. Fig. 2.20, taken from a declassified Los Alamos patent application, shows the increasing absorption selectivity of infrared photons as the temperature is reduced at an unspecified region of the R-branches of the $^{235}\text{UF}_6$ spectrum.

On the other hand, as the inlet to outlet pressure ratio increases, both the power and the capital investment required for recompression of the expanded gas increases correspondingly. Furthermore, a lower nozzle exit temperature increases the risk of condensation of the highly supersaturated UF_6 vapour. Condensation leads to undesirable light scattering and increased energy exchange reactions between excited and unexcited isotopic species. The probability of condensation can be reduced by lowering the inlet nozzle pressure. However, a lower system pressure will increase the compressor capacity requirement.

Expansion to supersonic velocities can be achieved either in continuum flow nozzles or in molecular beam nozzles. Although the absence of collisions eliminates the effect of 'scrambling' reactions, thereby increasing U^{235} recovery and separation efficiency, the low density and thus the low throughput attainable renders processes based on molecular beam expansion economically less attractive, and for this

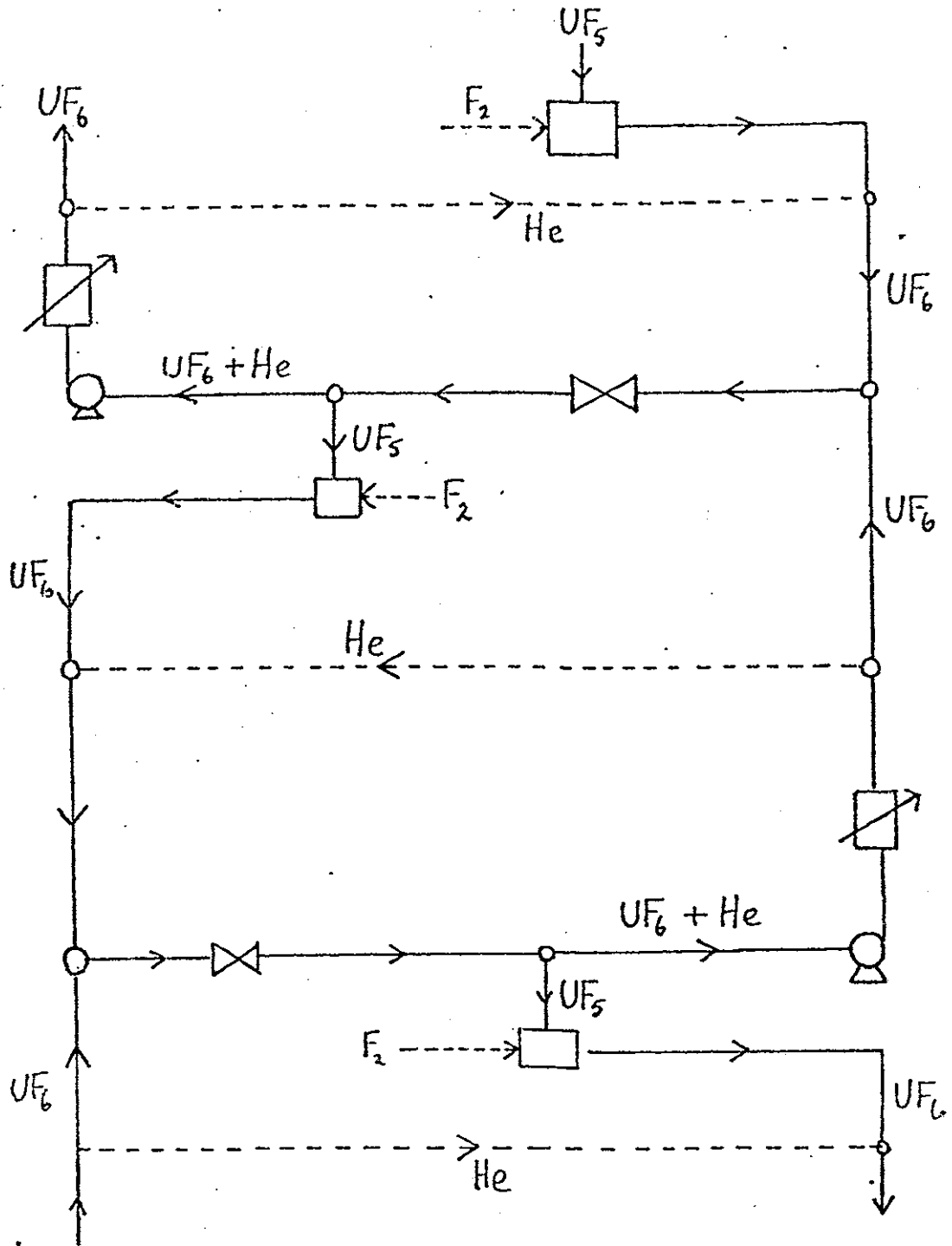


FIG. 2.19: 'ONE-UP ONE-DOWN' MLIS CASCADE SECTION

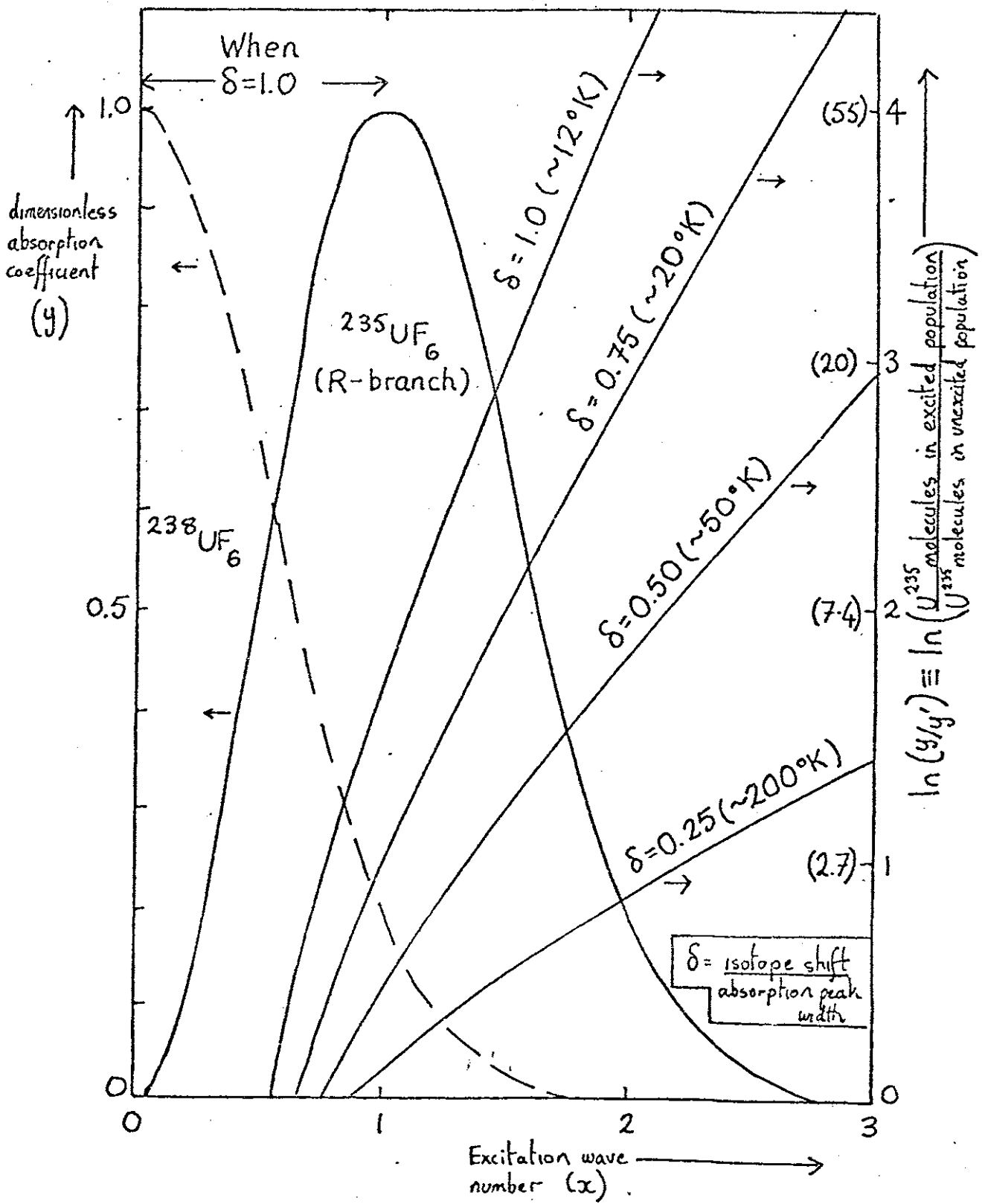


FIG. 2.20: ABSORPTION SELECTIVITY IN UF_6 AS A FUNCTION OF TEMPERATURE

[Source: C.P. Robinson et al, U.S. Patent App. S.N. 387,859, filed 14 Aug 1973]

reason the Los Alamos group indicates a preference for bulk flow nozzles of the type shown in Figs. 2.16 and 2.17.⁷⁸

Appendix I presents some calculations made for the reversible adiabatic expansion of a UF_6 :He mixture through a continuum flow nozzle. It is shown that in theory a mixture of 95% He and 5% UF_6 at room temperature (300K) and 1000 torr can be cooled to 30K by expansion through a nozzle with an area ratio (i.e. the ratio of exit area to throat area) of 12.3:1. The expanded gas will enter the constant area duct at the nozzle exit with a Mach Number of 5.3 (equivalent, at this temperature, to a velocity of 733 m/s), a pressure of 2.74 torr, and a number density of $9 \times 10^{17}/\text{cm}^3$.

In practice, the expansion will not be perfectly reversible. For example, it has been reported that when a gas mixture of 5% UF_6 and 95% He at a temperature of 300K and a pressure of about 1450 torr was expanded through a slit nozzle of area ratio 22:1, the pressure and temperature of the gas leaving the nozzle were 4 torr and 48K respectively.⁷⁹ (A reversible, adiabatic expansion with the same initial conditions would produce exit conditions of 1.5 torr and about 20K.)

After irradiation and separation of the dissociated uranium pentafluoride, the gas is decelerated in a supersonic diffuser prior to recompression. (See Fig. 2.17.) Sample calculations of the characteristic dimensions of the diffuser and of the compressor power requirements are also given in Appendix I.

Laser System

The laser system requirements can be characterized in terms of frequency, linewidth, stability, pulse repetition rate, pulse duration

and energy output. Since precise descriptions of the various transitions that might be utilized in an STS process of the type under development at LASL (cross-sections, state lifetimes, frequencies, isotope shifts, etc.) have not been discussed in the open literature, estimates of laser requirements must be speculative.

For the vibrational excitation in the infrared region, vibrations involving the ν_3 mode have received most attention. The frequencies of the fundamental ν_3 mode and some combination modes are shown in Table 2.5.

Table 2.5
Some vibrational frequencies for UF₆⁸⁰

<u>Vibration</u>	<u>E(cm⁻¹)</u>	<u>(Micrometers)</u>
ν_3	627.5 ± .5	15.9
$\nu_3 + \nu_1$	1290.9 ± .5	7.75
$\nu_3 + \nu_2$	1156.9 ± .5	8.64
$\ddot{\nu}_3 + \ddot{\nu}_5$	827.0 and 821	12.1, 12.2

Of these, the fundamental at 15.9 microns has the largest cross section.⁸¹ As the following paragraphs show, however, the availability of a tunable infrared laser in this spectral range with suitable characteristics is problematical.

The energy per pulse required of such a laser will depend on the desired irradiation path length, which will in turn depend on the absorption cross-section and UF₆ number density.

Consider, for example, the case described earlier, in which a 95%He/5%UF₆ gas mixture is adiabatically cooled to 30K, and enters the irradiation volume at a density of 10¹⁷/cm³ and a speed of about 730 m/sec. Measurements of the UF₆ absorption cross-section for the ν₃ transition, σ_a, have not been published, but one author has estimated a value of about 6 x 10⁻¹⁸ cm².⁸² The saturation pulse energy density, given by:⁸³

$$E_{\text{sat}} = \frac{h\nu}{2\sigma_a}$$

is thus, for 16 micron photons, about 1 millijoule/cm². If the UF₆ in the gas mixture is at an enrichment of 0.7% in U²³⁵, the photon interaction length:

$$l = \frac{1}{n^{235} \sigma_a^{235}}$$

for absorptions in ²³⁵UF₆ is about 5.3 meters. Thus, an irradiation depth on the order of ten meters is attainable using an infrared laser with a pulse energy density of a few millijoules/cm².

The pulse repetition rate will be determined by the velocity of the UF₆ molecules passing through the irradiation volume, and can be reduced by increasing the number of beam traverses across the slit. (See Fig. 2.16.) For example, for a typical laser beam diameter of 1 cm, a UF₆ velocity of 730 m/s, and ten beam reflections, the required pulse rate would be several kilohertz. This requirement could be further relaxed by multiplexing several lasers. (In practice, condensation of the supersaturated UF₆ may limit the length of the irradiation zone in the direction of gas flow to a few centimeters.)

The pulse duration will be determined by the lifetime of the intermediate excited state of UF_6 . Spontaneous decay rates and cross sections for vibrational energy exchange, from which excited state lifetimes could be calculated, are not available in the open literature; nevertheless, Jensen et al of Los Alamos have stated that the pulse length should not exceed one microsecond.⁸⁴

The tunability and linewidth required of the infrared laser are suggested by Fig. 2.11, which shows that good selectivity will be possible if the laser is accurate to $\pm 0.01\text{cm}^{-1}$ and has a linewidth of 0.05cm^{-1} or less.

The infrared laser requirements sketched above are summarized in Table 2.6. These needs have stimulated a widespread search for a suitable laser, which is still underway. No molecular transition has yet been found which can be made to lase in the 16 micron region with sufficient power. (Very low power tunable semiconductor diode lasers are being used for spectroscopic investigations of the UF_6 molecule, including those shown in Fig. 2.13, but such lasers are inherently unscalable to higher powers.) Many methods are under investigation which involve downshifting higher laser frequencies to the 16 micrometer range. Output from high power, efficient CO_2 lasers in the 10 micrometer region coupled with optical parametric oscillators of various kinds may be particularly suitable for these purposes.^{85,86} Other schemes potentially could avoid the need for a 16 micrometer laser altogether.*

* In an effort to circumvent the problem of finding a 16 micrometer laser, investigators at Northwestern University have suggested the use of a uranium compound which absorbs selectively in the more accessible 10 micrometer band. Recent reports indicate that some enrichment was achieved when a specially synthesized organic compound $\text{U}(\text{OCH}_3)_6$, was irradiated with a CO_2 laser.⁸⁷ (The U - O bond has a vibrational overtone in the 10 micrometer region. The vapour pressure of this compound at room temperature is only about 0.001 torr, however, and doubts have been expressed as to whether a significant throughput could be obtained with such a technique.⁸⁸

Table 2.6

Estimated requirements for infrared lasers in LASL STS
photodissociation process

Frequency	:	15.9 microns
Pulse energy density	:	several millijoules/cm ²
Pulse repetition rate	:	several kilohertz
Pulse length	:	1 microsecond
Accuracy	:	+ 0.01 cm ⁻¹
Linewidth	:	0.05 cm ⁻¹

The requirements for the second-stage, ultraviolet laser may be even more difficult to meet.⁸⁹ The calculated dissociation energy for gas phase dissociation of UF₆ to UF₅ of 76 kcal/mole indicates that a wavelength of 375 nm or less will cause dissociation.⁹⁰ In fact, it has been reported that the wavelength of the ultraviolet laser should lie within one of two broad regions: 220 to 310 nanometers and 370 to 400 nanometers. The precision required of the ultraviolet frequency is, of course, much less stringent than for the infrared laser, but the pulse repetition rate will be the same, i.e. in the kilohertz range.

Energy requirements for the ultraviolet laser can be estimated by noting that the ratio of the infrared and ultraviolet saturation energy densities is, to a first approximation, inversely proportional to the ratio of the absorption cross-sections:

$$\frac{E_{\text{sat}}^{\text{UV}}}{E_{\text{sat}}^{\text{IR}}} = \frac{a^{\text{IR}}}{a^{\text{UV}}}$$

Using the earlier estimate for $\frac{\text{IR}}{a}$ of $6 \times 10^{-18} \text{ cm}^2$, and a separate estimate of about 10^{-21} cm^2 for the photodissociation cross-section,⁹¹ the ultraviolet pulse energy density should be several joules/cm². The ultraviolet laser average power would therefore have to be on the order of ten kilowatts.*

Satisfying these criteria will place severe demands on ultraviolet laser technology. No laser has yet been found to meet them. At the present time, the rare gas halide class of excimer lasers appears to hold some promise of success. KrF lasers have already produced several hundred millijoules per pulse,⁹³ and overall efficiency may be as high as a few percent. (Excimer lasers in the 300 - 600 nm range are also of interest in laser fusion programs.)⁹⁴

No existing laser system, infrared or ultraviolet, yet meets the technical and economic requirements for commercial uranium enrichment by the LASL STS method.

The prospects for overcoming this barrier cannot now be assessed with any certainty. Nevertheless, in a careful study of laser costs recently performed by Shofner and Hoglund of the Oak Ridge Gaseous Diffusion Plant, the authors found that:⁹⁵

* Jensen et al of Los Alamos have estimated publicly that the ultraviolet laser would require repetition rates of at least 500 herz and average powers of at least one kilowatt.⁹²

. . . it is the considered opinion of many persons practising laser design and applications that, given the laser parameters, based on thorough understanding of the LIS process physics and engineering, the lasers can be developed, with high confidence level.

Energy requirements and dimensions of a commercially-sized MLIS plant

It is not yet known whether the "mainline" STS photodissociation process for uranium enrichment will ever be feasible on a commercial scale. Even at this early stage, however, rough estimates of the dimensions and energy requirements of a commercial-scale plant based on this process are useful.

A very simple model has been used to develop such estimates, and is described in more detail in Appendix II. The model calculates approximate values for some of the properties of a 1 million separative work unit per year (SWU/yr), ideal 'one-up one-down' cascade of LIS stages enriching about 1100 tons/year of natural UF_6 to 3% in U^{235} and generating a tails assay of 0.166% $U^{235}F_6$.

The choice of a 1 million SWU plant size was almost entirely arbitrary. Not enough is known about the process even to attempt to predict scale economies at this stage. As a point of reference, the optimum size for gaseous diffusion enrichment plants is in the region of 9 million SWU/yr, and current evidence suggests that gas centrifuge plants can be built economically in 1 - 2 million SWU/yr modules. A capacity of 1 million SWU/yr is sufficient to meet the annual enriched fuel requirements of several 1000 MWe light water reactors.

The choice of an ideal, 'one-up one-down' cascade configuration was less arbitrary, but equally difficult to justify from the available evidence. That some staging may be necessary to produce 3% enriched

uranium has been acknowledged by the Los Alamos group.⁹⁶ But whether the stages would be arranged in an ideal configuration - one in which there is no mixing of gas streams of different isotopic composition - is not clear. Neither is it obvious that a 'one-up one-down' configuration is optimal.*

Nevertheless, the equations describing conditions in an ideal 'one-up one-down' cascade are well-known and straightforward to apply,⁹⁸ and, given the current dearth of process information and the roughness of the estimates, this model is adequate for the calculation. The details are reported in Appendix II. In the following paragraphs, the main results are summarized.

- (1) Fig. 2.21 shows the variation in compressor power per unit of separative work as the number of stages in the cascade increases (i.e. as the stage separation factor decreases). Also shown is the effect of changes in the pressure ratio across the compressors. The results in the Figure have been calculated assuming isentropic expansion through the nozzles and a compressor isentropic efficiency of 100%. In practice, the compressors can be expected to operate at a lower efficiency. Results from the West German separation nozzle program indicate that a compressor operating under similar conditions in a small prototype facility exhibited

* Emanuel has recently shown that for cascades composed of high separation factor stages, ideal operation of a one-up one-down configuration does not necessarily minimize the separative work required for a given enrichment task; it is also shown that for such cascades the separative work is not a reliable guide for cost minimization.⁹⁷

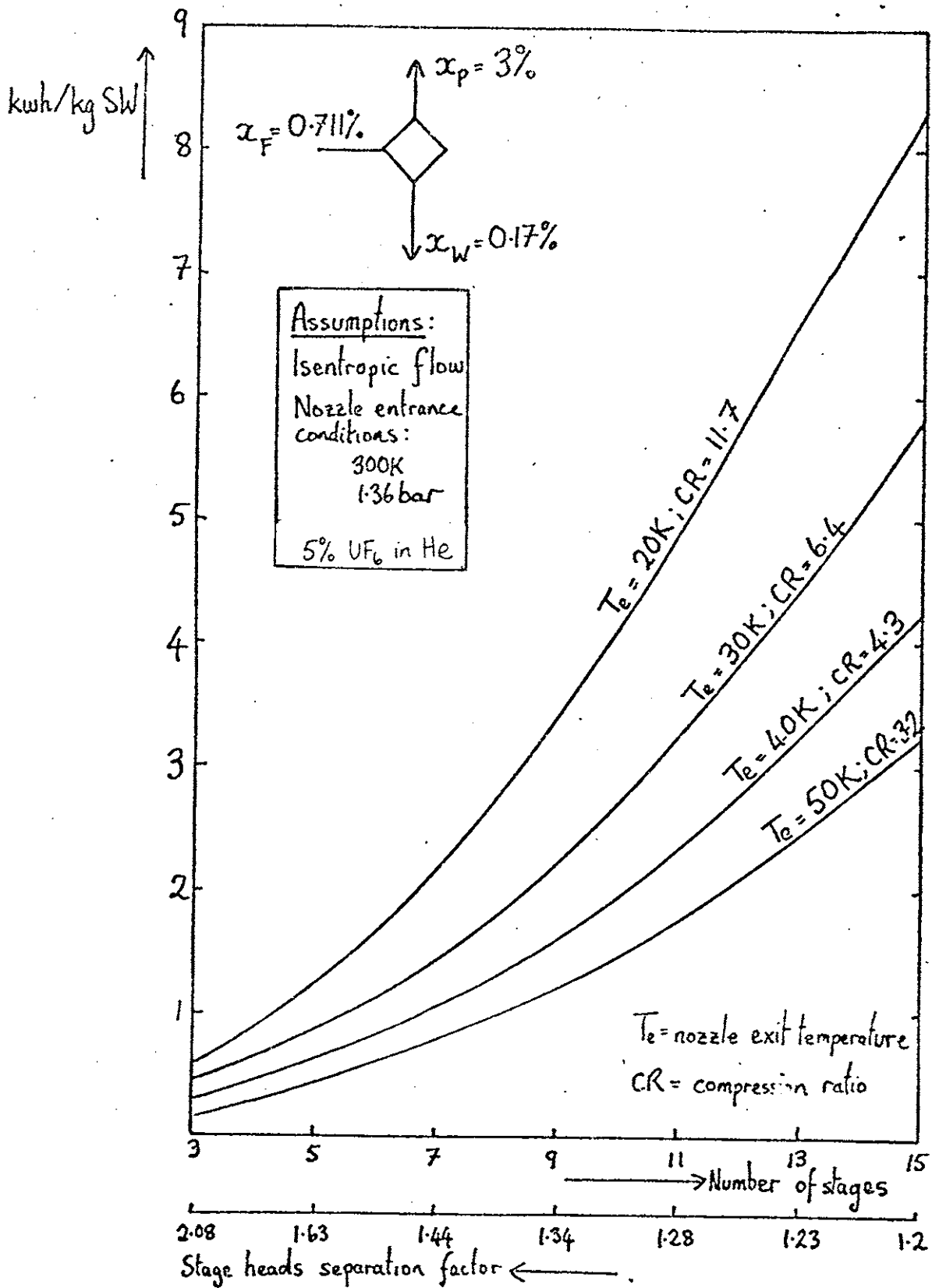


FIG. 2.21: COMPRESSION WORK FOR IDEAL, SYMMETRIC MLIS CASCADE

an efficiency of about 53%.⁹⁹ (For comparison, total energy consumption in a gas centrifuge plant is of order 100 kwhr(e)/kgSW.)

- (2) Figure 2.22 shows how the energy consumption per unit of separative work varies as a function of the heads separation factor for each of the three principal energy sinks in the cascade: the compressors, the infrared lasers, and the ultraviolet lasers. In this Figure, a 50% efficiency has been assumed for the compressors, a 1% overall or "wall plug" efficiency assumed for both IR and UV lasers, and a 100% photon utilization efficiency for both laser types.

It is not unreasonable to postulate 1% efficiencies for the IR and UV lasers. Overall efficiencies of order 1% have already been obtained for electron-beam pumped and e-beam sustained electric discharge rare gas halide lasers,¹⁰⁰ although pulse energies and repetition rates have been well below industrial LIS requirements. In the infrared spectrum, high-power CO₂ lasers with efficiencies up to 5% are routinely available, and efficiencies above 10% are not unknown, although, once again, techniques for achieving the IR laser performance criteria described earlier by downshifting CO₂ frequencies to the desired spectral region have yet to be demonstrated. Furthermore, any downshifting process is likely to reduce the overall efficiency. Despite these uncertainties, previous experience suggests that a 1% overall efficiency for LIS laser systems is not an unreasonable goal, a view shared by Shofner and Hoglund.¹⁰¹

- (3) The assumption of 100% photon utilization efficiency is unrealistic however. The actual efficiency will depend on several

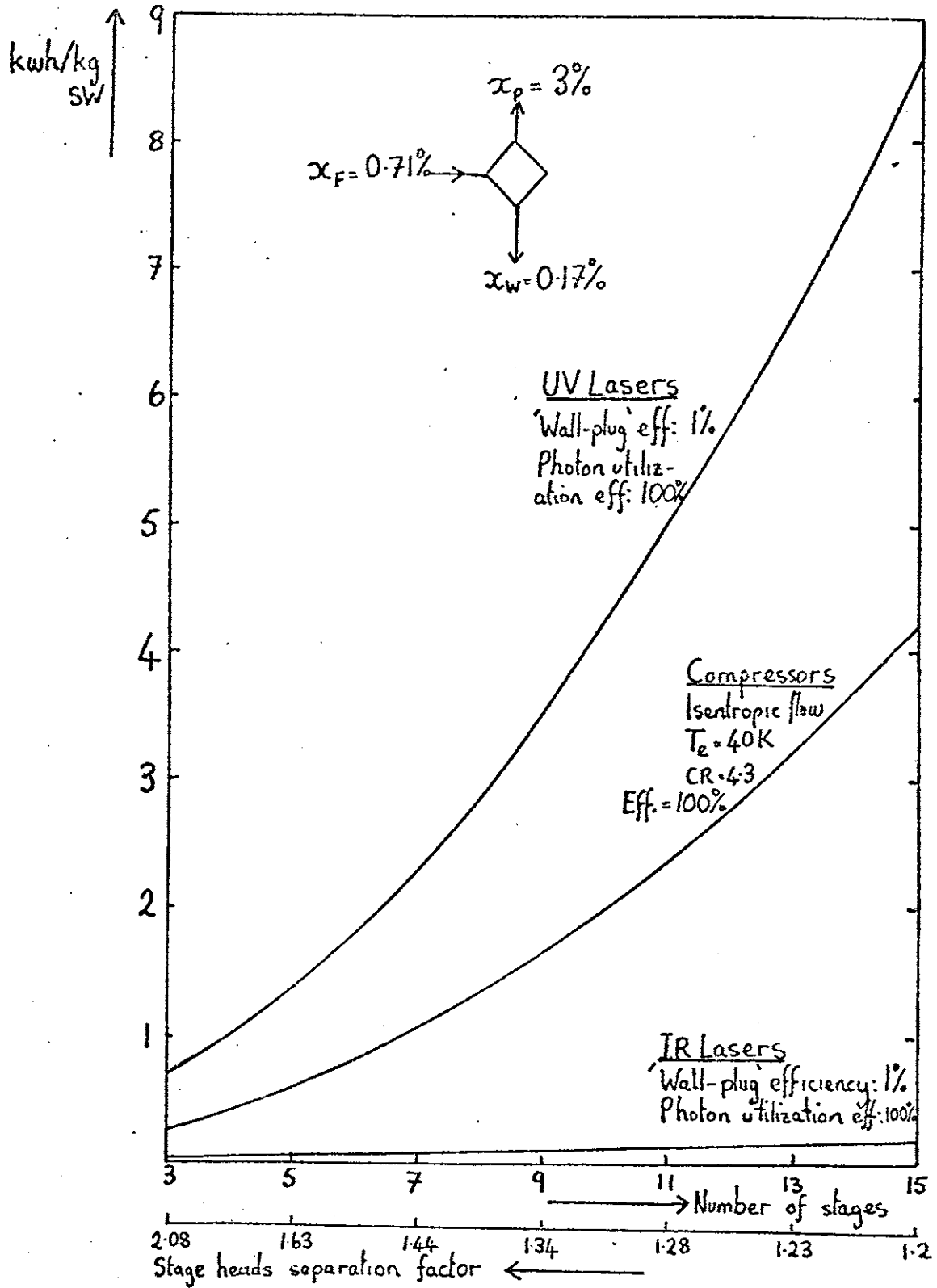


FIG. 2.22: PRINCIPAL ENERGY INPUTS: IDEAL, SYMMETRIC MLIS
CASCADE

factors whose significance cannot be estimated on the basis of the available information. These include unselective absorption of IR and UV photons in $^{238}\text{UF}_6$ molecules, vibrational energy exchange reactions between excited $^{235}\text{UF}_6$ and unexcited $^{238}\text{UF}_6$, $^{235}\text{UF}_6$ vibrational relaxation rates, solids collection inefficiencies, mirror reflection losses, and laser beam scattering and dumping losses.

Figure 2.23 merely shows parametrically the effect of decreasing efficiency on the overall cascade energy consumption for a 7-stage ideal 'one-up one-down' cascade. Also shown for comparison is the estimated specific energy consumption for the U.S. gas centrifuge plant to be constructed at Portsmouth, Ohio.

The graph illustrates the relative insensitivity of overall specific energy consumption to reduction in IR photon utilization efficiency, even to values of 1% or less. Also shown is the relatively small contribution to overall energy requirements made by the compressors. Far more important, however, is the impact of UV photon utilization inefficiencies for values below about 10%.

- (4) Table 2.7 provides an indication of the dimensions of a 1 million SWU/yr MLIS cascade. Specifically, the nozzle slit length, compressor power, and compressor capacity per stage have been estimated in ideal MLIS cascades for various assumed values of the stage heads separation factor. Such cascades are quite compact. In a 7-stage plant, for example, the total compressor capacity for all stages would be $3.2\text{m}^3/\text{sec}$ (or about 3 metric tons of UF_6/He gas per hour), and the total compressor power requirement for the cascade, assuming a 50% isentropic efficiency, would be about 240 kw. It is interest-

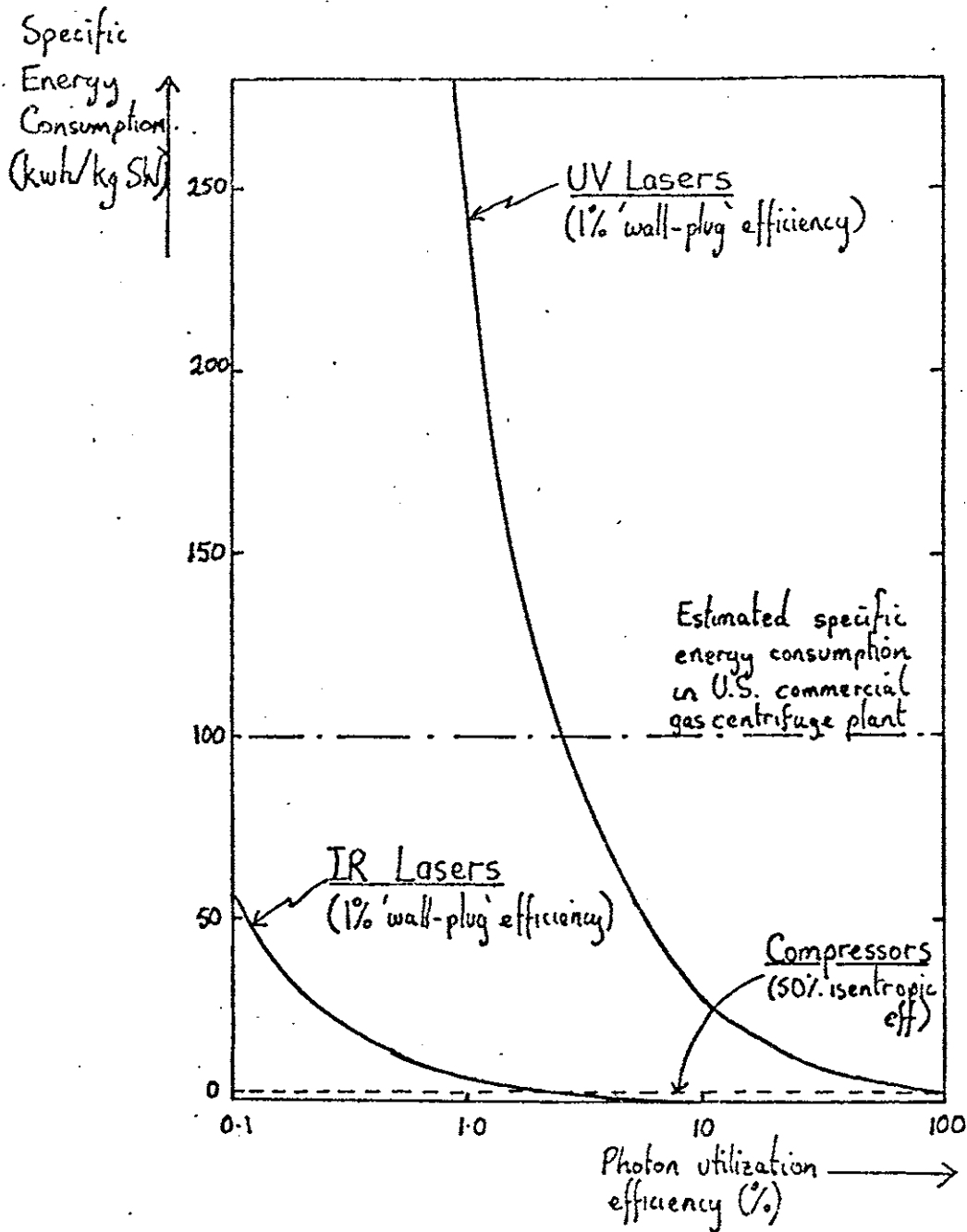


FIG. 2.23: MLIS CASCADE SPECIFIC ENERGY CONSUMPTION AS A FUNCTION OF LASER PHOTON UTILIZATION EFFICIENCY

7-stage ideal cascade
Stage heads separation factor, $\beta = 1.44$
 $x_F = 0.71\%$
 $x_p = 3\%$
 $x_w = 0.17\%$

Table 2.7

Stage Sizes for 1 MSWU/yr Ideal MLIS Cascade
 Producing 3% Product and 0.166% Tails from
 Natural UF₆ Feed *

Stage no.	$\alpha = 2.08$ ($n_T = 3$)			$\alpha = 1.63$ ($n_T = 5$)			$\alpha = 1.44$ ($n_T = 7$)			$\alpha = 1.34$ ($n_T = 9$)			$\alpha = 1.28$ ($n_T = 11$)		
	Slit lgth (m)	Comp pwr (kw)	Comp cap (m ³ /s)	Slit lgth (m)	Comp pwr (kw)	Comp cap (m ³ /s)	Slit lgth (m)	Comp pwr (kw)	Comp cap (m ³ /s)	Slit lgth (m)	Comp pwr (kw)	Comp cap (m ³ /s)	Slit lgth (m)	Comp pwr (kw)	Comp cap (m ³ /s)
1	.21	10.5	0.28	.23	11.4	0.30	0.24	11.9	0.32	.25	12.4	0.33	.25	12.6	0.33
2	.31	15.6	0.41	.36	18.5	0.49	0.40	20.3	0.54	.42	21.6	0.57	.45	22.5	0.59
3	.10	5.1	0.13	.45	22.9	0.60	0.52	26.1	0.69	.57	28.5	0.75	.60	30.3	0.80
4				.23	11.4	0.30	0.60	30.2	0.80	.67	33.7	0.89	.72	36.4	0.96
5				.09	4.3	0.12	0.36	18.2	0.48	.75	37.6	0.99	.82	41.2	1.09
6							0.20	9.9	0.26	.50	25.3	0.67	.89	45.1	1.19
7							0.08	4.1	0.11	.32	16.0	0.42	.64	32.4	0.86
8										.18	9.1	0.24	.44	22.5	0.59
9										.08	3.9	0.10	.29	14.7	0.39
10													.17	8.6	0.23
11													.08	3.8	0.10
Total	.62	31.2	.82	1.36	68.5	1.81	2.4	120.7	3.2	3.74	188.1	4.96	5.35	270.1	7.13

* Assumptions: 100% Compressor Efficiency
 Compression ratio: 4.3:1
 Isentropic Nozzle Exit Temp: 40K

ing to compare these parameters with the corresponding values for a single stage near the feed point of a 9 million SWU/yr commercial gaseous diffusion cascade. The compressor for such a stage, which would be one of the biggest of the several hundred or so stages in the cascade, typically might have a capacity of about $475\text{m}^3/\text{sec}$ (or about 600 metric tons of UF_6 per hour), and a power requirement of about 3000 kw.¹⁰²

- (5) Figures 2.21-2.23 also illustrate a key trade-off that will characterize MLIS plant designs. As the stage separation factor decreases, the compressor power requirements and capital investment requirements will increase, as Fig. 2.21 shows, and the amount of laser energy usefully absorbed will also increase, as is shown in Fig. 2.22. On the other hand, it seems at least plausible that an increase in stage separation factor will only be achievable at the cost of a reduction in the laser photon utilization efficiency, and this will entail an increase in laser capital and operating costs. Of course, insufficient information is available to allow prediction of the optimum design point.

2.4 Other applications of Laser Photochemistry

Until now, the discussion has dealt almost exclusively with laser isotope separation for uranium enrichment. It was noted at the beginning of the chapter, however, that uranium enrichment was only one of many potential applications of lasers in photochemistry, and, despite the fact that the uranium enrichment field has received by far the largest infusion of research and development funds, reflecting its overriding

economic importance, it is worthwhile mentioning some of the other areas of interest, both to set the preceding discussion in a broader technological perspective, and to provide a point of reference for some of the policy issues that will be raised in later chapters.

Basic research:

The unique properties of laser light - its spatial and temporal coherence, high intensity, monochromaticity, frequency tunability, short pulse duration, etc. - make lasers extraordinarily effective instruments for the investigation of the properties of matter on a molecular or atomic scale. The ability of lasers to stimulate and permit the observation of changes in the behaviour of individual atoms or molecules has opened up a vast reservoir of research opportunities throughout the physical and biological sciences.¹⁰³

The availability of lasers has stimulated rapid advances in the field of high-resolution molecular spectroscopy; laser radiation has also been considered for studies of the structure and behaviour of complex biological molecules such as DNA;¹⁰⁴ and lasers have been widely used in the study of chemical reaction mechanisms and chemical kinetics.¹⁰⁵

The list of current applications in basic research is far too long to report here, and the preceding paragraph serves only to provide a flavour of these activities.

Industrial applications:

Aside from fundamental research, lasers may also find applications in industrial photochemistry and chemical processing. After uranium enrichment, the largest demand for isotope separation arises in the production of heavy water, and laser-based methods for deuterium separation

are under investigation in a number of research establishments, including Lawrence Livermore Laboratory¹⁰⁶ and the research laboratories of Ontario Hydro.¹⁰⁷ Other isotopically pure materials are required for structural components in nuclear fission reactors (and also will be required in fusion plants), and certain isotopes are also used in non-nuclear applications such as production control, medical diagnosis, and environmental and agricultural studies. Letokhov and Moore note, however, that the current worldwide annual sales of all isotopes other than uranium and deuterium are under \$5 million,¹⁰⁸ and another scientist has warned against an over-emphasis on laser isotope separation methods at the expense of broader applications of lasers in chemical processing and research.¹⁰⁹

Some of these other applications are already under investigation. At Los Alamos, for example, an ArF laser has been used for the selective photodissociation and subsequent precipitation of impurities such as arsene, phosphene, and diborane from silane (SiH_4) gas.¹¹⁰ Silane purification by this technique could bring about a dramatic reduction in the cost of purified silicon used in electronic chips and solar cells. Similar techniques for chemical purification may be useful for the removal of toxic and carcinogenic substances from gas mixtures.¹¹¹ Laser radiation is also well-suited to the detection of trace amounts of materials, even at the level of single atoms or molecules.¹¹²

The opportunity provided by lasers to manipulate molecular bonds selectively has raised the possibility that lasers might be used efficiently to synthesize chemical compounds such as pharmaceuticals which previously have been difficult or even impossible to produce.

Finally, it has been suggested that laser photochemical reactions in the liquid phase might be used for the fractionation of high-level wastes generated during the reprocessing of spent fuel. Selective excitation and subsequent photochemical reaction schemes may permit the removal and subsequent processing of the more highly radioactive or longer-lived radionuclides which cannot be separated practically using conventional chemical methods.^{113,114} The task of confining the residual waste from the biosphere may be eased significantly as a result.

At this stage, the prospects for industrial applications of laser photochemistry in the non-nuclear field appear promising, but not unlimited. The great precision with which lasers can introduce energy into reactant media has led to speculation that the entire chemical processing industry may be revolutionized as a result. Scientists note, however, that bulk chemical production by 'stoichiometric' photochemistry (i.e. where there is a one-to-one correspondence between the number of molecules or atoms of desired product and the number of laser photons usefully used), is unlikely to be economic in the near future, if ever, if only because of the high capital cost and low energy efficiency of most lasers. In the case of pharmaceuticals and other high-value materials produced in low volume, of course, the economic prospects may be considerably more favourable.

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Appendix I: Approximate Calculation of the Behavior of MLIS Supersonic

Nozzle Cooling System

The following equations are useful for estimating the operating characteristics of supersonic nozzles:*

For adiabatic expansion of a perfect gas,

$$\frac{T_e}{T_o} = \left(\frac{P_e}{P_o} \right)^{\frac{\gamma-1}{\gamma}} \quad (1)$$

and,

$$\frac{T_o}{T_e} = 1 + \left(\frac{\gamma-1}{2} \right) M_e^2 \quad (2)$$

where,

$$M_e = \frac{V_e}{\sqrt{\gamma R T_e}} \quad (3)$$

and M_e is the nozzle exit Mach number, V_e is the exit flow velocity, T_e is the exit temperature, P_e is the exit pressure, and P_o and T_o are the nozzle entrance pressure and temperature respectively.

Since, for a perfect gas, $\frac{P}{\rho} = RT$, from (1) and (2)

$$\frac{\rho_o}{\rho_e} = \left(1 + \frac{\gamma-1}{2} M_e^2 \right)^{\frac{1}{\gamma-1}} \quad (4)$$

and

$$\frac{P_o}{P_e} = \left(1 + \frac{\gamma-1}{2} M_e^2 \right)^{\frac{\gamma}{\gamma-1}} \quad (5)$$

* The definitions of the various symbols appear in the section on nomenclature at the end of Appendix II.

For the isentropic expansion of an ideal gas through a converging-diverging nozzle, the following results apply:⁺ The nozzle throughput is maximized when the flow speed at the throat equals the speed of sound; under these conditions:

$$\left(\frac{w}{A}\right)_{\max}^* = \sqrt{\frac{\gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \cdot \frac{P_0}{\sqrt{T_0}}} \quad (6)$$

$$M^* = 1 \quad (7a)$$

$$\frac{T^*}{T_0} = \frac{2}{\gamma+1} \quad (7b)$$

$$\frac{P^*}{P_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \quad (7c)$$

$$\frac{\rho^*}{\rho_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \quad (7d)$$

where w is the mass flowrate, A is the nozzle flow area and the $*$ refers to conditions at the nozzle throat. The flow speed at the nozzle exit when the nozzle passes the maximum through-put is given by:

$$\frac{A_e}{A^*} = \frac{1}{M_e} \left[\left(\frac{2}{\gamma+1}\right) \left(1 + \frac{\gamma-1}{2} M_e^2\right) \right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (8)$$

where A_e is the flow area at the nozzle exit. The quadratic form of this equation reflects the fact that there are two possible exit conditions, one supersonic and one subsonic. For the remainder of this analysis, we shall only be concerned with the supersonic flow condition.

⁺ The following equations are extracted from A. Shapiro, Compressible Fluid Flow, (New York: Ronald Press, 1953).

Consider a gas mixture of 95% helium and 5% UF_6 , a typical composition for an MLIS process. The initial temperature and pressure of the gas are 300K and 1000 Torr respectively. The gas is to be expansion-cooled to 30K in order to achieve the desired isotopic selectivity in the irradiation region. The above equations may be used to estimate the nozzle characteristics and exit conditions.

It is assumed that the mixture behaves as a perfect gas and that the expansion is isentropic. Then, from equations (1), (4), and (2), the Mach Number, number density, and gas pressure at the nozzle exit are respectively 5.3, $9.1 \times 10^{17} \text{ cm}^{-3}$, and 2.74 Torr. From (3), the exit velocity is 733m/s. From (8), the nozzle area ratio, $\frac{A_e}{A^*}$, is 12.3:1.

Similarly, it can be shown that the isentropic expansion of a mixture of 95% He and 5% UF_6 , initially at 1650 Torr and 300K, through a nozzle of area ratio 22:1 would result in exit conditions of 20.6K and 1.5 Torr respectively. An experimental simulation of these conditions gave exit conditions of 48K and 4 Torr, indicating the extent of irreversibilities in the flow in practice.¹

The supercooled gas stream, after passing through the irradiation section and the solids separator, enters a supersonic diffuser, after which it is recompressed. (See Figs. 2.17 and 2.18) The compression work is calculated as follows: The diffuser throat width must be large enough to pass the maximum nozzle throughput (given by (6)). Because of the irreversibility associated with the shock front in the diffuser separating the supersonic and subsonic flow regions, the minimum diffuser throat width must be larger than the nozzle throat width; the area ratio is inversely proportional to the stagnation pressure ratio across the shock, i.e.,

$$\frac{A_d^*}{A^*} = \frac{P_{ox}}{P_{oy}} \quad (9)$$

where the stagnation pressure ratio is determined by the Mach Number on the upstream side of the shock according to the following equation:

$$\frac{P_{oy}}{P_{ox}} = \frac{\left[\frac{\frac{\gamma+1}{2} M^2}{1 + \frac{\gamma-1}{2} M^2} \right]^{\frac{\gamma}{\gamma-1}}}{\left[\frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma-1}{\gamma+1} \right]^{\frac{1}{\gamma-1}}} \quad (10)$$

When the shock occurs at the diffuser throat, the upstream Mach Number is at its lowest possible value. At this condition, the stagnation pressure loss (and thus the irreversibility), is minimized; the diffuser is thus functioning at its optimum operating condition.

In practice, the minimum diffuser throat area is determined not by the optimum operating condition but by the start-up condition, i.e. the throat must be large enough to pass the maximum nozzle flow when the shock front is located in the constant area duct upstream of the diffuser entrance; at this location, the irreversibility loss is greater.

Using the results of the first example above, the Mach Number in the constant area duct is 5.3. Then, from (10), the "start-up" stagnation pressure ratio is 0.113. From (9), the ratio of the diffuser throat area to the nozzle throat area is 8.8:1,* and thus the limiting contraction ratio of the diffuser is $\frac{8.8}{12.3} \sim 0.71:1$.

* It is assumed here that the change in γ that occurs owing to the photo-dissociation and removal of part of the UF_6 is negligible.

At the optimum operating condition for the diffuser, the shock occurs at the throat. At this location, the Mach Number on the upstream side of the shock is, from (8), 4.68.

Then, from (9), the stagnation pressure ratio at the optimum operating condition is 0.156, and the stagnation pressure of the gas entering the compressor is 156 Torr. The isentropic compression energy for an ideal gas is calculated from the well-known equation:

$$-W_c = \frac{1}{\gamma-1} P_1 V_1 \left\{ \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \quad (11a)$$

$$= \frac{1}{\gamma-1} RT_{oy} \left\{ \left(\frac{P_2}{P_{oy}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \quad (11b)$$

Since the expansion is adiabatic, the stagnation temperatures upstream and downstream of the shock are equal, i.e., $T_{oy} = T_{ox} = 300K$. Thus, for $P_2 = P_{ox} = 1000$ Torr, the compression energy ($-W_c$) is 4150 Joules/gm-mole of gas.

Note

1. C.P. Robinson et al, "Isotope Separation by Laser Means", U.S. Patent Application S.N. 387,859, filed 16 August 1973, (declassified 3 March 1978).

Appendix II: Scoping Calculations for a 1 MSWJ/yr-equivalent MLIS Cascade

In this appendix, approximate calculations are presented which may be used to estimate the energy requirements of a commercial MLIS plant.

Assumptions:

It is assumed that the plant is arranged in the form of a symmetric cascade (i.e., the enriching and stripping sections have the same number of stages). It is to produce 3% enriched uranium from natural feed; the symmetry condition requires that tails material will be produced at an assay of 0.166%. The capacity of the plant is set at 1 million kgSW/yr equivalent. Such a plant would produce roughly 210,000 kg/yr of 3%-enriched uranium; enough to meet the annual requirements of 6-8 1000 MWe LWRs. The plant flowsheet is shown in Figure II.1.(a).

The plant is based on the 'mainline' LASL selective two-step (STS) photodissociation process. (See Chapter 2, section 2.3.4).

It is assumed that the individual stages have identical separation factors and are arranged in the form of an ideal (i.e., no-mixing) 'one-up one down' countercurrent cascade, as shown in Figure II.1.(b). There is no reason to believe that this will be the case in practice. For cascades composed of high separation stages the ideal configuration typically will not correspond to the minimum separative work, as it does, for example, in close separation gaseous diffusion or gas centrifuge plants. Furthermore, for high separation MLIS cascades, even in the ideal mode, separative work may not be a useful measure of the enrichment cost. In practice, an optimized MLIS cascade may be neither ideal nor even necessarily arranged in a 'one-up one down' configuration.¹

Nevertheless, the equations for such cascades are well-known and straightforward to apply, and since insufficient information is available

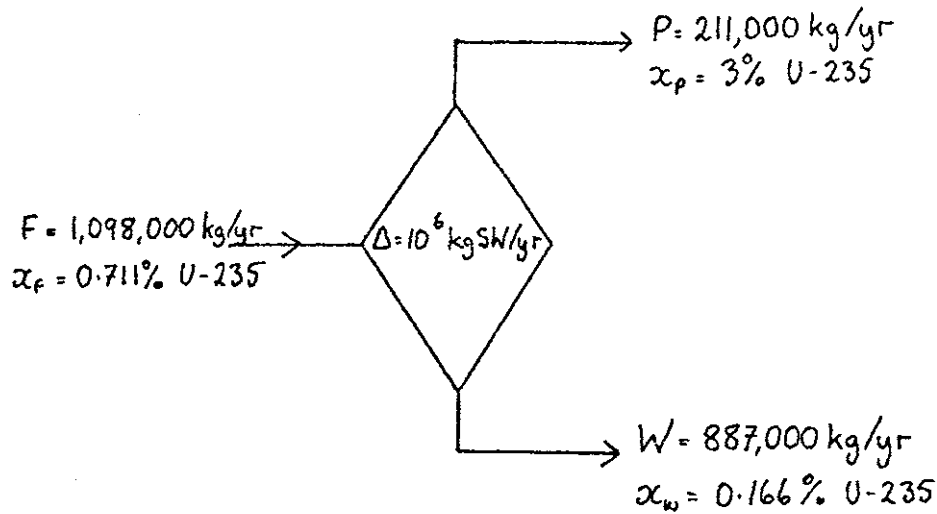


FIG. II. 1. (a): PLANT FLOWSHEET FOR IMSWU/YR SYMMETRIC MLIS CASCADE

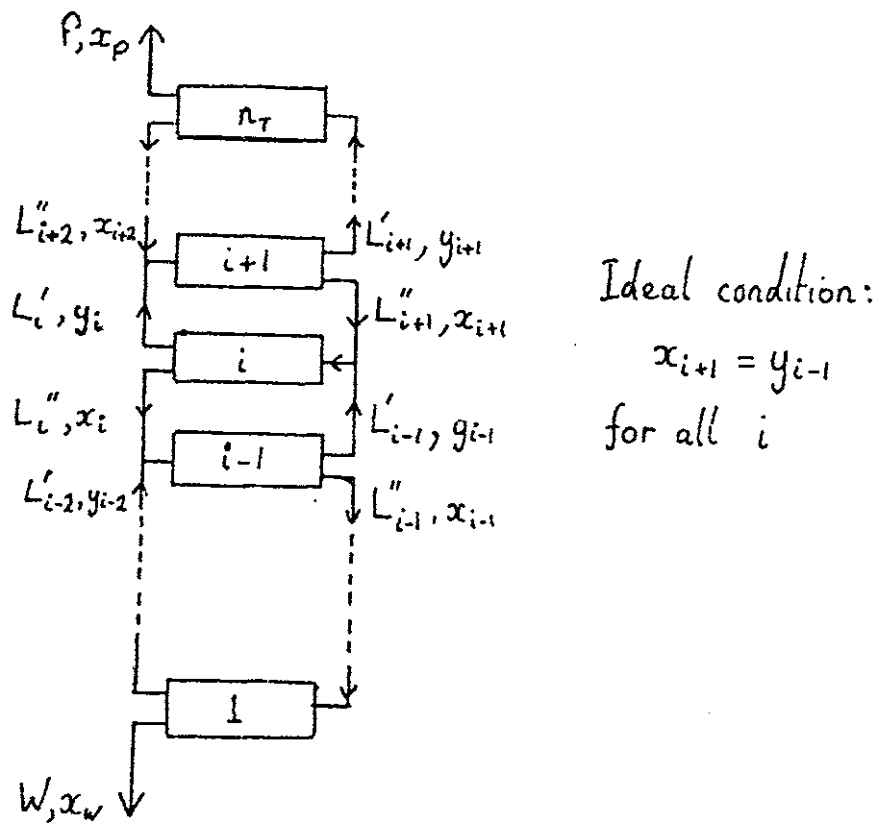


FIG. II. 1. (b): IDEAL 'ONE-UP ONE-DOWN' COUNTERCURRENT CASCADE CONFIGURATION

to predict the optimum configuration it is convenient to apply them here. The results will in any case meet the desired objective of providing rough estimates of key plant parameters.

Ideal Cascade Equations

The following equations are useful for calculating ideal cascade performance:²

$$\alpha = \beta^2 \quad (1)$$

where α is the overall stage separation factor, $\frac{y(1-x)}{x(1-y)}$, and β is the stage heads separation factor, $\frac{y(1-z)}{z(1-y)}$, and z , y , and x are the stage feed, product and tails compositions respectively.

The number of enriching stages,

$$n_P = \frac{\ln \frac{x_P (1-x_F)}{x_F (1-x_P)}}{\ln \beta} \quad (2)$$

The number of stripping stages,

$$n_W = \frac{\ln \frac{x_F (1-x_W)}{(1-x_F)x_W}}{\ln \beta} - 1 \quad (3)$$

and, since the cascade is symmetric,

$$n_W = n_P - 1 \quad (4)$$

The cut at stage i , θ_i , is:

$$\theta_i = \frac{1 + (\beta-1)Z_i}{\beta + 1} \quad (5)$$

The total internal flowrate in the cascade, J , is:

$$J = \frac{\beta + 1}{(\beta-1)\ln\beta} \left[P\phi(x_P) + W\phi(x_W) - F\phi(x_F) \right] \quad (6)$$

where,

$$\phi(x) = (2x-1)\ln \frac{x}{1-x} \quad (7)$$

In the enriching section, the tails flow from stage $i+1$, L_{i+1}'' , is:

$$\frac{L_{i+1}''}{P} = \frac{1}{\beta-1} \left[x_P (1-\beta^{i-n}) + (1-x_P) \beta (\beta^{n-i}-1) \right] \quad (8)$$

and the heads flow from stage i is:

$$L_i' = P + L_{i+1}'' \quad (9)$$

In the stripping section, the heads flow from stage j , L_j' , is:

$$\frac{L_j'}{P} = \frac{1}{\beta-1} \left[x_W \beta (\beta^j-1) + (1-x_W) (1-\beta^{-j}) \right] \quad (10)$$

and the tails flow from stage $j+1$ is:

$$L_{j+1}'' = W + L_j' \quad (11)$$

The stage separation factor that will be achievable in commercial MLIS plants cannot yet be predicted. The calculations are thus performed for a range of separation factors, where the particular values chosen correspond to integer values of the number of enriching and stripping stages in the cascade (see equations (2) - (4)). The values are tabulated below:

Total number of stages ($n_T = n_W + n_P$)	Stage heads separation factor (β)
1	4.32
3	2.08
5	1.63
7	1.44
9	1.34
11	1.28
13	1.23
15	1.20

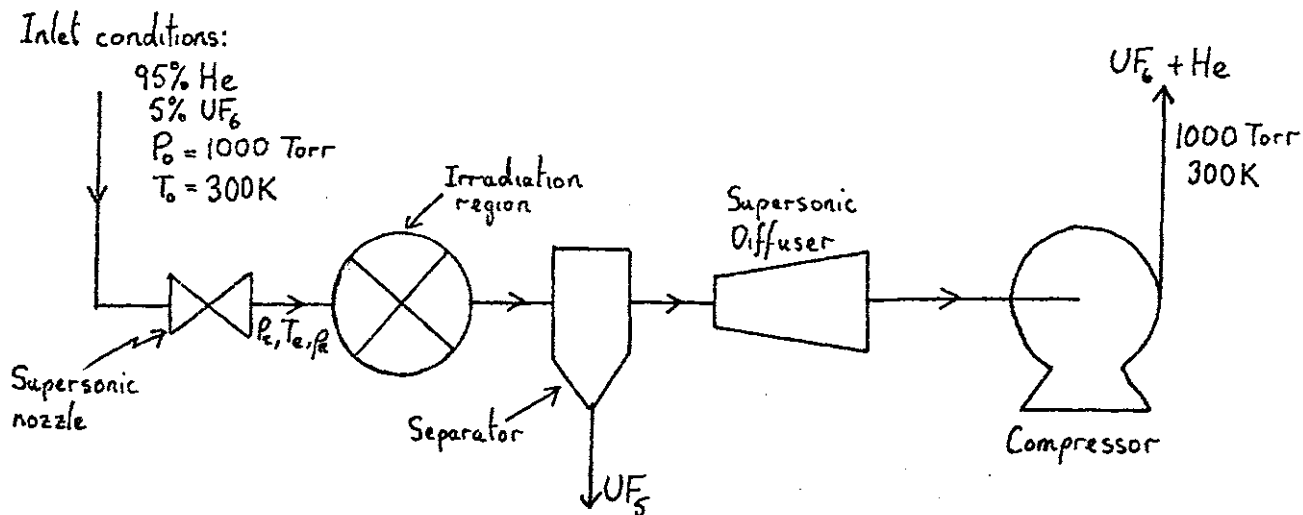
Cascade Energy Requirements

There are three major energy sinks in an STS photodissociation MLIS cascade: the gas compressors, the infrared lasers, and the ultraviolet

lasers. We estimate the energy requirements for each in the following sections.

(i) Compressor Power Requirements

Each stage is arranged as shown below:



The initial conditions are typical values for adiabatic cooling of UF_6 taken from a LASL patent.³ For any set of initial conditions and a given nozzle exit temperature, the compressor work per unit of gas flow can be calculated according to the procedure presented in Appendix I.

The relationship between the stage separation factor and the nozzle exit temperature has not been disclosed and the desired nozzle exit temperature cannot be predicted; the compressor work was therefore calculated for a range of nozzle exit temperatures. The specific compressor work, (i.e., the compressor work required per unit of separative work) can then be calculated from equation (1) in Appendix I and equation (6) above. The results for a range of values of nozzle exit temperature and stage separation factors are presented in Figure 2.19 in the main text.

(ii) IR and UV Laser Power Requirements

No information to speak of has been disclosed concerning the relation-

ship between the stage separation factor and the laser pulse intensity, and there is practically no information available on photon absorption and 'scrambling' collision cross sections and excited state lifetimes, etc. which would allow an estimate to be made of this relationship.

Consequently, the laser power requirements are estimated parametrically as a function of a photon utilization efficiency ν_{IR} or ν_{UV} , defined as:

$$\nu = \frac{\text{number of photons usefully absorbed in } U^{235} \text{ F}_6 \text{ molecules per laser pulse}}{\text{number of photons emitted per laser pulse}}$$

The rate at which photons are usefully absorbed is approximately equal to the total flowrate of U^{235} - bearing molecules in the heads streams from all stages. This flowrate can be calculated with the assistance of equations (8)-(10). The results are illustrated in Figures 2.22 and 2.23 of the main text.

Notes to Appendix II

1. George Emanuel, "High-Enrichment Steady-State Cascade Performance", Nuclear Technology, 43, 314 (1979).
2. M. Benedict and T. Pigford, Nuclear Chemical Engineering (New York: McGraw-Hill, 1957).
3. C.P. Robinson et al, "Isotope Separation by Laser Means", U.S. Patent Application S.N. 387,859, filed 16 August 1973, (declassified 3 March 1978).

Nomenclature: Appendices I and II

T_e = gas temperature at supersonic nozzle exit

P_e = gas pressure at supersonic nozzle exit

M_e = Mach number at supersonic nozzle exit

ρ_e = gas density at supersonic nozzle exit

V_e = gas speed at supersonic nozzle exit

$T_o, P_o, M_o, \rho_o, V_o$ refer to the corresponding gas properties at the nozzle entrance.

$T^*, P^*, M^*, \rho^*, V^*$ refer to the corresponding gas properties at the nozzle throat at the Mach 1 condition.

$A^*, A_e,$ and A_d^* are the flow areas at the nozzle throat, nozzle exit, and diffuser throat, respectively.

$P_{ox}, T_{ox},$ and P_{oy}, T_{oy} are the stagnation pressures and temperatures respectively upstream and downstream of the shock front in the diffuser.

γ = specific heat ratio for the gas

R = universal gas constant

w = mass flowrate of gas

$(-W_c)$ = specific compression work

α = overall stage separation factor (heads to tails)

β = stage heads separation factor (heads to feed)

L_i, L_i', L_i'' = feed, product, and tails flowrates for stage i

θ_i = stage i cut

Z_i, Y_i, X_i = feed, product, and tails compositions (mole fractions) for stage i .

F, P, W, x_f, x_p, x_w = cascade feed, product and tails flowrates and compositions (mole fractions)

n_p = number of stages in cascade enriching section

n_w = number of stages in cascade stripping section

n_T = total number of stages in cascade

CHAPTER 3

THE ECONOMICS OF LASER ENRICHMENT

This chapter consists of a preliminary analysis of the economic prospects for laser enrichment technologies. The utility of the separative work concept for high separation factor enrichment processes is first examined in section 3.1. Some preliminary estimates of laser enrichment costs are then presented, along with a brief discussion of the sensitivity of these estimates to changes in the costs of key inputs, including energy and laser capital costs. In sections 3.3 and 3.4, the potential contribution of laser enrichment technologies to nuclear electricity cost economies and uranium conservation measures is analysed. Nuclear power scenarios for the next half century are developed for the latter purpose. Finally, section 3.5 takes up the question of when the next generation of enrichment technologies might optimally be introduced into the marketplace. The supply and demand prospects for enrichment services over the next fifteen years are examined, first from a U.S. perspective, and then for the world as a whole.

3.1 Laser enrichment costs and separative work

Separative work is a measure of the amount of effort required to perform an enrichment task. The concept of separative work was originally developed in connection with the design and construction of large uranium isotope separation cascades in the United States during the war. In the following discussion, we shall use some expressions and a few results drawn from the theory of isotope separation cascades; in general, the terms used are defined in the text. In addition, however, Appendix 3.5 contains a brief discussion of terminology and presents some useful results from cascade theory. Other results are given in Appendix II of Chapter 2.

Consider the enrichment task of separating F kilograms of uranium with an initial U^{235} mole fraction x_F into P kilograms of product of composition x_P and W kilograms of 'tails' of composition x_W . In this case,

$$x_P > x_F > x_W$$

The separative work required for this task is defined as:

$$\Delta = P(2x_P - 1) \ln(x_P/1 - x_P) + W(2x_W - 1) \ln(x_W/1 - x_W) - F(2x_F - 1) \ln(x_F/1 - x_F) \quad (1)$$

This quantity only has physical significance when the enrichment task is performed in an 'ideal' cascade of separating units, i.e. a cascade in which the individual separating units are arranged so that nowhere is there any mixing of streams of different composition.*

In this case, the separative work is proportional to the total amount of material flowing through the cascade during the course of the separation.

Similarly, if a cascade is producing product and tails streams at rates \dot{P} and \dot{W} and with compositions x_P and x_W respectively from a feed stream of flowrate \dot{F} and composition x_F , the rate at which the cascade is doing separative work, or the separative power, is defined as

$$\dot{\Delta} = \dot{P}(2x_P - 1) \ln(x_P/1 - x_P) + \dot{W}(2x_W - 1) \ln(x_W/1 - x_W) - \dot{F}(2x_F - 1) \ln(x_F/1 - x_F) \quad (2)$$

And if the cascade is in the ideal configuration, then the separative power is proportional to the total internal flowrate in the cascade.

The importance of the total flow in a cascade is that often it is itself proportional to many of the properties which determine the cost of an enrichment task. In a gaseous diffusion cascade, for example, the total flowrate is proportional to the barrier area and total compressor

* It can be shown that for close separation cascades, i.e. those with stage separation factors close to unity, the ideal configuration of all possible cascade arrangements is the one for which the total material throughput (and thus the separative work) for a given enrichment task is minimized.

capacity, and since these components account for much of the capital investment in the cascade, the total flowrate is roughly proportional to the investment cost of the facility; also, the annual throughput of material determines annual operating costs such as the power cost. For such plants, therefore, the separative power is, to a good approximation, proportional to the annual capital charges and operating costs. The same is true for centrifuge plants. Since, for such plants, there is frequently sufficient operating flexibility that the available separative power (or separative capacity) can be held roughly constant over a broad range of external stream conditions (i.e., flows and compositions), a unit cost of separative work can be defined for a particular plant, and used to compute the total cost of performing any given enrichment task in the plant, provided that the allowable range of input and output conditions is not exceeded. The unit cost of separative work has become the standard measure of the economic performance of enrichment facilities.

For laser enrichment technologies, however, the concepts of separative capacity and separative work unit costs are useful only as a means of making economic comparisons. The AVLIS processes described in the previous chapter are of the single-stage type, designed for a specific enrichment task, i.e., the feed enrichment, flowrate, and stage separation factor are intrinsic design parameters. Separative capacity as defined in Eq. 2 has no physical significance in such a plant, and there is correspondingly no meaningful relationship between the amount of separative work and the cost of enrichment.

It is naturally possible to derive an "equivalent" unit cost of separative work for an AVLIS plant operating at its design condition. This cost can then be compared with the separative work cost of a centrifuge or diffusion plant. However, such a comparison is valid only for the particular

enrichment task for which the laser plant has been designed.*

MLIS plants will probably require staging, and it is possible that the cascade will be operated in the ideal mode. For high separation factor stages, however, the ideal configuration typically does not minimize either the total internal flow or the cascade separative work. Furthermore, even if high separation cascades are operated in the ideal mode, it is not necessarily correct to assume that the separative work output (and the total internal flow) are proportional to the total cost of the enrichment task. Thus, once again, there is no theoretical significance to the unit cost of separative work, and it seems prudent to assume that unit costs given for MLIS processes are valid only for the specified enrichment task, unless information to the contrary is available.

3.2 Laser enrichment cost estimates

A prominent feature of all current estimates of laser enrichment costs is the large uncertainty attached to them. Part of this is attributable to the existence of restrictions preventing the diffusion of relevant technical and economic information, and the rest to the relatively early stage of technology development. The latter species of uncertainty includes:

- (i) basic uncertainty as to the nature and design specifications of process components;
- (ii) uncertainty over the manufacturing costs of process components, many of which have never yet been constructed on an industrial scale or in industrial quantities, and some of which have no industrially mature analogues;

* Some of the issues involved in operating AVLIS plants at 'off-design' conditions are described in Chapter 4.

(iii) uncertainty over the operating behaviour of key process components due to lack of experience, particularly the reliabilities and lifetimes of lasers, optical elements, laser pumps, power supplies, uranium ovens, etc. Annual capital replacement, operating and maintenance costs may account for a substantial fraction of the total enrichment cost.

A great deal of additional engineering will be required before these and other uncertainties can be resolved. There have, nevertheless, been several preliminary attempts at laser enrichment cost estimation, some of which are presented in Table 3.1. Where possible, the estimated total separative work unit cost, unit capital cost, and specific energy consumption are shown, together with the assay range over which the estimates are valid. Shown for comparison are corresponding data for gas centrifuge and gaseous diffusion plants.

According to these estimates, both AVLIS and MLIS processes show significant advantages over conventional technologies in terms of both separative work unit costs and initial capital investment requirements. (No information on the economies of scale of laser processes is available, however, although JNAI has indicated that the minimum size for a depleted feed commercial AVLIS plant will require "thousands of tons of feed" per year, equivalent to 1 MSWU/year or more).¹

Interestingly, cost estimates for the Livermore AVLIS process are substantially lower than for the JNAI technology. The difference may be due to significant technical differences between the two programs. It is widely recognized, however, that differences in institutional perspective frequently lead privately owned, profit-making concerns to adopt a more conservative approach to the process of cost estimation than that practiced

Table 3.1

Enrichment Cost Estimates

Technology	Separative work cost (\$/kg SW)	Capital cost (\$-yr/kg SW)	Energy consumption (kwh (e)/kg SW)	Assay Range	Source
AVLIS	<40	<110		n.s. ^j	Davis, Livermore ^a (1979)
AVLIS		195	175	feed: ~0.7% product: ~3% tails: n.s.	G.S. Janes et al, ^b JNAI (1977)
AVLIS	~54	~ 225 - 310	160	feed: ~0.2% product: ~3% tails: ~0.08%	JNAI (1979) ^c
AVLIS/MLIS	< 50			feed: ~0.2% product range: 0.711% - 3% tails range: 0.05% - 0.1%	DOE (1979) ^d
MLIS	23 - 29	92 - 107		feed: 0.2% - 0.7% product: 3% tails: <0.1% ^k	<u>Nuclear Fuel</u> (1979) ^e
MLIS		15	24	n.s.	Jensen et al, ^f LASL (1976)
Gaseous diffusion	110 - 140 (\$1978)	200 (\$1974) 463 (\$1979)	~ 2500		Eurodif ^g
Gas centrifuge	85 - 95 (\$1978)	480 (\$1978)	105		DOE (1978) ^h

Notes to Table 3.1

- a. James Davis, Lawrence Livermore Laboratory, Interview, 16 March 1979
- b. G.S. Janes et al, Am. Inst. Chem. Eng. Symposium Series, 73 (169), 62-68 (1977)
- c. H.K. Forsen, Exxon Nuclear Co., Interview, 4 December 1978. The unit separative work and capital costs are the author's own estimates based on an assumed 15% return on investment and several pieces of information provided on various occasions by JNAI. The derivation of this estimate is presented in Appendix 3.1.
- d. N. Haberman, Office of Advanced Isotope Separation, U.S. Department of Energy, Interview, 11 April 1979
- e. Nuclear Fuel, May 14, 1979, 11
- f. R.J. Jensen et al, "Prospects for uranium enrichment", Laser Focus, May 1976, 51-63
- g. The data presented refer to the Eurodif diffusion plant at Tricastin, France. The sources for the three items were: Jean-Francois Petit, "Uranium enrichment by Eurodif/Coredif", Atomic Industrial Forum International Conference on Uranium Enrichment, New Orleans, January 31 1978; Nuclear News, May 1979, 62; Jean-Pierre Rougeau, Director-General of marketing, Eurodif, reported to the author by Carolyn Heising, Department of Nuclear Engineering, M.I.T., July 1979. The specific energy consumption of 2500 kwh/kg SW corresponds closely

to the value of 2330 kWh/kg SW reported for the upgraded DOE gaseous diffusion complex. See: M. Benedict et al, Nuclear Chemical Engineering, (2nd ed.), Ch. 14 (draft).

- h. R.A. Wolfe, "U.S. Gas Centrifuge Program", Atomic Industrial Forum International Conference on Uranium Enrichment, New Orleans, January 30, 1979.
- j. n.s. = not specified
- k. John Marinuzzi, Los Alamos Scientific Laboratory, New Mexico, Telephone interview, July 24, 1979.

by the national laboratories. It is not clear to what extent such factors might have intervened in this particular case.

Table 3.1 also suggests that for both AVLIS and MLIS, as for the gas centrifuge process, the contribution of energy costs to the total cost of separative work will be relatively small (less than 10% for all three cases).

For the JNAI process, only about 13% of the total energy consumption is used by the laser system. Thus, even a 10-fold improvement in laser efficiency (from the current level of about 0.2%) or in the photon utilization efficiency would only reduce energy costs by about 40¢/kg SW. Some 50% of the total energy is required for uranium vaporization; most of the remainder is divided among the uranium metal preparation, dye processing, and uranium recovery systems.²

For the 'mainline' LASL STS MLIS process, most of the energy required will be consumed by the compressors, infrared lasers and, especially, the ultraviolet lasers. Calculations presented in Chapter 2 show that compressor power requirements would be in the range 1 - 10 kWh(e)/kg SW for an ideal cascade, the actual amount depending on specific process parameters and compressor efficiency. (See Figs. 2.21 and 2.22.) As Fig. 2.23 shows, the UV photon utilization efficiency is an important parameter in the overall energy economy of the process. At a laser efficiency of 1%, the UV photon utilization efficiency in such a cascade would have to be on the order of 10% or more for total energy consumption to be significantly lower than in centrifuge facilities (see Fig. 2.23). But once again, a 10-fold improvement in either of these two efficiencies would only reduce total energy costs by \$1/kg SW or less.

A related consequence of the generally low energy cost component for AVLIS, MLIS and the centrifuge process is that the relative costs of the

three will be quite insensitive to changes in electricity price. For example, even though AVLIS is projected to consume nearly 70% more energy than gas centrifugation, electricity prices would have to increase 18% per year faster than the prices of other goods and services if the unit costs of separative work from the two types of plants were to have equalized by the year 2000. In comparison, the same escalation rate differential was only about 4% during the period 1970-77, when general price levels rose on average by 6.4% per year, and electricity prices rose by 10.5% per year.³ If this trend were to continue, price equalization for the two processes would not occur until 2050.

Other components of the unit cost of separative work are not specified in the estimates of Table 3.1, and the current scarcity of process information prevents attempts at detailed cost breakdowns. A consideration of potential laser system costs is indicative of the difficulties involved.

Typical laser output powers for the JNAI AVLIS process are expected to be on the order of 100 watts. Commercially available pulsed lasers of several kinds (e.g., CO₂, dye, neodymium:yag) in this range are known to have capital costs of about \$200/watt. (See Fig. 3.1 for recent price data taken from the 1978 Laser Focus Buyers' Guide.) These figures do not incorporate costs of associated optics and other accessories. AVLIS lasers will require highly specialized beam determination, stabilization, combination, synchronization, transport and control features, as well as sophisticated high voltage power supplies and conditioning equipment. How closely the costs of such systems might ultimately compare with commercially available units remains to be seen. One estimate suggests that the difference might amount to a factor of 2 or 3.⁴ A laser system cost of \$600/watt of photon output would contribute a modest \$3-4/kg SW/yr to the initial investment

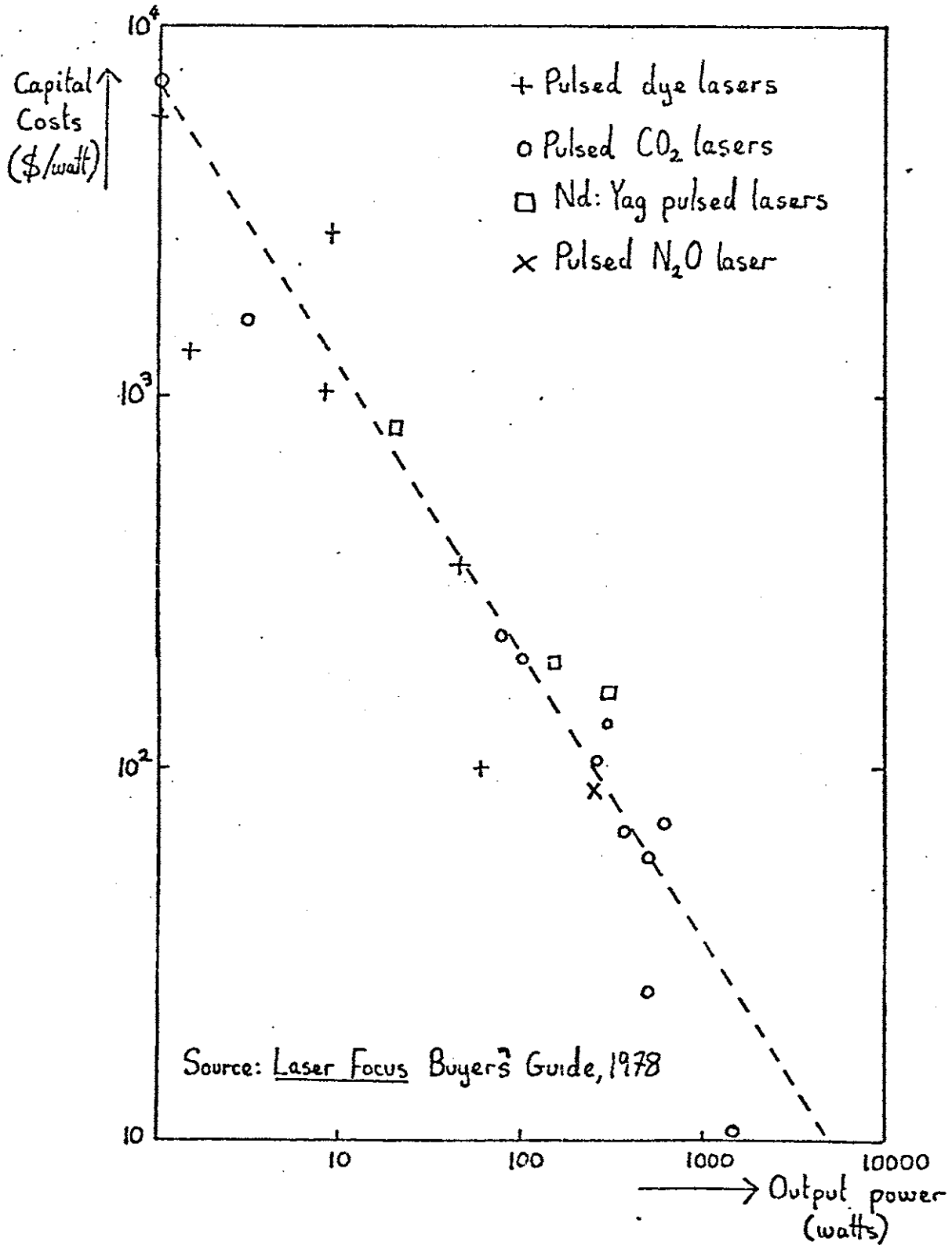


FIG 3.1: COMMERCIAL LASER CAPITAL COSTS VS. OUTPUT POWER

cost of the plant. The contribution to the unit separative work cost could be relatively much higher, however, depending on the mean time to failure (MTTF) of the various system components. Typical MTTF's for a CW-pumped Q-switched Nd:Yag laser producing 300 watts of output at 20 kHz range from 20 years for the mechanical support structure to 300 hours for the krypton arc lamp pumps.⁵ For CW CO₂ lasers, the weakest components are the optical elements, particularly the partially transmitting front mirrors, which typically exhibit a MTTF of 1000 hours.⁶ The pump-pulsing scheme apparently adopted for the JNAI dye laser system will place heavy demands on the reliability of the power supply system components and flashtubes, in view of the high pulse rates and pulse energies involved. The lifetime of the optical elements exposed to uranium vapor in the irradiation region may also be a crucial factor in the overall economics of the process. Not only capital replacement costs but also maintenance labor costs are sensitive to component failure rates.

Similar considerations apply to other elements of both AVLIS and MLIS processes. Clearly, until substantial reliability testing of the various system components has been conducted, both in isolation and on an integrated basis, laser enrichment separative work cost estimates will continue to be subject to a great deal of uncertainty.

Moreover, the prospects for future technological improvements provide another source of considerable uncertainty in present attempts to estimate costs.

Variation of laser enrichment costs with assay range

The prospective dependence of laser enrichment costs (expressed per unit of separative work) on the specific enrichment task (i.e., product,

tails, and feed assay) was discussed in Section 3.1. As we shall see shortly, the nature of this dependence may have substantial implications for pending uranium enrichment policy decisions. In principle, laser enrichment plants could be introduced into the commercial enrichment sector in several different ways. These alternatives are sketched in Figure 3.2. In case B, laser plants are used to enrich the tails stream from conventional enrichment facilities (i.e., gaseous diffusion or gas centrifuge), and also material drawn from the large stockpile of depleted uranium accumulated during the past thirty years of gaseous diffusion plant operations, up to 0.711% (the natural assay). In this mode, the laser enrichment capacity is substituting only for purchases of natural uranium. The scheme will be economic provided that:

$$C_S^B(.00711, .002, x_W) < \frac{C_U}{\frac{\phi(.00711) + \frac{.00711 - .002}{.002 - x_W} \phi(x_W) - \frac{.00711 - x_W}{.002 - x_W} \phi(.002)}$$

where C_U = cost of natural uranium (\$/kg)

C_S^B = cost of laser separative work for the specified assay range (\$/kg SW)

$$\phi(x) = (2x-1) \ln(x/1-x)$$

Thus, for a natural uranium price of \$110/kg (~\$40/lb U_3O_8) and a stripped tails assay of 0.08%, the maximum cost of laser separative work for economic tails stripping in this mode is about \$42/kg SW, and a uranium saving of about 15% with respect to case A is achieved. (Diminishing returns of a sort set in quite rapidly for this mode. For example, the maximum laser separative work cost for economic tails stripping to 0.05% would be \$32/kg SW, but the uranium savings would only have increased to about 18%. If the separative work unit cost were halved, to \$21/kg SW, the minimum

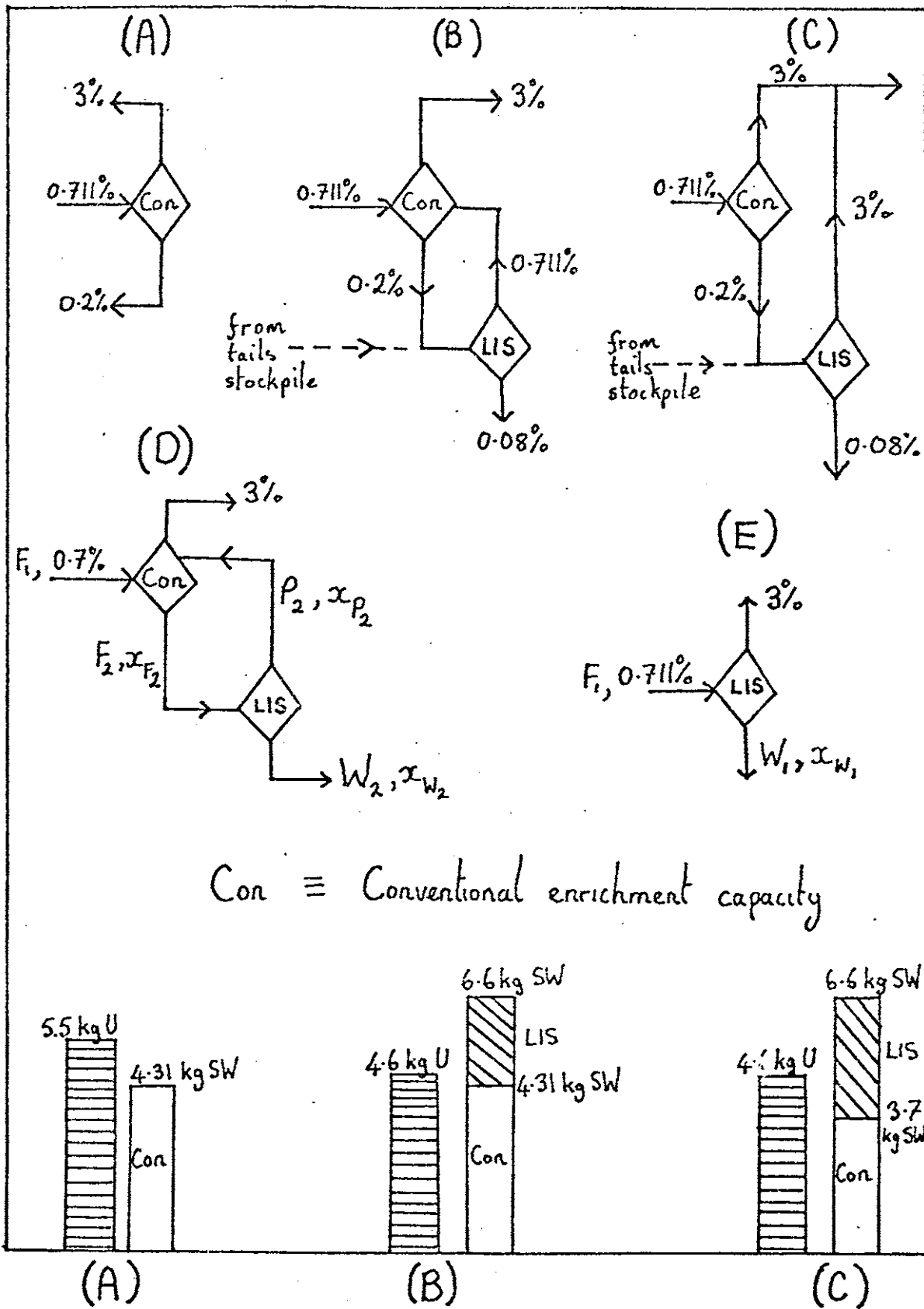


FIG 3.2: ALTERNATIVE LIS DEPLOYMENT STRATEGIES

economic stripped tails assay would be 0.02%, and the uranium savings with respect to case A would only be about 21%.)

In case C, laser enrichment plants enrich conventional plant tails directly to reactor-grade assay. If natural uranium costs \$110/kg, conventional separative work \$100/kg SW, and the stripped tails assay is 0.08%, as before, then a similar calculation shows that the maximum cost of laser separative work for economic operation in mode C is \$55/kg SW. In this case, as in case B, about 15% of the uranium consumed in A is saved; in addition, the 'conventional' separative work requirement per unit of product is also reduced by about 15%.

More generally, if the laser separative work unit cost function, $C_2(x_{P2}, x_{F2}, x_{W2})$, is known, then the optimum combined configuration for the conventional and laser enrichment plants (Mode D in Figure 3.2) can be established by minimizing the product unit cost function, C_p , where:

$$C_p = F_1 C_U + C_1 \left[\phi(.03) + F_2 \phi(x_{F2}) - P_2 \phi(x_{P2}) - F_1 \phi(.00711) \right] + \\ + \left[C_2(x_{P2}, x_{F2}, x_{W2}) \right] \cdot \left[P_2 \phi(x_{P2}) + W_2 \phi(x_{W2}) - F_2 \phi(x_{F2}) \right]$$

and C_1 is the unit cost of separative work in the conventional enrichment plant.

The optimal assays x_{P2} , x_{F2} and x_{W2} can then be found by setting:

$$\frac{\partial C}{\partial x_{P2}} = \frac{\partial C}{\partial x_{F2}} = \frac{\partial C}{\partial x_{W2}} = 0$$

and applying the necessary material balance conditions. In the event that $C_2 < C_1$, for all (x_{P2}, x_{F2}, x_{W2}) , the optimum condition will clearly be as shown in case E, in which the laser plants have replaced all conventional capacity.

*

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The cost estimates presented earlier in this section are now used to examine the potential impact of LIS technologies on the economics of the nuclear fuel cycle.

3.3 Enrichment Economics, LWR Electricity Costs and Uranium Conservation

It is now the general practice throughout the international enrichment industry to offer enrichment services on a 'toll' basis; that is, the responsibility of providing natural uranium feed is left to the enrichment customers, and the owners of the enrichment plant rent out the use of their facilities. Under current economic conditions, the cost of acquiring naturally occurring uranium ore concentrates and the cost of enrichment services are the two principal components of the overall nuclear fuel cycle cost for a light water reactor. Typical costs for the various stages of the nuclear fuel cycle for an 'average' light water reactor, as recently reported by engineers at a large U.S. utility, are shown in Table 3.2.a. The table shows that natural uranium (yellowcake) and enrichment costs together account for about 75% of the total fuel cycle cost; enrichment costs alone contribute some 25% of the total.

Fuel cycle costs actually only amount to a relatively small fraction of the total cost of electricity supplied by nuclear plants. The other components of the total cost are power plant operating and maintenance costs and, especially, the fixed or capital charges. The same utility engineers estimate a total 'bus-bar' generating cost for future light water plants of 35 mills/kwh(e) (in 1977 dollars) to which fuel cycle costs contribute 20% and capital charges almost 75%. Thus, to a rough first order approximation, a 50% cut in enrichment costs would only result in a reduction of about 2 1/2% in the total cost of nuclear electricity. Although small in relative

Table 3.2

(a) Nuclear Fuel Cycle Costs for Light Water Reactors*

(1977 dollars)

<u>Operation</u>	<u>Unit Cost</u>	<u>Cost (mills/kwh(e))</u>
Yellow Cake	\$40/lb	3.5
Conversion to UF ₆	\$2.75/lb	0.1
Enrichment (0.2% tails assay)	\$75/SWU	1.8
Fuel fabrication	\$110/kg uranium	0.7
Net salvage cost	-	<u>1.0</u>
		<u>7.1</u>

(b) Estimated Total Bus-Bar Generating Costs
for Future Light Water Reactors*

(1977 dollars)

	<u>mills/kwh(e)</u>
Fuel cycle	7
Operation and maintenance	2
Carrying charges	<u>26</u>
	<u>35</u>

* Source: A.D. Rossin and T.A. Rieck, Commonwealth Edison Company, Chicago, Ill., in Science, 201, 18 August 1978, 582.

terms, such a reduction would nevertheless provide an annual saving of \$5 1/2 million for a 1000 MWe reactor operating with a 70% load factor.

In practice, a more sophisticated calculation is necessary to determine the exact impact of a change in enrichment costs on the overall cost of nuclear electricity, although the above conclusions would remain essentially unchanged. Because separative work and natural uranium are substitutable for each other to a significant degree, enrichment cost increments exert a 'multiplier' effect throughout the nuclear fuel cycle.

Choice of the tails assay in enrichment plants determines the relative size of the inputs of natural uranium and enrichment services to the production of LWR fuel; as the tails assay is reduced, the separative work and natural uranium required to produce a unit of low-enriched fuel are respectively increased and decreased. For any combination of natural uranium and enrichment costs, there is an optimum value of the enrichment plant tails assay at which the total cost of low enriched uranium fuel is minimized. Equations for the optimum tails assay, x_0 , and the minimum unit cost of low-enriched uranium, C_p , are presented in Appendix 3.5. The dependence of x_0 on natural uranium and separative work costs is shown graphically in Fig. 3.3.

Thus, if natural uranium fuel costs \$111.2/kg (\$40/lb for yellowcake and \$2.75/lb for conversion) and separative work costs \$75/kg SW, the optimum tails assay is, from Fig. 3.3, approximately 0.185%, and the optimized cost of 3% enriched uranium product is \$906/kg. A 50% reduction in the cost of separative work, to \$38/kg SW, would reduce the optimum tails assay to 0.125% and the optimized cost of 3% enriched product to \$728/kg, a cut of almost 20%. In addition, with the lower tails assay, natural

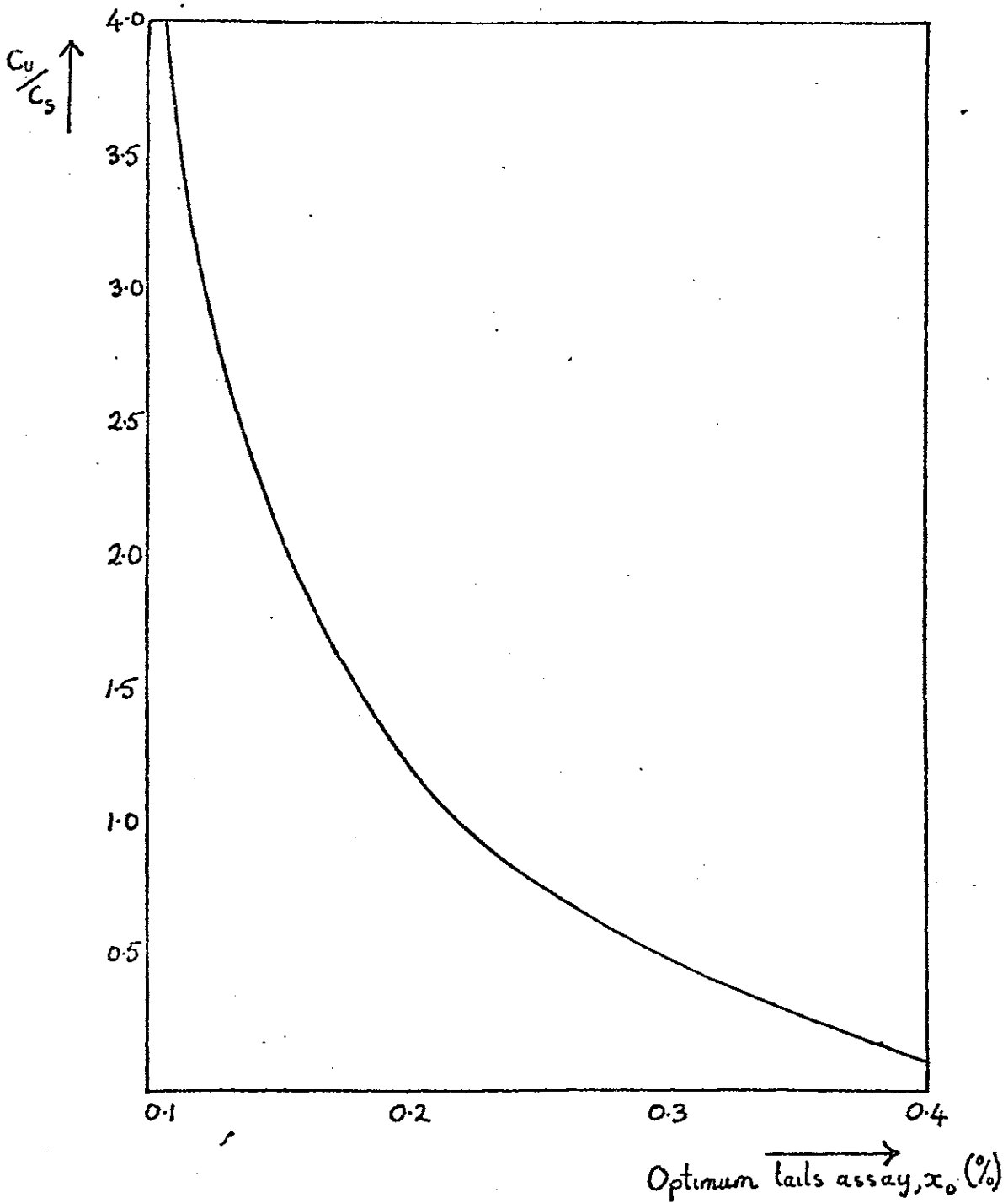


FIG 3.3 : OPTIMUM TAILS COMPOSITION AS A FUNCTION OF THE UNIT COST RATIO OF NATURAL URANIUM (C_u) AND SEPARATIVE WORK (C_s)

uranium consumption would be reduced by 8,5%.*

A reduction in separative work costs thus provides both a direct saving in nuclear fuel costs and an opportunity for improved uranium utilization efficiency. In Appendix 3.2, a highly simplified fuel cycle cost model for a 1060 MWe PWR is used to calculate the impact of separative work costs on total fuel cycle costs and uranium requirements. The results, for two assumed yellowcake costs of \$40/lb and \$100/lb, are summarized in Figure 3.4.

It was assumed in the preceding calculations that enrichment services would be provided at the optimum tails assay for an ideal cascade configuration. For high separation factor laser enrichment processes, especially the single stage AVLIS processes, the optimum operating tails assay will be dictated by intrinsic design constraints, and not by cascade theoretical considerations, as discussed in Section 3.2. Thus, Figure 3.4 provides an indication rather than an accurate quantification of the potential economic and resource conservation benefits offered by laser enrichment technologies.

More generally, Figure 3.5 shows the percentage reduction in uranium requirements achieved as the enrichment tails assay is reduced below current 'conventional' levels (generally lying in the range 0.2 - 0.25%). The JNAI-type AVLIS plant designed to strip 0.25% tails down to 0.08% would reduce uranium requirements by over 15%. (The maximum theoretical uranium saving that could be achieved by stripping 0.2% tails down to zero assay is 23%.)

* Historically, enrichment plant tails assays have been determined unilaterally by the operator, and have rarely corresponded to the economically optimal value for the customer. There is now a trend in the international enrichment industry towards offering customers greater flexibility in the choice of tails assay.⁷

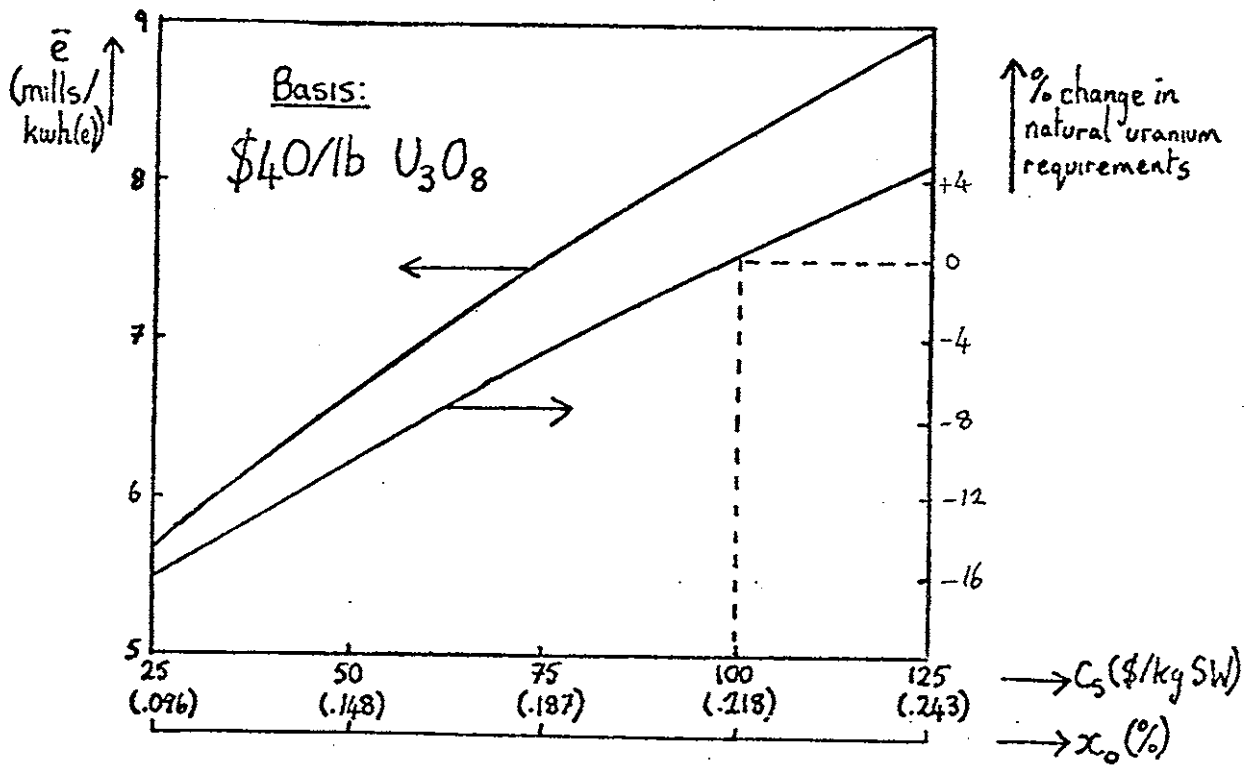
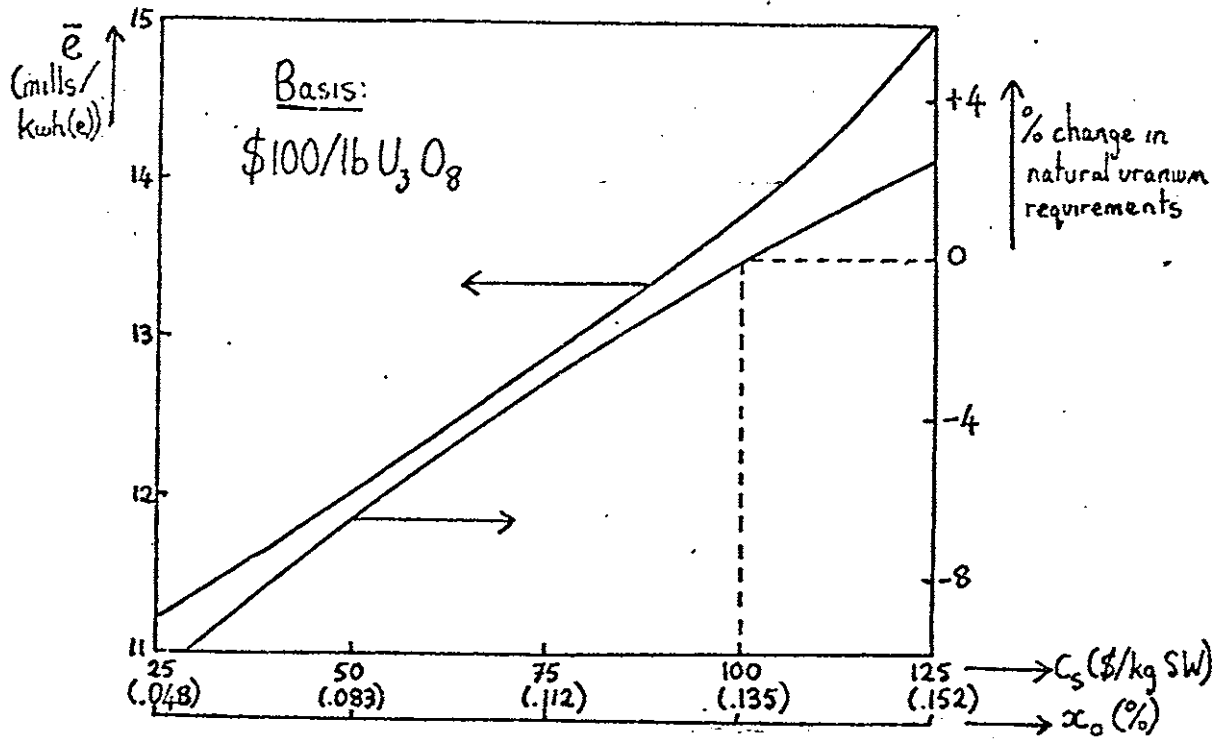


FIG 3.4: EFFECT OF SEPARATIVE WORK COST (C_s) ON FUEL CYCLE COST (\bar{e}) AND NATURAL URANIUM REQUIREMENTS FOR A 1060 MWe PWR

[x_0 is the optimized enrichment plant tails assay]

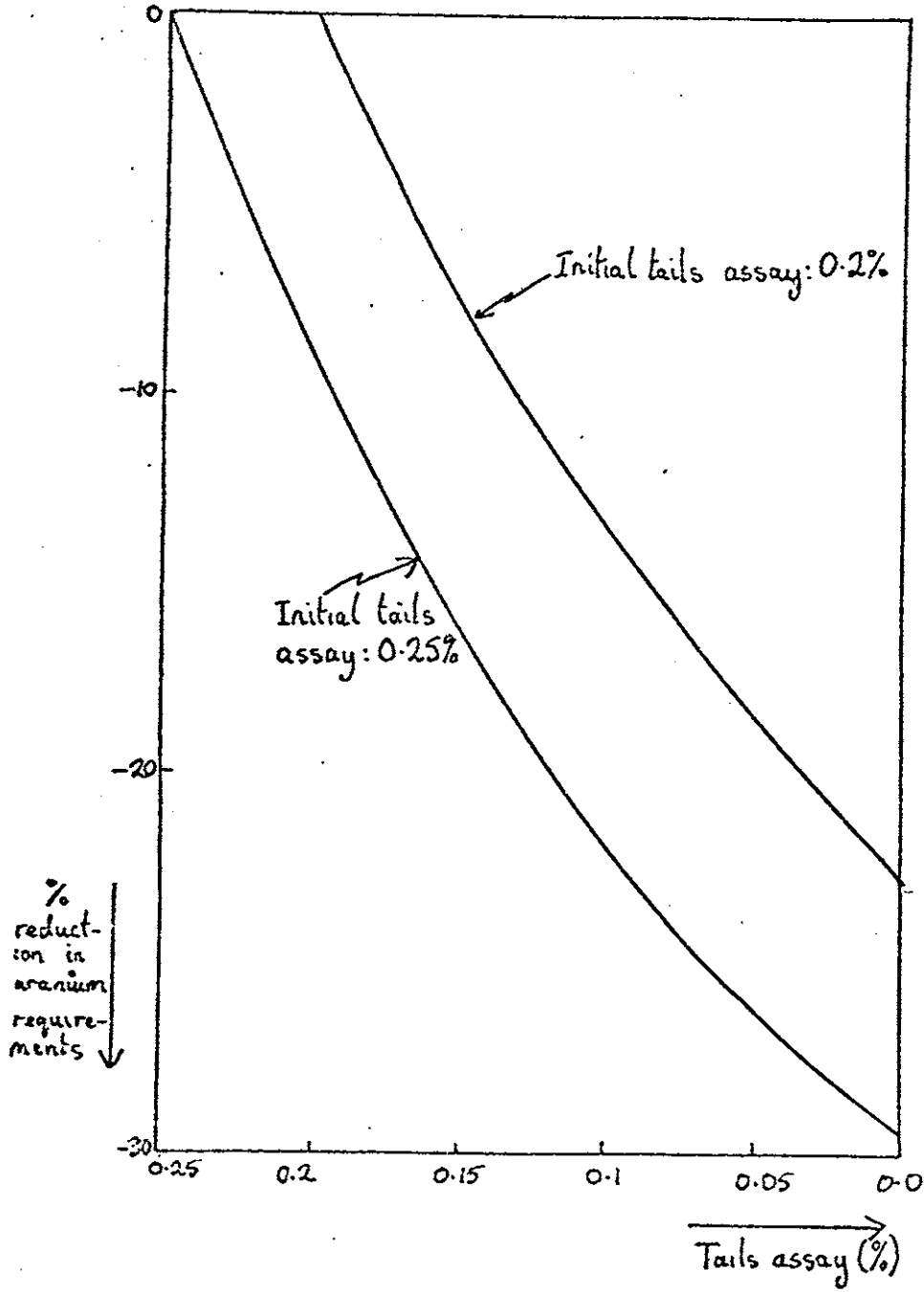


FIG. 3.5: EFFECT OF TAILS ASSAY REDUCTIONS
ON URANIUM REQUIREMENTS

Finally, it should be emphasized that in principle there is no reason why current enrichment facilities could not also be operated at lower tails assays. The practical constraints are primarily economic, not technical. For example, a gas centrifuge plant providing separative work at \$100/SWU would, at current uranium prices of about \$40/lb, operate optimally with a tails assay of 0.218%, and the levelized fuel cycle cost at this assay would be 8.25 mills/kwh(e) for the cost structure in Table 3.2.a. (See Fig. 3.4.) For a tails assay of 0.08% to be optimal, the uranium price would have to be \$215/lb. Nevertheless, even at the current price of \$40/lb, operating the enrichment plant at a tails assay of 0.08% would result in a levelized fuel cycle cost of 8.42 mills/kwh, an increase of only 2% over the minimum. Thus, even for gas centrifuge facilities, an economic premium of only 2% in the fuel cycle cost (much smaller still when compared to the total cost of nuclear electricity) would bring about an 18% reduction in uranium requirements.

3.4 Laser enrichment and the demand for uranium: 1980-2030

In recent years, hitherto long-standing assumptions concerning the need for a transition from the current 'once-through' uranium-based nuclear fuel cycle to more uranium-efficient cycles involving spent fuel reprocessing, plutonium recycle in thermal reactors, and, ultimately, plutonium-fueled fast breeder reactors have become increasingly subject to question, especially in the U.S. The view that world uranium resources may previously have been conservatively estimated and the recognition that significant improvements can be made in the uranium utilization efficiency of existing, once-through fuel cycles have both figured prominently in the debate over the use of plutonium as a commercial fuel. In this section, the potential impact of laser enrichment technologies (and advanced enrichment technologies in general) on the U.S. demand for uranium over the next half century will be examined.

Uranium demand in the U.S.: 1980-2030

Profound uncertainties surround the future of nuclear power in the U.S., and the generation of reliable predictions of nuclear development from which future uranium demand could then be derived is an unrealistic objective. The difficulties presented by these uncertainties are eased, however, if, rather than seeking an accurate prediction of what will happen, a range of alternative 'scenarios' of what might happen is developed instead. Such scenarios would be selected so as to span the range of development paths that might reasonably be expected to occur. Even for this much less ambitious approach, the problem of uncertainty is still very much in evidence, but no longer does it necessarily create insurmountable obstacles. On the contrary, the development of alternative scenarios so as to be able to address a range of 'what if' questions associated with

the introduction of a new technology (or the management of an existing one) is an essential analytical tool if unresolvable uncertainties are to be successfully managed.

U.S. Nuclear Power Scenarios

Four U.S. nuclear power scenarios have been developed for this assessment. They are presented graphically in Fig. 3.6 as the "HIGH", "MID", "CONAES-I" and "LOW" cases. In each case, the scenarios are developed to the year 2030.

The scenario period chosen, 1980-2030, is a compromise between two opposing requirements. On the one hand, the period should extend far enough to allow the impact on uranium demand of the advanced enrichment technologies to be compared with those of other uranium-conserving strategies, especially the plutonium-fueled fast breeder reactor; thus the period should be significantly longer than the longest of the lead-times required for the large-scale deployment of the technologies in question. On the other hand, the period should not extend so far that the inevitable increase of uncertainty with time prevents the selection of even a reasonable range of alternative scenarios.

A final requirement is that any conclusions drawn from the scenario analysis should not be overly sensitive to the length of the period chosen.

HIGH Case:

This scenario is based on a projection to the year 2000 recently presented by Steyn.⁸ A simple polynomial extrapolation was used to extend the Steyn projection out to the year 2030. The HIGH case figure of 363 GWe installed nuclear capacity in the year 2000 corresponds, to within about a year, to the most recent (September 1978) 'high' projection of 395 GWe made by the Energy Information Administration of the U.S. Department of Energy.⁹

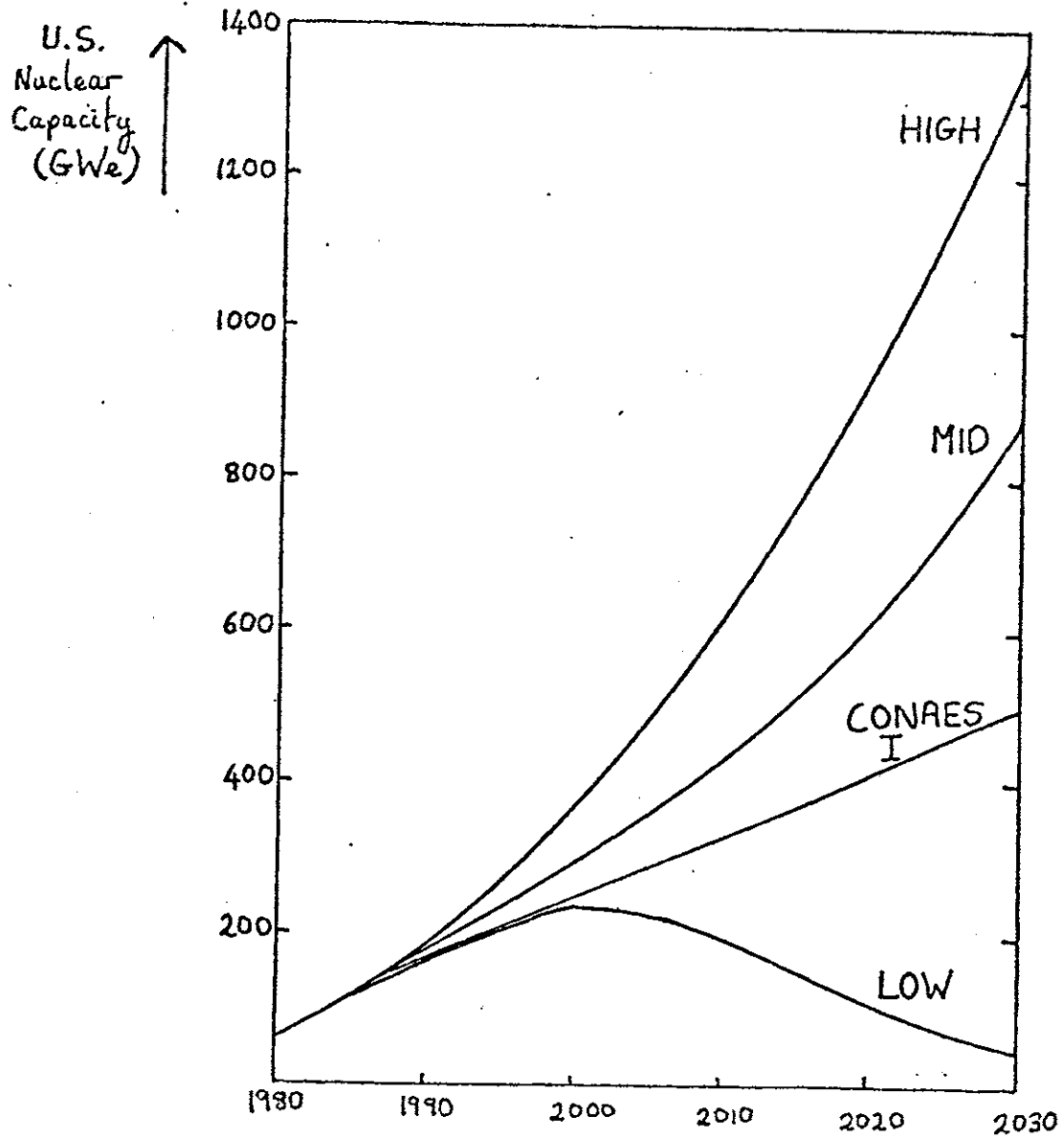


FIG. 3.6: U.S. NUCLEAR POWER SCENARIOS: 1980-2030

Official government projections of U.S. nuclear power growth have been steadily revised downwards for the past several years. The HIGH scenario selected here, while much lower than DOE projections made only a few years earlier, nevertheless implies that nuclear plants will constitute roughly half or more of all replacements and additions to U.S. baseload electric generating capacity during the coming decades* - an unlikely target considering both the current political difficulties facing the nuclear industry and the heavy emphasis on coal as a fuel for baseload generation that has emerged in U.S. energy policy in recent years.¹²

Even though the HIGH scenario now seems improbably high, it is interesting to note that the implied ordering rate of less than 20 GWe/year of new nuclear capacity during the next decade falls well within the current supply capability of U.S. reactor manufacturers of about 30 GWe/year.¹³

LOW case:

In the current climate of uncertainty, with the Three Mile Island accident only a few months old, it would not be unreasonable to speculate that no further nuclear power plants will ever be built in the U.S., and that the existing ones will be phased out of service as rapidly as possible. Although such a scenario would be a realistic lower bound for the future U.S. nuclear power system, it would also render the remaining discussion of uranium conservation irrelevant. For the purposes of this

* Even for what are today considered high projections of future U.S. electric power growth - 5 1/2%/yr until 2000 and 4 1/2% thereafter - the HIGH scenario implies that about 46% of all replacement and new baseload electric generating capacity until 2010 would be nuclear.¹¹

study, therefore, the *LOW* scenario is arbitrarily defined by the criterion that nuclear power plant ordering will continue until 1997, thirty years (or about one reactor lifetime) after the inception of large scale nuclear ordering in the U.S. Utility ordering behavior is also assumed to follow a logistic growth curve under this scenario.

MID Case:

The MID scenario bisects the HIGH and LOW curves.

CONAES I:

The fourth scenario, adopted from one of the projections examined in the forthcoming National Academy of Sciences study on nuclear and alternative energy systems (CONAES),¹⁴ was chosen not because it was felt to represent the 'most likely' of the several CONAES scenarios but because it conveniently fills a rather wide gap between the MID and LOW cases.

Uranium Conservation Strategies

Apart from enrichment tails assay reductions, several other uranium conservation techniques can be applied to the current once-through LWR fuel cycle which do not require spent fuel reprocessing and plutonium recycle. Some of these have been reviewed by Till and Chang:¹⁵

(i) Higher fuel burnup:

LWR fuel discharge burnup can be increased, and natural uranium consumption reduced, by increasing the enrichment of fuel charged to the reactor.

(ii) Reduced metal/water ratio:

Reducing the volumetric metal:water ratio in LWR cores increases the degree of neutron thermalization, and the required core fissile inventory may be reduced as a result.

(iii) Spectral shift control:

The neutron economy in LWRs can be improved, in principle, by the use of a D_2O/H_2O mixture as coolant; in such a scheme, the core reactivity is controlled by varying the proportion of heavy water in the coolant, rather than using neutron poisons, as at present. Spectral shift control increases the rate of neutron capture in fertile U-238, an advantage which can only be fully realized by spent fuel reprocessing and recycle of plutonium.

(iv) More frequent refueling:

By reducing the interval between refuelings, reactivity requirements at the beginning of cycle are reduced, and the fissile loading can be reduced as a result.

(v) Thermal coastdown:

Reducing the reactor power output at the end of the burnup cycle increases the core reactivity, enabling more energy to be extracted from the fuel than could have been produced by full-power operation.

(vi) Heavy water reactors:

Natural uranium fueled heavy water reactors are inherently more efficient consumers of uranium than LWRs. Lifetime uranium requirements for CANDU-type heavy water reactors (HWRs) are over 20% less than for LWRs. Moreover, if CANDU fuel is slightly enriched, uranium consumption is reduced still further; for example, by using 1% enriched fuel, CANDU-HWR lifetime uranium requirements are as much as 25% less than if natural uranium fuel is used. (See cases HWR_{XI} and HWR_{XII} in Table 3.3.1 of Appendix 3.3.)

Each of the first five modifications to the LWR fuel cycle can theoretically conserve 10% or more of current uranium requirements. Each,

however, is also characterized by cost increases, operational inconveniences, or safety problems which generally tend to reduce the savings that can be achieved in practice, in some cases to marginal levels. Out of the five LWR cycle modifications, Till and Chang suggest that the increased discharge burnup option will be more attractive than either increasing lattice spacing or using spectral-shift reactivity control. Even here, however, fuel rod performance degradation at high burnups and safety problems from increased power peaking associated with higher core enrichment levels will constrain uranium conservation efforts. More frequent refueling and thermal coastdown, while not requiring any significant technological innovations, nevertheless will each tend to reduce plant load factors, and may also be in conflict with utility refueling shutdown schedules, which tend to coincide with the slack demand periods of the Spring and Fall.

In Table 3.3, estimates of the uranium savings obtainable from some of these conservation techniques are compared with the uranium requirements of a current generation, 1000 MWe PWR operated in the standard once-through 'mode'. A more extensive comparison is presented in Appendix 3.3.

*

*

*

These results are now used in conjunction with the four nuclear power scenarios presented in the previous section to estimate the impact during the next half century of various integrated uranium resource conservation strategies for the once-through fuel cycle. Three specific conservation strategies have been chosen:

- A - Reduction of enrichment tails assay to 0.05% starting in 1988;
- B - Reduction of enrichment tails assay to 0.05% starting in 1988;
increase in fuel discharge burnup to 50,000 MWD/MT for all
reactors starting in 1990;

Table 3.3

Effect of once-through fuel cycle modifications on uranium requirements^a

(Basis: 1000 MWe PWR)

CASE ^b	DESCRIPTION					Initial core inventory requirement	Annual reload requirement (S T U ₃ O ₈)	Lifetime requirement ^c	% reduction in lifetime requirement
	Initial enrichment (%)	Steady-state feed enrichment (%)	Discharge burnup (MWD/MT)	Tails assay (%)	Capacity factor (%)				
LWR _I	2.07	3.1	30132	0.2	75	411	213	6590	-
LWR _{IV}	2.07	4.175	50220	0.2	75	411	175	5490	16.8
LWR _{VI}	2.07	3.1	30132	0.05	75	344	173	5360	18.7
LWR _{II}	1.89	3.05	31043	0.2	60	372	157	4920	25.3
HWR _{XI}	1.0	1.0	16000	0.2	75	257	114	3563	45.9

a. For a more extensive presentation of these results, see Appendix 3.3.

b. LWR_I - Standard once-through PWR cycle

LWR_{IV} - High burnup once-through PWR cycle

LWR_{VI} - Low tails assay once-through PWR cycle

LWR_{II} - Low capacity factor standard once-through PWR cycle

HWR_{XI} - Slightly enriched uranium once-through HWR cycle

c. Lifetime requirements are calculated on the basis of 1 initial core load + 29 steady state reloads. In practice, it may take several years to reach the equilibrium condition.

C - Reduction of enrichment tails assay to 0.05% starting in 1988; increase in fuel discharge burnup to 50,000 MWD/MT for all reactors starting in 1990; all reactors built after 2000 will be of the heavy water type, fueled with 1% enriched uranium.

In calculating the impact of these strategies, an average capacity factor of 75% was assumed. The details of the various strategies are summarized in Table 3.4.

In selecting these strategies, there was no attempt to reflect the likely outcome of current U.S. fuel cycle policies. For example, existing AIS development programs, even if successful, are most unlikely to result in full-scale commercialization by 1988; the mid-1990s is a more likely date. (In practice, however, cumulative uranium consumption would probably be unaffected by delay, since accumulated tails could be reworked to lower assays in new tails stripping facilities.) Also, it is uncertain as to whether a tails assay as low as 0.05% will be practically achievable even in specially designed tails stripping plants. (As noted in Chapter 2, the design target for the single stage tails stripping AVLIS process under development by JNAI is 0.08%, which, if realized, would provide 3% less uranium savings.) Thirdly, average burnups of 50,000 MWD/MT may require substantial design changes to LWR fuel, although there is no doubt that some improvement in burnup could be achieved without such changes well before 1990.¹⁶ Finally, there are no indications that utilities would be prepared to commit themselves fully to heavy water reactors by the end of the 1980s - a necessary condition for 100% HWR market penetration by the year 2000. On the other hand, other possible resource conservation techniques discussed earlier, such as thermal coastdown, fuel lattice changes, etc., have not been included here.

Table 3.4

Alternative uranium conservation strategies for the
once-through fuel cycle

Reference case (0): All -- PWR economy¹
 0.2% enrichment tails assay
 Average discharge burnup = 30100 MWD/MT
 Capacity factor = 75%

Uranium conservation strategy	Reduce tails assay to 0.05% in 1988	Increase discharge burnup to 50000 MWD/MT in 1990	100% penetration of 1% - U fueled HWRs by 2000	Capacity factor (%)
A	Yes	No	No	75
B	Yes	Yes	No	75
C	Yes	Yes	Yes	75

1. In the U.S. at present, PWRs outweigh BWRs by a ratio of about 2:1. Lifetime natural uranium requirements for the two reactor types differ at most by a few percent, however, and in light of the many other assumptions used here, the error introduced by assuming an all - PWR economy is relatively small.

Thus, the strategies summarized in Table 3.4 should not be considered 'probable'. The purpose is rather to provide estimates of what could potentially be achieved by advanced enrichment technologies either alone or in combination with certain other resource conservation methods.

Figures 3.7-3.9 show the impact of conservation strategies on cumulative natural uranium commitments (i.e., the lifetime uranium requirements of all reactors then in operation or previously retired) for the HIGH, MID and CONAES I scenarios. In practice, the cumulative commitment curves should be brought forward by about a decade, since the commitment for uranium is effectively made at the time that the power plant is ordered, roughly ten years before it enters operation, although of course another forty years would pass before the last of the committed uranium was actually consumed.

Also shown in the Figures are two recent estimates of total U.S. uranium resources. The higher, made by the Department of Energy, includes reserves and probable, possible and speculative classes of potential resources producible at forward costs up to \$50/lb U_3O_3 .¹⁷ The lower estimate was made by the Sub-group on Uranium Resources (URG) of the National Academy of Sciences' Committee on Nuclear and Alternative Energy Systems (CONAES).¹⁸ The URG based its estimate on DOE's own estimates, but argued that the possible and speculative classes of potential resources could not realistically enter into total resource estimates, and consequently included only DOE's estimate of probable potential resources in its own best estimate of total resources; moreover, only uranium producible at forward costs up to \$30/lb was considered by the URG.

Figures 3.7-3.9 show that for each of the scenarios a reduction in the tails assay alone, although providing an 18% saving in uranium requirements, exerts only a modest braking effect on the curve of cumulative

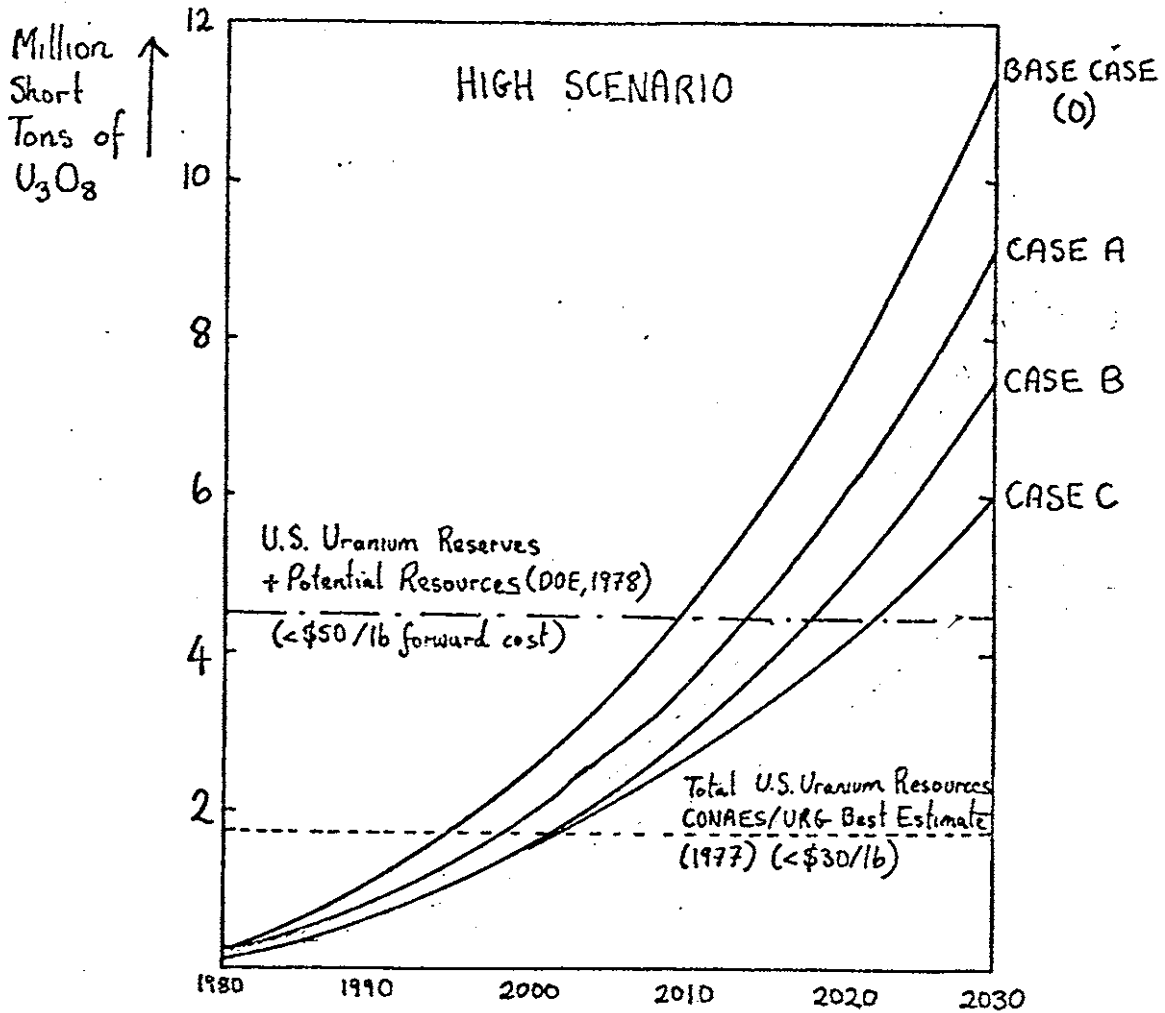


FIG. 3.7: CUMULATIVE U.S. URANIUM COMMITMENTS:
HIGH SCENARIO

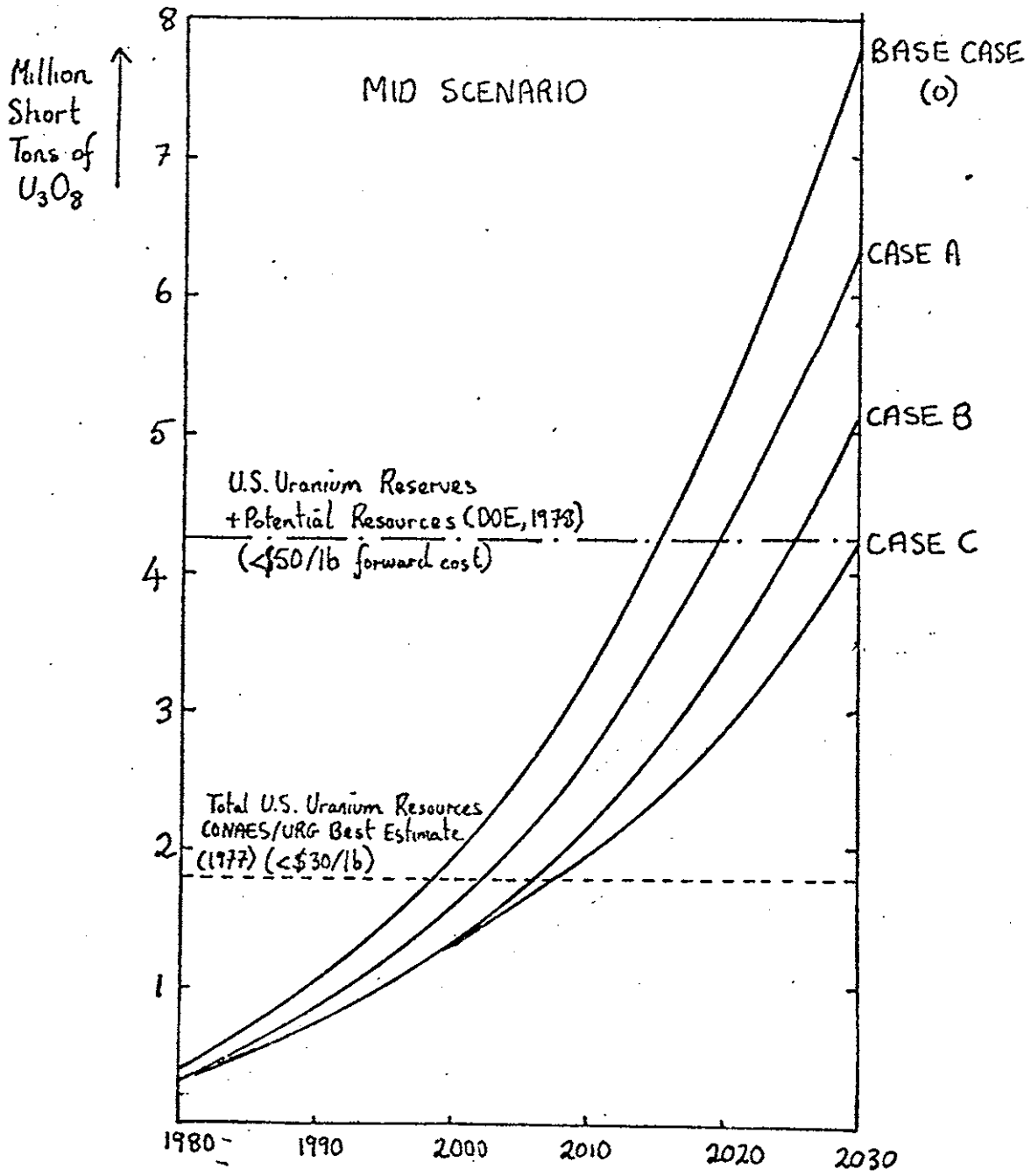


FIG. 3.8: CUMULATIVE U.S. URANIUM COMMITMENTS:
MID SCENARIO

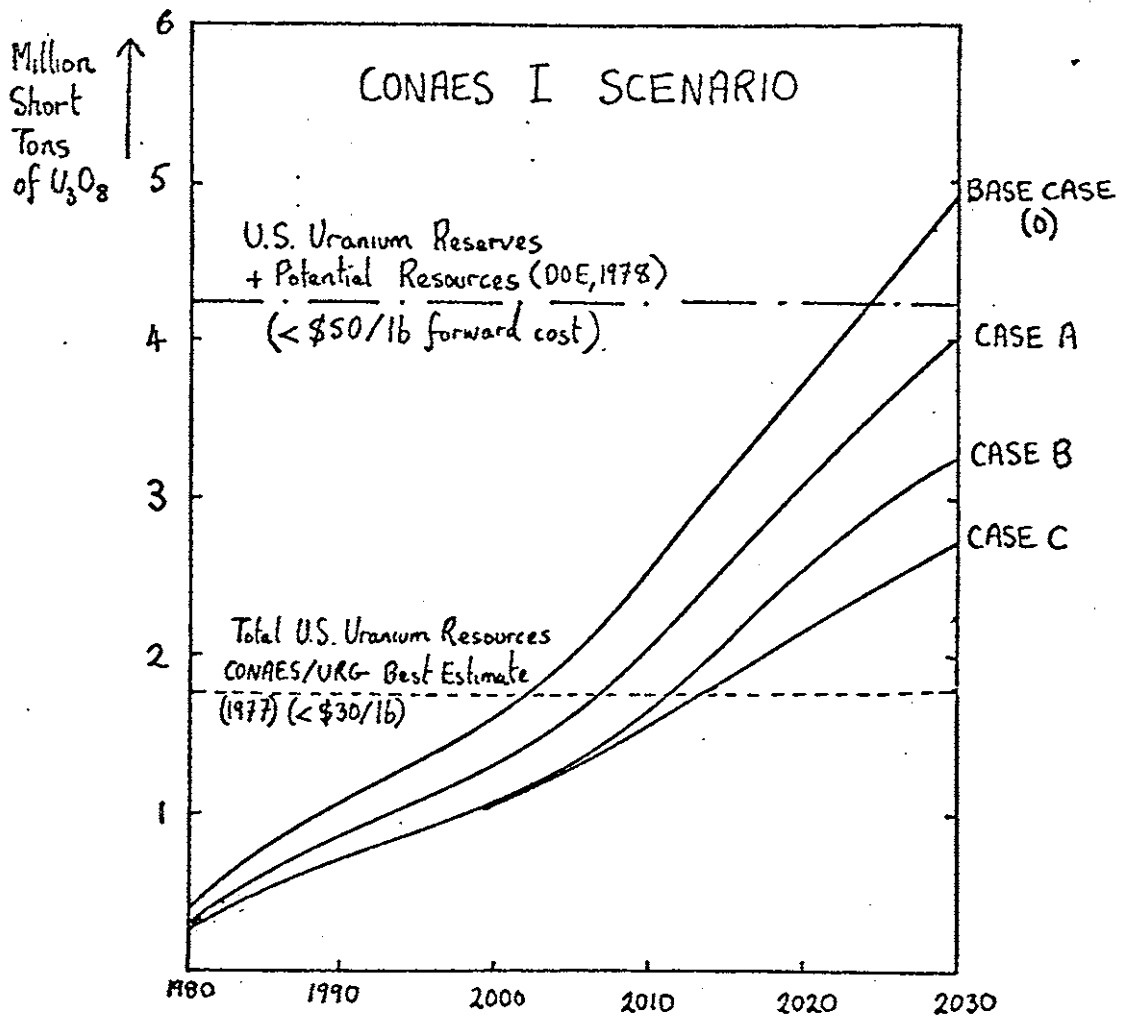


FIG. 3.9: CUMULATIVE U.S. URANIUM COMMITMENTS:
CONAES I SCENARIO

commitments. For the CONAES I case, the date beyond which cumulative commitments begin to exceed the DOE estimate of total U.S. resources is pushed back eight years. For the HIGH case, the corresponding delay is only three years.

However, when tails assay reductions are combined with other conservation measures, as in strategy C, significant curbs on consumption can result. For example, for the MID scenario, the year during which nuclear plant orders will raise the amount of uranium collectively committed above the DOE estimate of total U.S. uranium resources slips 15 years to 2020. For the CONAES I case, the corresponding date recedes by at least 30 years to 2040 or beyond. In the HIGH case, the potential contribution of improvements to once-through fuel cycles is smaller; the 'cross-over' point is pushed back only about ten years, and the need for more effective conservation measures arises much earlier.

If the URG's total resource estimate is used, the breathing space provided by conservation strategy C is considerably reduced. As Figure 3.9 shows, even for the CONAES I case only about eleven years are gained, and the 'cross-over point' is reached by about 2004.

The extent of U.S. uranium resources is clearly central to U.S. fuel cycle strategic planning, and especially to the future of fuel reprocessing and the breeder. Discussion of uranium resource estimates has become highly politicized; opponents of the breeder in the U.S. argue that the estimates made by the URG (and similar ones made by others) are too conservative, and will encourage an unnecessarily premature commitment to breeder commercialization, while others believe that the uncertainties associated with higher resource estimates prevent such estimates from contributing to a prudent planning base. It is sometimes difficult to

tell whether positions taken in the debate on breeder policy are influenced by views of the uranium resource situation, or vice versa.

But while the breeder policy debate frequently founders on the fundamentally unresolvable uncertainty associated with estimates of total U.S. uranium resources, an equally important issue affecting breeder policy concerns the ability of the uranium industry to locate and produce uranium at a rate commensurate with the growth in demand. Figures 3.10-3.12 show the impact on annual uranium requirements of conservation strategies A, B, and C.¹⁹ Also shown are three projections of annual uranium production made by the URG based on different sets of assumptions concerning the political and economic environment for the uranium supply industry.²⁰

In the calculations underlying the demand projections it was assumed that tails stripping would begin immediately. If current development plans are implemented, the impact of tails stripping in fact will be relatively less pronounced than the Figures imply before the mid-1990s, and relatively more so afterwards, when the backlog of accumulated tails would be worked off.* In any case, annual uranium savings from this source would be likely to stabilize at around 18% before 2010 for all scenarios.

In absolute terms, this potential saving is quite large. For the HIGH scenario, it would amount to about 43,000 ST U₃O₈/yr in 2010 - almost three times the total U.S. production in 1977. The saving in terms of cumulative output would also be considerable; for the HIGH case, about 750,000 ST U₃O₈ by 2010, an amount equivalent to almost 90% of current U.S. uranium reserves producible at forward costs of \$50/lb or less.²²

* It should also be noted that the uranium demand projections do not incorporate the potential savings available from stripping the existing tails stockpile, which is estimated to be equivalent to about 92,000 ST U₃O₈,²¹ about 6 times the total U.S. production in 1977.

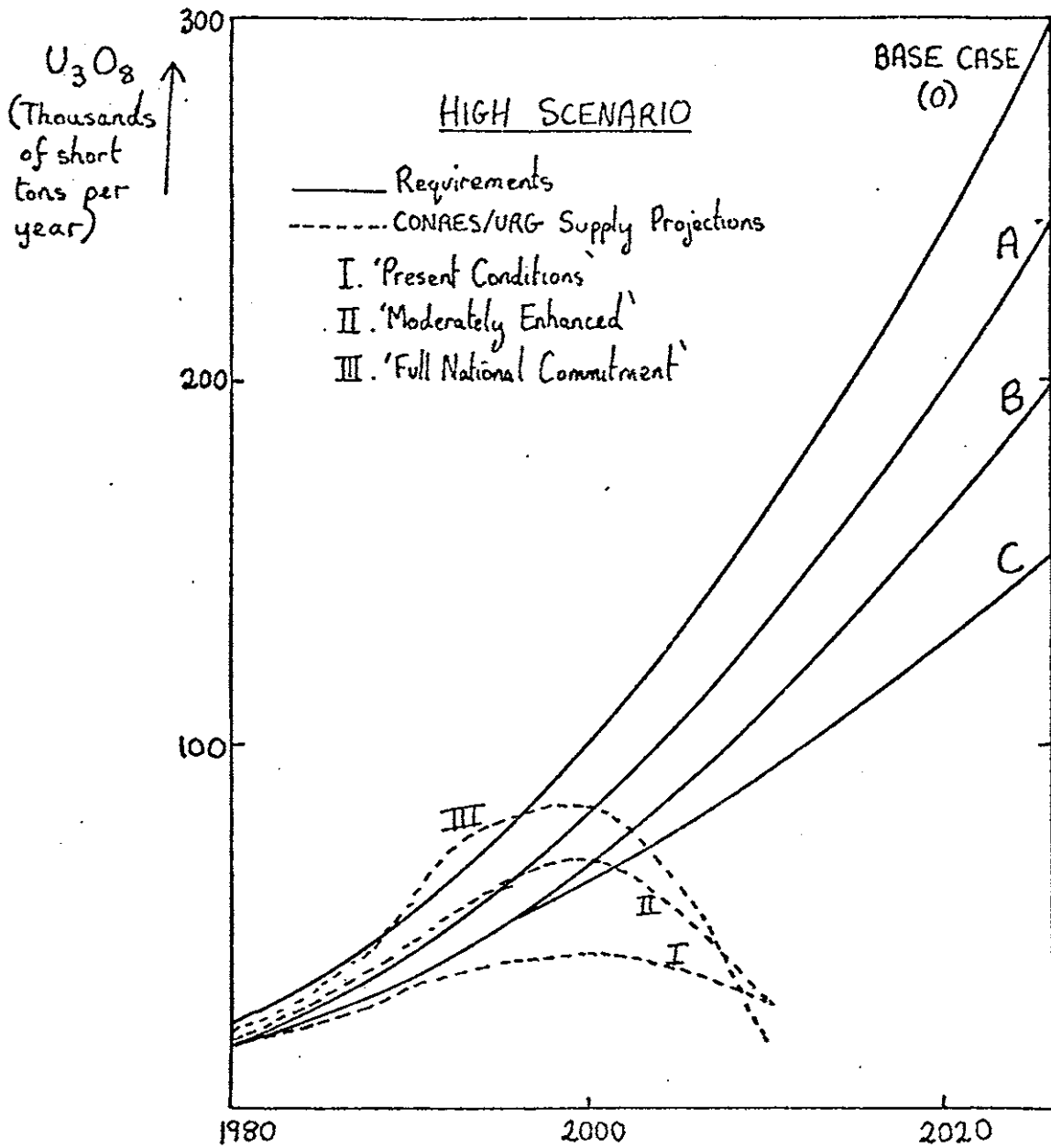


FIG. 3.10: ANNUAL U.S. URANIUM REQUIREMENTS:
HIGH SCENARIO

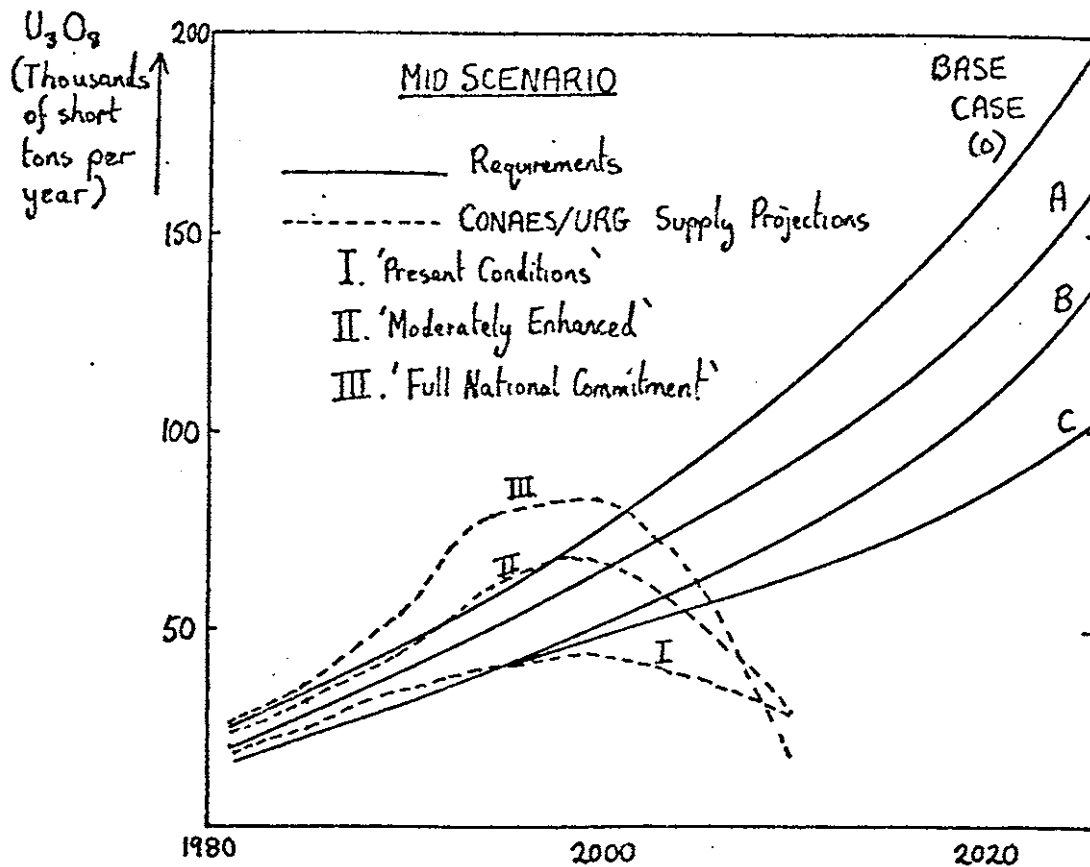


FIG. 3.11: ANNUAL U.S. URANIUM REQUIREMENTS:

MID SCENARIO

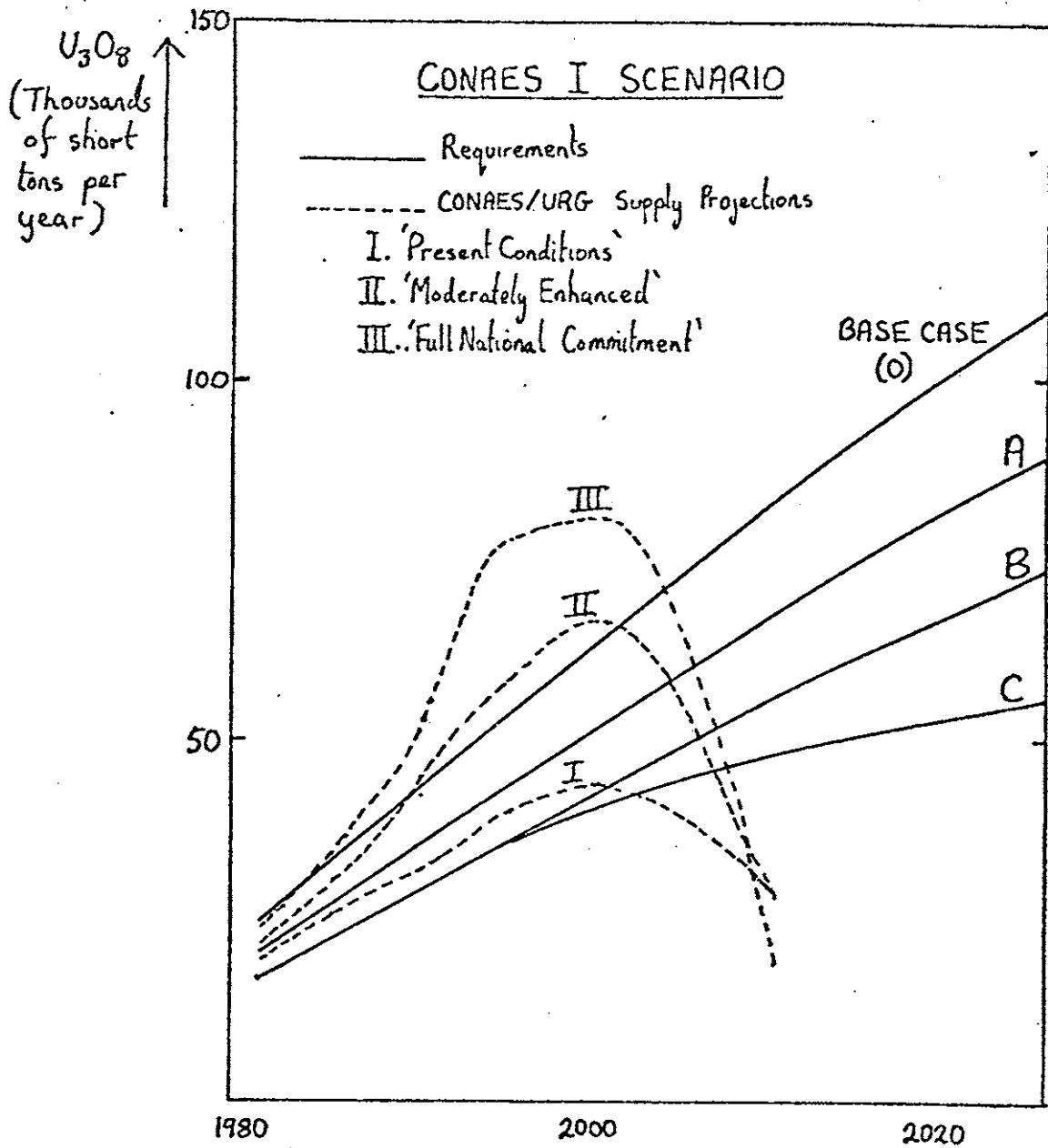


FIG. 3.12: ANNUAL U.S. URANIUM REQUIREMENTS:

CONAES I SCENARIO

When tails stripping is combined with other conservation measures, the impact on annual uranium demand is potentially very large. For example, annual requirements in all three scenarios would decline by about 43% in 2010 if strategy C were implemented, and cumulative production would be reduced by about 39%. (For the HIGH scenario, annual savings of 72,000 tons/year and cumulative savings of 1.6 million tons would be achieved.)

These savings would prolong the period during which domestic uranium production could keep pace with demand. The length of the extension is, however, uncertain. According to the supply projections developed by the URG, all of which fall off very rapidly after the year 2000, the extension is very limited; in no case would it exceed ten years, and in most cases it would be substantially less. The applicability of the URG supply projections to this particular set of nuclear power growth scenarios is unclear, however; moreover, the projections are based on total resource estimates which many consider to be overly conservative, as noted earlier. A more optimistic view of uranium supplies may lead to quite different conclusions. In the CONAES I case, for example, implementation of conservation strategy C would defer the date at which annual demand exceeded 50,000 ST U_3O_8 by about 20 years, to 2015; stated in another way, implementation of strategy C would lower the required annual rate of increase of domestic uranium production from 7% to about 3.2%.

Two principal conclusions may be drawn from these results:

1. The political and economic conditions under which fast breeder reactors would substitute for the current generation of thermal reactors in the U.S. are highly uncertain. Major sources of uncertainty include the rate of growth of nuclear generating capacity,

the extent of U.S. uranium resources, and the rate at which these resources can be developed and produced. Under certain conditions, uranium conservation measures applied to the current once-through fuel cycle would have little effect on the timetable for breeder deployment; if, for example, nuclear power growth turns out to be at the high end of the current range of estimates, or if uranium supplies follow the trend projected by the URG of CONAES. On the other hand, there is an 'envelope' of plausible nuclear power growth and uranium supply scenarios under which a combination of uranium conservation measures applied to the once-through fuel cycle could delay the need for breeder deployment on a significant scale by at least ten years and possibly by much more.

In practice, the extent to which these uranium conservation measures will be economically attractive substitutes for the breeder will depend on many factors, such as the cost of their implementation, uranium fuel costs, and breeder capital and fuel cycle costs, almost all of which are presently highly uncertain.

2. Tails assay reductions and other uranium conservation measures applied to the current once-through fuel cycle can significantly reduce the pressure of demands made on the U.S. uranium supply industry; furthermore, these measures can be implemented well in advance of any similar impact that could arise from the deployment of fast breeder reactors. Thus, if nuclear power in the U.S. is to expand beyond current levels, there is an important role for such uranium conservation measures in any fuel cycle strategy, irrespective

of whether breeder commercialization is a longer term objective.

3.5 Laser enrichment and the demand for separative work: 1980-95

While the potential benefits offered by advanced uranium enrichment technologies in the long term are relatively straightforward to evaluate, the nearer term question of when such technologies might optimally enter the enrichment marketplace is subject to a great deal of uncertainty.

In recent years, projections of world nuclear power growth during the remainder of the century have fallen drastically; many orders for new nuclear power plants have been cancelled or postponed, and there have been widespread delays in existing nuclear plant construction projects. At the same time, decisions taken several years ago to develop new enrichment facilities to supplement existing U.S. and Soviet capacity are beginning to bear fruit. In Europe, the Eurodif gaseous diffusion plant and the Urenco centrifuge facility both recently began operation, while in the U.S. a program to upgrade the capacity of the gaseous diffusion plants is nearing completion and the Carter Administration is implementing a decision taken in early 1977 to construct a large gas centrifuge plant as the next increment of U.S. enrichment capacity.

The result of these developments is that the fears of an enrichment shortage in the 1980s of only a few years ago have now yielded to expectations of a supply surplus throughout much of the next decade.²³ In such a context, schedules for future development and commercialization of advanced enrichment technologies, including LIS, have become increasingly problematical.

The institutional and political implications of this situation are examined in Chapters 5 and 6. Here, a quantitative analysis of the

enrichment supply/demand balance during the next 10-15 years is presented, first from a U.S. perspective, and then for the world.

United States

The U.S. government's three gaseous diffusion plants currently provide enrichment services to all U.S. nuclear utilities and a sizeable fraction of the overseas market; at present, supplies are divided between domestic and foreign customers in a ratio of about 2 to 1. In addition, a relatively small fraction of total U.S. capacity (less than 10%) is assigned to meet government requirements for military programs.

Prediction of demand for U.S. enrichment services over the next ten years is complicated by several factors. First, many uncertainties surround existing nuclear power plant construction programs; in recent years, delays and reduced electricity demand growth rates have contributed to increases in the average length and also the unpredictability of power plant lead-times in the U.S. and elsewhere.²⁴

Second, the fraction of the non-U.S. enrichment demand that will be captured by the DOE plants is also highly uncertain.

Third, a temporary source of uncertainty has arisen as a result of changes in contracting arrangements instituted by the Department of Energy within the last year. Until recently, DOE entered into enrichment service supply arrangements under so-called Long-Term Fixed Commitment (LTFC) contracts, which required customers to specify requirements many years in advance of delivery, and which offered only limited interim opportunities for adjustments to long-term delivery schedules. As nuclear power programs slowed in the second half of the 1970s, an increasingly large gap opened up between commitments to procure separative work made by utilities under LTFC contracts and actual needs for enriched fuel. Partly in response to

customer requests for relief (and partly also in recognition of the emergence of competition in enrichment markets from the new European suppliers), DOE recently introduced new, more flexible contracting terms and conditions.

Under the new Adjustable Fixed Commitment (AFC) contracts, a shorter lead-time between contract execution and initial deliveries is permitted, and customers are generally provided with greater flexibility in scheduling and adjusting their requirements. Existing customers have been given until September 30, 1979 to decide whether to terminate old contracts and/or convert to new ones, and to specify delivery schedules under the new arrangements. As of this writing, the effect of DOE's new contracting policies on its separative work delivery schedule remains to be seen.

Each of these factors makes the business of projecting enrichment demand highly uncertain at present. The most recent DOE estimate of demand to have been released to the public was prepared in February 1979, and, despite the fact that it will almost certainly have to be modified shortly, provides the 'reference' demand schedule for this analysis.²⁵

DOE has also recently announced changes to its expected production schedule during the next decade. In anticipation of reductions in demand, production during the next two years (FY 80 - 81) will amount to only about 50 - 60% of available capacity. In addition, while the two programs to increase the capacity of the gaseous diffusion complex - the so-called Cascade Improvement and Upgrading Programs (CIP and CUP) - will reportedly be completed on schedule in 1981, the additional output available from them apparently will not be fully utilized until 1985. Thirdly, within the last year, the plan originally announced by President Carter in 1977 to build an 8.8 MSWU gas centrifuge facility (GCEP) at Portsmouth, Ohio

by 1988 has been deferred;* the Administration now intends to complete only 2.2 MSWU of centrifuge capacity by 1988, with the remainder of the plant added incrementally over the following five years.²⁶ Finally, in late 1978 DOE announced that the operating tails assay for the gaseous diffusion plants would henceforth be reduced from 0.25% to 0.2%; the Department expects that the assay can be maintained at this level until the late 1980s.²⁷ A summary of DOE's anticipated production schedule incorporating these new policy developments was presented in May 1979.²⁸ The May 1979 production plan and the February 1979 demand schedule are listed in Table 3.4.1 of Appendix 3.4, which also shows how the separative work surplus will develop under the assumed conditions. The behaviour of the surplus is shown graphically in path P of Figure 3.13.** (Paths Q and R are discussed shortly.) Under this scenario, the DOE stockpile can be maintained at about 17 MSWU into the 1990s, above the 14 MSWU level recently identified by DOE as the minimum required for working inventory and strategic contingencies. (Without the gas centrifuge plant, the separative work inventory would fall to unacceptably low levels by the beginning of 1991, as curve P' shows.) According to this supply/demand scenario, therefore, the next increment of enrichment capacity beyond the GCEP would not be required until the mid-1990s, unless annual demand rose significantly above 34 MSWU (at 0.25% tails assay) any earlier.*** Any interim commercial role for one or other of the advanced enrichment

* 1 MSWU = 1 million kg SW

** In Figure 3.13, it is assumed that DOE stockpile will remain at approximately its 1978 level of 34 MSWU (evaluated at 0.2% U²³⁵) until January 1, 1980.²⁹

*** In DOE's February 1979 forecast, demand is projected to stabilize at around 34 MSWU/yr (at 0.25% assay) after 1990. At steady-state, 34 MSWU/yr could meet the requirements of approximately 310 GWe of LWR capacity.

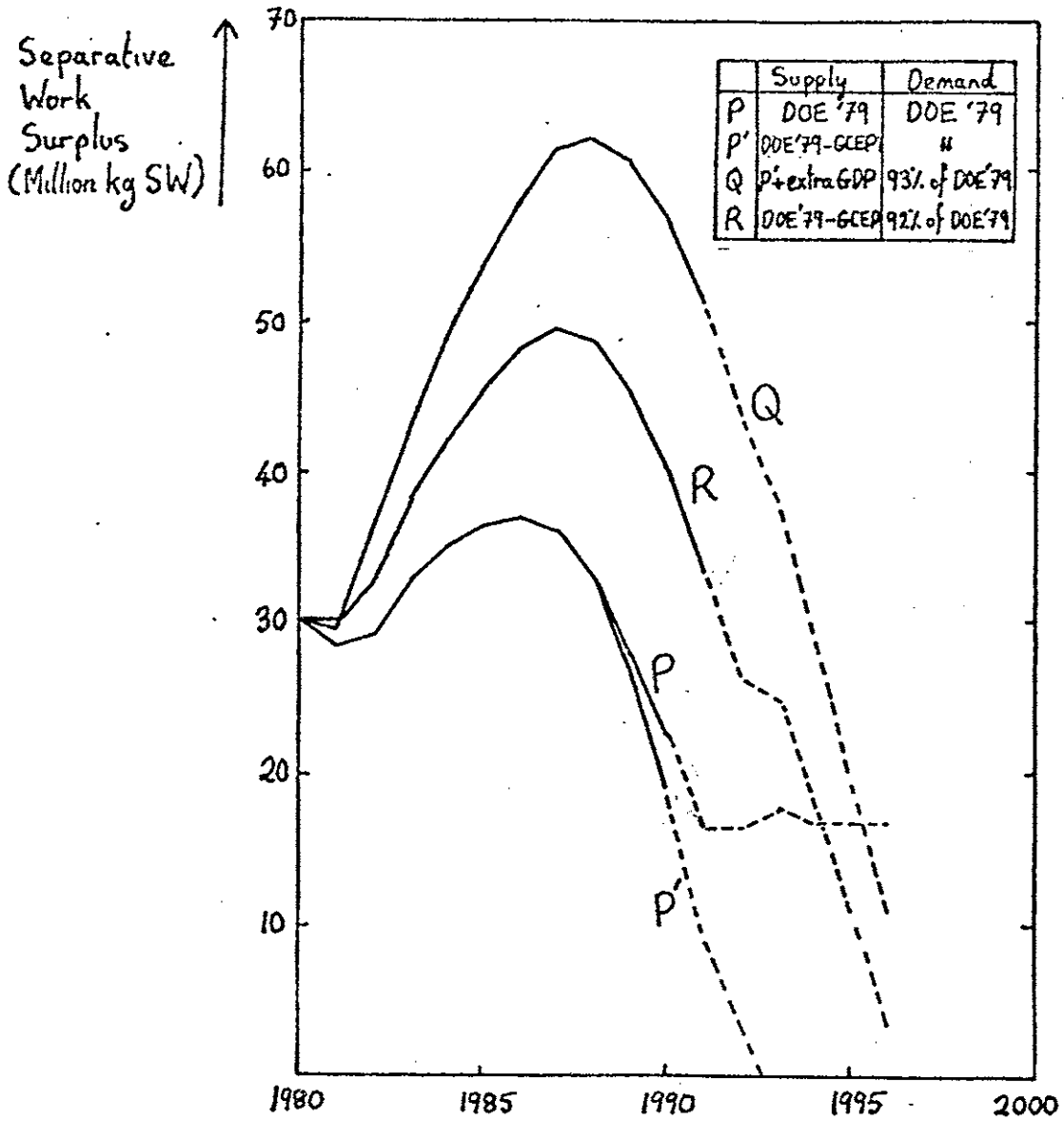


FIG. 3.13: U.S. DOE SEPARATIVE WORK STOCKPILE PROJECTIONS, 1980-96

(Basis: 0.25% assay)

technologies would thus be limited to the enrichment of conventional uranium tails (0.2% U²³⁵) to the assay of natural uranium.

While the above scenario closely matches the most recent analysis of separative work supply and demand released to the public by DOE, other scenarios should also be considered. For example, fears have been expressed that DOE's current operating plan may underestimate demand, and, if implemented, result in a supply shortfall. In this context, the results of a July 1978 survey of DOE domestic and foreign enrichment customers are cited; the survey, which requested utilities to resubmit estimates of their likely requirements under the new AFC contracts, indicated that cumulative separative work requirements to 1990 predicted by the utilities themselves would be as much as 40 MSWU higher than those projected by DOE in February 1979.³⁰ (See Figure 3.14.) For these and other reasons, it has been proposed that the Portsmouth centrifuge plant be restored to its original schedule.

But utilities have traditionally been slow to adjust to probable schedule slippages,³¹ and have tended to make contractual commitments for separative work on the basis of currently announced construction and operating plans which usually exceed actual needs.³² For example, the response of U.S. utilities to the July 1978 survey was only 9% lower than its response to another survey conducted in June 1977. And yet, official U.S. government projections of domestic nuclear capacity installed by 1990 fell during a roughly coincident period by over 30%. (See Fig. 3.14.) Since July 1978 nuclear power projections have fallen once again, and these delays seem likely to be reflected in later downward adjustments to separative work requirements.³³

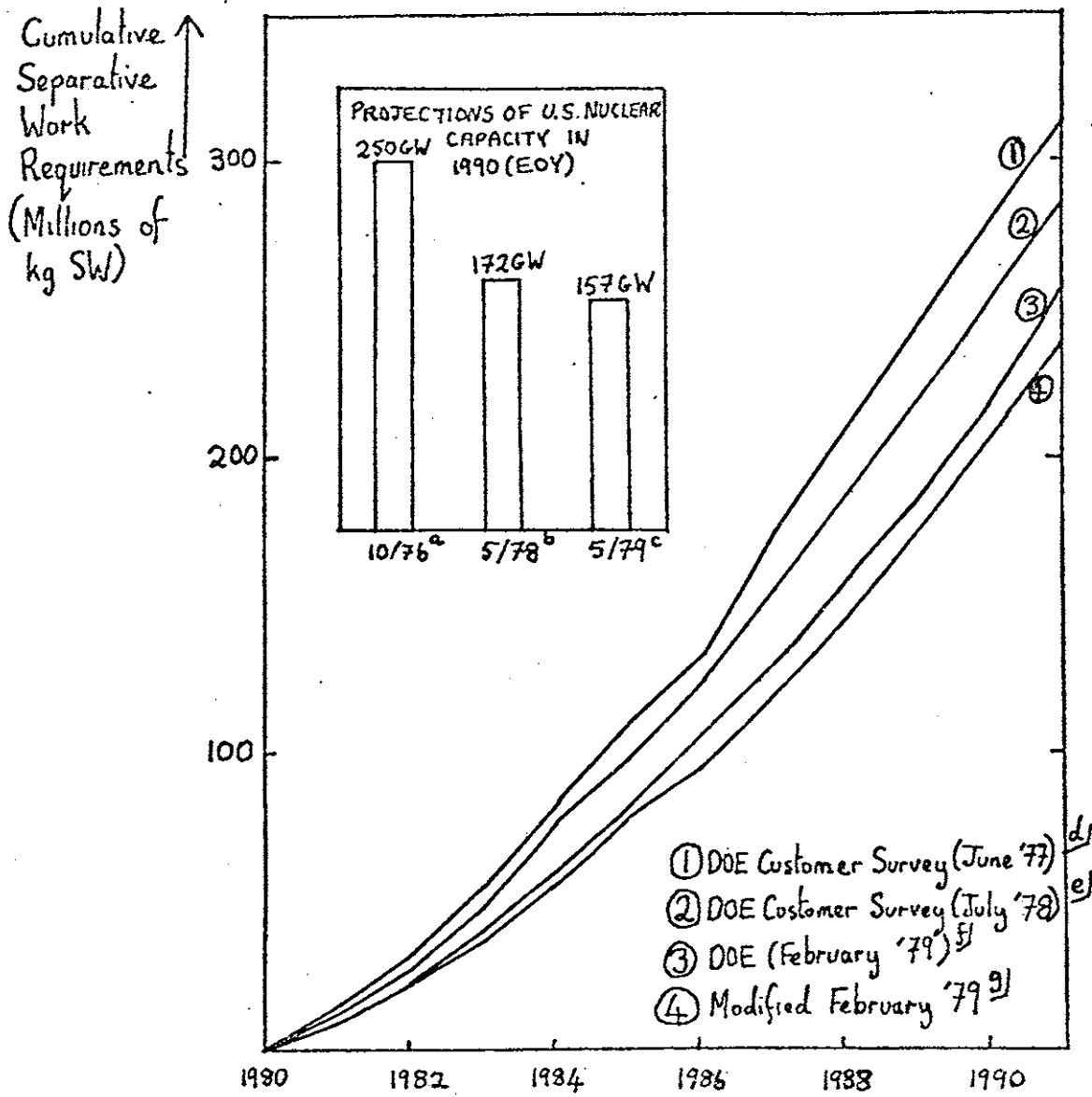


FIG. 3.14: PROJECTIONS OF CUMULATIVE DEMAND FOR DOE ENRICHMENT SERVICES, 1980-1990

Notes to Figure 3.14

- a. R.W. Bown and R.H. Williamson, "Domestic Uranium Requirements", paper presented at the U.S. Department of Energy Uranium Industry Seminar, Grand Junction, Colorado, October 26, 1977.
- b. Energy Information Administration, U.S. DOE, in Nuclear Fuel, 15 May 1978
- c. Energy Information Administration, U.S. DOE, in Nuclear Fuel, 14 May, 1979
- d. Nuclear Fuel, 15 May 1978
- e. Nuclear Fuel, 18 September 1978, 2
- f. Nuclear Fuel, 14 May 1979
- g. DOE's February 1979 projection has been modified by subtracting 13.8 MSWU of actual and potential contract cancellations between 1980 and 1990, and further by reducing the residual demand by 5%.
(1 MWSU = 1 million kg SW.) The modified 1979 projection provides the basis for path R in Figure 3.13.

More directly, since the preparation of DOE's February 1979 separative work demand estimate (which was itself based on nuclear power growth projections of the previous summer,)³⁴ several foreign customers have cancelled a total of 7.8 MSWU of enrichment services originally scheduled for delivery between 1979 and 1990, and it is rumored that a further 6 MSWU currently under contract will also be terminated shortly.³⁵ In light of these developments, the need for the GCEP may be postponed even further. This possibility has been reinforced in the aftermath of the accident at Three Mile Island and the subsequent slowdown in reactor construction schedules widely experienced throughout the U.S.

A combination of delays and terminations with certain modifications to DOE's proposed operating strategy could conceivably defer the required startup date for the first increment of gas centrifuge capacity until some time in the early 1990s. One such scenario is shown in curve Q of Figure 3.13. The demand is assumed to correspond to the DOE February 1979 projection, except with the 13.8 MSWU of actual and potential cancellations subtracted. On the supply side, it is assumed that production will be increased by about 14% above current plans for 1981-84, (still well under the ceiling of available capacity), that an operating tails assay of 0.25% will be introduced in 1985 (rather than in 1991, as currently anticipated), and that the startup date for the next increment of enrichment capacity will be determined by the criterion that the separative work stockpile should not be allowed to fall to unacceptable levels (i.e., less than about 15 MSWU). The quantitative details of case Q are presented in Table 3.4.2 of Appendix 3.4.

Under these conditions, the first centrifuge capacity increment would not be required until about 1994, again provided annual demand did not

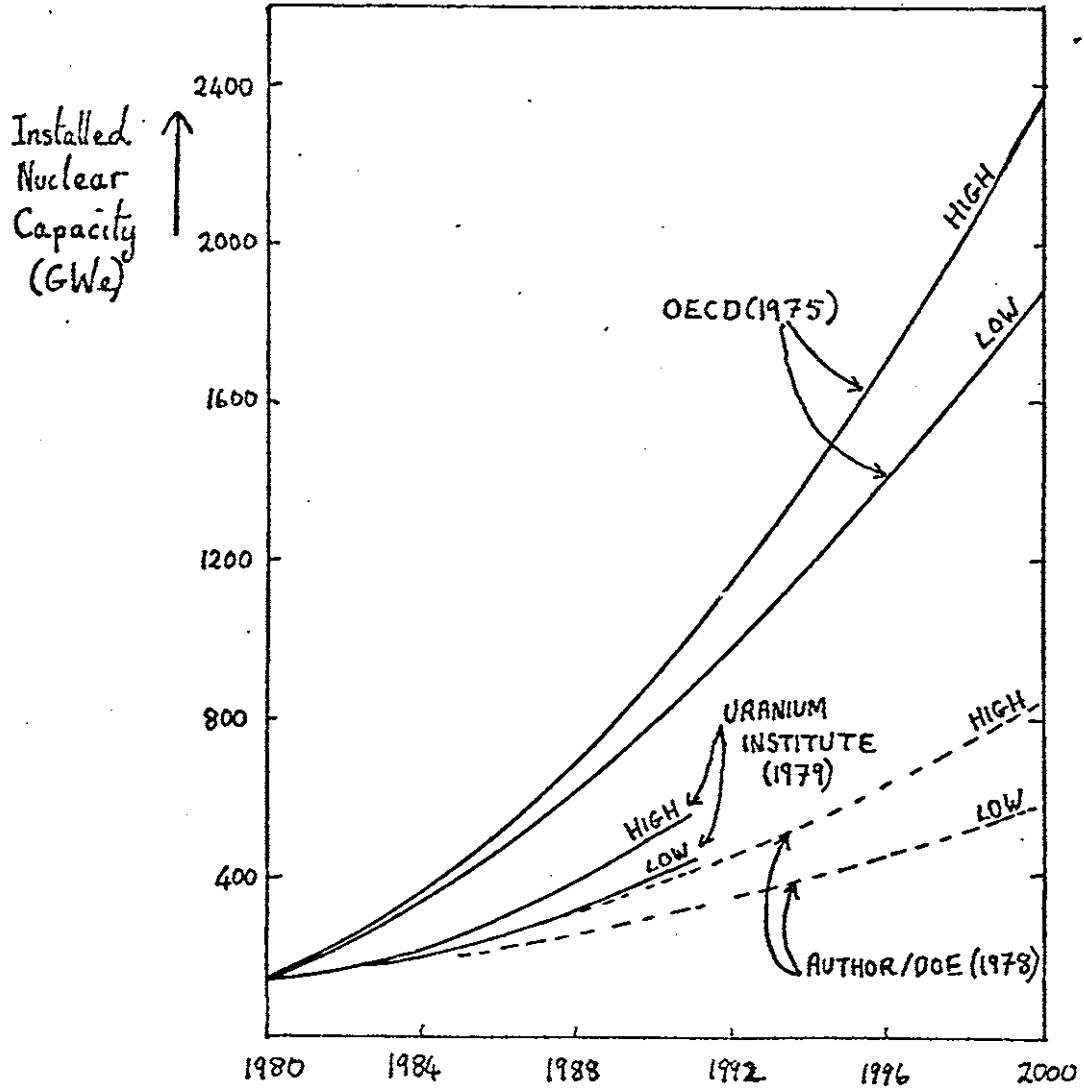


FIG 3.15: WORLD NUCLEAR POWER GROWTH PROJECTIONS

exceed 34 MSWU in the preceding years. About 17 million kilograms of additional natural uranium would be required to boost separative work production 14% from 1981 to 1984, and a further 17.5 million kilograms would be needed to support the earlier increase in tails assay.*

Since U.S. AIS development programs are now targeted for a commercialization date in the mid-1990s, case Q raises the possibility that the gas centrifuge process might be replaced by one or other of the new enrichment technologies as the economic choice for the next increment of capacity, rather than, as current plans indicate, the one after. At the very least, a consequence of this scenario would be to increase the likelihood of direct economic competition between the later stages of the 8.8 MSWU centrifuge plant and the next generation of enrichment technologies.

Other scenarios suggest similar consequences. Curve R in Figure 3.13 illustrates the effect of a 5% reduction in demand below DOE's estimate of February 1979 (adjusted for the 13.8 MSWU of actual and potential cancellations mentioned previously.) As shown in Figure 3.14, these changes are equivalent to a slippage of less than six months from the February '79 estimate - which, it will be recalled, was based on nuclear power growth projections prepared in the summer of 1978 - and indeed probably underestimate the actual slippage that has occurred in the meantime. Production in this case is assumed to match DOE's latest operating plan, minus the anticipated contribution from the Portsmouth plant. The details are summarized in Table 3.4.2 of Appendix 3.4. In this scenario, which in

* The inventory of natural uranium held by DOE currently stands at about 30 million kilograms. Case Q would thus require a combination of stockpile depletion and either additional uranium procurement by the U.S. Government or the institution of a policy mandating early feed deliveries by customers.

fact represents only a very modest departure from DOE's recent estimate of the forthcoming enrichment supply/demand balance, the first increment of the centrifuge plant would not be required until about 1992 or 1993.

Once again, a delay increases the possibility that there will be a pool of new technologies from which to choose for the next increment of U.S. enrichment capacity, rather than only the gas centrifuge process.

How to cope with this emerging possibility in current policy is one of the principal questions addressed in Chapter 6. But already some of the issues are apparent: How will alternative policies affect the size of the U.S. stockpile of enriched uranium over the next decade, and who will bear the costs? What will be the impact of these policies on the uranium industry? How will further delays affect the viability of the Portsmouth centrifuge project? Will a loss of continuity increase project costs? What is the appropriate development schedule for the advanced isotope separation technologies? Will higher AIS program budgets produce results useful to decision-makers significantly quicker? Will a delay in the Portsmouth plant constrain the government's efforts to maximize the U.S. share of the international enrichment market, and will it generate fears of a supply shortfall? Other pertinent issues will be raised in the next two Chapters, which deal respectively with the proliferation implications of the new technology, and the institutional environment in which it is being developed.

World Enrichment Supply/Demand Balance

The world enrichment market also seems almost certain to experience a substantial supply surplus for most of the next decade. Projected world enrichment demand has fallen sharply in recent years, while two large new commercial facilities have entered operation in Europe, and more capacity increments are planned in the future. We present the expected supply picture first, and then some recent demand projections.

Supply:

The supply situation over the next decade is summarized in Table 3.5. The sources of supply are divided into three categories: 'firm', 'expected' and 'planned'.

- (i) EURODIF - The Eurodif plant, at Tricastin, France, is a gaseous diffusion plant owned by a five-nation consortium. The venture is led by France, and also includes Belgian, Spanish, Italian and Iranian interests. Within three years, the plant will have achieved its full capacity of 10.8 MSWU/yr; currently, 2.6 MSWU/yr of capacity is in operation.
- (ii) URENCO - The Urenco gas centrifuge complex is jointly owned by British, Dutch and German firms. A total of about 0.4 MSWU/yr of capacity is currently in operation at two sites in Holland and Britain. Firm contractual commitments to supply 2 MSWU/yr have been made by Urenco, and the complex should reach this capacity by 1984. It is expected that the capacity will eventually increase to about 9 MSWU; the additions will be related to future contractual commitments, however, and the figures shown in the 'expected' category are projections only.³⁷

Table 3.5

World Enrichment Supplies, 1980-1990³⁶

	<u>Firm Production</u> (10 ⁶ kg SW/yr)					<u>Expected Production</u> (10 ⁶ kg SW/yr)			<u>Planned Production</u> (10 ⁶ kg SW/yr)		
	<u>Eurodif</u>	<u>Urenco</u>	<u>USSR^a</u>	<u>USGDP</u>	<u>Subtotal</u>	<u>USGCEP</u>	<u>Urenco</u>	<u>Subtotal</u>	<u>Coredif</u>	<u>PNC</u>	<u>Total</u>
1980	6.0	0.5	3.9	10.5	20.9	-	-	20.9	-	0.02	20.9
1981	8.5	0.7	4.1	15.0	28.3	-	-	28.3	-	0.05	28.4
1982	10.8	1.0	4.0	21.6	37.4	-	-	37.4	-	0.05	37.5
1983	10.8	1.5	4.4	21.6	38.3	-	-	38.3	-	0.05	38.4
1984	10.8	2.0	3.4	23.6	39.8	-	-	39.8	-	0.15	40.0
1985	10.8	2.0	3.4	25.6	41.8	-	0.5	42.3	-	0.35	42.7
1986	10.8	2.0	3.2	25.6	41.6	-	1.5	43.1	2.0	0.55	45.7
1987	10.8	2.0	3.3	25.6	41.7	-	3.0	44.7	4.0	0.55	49.3
1988	10.8	2.0	3.2	25.6	41.6	0.9	4.5	47.0	6.0	1.35	54.4
1989	10.8	2.0	2.5	25.6	40.9	2.8	6.0	50.0	8.0	1.95	60.0
1990	10.8	2.0	2.4	25.6	40.8	4.0	7.0	52.0	10.0	2.5	65.0

a. The figures for the USSR (Techsnabexport) are based on nominal export commitments to Western countries. Supply and demand within the countries of the Soviet bloc are excluded from this analysis.

- (iii) USSR (Techsnabexport) - The full capacity of the Soviet enrichment plants is unknown. The figures presented in Table 3.5 only include commitments already entered into. It is believed that the Soviet Union could export enrichment services in larger quantities in future if necessary.
- (iv) U.S. DOE - In line with the discussion in the previous section, the anticipated production schedule for DOE's expanded gaseous diffusion complex is entered in the 'firm' category, while the gas centrifuge 'add on' capacity appears in the 'expected' column.
- (v) COREDIF - For several years, a multinational consortium involving the Eurodif partners has been planning to build a second large gaseous diffusion plant. With the probable excess of supply until 1990, however, the Coredif project has lost momentum, and the production estimates given in Table 3.5 will almost certainly be pushed back.
- (vi) JAPAN (PNC) - The Power Reactor and Nuclear Fuel Development Corporation (PNC) is currently developing the gas centrifuge process and expects to complete construction of a demonstration plant by 1984. A commercial-scale plant is planned for later in the decade.

Other enrichment projects in Brazil, South Africa, and Australia are at an earlier stage of planning, and are not shown in Table 3.5. More information on these projects is given in Section 4 of Chapter 4.

Demand:

Future world enrichment demand is highly uncertain. World nuclear power growth projections have fallen rapidly in recent years. Figure 3.15

compares a projection based on data published by the OECD in December 1975 with a recent (February 1979) forecast made by the Uranium Institute of London. As shown, estimates of installed nuclear capacity in 1990 have fallen by a factor of two in a little over three years. The Uranium Institute projection may itself be too high. Figure 3.15 also shows a lower projection made by the author based on data released in an unofficial publication by DOE's Energy Information Administration in 1978. Also, recent projections made by the secretariat of the International Energy Agency in Paris indicate that actual growth will be a good deal lower than even the 'low' Uranium Institute projection suggests.³⁸

Another source of uncertainty is the imbalance between contractual commitments for enrichment supplies and expected reactor requirements which has been a feature of the recent period of falling nuclear power forecasts. (See Table 3.4.3 in Appendix 3.4.) Some of the confusion may be removed after publication in early 1980 of the analyses of Working Groups 1 and 2 of the International Nuclear Fuel Cycle Evaluation (INFCE), which have spent the past two years studying the demand for nuclear fuel and its availability.

In the meantime, Figure 3.16 compares the separative work supply schedule in Table 3.5 with demand estimates derived from the Uranium Institute's 'low' nuclear power growth projection in Fig. 3.15.* As shown,

* To arrive at the separative work demand for Figure 3.16, the demand estimates in Table 3.4.3 were augmented by projected U.S. government requirements, which will be met out of DOE production. Also, the estimates in Table 3.4.3 were brought forward by one year, to account for ordering and delivery lead-times. Finally, it is assumed in Figure 3.16 that a separative work surplus of 46.4 MSWU (evaluated at 0.2% U²³⁵) will exist on January 1, 1980. In fact, stocks in the non-Communist world amounted to approximately this figure in 1977 - 34 MSWU at the U.S. DOE plants,³⁹ and a further 12.4 MSWU held by U.S., European and Japanese utilities and agents.⁴⁰ Since further stockpiling has almost certainly occurred in the meantime, the 46.4 MSWU assumption for 1980 is probably conservative.

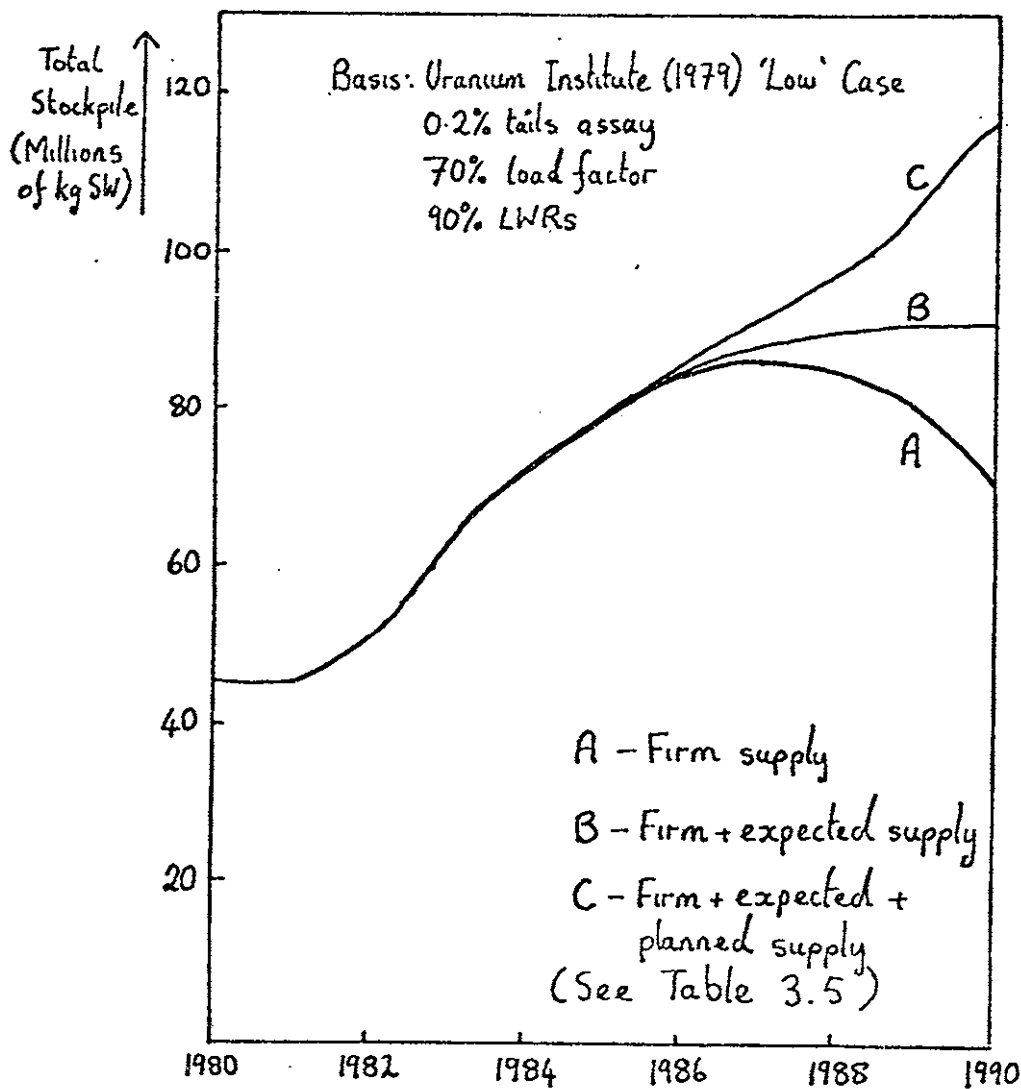


FIG. 3.16: WORLD SEPARATIVE WORK SURPLUS; 1980-90
(Excludes Communist countries except Yugoslavia)

world stocks will build up to very high levels during the 1980s, according to this scenario. For example, by 1987, the surplus would be large enough to meet the fuel requirements of the projected 1987 LWR population of 231 GWe for three years. It is probable that stocks would be allowed to fall somewhat before new deliveries were taken. According to this scenario, therefore, the next increment of enrichment capacity beyond the U.S. and Eurodif diffusion plants and the first 2 MSWU of the Urenco plant would not be required until 1989-90 at the earliest. If, as seems likely, actual requirements during the 1980s turn out to be lower than those associated with the Uranium Institute 'low' growth projection, the next increment may then not be required until the early 1990s. (This would be consistent with the deferral strategy for the Portsmouth GCEP plant discussed in the previous section.) At that time, the U.S., Urenco, and Japanese centrifuge plants (and the Coreidif project, if it was still alive) would be the principal competitors for whatever new enrichment business became available.

A more rigorous analysis of the world enrichment sector, including more recent nuclear power growth projections and a more sophisticated treatment of stockpiling policies, is clearly necessary. Nevertheless, the preceding discussion suggests that the deferral of the GCEP plant discussed in the previous section may also not be inconsistent with world enrichment market trends.

Notes to Chapter 3

1. Report of the JNAI Laser Enrichment Review Panel, Laser isotope separation: proliferation risks and benefits, February 27, 1979, vol. II, App. D
2. The following estimated power requirements for a conceptual 2800 MTSW/yr AVLIS plant enriching 0.2% material to 3% and discharging tails at an assay of 0.08% were recently provided to the author by JNAI officials:

laser system:	9 MW
uranium evaporators:	34 MW
dye recovery, metal revapourization, and metal preparation:	20 MW
miscellaneous:	5 MW
<hr/>	
Total	68 MW
<hr/>	

3. These figures were calculated from the following data assembled in an unpublished study by R. Marlay, Department of Nuclear Engineering, M.I.T. (1978):

<u>Year</u>	<u>Average electricity revenues (mills/kwh)</u>	<u>1977 GNP multiplier</u>
1970	15.9	1.5468
1971	16.9	1.4718
1972	17.7	1.4132
1973	18.6	1.3357
1974	23.0	1.2181
1975	27.0	1.1112
1976	28.9	1.0556
1977	32.1	1.0000

4. F.M. Shofner and R.L. Hoglund, "Laser cost experience and estimation", Oak Ridge Gaseous Diffusion Plant, K/OA-403A, Oak Ridge, Tennessee, June 28, 1977, 20
5. Ibid., 53
6. Ibid., 50
7. C. Allday, G. Besse, P. Jelinek-Fink, W.R. Voigt, "Front End of the Fuel Cycle", Paper presented at European Nuclear Conference, Hamburg, May 6 - 11, 1979, 10
8. J. Steyn, "Worldwide separative work supply/demand", presented at the Atomic Industrial Forum International Conference on Uranium Enrichment, New Orleans, Louisiana, January 30, 1978
9. "DOE Projections of U.S. Nuclear Power Growth", September/October Energy Update, 1978
10. "28th Annual Electrical Industry Forecast", Electrical World, September 15, 1977, p. 54
11. The calculation assumes that nuclear plants will continue to be used largely as baseload units, and that the fraction of total installed electrical generating capacity that is baseloaded will continue to be about 50%. (See: Vince Taylor, "The Myth of Uranium Scarcity", Pan Heuristics: Los Angeles, California, 1977)
12. See: The National Energy Plan, Executive Office of the President, April 29, 1977 (published by the U.S. Government Printing Office) and,

more recently, "Remarks of the President before the National Association of Counties", New York Times, 16 July 1979

13. M. Lonnroth and W. Walker, "Viability of the Nuclear Industry", Draft interim report prepared for the International Consultative Group on Nuclear Energy, (Co-sponsors, the Rockefeller Foundation and the Royal Institute for International Affairs), January 1979, 10
14. National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems, Report of the Supply and Delivery Panel, Washington, D.C., Dec. 11 1978, 5 - 34
15. C.E. Till and Y.I. Chang, "Once-through fuel cycles", Invited paper presented at 18th Annual ASME Symposium, Non-Proliferation: Reality and Illusion of a Plutonium-Free Economy, Albuquerque, New Mexico, March 16-17, 1978
16. A demonstration project is already underway at a U.S. utility in which fuel of current design is expected to be taken to over 40,000 MWD/MT. (See: Peter M. Lang, "Improving LWR fuel utilization", Nuclear Engineering International, February 1979, 13)
17. "DOE ups U estimates", Nuclear News, 21 (7), May 1978, 47.
18. Leon T. Silver et al, "Analysis of United States Uranium Resources, 1976, and Projections of Uranium Supply to the Year 2010", CONAES Uranium Resource Subpanel Report, April 6, 1977 (2nd revised draft)
19. The basic data for Figures 3.10 - 3.12 were provided by the scenarios in Figure 3.6 and the uranium requirements for various reactor/fuel

cycle systems summarized in Table 3.3.1 of Appendix 3.3. It was further assumed that utilities will procure natural uranium an average of 1 1/2 years before the fuel is loaded to the reactor, and that U.S. utilities will maintain uranium stockpiles equivalent to one year of annual requirements. Actual utility stockpiling behaviour will be a complicated function of the amounts of nuclear capacity in operation, under construction and on order, the extent of previous construction slippages, current perceptions of the uranium market and of the security of supply, etc. Since the purpose of these calculations was to estimate the relative impact of various technical conservation measures on uranium requirements under otherwise constant conditions, the construction of an elaborate model to account for stockpiling behaviour was deemed unnecessary.

20. Silver et al, op. cit.
21. Laser Isotope Separation: Proliferation Risks and Benefits, Report of the Laser Enrichment Review Panel (Chairman: T. Keith Glenman) to JNAI, Inc., February 27, 1979, vol. 2, App. E.
22. Nuclear News, 21 (7), May 1978, 48
23. See: Allday et al, op. cit., 9
24. Richard K. Lester, "Nuclear Power Plant Lead-times", Report to the International Consultative Group on Nuclear Energy, published by the Rockefeller Foundation and the Royal Institute for International Affairs, London and New York, October 1978
25. Nuclear Fuel, May 14, 1979, 4

26. Ibid.
27. Nuclear Fuel, 30 October 1978, 3.
28. C. Allday et al, op. cit.
29. Nuclear Fuel, June 12, 1978, 6
30. See Nuclear Fuel, September 18, 1978, 1-2
31. In 1977, analysts at the (then) Federal Energy Administration estimated that installed nuclear capacity by the end of 1987 would amount to 144 GWe, taking account of schedule slippages. At the time, utility plans were calling for 194 GWe to be installed by that date. See: Nuclear News, 20 (15), December 1977, 51
32. Nuclear Fuel, September 4, 1978, 8
33. Nuclear Fuel, September 18, 1978, 2
34. Roger Gagney, Division of Uranium Resources and Enrichment, U.S. Department of Energy, telephone interview, July 25, 1979
35. See Nuclear Fuel, 19 February 1979, 9; 16th April 1979
36. Table adapted from C. Allday et al, op. cit., Table 7
37. Ibid., 7
38. Nuclear Engineering International, July 1979, 3
39. Nuclear Fuel, June 12, 1978, 6

40. Michael J. Connor, Nuclear Assurance Corporation, personal communication, 22 August 1977. At this time, the distribution was reported to be as follows: U.S. utilities, 0.4 MSWU; Japanese utilities, 8.6 MSWU; European utilities, 1.5 MSWU; and European agents, 1.9 MSWU.

Appendix 3.1: Estimate of separative work and capital costs for JNAI-type AVLIS plant.

Basis: Nominal 2800 MTSW/yr AVLIS plant producing 3 % product and 0.08 % tails from 0.2 % feed. The specific energy consumption of such a plant is estimated to be about 160 kWh(e)/kg SW. (See Table 3.1)

JNAI officials have estimated that a commercial tails stripping plant based on their technology could provide a 15 % return on investment if natural uranium feed is valued at \$40/lb U_3O_8 and separative work from conventional enrichment plants is valued at \$90/swu. These values correspond roughly to current (1979) commercial prices.

Other useful data include estimates by JNAI that power costs will amount to 40 % of total annual operating costs, and that annual capital replacement costs will be equivalent to roughly 25 % of total annual operating costs. JNAI typically assumes an electric power cost of 22 mills/kwh(e).

The optimal tails assay for the conventional enrichment plant is 0.21 % (a \$5/kg U charge for conversion to UF_6 is added to the yellowcake cost) and the total cost per kilogram of 3 % enriched product is \$1022, from equations (5) and (6) in Appendix 3.5. A total of 18.84 kg of separative work is required to produce 1 kg of 3 % product in the reference AVLIS tails stripping plant (calculated from equation (4) in App. 3.5.). If it is assumed that the 0.2 % feed material has no cost, then the equivalent unit cost of separative work in the plant must be no more than:

$$\frac{1022}{18.84} = \$ 54.2/\text{kg SW}$$

Let I = initial investment cost of the plant (\$)

C = capital replacement cost (\$/kg sw)

O = operating cost other than energy (\$/kg sw)

E = energy cost (\$/kg sw)

Then, for a 15 % return on investment,

$$- I + 2800 \times 10^3 \times L \times (54.2 - E - O - C) (P/A, 15 \%, N) = 0$$

where L = plant capacity factor

N = plant lifetime

$$(P/A, 15 \%, N) = \frac{1.15^N - 1}{0.15 \times 1.15^N} = \text{uniform series present worth factor}$$

and it is assumed that C, O, E remain constant over the plant lifetime.

The following table shows how the unit capital cost (in \$/kg sw/yr)

varies for different assumed values of L and N:

	N (yrs)		
	15	20	25
<u>L (%)</u>			
80	225	240	250
100	280	300	310

The estimated total capital cost for these assumptions is in the range \$670 - \$835 million.

Appendix 3.2: Simplified fuel cycle cost model

In this section, a highly simplified model is developed which can be used to estimate the effect of changes in separative work costs on the total fuel cycle costs and uranium requirements for a 1060 MWe pressurized water reactor. Data for the model have been derived from¹ calculations performed some years ago by H.Y. Watt.

The following assumptions are made.

1. The reactor is refueled annually, according to a 3-zone modified scatter scheme. The irradiation lifetime of the fuel is thus 3 years.
2. The average reactor load factor is 0.75, including refueling outages. The energy generated per cycle is thus 6970 GWe, and for 3-zone modified scatter refueling, the steady state feed enrichment for² such a cycle is 3.1 %.
3. Each fuel lot contains 30,119 kg of uranium, and the reactor³ thermal efficiency is 33 %. Thus, the steady state fuel burn-up is 29200 MWD(t)/MTU.
4. The schedule of payments and receipts for fuel cycle services is as follows:
 - (a) yellowcake, yellowcake conversion, enrichment services, and fuel fabrication are all paid for 1 year before the fuel is loaded to the reactor.
 - (b) payment for transport and long-term storage of spent nuclear fuel is made 10 years after the fuel is discharged from the reactor.
 - (c) the effective time at which revenue is received for the generation of electricity by a particular fuel lot occurs

three-quarters of the way through the irradiation lifetime of that fuel lot.

A simplified expression for the levelized cost of electricity from each lot of fuel, \bar{e} , is:

$$\bar{e} = \frac{(1+r)^{0.75t_R+1}}{E} \left[(Z_u + Z_c + Z_s + Z_f) + \frac{Z_d}{(1+r)^{t_R+1}} \right] \quad (1)$$

where:

- Z_u = total cost of yellowcake purchased per fuel lot
- Z_c = total cost of yellowcake conversion per fuel lot
- Z_s = total cost of separative work per fuel lot
- Z_f = total cost of fuel fabrication per fuel lot
- Z_d = total cost of spent fuel transport and disposal per fuel lot
- E = cycle electrical energy
- t_R = fuel irradiation period
- r = discount rate

The unit fuel cycle costs (1977 dollars) presented in Table 3.2.a. of the main text are again used here, i.e.:

Unit cost of yellowcake = \$40/lb.

Unit cost of conversion to UF_6 = \$2.75/lb.

Unit cost of fabrication = \$110/kg U

The unit cost of spent fuel transportation and ultimate disposal is assumed to be \$130/kg. ⁴ An annual discount rate of 15 % is also assumed. Finally, it is assumed that the enrichment tails assay is set at the optimum value. (See Section 3.3 of the main text.)

With these assumptions, equation (1) above may be used to estimate the variation in levelized fuel cycle costs for changes in separative work costs. The results are shown in Figure 3.4 of the main text.

The results of a similar set of calculations, this time with an assumed yellowcake cost of \$100/lb U_3O_8 , are also shown in Figure 3.4.

Notes to Appendix 3.2

1. Calculations performed by H.Y. Watt, reported in M. Benedict, "Fuel management in large pressurized water reactors," classnotes, course 22.34, Nuclear Power Economics, M.I.T. Department of Nuclear Engineering, Spring 1975.
2. Ibid.
3. Ibid.
4. Unit costs of \$115/kg heavy metal (1976 dollars) for spent fuel transportation and disposal were reported in D.R. Haffner et. al., "An evaluated uniform data base for use in nuclear energy systems studies," Hanford Engineering Development Laboratory, October 18, 1977. The figure of \$130/kg (1977 dollars) assumed here corresponds to an escalation factor of 13 %.

Appendix 3.3: Impact of modifications to the current LWR once-through fuel cycle on uranium consumption

Table 3.3.1 presents estimates of the uranium savings available from some of the uranium conservation strategies discussed in Section 3.4 of the main text. The reference case ('LWR_I') is a 1000 MWe pressurized water reactor operating in a standard once-through fuel cycle mode. As in the case of the preceding Appendix, the LWR fuel cycle data were developed based on earlier calculations by H.Y. Watt. The results of core burnup simulations using the codes CELL and CORE performed for a 1060 MWe PWR showing how the fuel discharge burnup varies with the steady state reload batch fraction and enrichment assay¹ were particularly useful for this work. The results used here were calculated for a modified scatter refueling scheme.

Notes to Appendix 3.3

1. See: M. Benedict, "Fuel management in large pressurized water reactors," classnotes, course 22.34, Nuclear Power Economics, M.I.T. Department of Nuclear Engineering, Spring 1975, Figs. 4.9 and 4.10.

Table 3.3.1: Natural uranium savings from once-through fuel cycle
a
modifications

(Basis: 1000 MWe PWR; annual refueling)

CASE	DESCRIPTION					Initial core inventory requirement (S T U ₃ O ₈)	Annual reload requirement	Lifetime requirement	% reduction in lifetime requirements
	Initial enrichment (%)	Steady-state reload enrichment (%)	Discharge burnup (MWD/MT)	Tails assay (%)	Capacity factor (%)				
LWR _I	2.07	3.1	30100	0.2	75	411	213	6590	---
LWR _{II}	1.89	3.05	31000	0.2	60	372	157	4920	25.3
LWR _{III}	2.07	3.63	40200	0.2	75	411	189	5880	10.8
LWR _{IV}	2.07	4.175	50200	0.2	75	411	175	5490	16.7
LWR _V	2.07	4.75	60300	0.2	75	411	167	5255	20.3
LWR _{VI}	2.07	3.1	30100	0.05	75	344	173	5360	18.6
LWR _{VII}	2.07	3.63	40200	0.05	75	344	152	4755	27.8
LWR _{VIII}	2.07	4.175	50200	0.05	75	344	140	4420	33.0
LWR _{IX}	2.07	4.75	60300	0.05	75	344	133	4210	36.1
LWR _X	1.89	3.05	31000	0.05	60	313	127	4000	39.3
HWR _{XI}	0.711	0.711	7500	n.a.	75	164	156	4690	28.9
HWR _{XII}	1.0	1.0	16000	0.2	75	257	114	3560	45.9
HWR _{XIII}	1.0	1.0	16000	0.05	75	236	105	3270	50.4
HWR _{XIV}	1.0	1.0	n.s.	n.s.	60	236	84	2670	59.0

a.

The heavy water reactor fuel cycle data have been extracted from: C.E. Till and Y.I. Chang, "Once Through Fuel Cycles," presented at the 18th Annual ASME Symposium, Albuquerque, New Mexico, March 16-17, 1978.

Appendix 3.4: Separative work supply and demand projections, 1980 - 1995

The following three Tables contain the data used to calculate the separative work supply/demand balances presented in section 3.5 of the main text.

Table 3.4.1 contains the supply and demand data for paths A and A' in Figure 3.13.

Table 3.4.2 contains the corresponding data for paths B and C in Figure 3.13.

Table 3.4.3 compares estimated separative work requirements, derived from the Uranium Institute reactor projections in Figure 3.15 in the main text, with total known commitments to supply enrichment services. The overcommitment, which even here is substantial, may in practice be greater still, since actual nuclear power growth seems likely to be even slower than the 'low' Uranium Institute projection suggests.

Table 3.4.1

Separative Work Supply and Demand Projections for Figure 3.13,
Paths P and P'

(10⁶ kg SW/yr)

	Operating tails assay ^a	Supply ^a		Demand ^b (at operating tails assay)	Surplus (evaluated at 0.25% assay)	
		(P)	(P')		(P)	(P')
1979					30.1	30.1
1980	0.2%	10.5	10.5	12.1	28.7	28.7
1981	"	15.0	15.0	14.3	29.3	29.3
1982	"	21.6	21.6	17.4	33.0	33.0
1983	"	21.6	21.6	19.4	35.0	35.0
1984	"	23.6	23.6	21.9	36.5	36.5
1985	"	25.6	25.6	25.0	37.0	37.0
1986	"	25.6	25.6	26.0	36.1	36.1
1987	"	25.6	"	29.4	32.7	32.7
1988	"	26.5	"	32.1	27.8	27.0
1989	"	28.4	"	34.3	22.6	19.3
1990	"	29.6	"	36.2	16.7	9.9
1991	0.285%	30.9	"	30.7	17.0	3.6
1992	0.25%	32.4	"	31.8	17.6	-1.6
1993	0.25%	33.7	"	34.5	16.8	-
1994	0.25%	34.4	"	34.4	16.8	-
1995	0.25%	34.4	"	34.6	16.8	-

a. The supply data for case P correspond to the production plan announced by DOE in May 1979. (See Nuclear Fuel, 14 May 1979, 4.) The data for case P' are identical, except that the contribution of the Portsmouth centrifuge plant has been removed.

b. The demand data are taken from DOE's most recent public estimate, released in February 1979. (See Nuclear Fuel, 14 May 1979, 4.)

Table 3.4.2

Separative Work Supply and Demand Projections for Figure 3.13, paths Q and R

(10⁶ kg SW/yr)

	PATH Q				PATH R			
	Operating tails assay	Supply	Demand ^a	Surplus (at 0.25%)	Operating tails assay	Supply	Demand ^a	Surplus (at 0.25%)
				30.1				30.1
1980	0.2%	10.5	10.8	29.8	0.2%	10.5	10.3	30.3
1981	"	20.0	13.1	35.9	"	15.0	12.4	32.6
1982	"	23.6	16.2	42.5	"	21.6	15.3	38.1
1983	"	25.6	18.2	49.0	"	21.6	17.2	42.0
1984	"	"	20.6	53.5	"	23.6	19.6	45.6
1985	0.25%	"	21.0	58.1	"	25.6	22.6	48.2
1986	"	"	22.4	61.3	"	"	24.1	49.6
1987	"	"	24.9	62.0	"	"	26.7	48.6
1988	"	"	27.3	60.3	"	"	29.3	45.3
1989	"	"	29.2	56.7	"	"	31.4	40.2
1990	"	"	30.9	51.4	"	"	33.2	33.5
1991	"	"	33.2	43.8	0.285%	"	29.2	26.6
1992	"	"	31.8	37.5	0.25%	"	30.2	25.0
1993	"	"	34.5	28.7	"	"	32.8	17.8
1994	"	"	34.4	19.9	"	"	32.7	10.7
1995	"	"	34.6	10.9	"	"	32.9	3.4

a. Separative work demand is evaluated at the operating tails assay

Table 3.4.3

Separative Work Requirements Compared With
Known Supply Commitments^a

(10⁶ kg SW/yr)

	<u>Reactor Requirements</u> ^b		<u>Commitments</u>
	Low	High	
1980		18	21
1981		21	29
1982		23	34
1983		25	40
1984	29	35	40
1985	32	40	46
1986	35	44	47
1987	39	49	48
1988	42	56	51
1989	45	61	51
1990	49	62	50

a. Source: C. Allday, G. Besse, P. Jelinek-Fink, W.R. Voigt, "Front End of the Fuel Cycle", presented at the European Nuclear Conference, Hamburg, May 6-11, 1979.

b. Derived from the Uranium Institute reactor projections in Figure 3.13. A tails assay of 0.2% and a 70% reactor load factor are assumed.

Appendix 3.5: Notation, Terminology and Useful Equations from Cascade Theory

For most enrichment processes, the degree of isotope separation that can be achieved in a single separating unit (e.g. a diffuser in a gaseous diffusion plant, or a single centrifuge machine in a gas centrifuge plant) is small compared with the separation required. The separating units must therefore be combined in series, with the product from one serving as the feed to the next.

It may also be necessary to combine two or more separating units in parallel, such that each receives feed of the same composition (and thus generates product and tails streams of the same composition). The parallel separating units are collectively referred to as a 'stage'. In gas centrifuge plants, for example, each stage consists of many centrifuges; but gaseous diffusion plant stages generally consist of a single diffuser/compressor assembly.

The complex of series-connected stages is called a cascade. The relationship between cascades, stages and separating units is shown schematically in Figure 3.5.1.

The enriched product from each stage is sometimes referred to as the 'heads', and the depleted fraction, the 'tails'. ('Tails' is also generally used to denote the depleted product from a cascade.)

Let the heads, tails, and feed flows and compositions for a given stage i be L_i^1 , L_i^2 , L_i and y_i , x_i , z_i respectively. Then the stage 'cut', θ_i is $\frac{L_i^1}{L_i}$. The stage separation factor,

$$\alpha = \frac{y_i (1-x_i)}{(1-y_i)x_i}$$

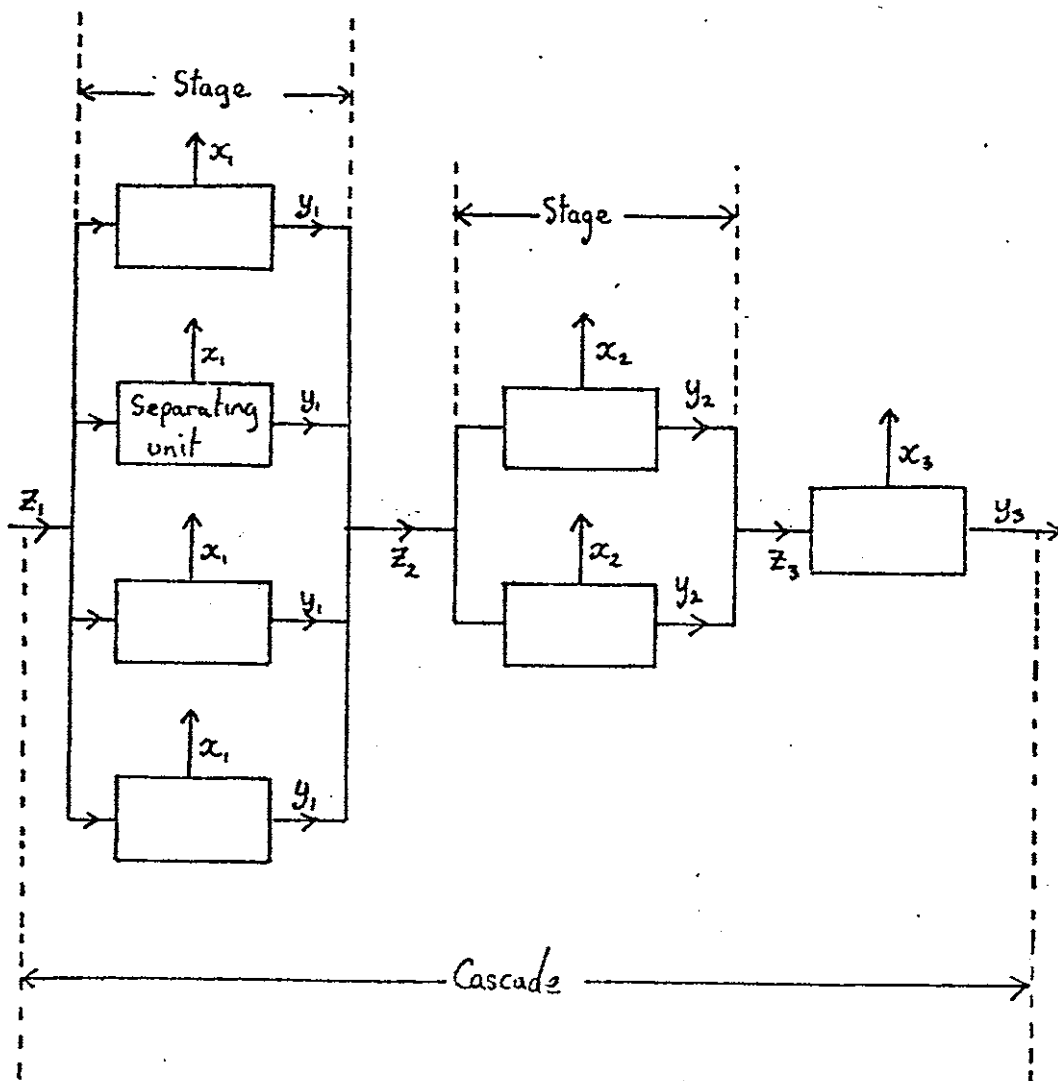


FIG. 3.5.1: CASCADE TERMINOLOGY

and the stage heads separation factor,

$$\beta = \frac{y_i (1-z_i)}{(1-y_i)z_i}$$

In a countercurrent cascade, the tails flow from one stage is recycled through preceding stages while the heads flow is fed to stages higher in the cascade for further enrichment. The simplest form of countercurrent cascade is one in which the heads and tails streams from each stage are fed to the two adjacent stages. This configuration is known as a 'one-up one-down' or symmetrical countercurrent cascade.

An 'ideal' cascade is one in which there is no mixing anywhere of streams of different composition. A 'one-up one-down' ideal cascade is shown in Figure 3.5.2. As might intuitively be expected, it can be shown that for close separation cascades, i.e. cascades in which the stage separation factor is not much greater than unity, the ideal configuration, of all possible configurations, is the one which minimizes the magnitude of the effort required to perform a given enrichment task.¹ For high separation cascades, however, the situation may be quite different.²

Useful equations:

Let F, P, and W be the feed, product and tails flows, (in kilograms), for a given cascade, and let the respective isotopic compositions of these streams be x_F , x_P , and x_W .

These parameters must satisfy the following material balance relations:

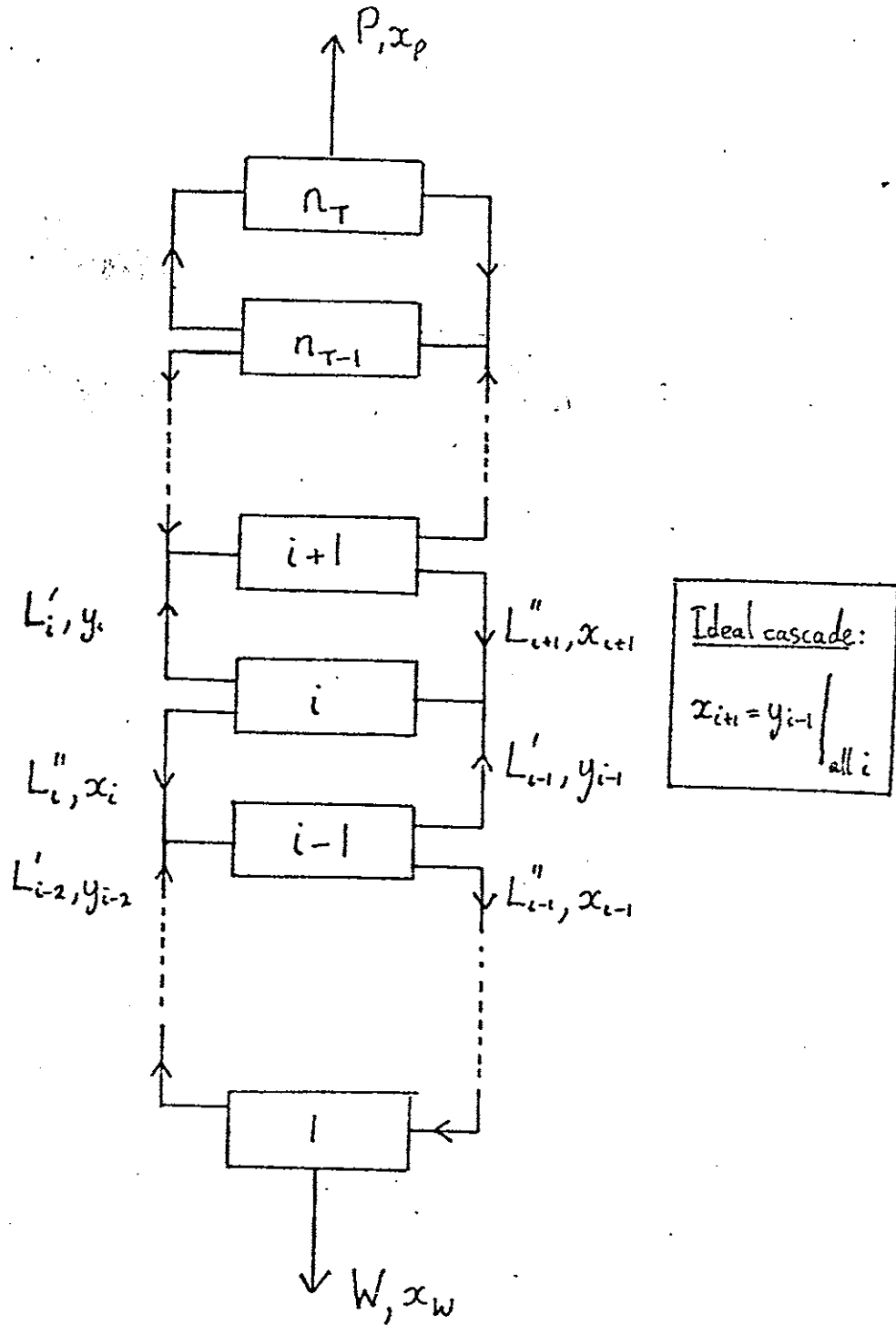


FIG. 3.5.2: IDEAL ONE-UP ONE-DOWN CASCADE

$$F = W + P \quad (1)$$

$$Fx_F = Wx_W + Px_P \quad (2)$$

The separative work required for this enrichment task is defined as:

$$\Delta = P(2x_P-1)\ln(x_P/1-x_P) + W(2x_W-1)\ln(x_W/1-x_W) - F(2x_F-1)\ln(x_F/1-x_F) \quad (3)$$

where Δ is measured in kilograms.

Using equations (1) and (2), the separative work may also be expressed per unit of product in the following way:

$$\frac{\Delta}{P} = (2x_P-1)\ln(x_P/1-x_P) + \left(\frac{x_P-x_F}{x_F-x_W}\right)(2x_W-1)\ln(x_W/1-x_W) + \left(\frac{x_P-x_W}{x_F-x_W}\right)(2x_F-1)\ln(x_F/1-x_F) \quad (4)$$

where the units of Δ/P are kg of separative work/kg of product (or kg SW/kg product).

The optimum tails assay for the cascade, x_0 , is a function of the ratio of the unit costs of uranium feed and separative work, and is given by the following expression:

$$\frac{C_U}{C_S} = (2x_F-1)\ln\left[\frac{x_F(1-x_0)}{x_0(1-x_F)}\right] + \frac{(x_F-x_0)(1-2x_0)}{x_0(1-x_0)} \quad (5)$$

where C_U is the unit cost of uranium feed (in \$/kg U) and C_S is the unit cost of separative work (in \$/kg SW). The unit cost of enriched uranium product (in \$/kg enriched uranium) is,

$$C_P = C_U \frac{x_P-x_0}{x_F-x_0} + C_S \cdot \Delta \quad (6)$$

Notes

1. M. Benedict and T.H. Pigford, Nuclear Chemical Engineering, 394 (New York: McGraw-Hill, 1957)
2. G. Emanuel, "High Enrichment Steady-State Cascade Performance", Nuclear Technology, 43, 314 (1979)

CHAPTER 4

LASER ISOTOPE SEPARATION AND THE PROLIFERATION
OF NUCLEAR WEAPONS

4.1 Introduction

In principle, all enrichment technologies are capable of producing nuclear explosive materials, and thus contribute to the risk that nuclear weapons proliferation will occur. An evaluation of the incremental contribution to be expected from LIS processes is therefore a necessary element of an overall assessment of these technologies.

Knowledge of the extent to which LIS technologies reduce the technical barriers to proliferation is only part of the problem, however, and does not in itself provide a sufficient foundation for policy-making. The risk (or, more accurately, the probability) that proliferation will occur is a combined function of both technical capabilities and an array of political, military and economic incentives and disincentives to proliferate. And, of course, the significance of the weapons themselves depends not only on their destructive potential but also on the possibility that they will be used.

In a world free of incentives to proliferate, the additional technical capabilities offered by LIS would have no relevance. On the other hand, in a world racked with tensions and suspicions among and within nations, the extra capabilities offered by a new technology might themselves aggravate feelings of insecurity or create new temptations, or both, in all cases reinforcing existing incentives to proliferate.

Clearly, therefore, the risks posed by LIS technologies can only be analysed within the context of a particular political, military and economic milieu, and what is of interest in policy-making is the nature of the interaction of these technologies with the environment in which they are placed (including their own political and institutional arrangements).

Moreover, the appropriate measure of this interaction is not simply the degree to which the technologies enhance proliferation capabilities, nor is it the incremental probability that one or more weapons will be produced as a consequence of their development and application, though both of these factors are important. Rather, it is the extent to which each of the various indices of the security of nations or individuals is perturbed by the technological innovation.

In this broader, if less tangible formulation, it is not sufficient to regard proliferation simply as the physical 'act' of acquiring one or more nuclear weapons. At issue is the entire process of proliferation - the various sequences of events, decisions and actions which may lead to the possession of nuclear weapons, and the assorted external reactions and counteractions to such developments. Unless otherwise indicated, it is in this latter sense that the term proliferation will be used for the remainder of the analysis.

It is also necessary to define the geopolitical scope of the analysis. An 'objective' approach would be to consider the ramifications of the technologies for the security of nations in general. But how is 'international security' to be defined? And how is it influenced by the nuclear weapons 'state' of a particular nation (where this 'state' is now a function

not only of the technical capabilities of a country to acquire weapons, but also of its incentives to do so, of the level of its aspirations - i.e., the size and sophistication of the armament it desires - and of the strength of the constraints that it would face in such an attempt)? Even if an objective definition for the former were possible, the latter relationship would still be difficult to establish. For example, although the idea of a monotonic relationship between a country's political and technical proximity to weapons and the resulting threat to international security is temptingly straightforward, the fact remains that a country hovering on the edge of acquiring nuclear weapons may be a more provocative target for military attack than if it already had them. Similarly, 'balances' of nuclear terror, no matter how odious, may be less destabilizing than gross nuclear asymmetries.

If anything, the definitional problem is even more severe. In this regard, proliferation risk assessment is very different from the assessment of other problems generally associated with nuclear power, such as reactor safety, nuclear waste disposal, and the effects of low-level radiation. In every case, including that of proliferation, two kinds of argument are conducted simultaneously, one over the magnitude of the risk, and the other over the level of risk that is socially acceptable.¹ The latter issue is, in all cases, a political one. As far as the health and safety risks to the public are concerned, the former question is largely quantitative, and can be defined and analysed within the framework of the physical sciences. But in the case of proliferation, the nature of the risk - the erosion of security in the face of potential or actual human aggression - is itself political. Security is not an absolute state, but

perceived, and by its very nature international security lacks a unique subject. There is no obvious way to synthesize the inevitably different perceptions of how the security of a region is affected by the nuclear weapons 'state' of a particular country. The difficulties are compounded when, as the the previous formulation implies, the ultimate task is to assess the global security implications of proliferation by combining these individual results.

Given this methodological vacuum, it is inevitable that the analysis of proliferation risks itself tends to become politicized. Indeed, simply by stipulating that the purpose of the analysis is to assess the global implications of nuclear weapons proliferation, there is an unavoidable bias towards these few nations, principally the U.S. and U.S.S.R., whose security interests are global in scope.

Faced with such apparently intractable problems even in developing a general understanding of the security implications of proliferation, the goal of assessing the perturbation caused by a particular new technology seems unattainable.

The situation is not entirely hopeless, however. Some useful empirical evidence is available. There is, after all, a general (although not universal) international consensus that the spread of nuclear weapons to additional countries should be avoided. This consensus view is embodied in the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), under which 101 non-nuclear weapons states have unilaterally renounced their right to acquire nuclear explosives of any kind. Furthermore, many of those states which are not parties to the Treaty have taken the position that they, too, are opposed to the further spread of nuclear weapons.

That there should be a clear international norm against additional weapons states in turn indicates general agreement that an increase in the number of such states is likely to impair the common security. This implied consensus view provides the central point of reference in any calculus of proliferation risk.

There is, however, a notable lack of international consensus on the extent of the risks posed by activities which, while falling short of actual weapons acquisition, nevertheless increase the capability of a nation to manufacture weapons, and/or the fear that it will do so. This class of activities, including particularly uranium enrichment and spent fuel reprocessing, is not subject to any general international norms which might provide additional guidelines in proliferation risk analyses. Indeed, recent efforts by nations, either individually or multilaterally, to establish norms for such activities have generated a great deal of international controversy.

Confronted not only with major theoretical difficulties in assessing the international security implications of proliferation, but also with the absence of a comprehensive set of empirically available political and legal norms which might have made the task easier, proliferation analysts dealing with the emergence of new nuclear technologies have resorted to more manageable, but also less intellectually satisfactory partial approaches to the problem.

4.2 Proliferation Resistance Analysis

One such approach is based on the idea of 'proliferation resistance'; that is, the obstacles to weapons acquisition raised by various nuclear fuel cycle facilities and practices. In recent years, this analytical approach has received much attention, particularly in the United States.

That different nuclear facilities and systems present different opportunities for the acquisition of nuclear explosive material has been well recognized ever since the beginning of the nuclear era, and this recognition has been an important factor in the development of the nuclear industry internationally for three decades.

However, as the proliferation issue grew in prominence during the 1970s, increasing attention began to be paid to the relative proliferation resistance of different nuclear fuel cycles.² The idea entered the mainstream of political thinking in the U.S., at least, when President Carter, in announcing a new nuclear policy in April 1977, called for increased efforts to develop alternative fuel cycles. It was hoped that these cycles would offer less opportunity for nuclear weapons acquisition than the uranium-plutonium cycle which until then had been planned as the next step for thermal reactors, and then breeders.

Since then, a Non-Proliferation Alternatives System Assessment Program (NASAP) has been launched in the U.S. to investigate the proliferation resistance of a very large number of alternative fuel cycles. In parallel, the U.S. has been collaborating with over fifty countries in the International Nuclear Fuel Cycle Evaluation ('INFCE'), an international assessment of alternative nuclear fuel cycles which might advance the use of nuclear power while simultaneously reducing the risks of proliferation.

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There are two kinds of fissile material suitable for use in nuclear weapons: uranium highly enriched in one or other of the two fissile isotopes (U-233 and U-235), and plutonium. In each case, the metal is the preferred chemical form of the material for use in the core of a bomb; however, the oxide form may also be used directly.

In principle, these materials may be obtained from commercial nuclear fuel cycle facilities, from non-commercial facilities built either for research or expressly for the purpose of producing nuclear explosives, or from some combination of each. Alternatively, the material (or even a complete weapon) may be stolen or purchased on a black or gray market, or acquired as a 'gift'. The routes by which weapons material can be acquired are sketched in Figure 4.1, and may be further characterized by the 'mode' of acquisition, i.e., whether the material is obtained covertly or overtly. Of course, many intermediate strategies are possible. For example, a dedicated enrichment facility might be built covertly, and then, once completed, low-enriched uranium might be overtly removed from the commercial fuel cycle and used as feed for the plant.

The proliferation resistance of nuclear facilities and fuel cycles is usually assessed in the literature in terms of various 'attributes' of the technologies themselves and of their institutional environment.³ These attributes are defined differently by different authors, but the following list is generally included by all:*

1. the time necessary to acquire weapons
2. the financial cost of weapons acquisition

* Acquisition of weapons obviously involves other activities in addition to the production of nuclear explosive material, including weapons design, high-explosive development and testing, weapons fabrication,

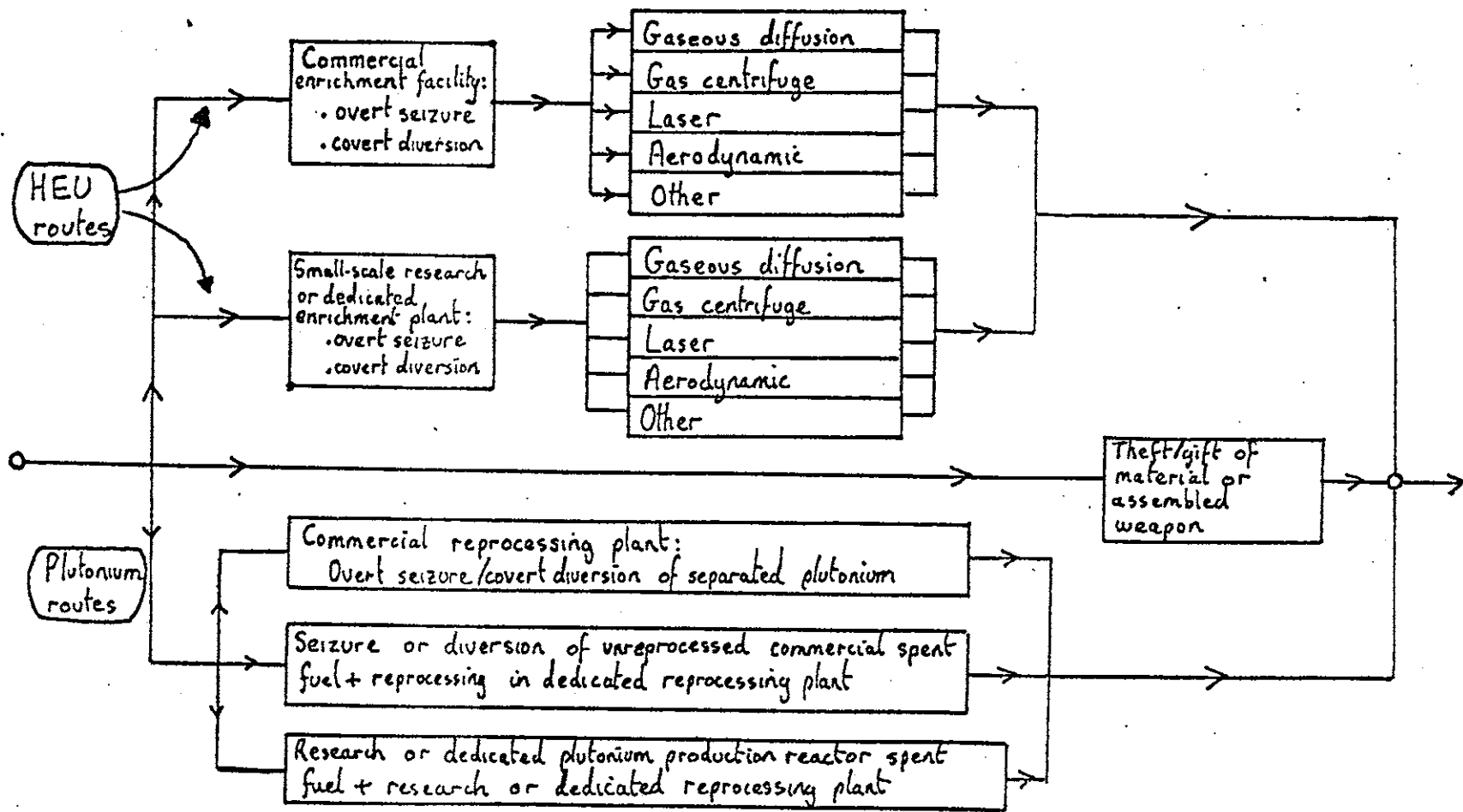


FIG. 4.1: ROUTES TO NUCLEAR WEAPONS MATERIAL

3. the technical difficulty of weapons acquisition
4. the visibility/detectability of the acquisition process
5. the vulnerability of the acquisition process, once observed, to externally induced interruptions.

These characteristics are clearly not all independent of each other; moreover, more precise definitions are necessary before they can serve useful functions.⁵

Extensive analyses of the proliferation resistance of various fuel cycle systems have been carried out in the U.S., in the NASAP program and elsewhere, and the approach has gained some degree of acceptance abroad. There has been a tendency on the part of some analysts to stress the applicability of the proliferation resistance concept to commercial nuclear fuel cycles.⁶ Others have suggested that a greater emphasis on research and dedicated facilities is necessary.⁷ In principle, however, there is no reason why these techniques should not be applicable to all nuclear facilities, whether they belong to the commercial fuel cycle or not.

Nevertheless, proliferation resistance assessments are inherently limited in scope, and their uncritical use as a basis for policy leads to problems.

(contd.)
and the development of delivery systems. These steps may contribute to the visibility of the proliferation process. It is generally agreed, however, that for most countries the skills and facilities required for the design and construction of a nuclear weapon have been less of a technological obstacle to their production than has the lack of access to weapons-usable material.⁴ On the other hand, the challenge of developing a sophisticated delivery system may be much greater than the problem of acquiring the fissile material.

In the first place, since such assessments focus on the technological and institutional characteristics of fuel cycle systems or facilities, there is an inevitable tendency to stress national capabilities to proliferate, at the expense of those factors which might influence the nation's incentives or disincentives to do so. Proliferation mistakenly comes to be defined and perceived in the language of technological determinism.

Furthermore, the preoccupation with technological systems draws attention to the intrinsic differences between these systems, but not to the differences in aspirations, incentives, disincentives, and capabilities of different countries. To be sure, the latter may be included in such assessments via abstract 'scenarios', in which a hypothetical set of political and strategic objectives are often ascribed to an imaginary country. According to at least one group of workers, the proliferation resistance methodology "is intended to be sufficiently comprehensive to cover all cases of potential interest;"⁸ and this objective combined with a technological orientation does indeed provide a methodology which has a kind of global applicability.

But the same combination, if carried forward undiluted into the policy process, also tends to promote a 'systems analytical' approach to the non-proliferation issue, in which the technocratic elements of policy, the so-called technical and institutional 'fixes', take precedence over those which lie beyond the immediate scope of the nuclear fuel cycle. It is in this context that Richard Betts has written of a "technicist fallacy" found among analysts of non-proliferation, which is characterized in part by "tendencies to think of candidates for proliferation as an undifferentiated mass of 'Nth' countries, and to direct all attention to ways of stopping the diffusion of sensitive components of nuclear technology".⁹

The prominent role played by proliferation resistance assessments in the recent evolution of U.S. non-proliferation policy may actually be more of a symptom than a cause of these difficulties, and a full exposition of this question belongs to another study. Nevertheless, the possibility of a relationship between the analytical underpinnings of U.S. policy and the political disagreements with other countries stimulated by the policy should not be overlooked. A globally applicable methodology, emphasizing technology as the unifying factor, the 'lowest common denominator' in all scenarios, is well suited to the American perception of the proliferation problem as a global phenomenon which must be 'contained'. But it is much less well matched to the perceptions of most other countries, which view themselves generally, and proliferation in particular, largely in the context of a specific region.

This is not to suggest, of course, that the threat of regional proliferation would be regarded less seriously by the countries of that region than by the U.S. Rather, such countries would tend to perceive the associated technological developments more as a perturbation to and a consequence of evolving regional political and military relationships in which they have long been intimately involved than as the ahistorical, self-contained phenomenon that is frequently evoked by assessments of proliferation resistance.

But despite these potential pitfalls, proliferation resistance analysis can fulfill a valuable, and indeed a necessary function in the development of non-proliferation policy, provided its limitations are understood. It is in this spirit that the assessment of the proliferation resistance of laser enrichment technologies in the following section is presented.

Thus, the assessment is advanced as an aid to the formulation of non-proliferation policy, not as a substitute for it. In subsequent sections of this chapter, a brief history of the spread of enrichment technology and the evolution of the international enrichment industry is presented. An understanding of the principal incentives, disincentives and constraints to have influenced the diffusion of enrichment technology in the past is of central importance to the development and evaluation of policies relevant to laser isotope separation. Then, with this technical and historical background, the final section of this chapter will review the existing policy environment, and ways in which it might be modified in response to the new technological developments.

4.3 Proliferation resistance of laser enrichment technologies

In the past few years, many references have been made to the proliferation potential of LIS technologies. Much concern has been expressed over the possibility that a cheap, compact, quick and technologically straightforward way to produce weapons-grade material from natural uranium may emerge from current LIS research and development programs. Images of 'garage technologies', 'bucket shop operations', and 'bombs in the basement' have been evoked from time to time. One analyst has urged consideration of a moratorium on future LIS development in the U.S.¹⁰ Another has counseled that, while he "was not yet about to tear off (his) shirt, it might be prudent to loosen a few buttons."¹¹ And last year the then director of the Los Alamos Scientific Laboratory is said to have remarked that LIS may evolve into a "cottage industry" for proliferation within a few years.¹²

On the other hand, a report prepared by a panel of distinguished independent experts, convened by Exxon Nuclear and Avco Corporation, found of the JNAI atomic uranium vapour technology that:¹³

The JNAI laser isotope separation process, far from being a simple technology capable of being mastered by many countries and even sub-national groups, is extraordinarily complex and difficult. Its practical application remains at least a decade away. It cannot properly be characterized as 'garage' technology.

Moreover, a study prepared for the Department of Energy reportedly has concluded that laser isotope separation technology is so sophisticated that the proliferation risk from it will be low.¹⁴

The question is of course complicated by the strict secrecy which generally surrounds LIS development programs. The report to JNAI is unclassified, but some panel members had access to restricted information,

which may have been of assistance in their deliberations. The Government study cited above is secret.

The case for attempting an unclassified assessment of the problem has already been made in the introductory chapter. It is worth re-emphasizing, however, that the purpose of the present assessment is not in any way to second-guess the conclusions of studies which have been conducted on a classified basis, or with access to classified data. That would be futile. Instead, three objectives are sought:

- (i) To develop a framework for a constructive public debate on the subject;
- (ii) To determine the value to such a debate that can be derived from the information that is now available;
- (iii) To identify clearly the questions relevant to a public debate which cannot be addressed satisfactorily without additional information.

4.3.1 Proliferation pathways

Two routes to the acquisition of nuclear weapons material involving LIS technology are of primary interest:

- (A) Misuse of a commercial LIS enrichment facility, designed to produce low enriched uranium (LEU) for light water reactor fuel, for the purposes of high-enriched uranium (HEU) production;
- (B) Independent construction of an LIS enrichment plant dedicated to the production of highly enriched uranium for nuclear weapons.

Each of these routes might be attempted either overtly or in complete secrecy, or alternately in an intermediate mode. Also, each might be undertaken either by a national government or a subnational group. In

this analysis, the emphasis will be on the former. No attempt is made in the case of route A to speculate on the likelihood of a commercial enrichment plant actually being located on the soil of a potential proliferator state. For the purposes of this stage of the assessment, it is simply assumed that such is the case. The general question of the spread of commercial enrichment facilities is, however, of fundamental importance, and is taken up in detail in subsequent sections of this chapter.

The two routes clearly do not exhaust all of the possible ways in which LIS technology might be involved in a proliferation attempt, but together they address most of the key technical issues that would be raised in the other scenarios.¹⁵

4.3.2 Proliferation resistance attributes

Papazoglou et al have developed a set of five criteria to describe the proliferation resistance of various pathways to nuclear weapons:¹⁶

- (i) Weapon development time
- (ii) Monetary cost
- (iii) Inherent difficulty of fissile material acquisition
- (iv) Inherent difficulty of weapon design and fabrication
- (v) Likelihood of external intervention.

How these various criteria would actually be weighted in decisions on whether and in what way to proliferate obviously depends on the particular situation at hand. The original authors have proposed a complicated and comprehensive methodology for answering this question. The methodology is designed to evaluate the proliferation resistance of entire nuclear systems (defined as a 'full' or 'partial' nuclear fuel cycle along with the associated institutional arrangements) in the context of a particular country with a particular set of nuclear weapons ambitions.

Using methods based on multi-attribute utility theory, a set of attributes derived from the above criteria is used to assess the proliferation resistance of individual proliferation pathways presented by these systems, and thus ultimately of the systems as a whole.¹⁷

The objective here is more modest. The two scenarios outlined earlier are to be used to assess the extent to which LIS technology will perturb the spectrum of proliferation risks generated by the existing reservoir of weapons applicable technologies. Moreover, at this stage, the emphasis is on the technical aspects of the problem. The political implications are analysed in more detail later.

Thus, instead of attempting to analyse the proliferation resistance of entire nuclear systems, it is sufficient to compare routes A and B with equivalent scenarios in the absence of LIS technology. For route A, the corresponding scenario might involve a commercial gaseous diffusion, gas centrifuge or aerodynamic enrichment plant. Since the gas centrifuge process increasingly appears to be the technology of choice over the long dominant gaseous diffusion process for commercial plants, (the U.S., the three Urenco countries and Japan have all recently elected for the former), we choose it to provide the 'reference' case for route A. For route B, the comparison could be with any of several technologies that might be utilized to produce weapons-grade material in dedicated facilities: on the enrichment side, gas centrifuge technology once again, but other processes too, including electromagnetic separation, which is unattractive economically compared with gaseous diffusion, but which was nevertheless used for the first kilogram-scale separation of U-235 during World War II; and for plutonium production, dedicated reprocessing plants and irradiated fuel from research or production reactors, or seized or diverted from spent commercial power reactor fuel storage.

The more modest goals of this assessment compared with those of Papazoglou et al also permit modifications to be made to the proliferation resistance attributes originally derived from the five criteria above,¹⁸ as follows:

(i) Weapon development time:

Here, we are particularly concerned with the time required to produce enough fissile material for one or more nuclear weapons. This includes the time required for preparatory activities, such as research and development and personnel training; for the design and construction of the production facilities; for the materials acquisition itself; and for the conversion of the material into a chemical form suitable for use in weapons (i.e. the metal, oxide, or, less likely, carbide). Not included is the time required to design the weapon(s) or the time required to manufacture them, once the material is available. The design and manufacture of the weapon (except for the weapons-grade material) could be carried on in parallel with the production of the weapons-grade material. Moreover, if the weapons material is to be highly-enriched uranium, a natural uranium mock-up weapon could be assembled in advance, including all the chemical and metallurgical steps, whereas this would not be the case with plutonium. But while the incremental time for weapons design and manufacture will vary depending on the nature of the fissile material, the variation is unlikely to be large enough to make it a dominant factor in the choice of routes to weapon materials acquisition.

(ii) Financial cost:

This includes the direct costs of equipment, material, personnel training and employment, facilities construction, etc. In the case of route A and its reference scenario, the cost would include the indirect costs incurred in the event of loss of production from the commercial enrichment plant, but not, of course, the original cost of the plant.

(iii) Inherent difficulty of weapons material acquisition:

This is a measure of the scientific and technological complexity of the process, the personnel requirements, and the necessary organizational and management skills. Again, in the case of route A, it is the requirements beyond those associated with the normal operation of a commercial enrichment plant that are of interest.

(iv) Difficulty of weapons fabrication:

The nature of the fissile material available, i.e. whether it is U-235, U-233, reactor grade plutonium or plutonium whose isotopic composition has been optimized for explosives use, will affect the technical difficulty of weapons design and manufacture.¹⁹

Moreover, as noted in (i), design and manufacture of an enriched uranium weapon might take place more completely in parallel with the production of the weapon material than for a plutonium weapon. But since the production of weapons-usable material is generally thought to present more difficulties than the manufacture of the weapons themselves,²⁰ for the purposes of this assessment we focus

on the potential impact of LIS technology on the former, and eliminate the question of weapons fabrication from further consideration.

(v) Likelihood of detection:

Here, we are concerned with the probability of detection (in the case of covert attempts) during the process of acquiring the fissile material.²¹ Detection might occur because of a violation of IAEA safeguards, through national intelligence, or by other means.

In addition, an assessment of the viability of a particular proliferation route ought properly to consider the effectiveness of external attempts to interrupt the process, once detected. This involves the question of the sanctions that might be available and the probability that they would in fact be levied. These issues go beyond the bounds of the technical phase of the analysis that is presented here. However, it should be noted that if a proliferation effort relies on a continuing flow of equipment or materials from outside the country, this will affect not only the detectability but also its vulnerability to counteraction.

4.3.3 Route A - Misuse of a commercial enrichment plant for high-enriched uranium production

Depending on the circumstances, a commercial enrichment plant designed for low enriched uranium (LEU) production might be misused in one of two ways. First, the entire plant might be adapted to the production of high enriched uranium (HEU). If such a plant were under international safeguards, the action would be self-announcing, and would involve either unlawfully abrogating or legally withdrawing from the relevant safeguards

agreement. Alternatively, a covert attempt might be made to produce smaller quantities of highly enriched uranium from the plant while it was still under international safeguards.

We shall compare the proliferation potential of atomic vapour LIS (AVLIS) and molecular LIS (MLIS) enrichment plants with a commercial gas centrifuge plant for both of these pathways. Since little design information relevant to future commercial LIS plants of either kind has yet been made available, the discussion will necessarily be highly speculative, and will run the risk of overstating the importance or immutability of what little is known. For the AVLIS plant, since somewhat more information is available on the JNAI process than the work at Livermore, the emphasis is on the former.

The comparisons will be based on plants with a design rating of 3000 tons of separative work per year. A natural feed plant of this capacity would provide enough LEU fuel for the annual needs of about 20 1000 MWe LWRs, a depleted feed plant about 5. Whether in fact it will prove to be a typical size for commercial LIS plants remains to be seen.

4.3.3.1 Full-scale conversion to HEU production;

Atomic vapour LIS process

For 3% enriched product, the plant heads separation factor (the ratio of product and feed abundance ratios) for a natural feed plant would be 4.3, and for a depleted (0.2%, say) feed plant it would be 15.4. The indications are that, even for depleted feed, enrichment to 3% in a single step will be possible in an AVLIS facility based on the JNAI process. Thus, the plant designed for depleted feed would probably present the more

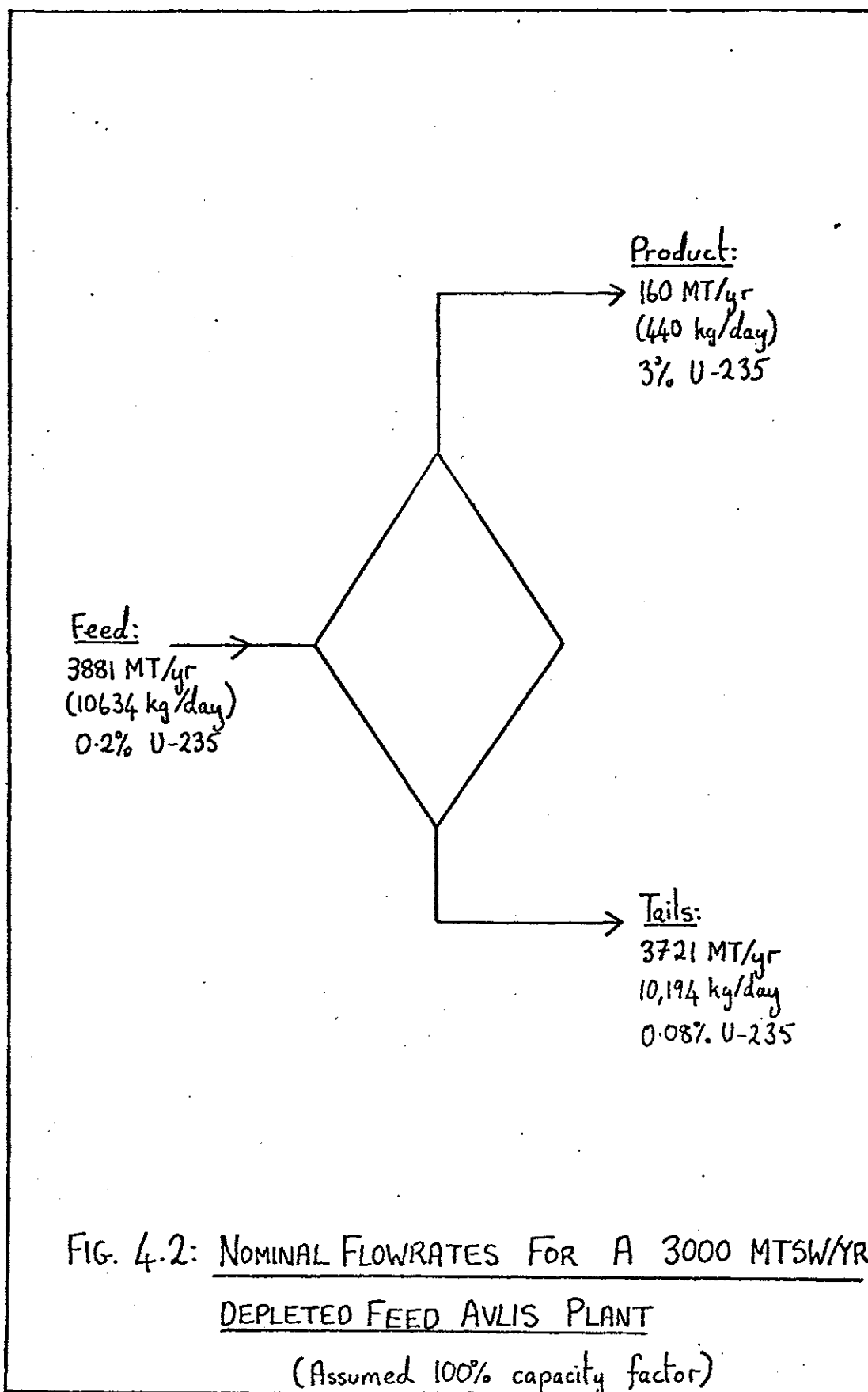
attractive prospect for a would-be proliferator in view of its higher stage separation factor. The nominal flowrates for a 3000 MTSW/yr plant designed to enrich 0.2% feed are shown in Figure 4.2. The product and tails assays correspond to those in a recent JNAI report.²³

Such a plant might be adapted to produce HEU in one of two ways. First, the stage separation factor might be increased such that HEU was produced in a single pass; to achieve this, changes in plant operating conditions, physical modifications, or a combination of both might be required. If 3% enriched feed were available, the heads separation factor (β) would have to be raised from 15.4 to 32.3 for 50% enriched product and to 291 for 90% product. If only natural feed were available, the separation factors for the same product enrichments would be 140 and 1257 respectively.

Alternatively, the plant could be operated in a 'batch recycle' mode, in which successive product batches were recycled as feed in a multi-stage process.

For the former option, insufficient information is available to determine whether even major modifications could increase the separation factor sufficiently. According to the JNAI review panel, which reported that it had access to all relevant information, "the feasibility (of such an option) is unknown and a lengthy R. and D. effort would be required to develop and demonstrate an approach, followed by significant plant modifications once a definite attempt was initiated".²⁴ Whether such a conclusion would apply to all commercial AVLIS facilities is unknown.

Many uncertainties characterize the batch-recycle option also. One of the major issues concerns the behaviour of the separation factor as the



feed enrichment increases. If the feed flowrate (and hence the overall density in the plasma extractor region) were held constant as the feed assay was successively raised, the ion density in the extraction region would increase correspondingly. Intuitively, one might expect that the resulting increase in self-shielding from the collector electric field would adversely affect the ion extraction efficiency, and thus reduce the separation factor.

In a study of the proliferation resistance of their process conducted for DOE under the NASAP program, JNAI assumed that the stage separation factor could be held constant if the feed flowrate was adjusted such that the ion density in the extractor region remained the same. JNAI officials suggest that in practice the separation factor would probably be lower than the design value under these conditions.²⁶ Auer agrees that a constant separation factor is "the most liberal (and rather unlikely) assumption one can make in favour of the proliferator", and notes that "theoretical considerations lead one to predict that the (heads separation factor) value achieved under such conditions could not be maintained at the original high design value without additional plant modifications - the nature of which could only be determined by extensive experimentation."²⁷

One problem encountered at lower feed flowrates and densities is the reduced collisional cooling of the uranium vapour atoms as they leave the surface of the crucible. It will be recalled that the JNAI process employs a '3-step, 4-colour' excitation scheme, in which laser photons of two frequencies are used to excite selectively uranium atoms in the ground and first excited energy states to the same intermediate level, after which two further sequential photon absorptions result in ionization. Under normal operating conditions, it is apparently collisional relaxation which causes

most of the uranium atoms to return to the lowest energy states by the time they enter the irradiation region, and which therefore permits a high yield of U-235 in the product. With reduced cooling, more U-235 atoms will remain in higher energy states, the fraction of U-235 that can be selectively excited by the two first-step lasers will be reduced, and thus the overall separation factor will be eroded. (One possible way to counteract this difficulty might be to increase the collision rate by introducing a buffer gas at the surface of the evaporator. On the other hand, such an approach might also lead to difficulties, since it would involve containing the buffer gas at the surface of the crucible, while maintaining the rest of the module at very high vacuum.)

Other factors might be expected to promote an increase in the separation factor at a reduced process density. For example, as the ion: neutral density ratio increases in the extractor region, the probability of charge exchange or momentum exchange reactions will decline, enhancing the recovery of U-235 on the product plates. Also, as the neutral atom density is decreased, the neutral - neutral scattering collision rate which might otherwise contribute to the deposition of unwanted U-238 on the product plates will decline. It was perhaps on account of these factors that IBM physicist Richard Garwin, who was later to serve with Auer on the JNAI review panel, suggested in mid-1977 that by reducing the total vapour throughput in order to keep the U-235 ion density constant at higher feed assays, the separation factor would probably increase.

The panel as a whole was silent on this issue, although it suggested that the production of HEU by batch recycling would be more likely to require both changed operating conditions and equipment modifications than just the former. In the panel's report, greater emphasis was placed on

the difficulties of undertaking such an operation, and, more importantly, on the large uncertainties which themselves would constitute a major deterrent to a would-be proliferator. It was the panel's judgement that the uncertainties could only be overcome by a substantial research and development effort, "employing facilities comparable to those used in the development of the process itself".²⁹ While such an effort would increase the risk of detection, failure to undertake it would increase the risk that an actual attempt to produce HEU would end in failure, or at least be subjected to lengthy delays.

The importance ascribed to the deterrence value of technological uncertainty suggests a possible dilemma. Although the large size of the research and development effort required to reduce this particular uncertainty, if the panel's assessment of it is correct, presumably would absolve JNAI from the responsibility of pursuing the investigation, there may be occasions when the issue is less clear cut. On the one hand, when a process with good commercial prospects also has potential military applications, there is a clear need to examine the magnitude of the latter potential before widespread commercial deployment takes place. Yet, even aside from the financial burden of such measures, if there is a value to the preservation of uncertainty, where is the investigative line to be drawn? Should this decision be left to the developers? And does it make any difference if the developers are in the private or public sectors? How might the costs of the investigation influence the decision? We shall return to these questions in Chapter 6.

It is possible to derive an estimate for the minimum time required for batch recycle operation of an AVLIS plant to produce enough HEU for one or more nuclear weapons, based on the assumption that the separation factor will remain at the design value if the U-235 throughput is held constant. The calculation is presented in Appendix I of this chapter. The results show that a minimum time of approximately two weeks would be needed to produce enough HEU for a single weapon in a 3000 MTSW/yr depleted feed plant. By making certain additional conservative assumptions, the total number of weapons that could be produced in a year by such a plant could theoretically be as high as 65, although the actual number would probably be much lower. Once again, it must be emphasized that these conclusions are not necessarily applicable to all AVLIS processes.

An interesting variant of the batch recycle scheme is worth mentioning. Above a certain U-235 feed assay, it may become easier to adjust the laser frequencies so as to achieve separation by the selective photoionization of the residual U-238; the 'tails' in this case would be further enriched in U-235. To a first approximation, as the U-235 feed assay increased above 50%, the problems of adjustment associated with higher ion densities in the collector region would become less rather than more demanding with this scheme. Moreover, since the U-238 spectrum, unlike that of U-235, shows no hyperfine splitting, the problem of generating enough laser frequency components to excite all of the desired atoms (as discussed in Chapter 2) is no longer present.

Molecular LIS process

At the present time, even less is publicly known of the potential design characteristics of a commercial MLIS plant than of the JNAI AVLIS

process discussed in the previous section. It does seem clear, however, that, even for natural feed, unless major advances are made, the single-stage separation factor will not be high enough to produce 3% uranium without staging. For convenience, we shall base this assessment on the materials balance flowsheet calculated in Chapter 2 for a 3-stage ideal MLIS cascade accepting natural feed. (See Appendix II of Chapter 2.) The overall stage separation factor (α) of 4.3 for this cascade apparently lies within the range for MLIS currently anticipated by DOE.³⁰ A cascade capacity of 3000 MTSW/yr is again assumed.

There are several ways in which the cascade might be modified to produce HEU. The operating conditions and/or certain plant components might be adjusted to increase the stage separation factor at each stage such that the overall plant separation was high enough for HEU production. Alternatively, the cascade could be operated in a batch recycle mode. A third option would be feasible if one or more of the stages consisted of two or more separation modules in parallel. If this were the case, the cascade modules could be 'repiped' to produce a longer, thinner cascade, i.e., one with more stages and lower flowrates at each stage. (If the stage separation factor was unchanged in the repiped configuration, about 7 stages would be required to produce 80% U from 3% feed.) If, on the other hand, each stage consisted of a single module, (and there is no obvious reason why this should not be so), repiping would be ruled out. A final alternative would be to add more stages to the top of the cascade.

Which of these options would be the most attractive to a would-be proliferator is not yet possible to assess.

For batch recycle operation, behavior of the stage separation factor with increasing feed enrichment is once again at issue, and the uncertainty

might once again contribute to the proliferation resistance of the process, although in view of the staged configuration of the commercial plant itself, the operator in this case might normally be expected to have some working knowledge of the effect of increasing assays on separator performance, if only at relatively low assays.

Based on several crude assumptions, calculations presented in Appendix I of this chapter suggest that from 24-36 hours would be required, at a minimum, to produce enough HEU for a single weapon from a 3000 MTSW/yr MLIS plant operated in the batch recycle mode, and a theoretical maximum of 2000 weapons could be produced by such means in a year.

It is possible that significant equipment modifications would be required to maintain good separation at high feed assays, in which case the above estimates would be highly optimistic. In any case, criticality problems seem certain to become important in the later cycles, in view of the need to handle UF_5 solids within the process. Solids flowrates are high, (roughly 5 kg/minute of 91% UF_5 are produced in the final cycle of a batch recycle operation, according to Table 1-2 in Appendix I), and modifications in the original plant design would be one way of increasing the proliferation resistance of the facility.

On the other hand, in at least one important respect, an MLIS plant may be inherently less sensitive to the perturbations associated with batch recycling than an AVLIS plant. In the latter case, the reportedly serious problems encountered in achieving good laser beam propagation, such as the instabilities arising from temperature and absorptivity gradients and other non-linearities in the atomic vapour medium, are compounded by the long optical path length necessary in such plants (as much as several hundred meters in the 3000 MTSW/yr plant).³¹ By contrast, the higher

process density achievable in MLIS plants means that the irradiation path is likely to be much shorter, perhaps on the order of ten meters.³²

Also, since staging will be necessary in commercial MLIS plants in any case, the materials processing required between batches would be expected to create fewer additional demands than it would for a single-stage AVLIS plant.

Gas Centrifuge Plant

From a proliferation resistance perspective, a commercial gas centrifuge enrichment plant will probably differ from LIS facilities of either kind in several important respects which, in turn, are attributable to fundamental physical differences in the separation process. Compared with the LIS processes, individual centrifuge separation factors are low: depending on the machine, the α might vary from 1.15 - 1.14. Thus, for an α of 1.3, an ideal centrifuge cascade designed to produce 3% enriched uranium from natural feed at a tails assay of 0.2% would require 12 stages in the enriching section and 9 more in the stripping section.

Furthermore, because of physical limits on the size of individual centrifuge machines, each stage will actually consist of many centrifuges connected in parallel. Several hundred thousand machines of the type developed by the Urenco consortium in Europe would be required for a 3000 MTSW/yr facility, and the largest stages would contain more than ten thousand centrifuges.* In practice, a plant of this size will be divided into a number of sub-cascades operated in parallel, each composed of several thousand machines; modular designs facilitate plant maintenance

* The machines that are to be used in the new U.S. commercial centrifuge plant are reportedly as much as ten times larger, and correspondingly fewer would thus be required in a plant of the same capacity.

and control, and offer greater flexibility in the choice of product assay.

Once a decision is taken to convert such a plant entirely to the production of highly enriched uranium, two principal options are available. The product stream could be recycled as feed to the plant, either batchwise or continuously, until uranium of sufficiently high assay is available. Alternatively, the centrifuge machines could be rearranged into a configuration with enough stages to produce HEU directly.³³ For machines with an α of 1.3, about 50 stages would be required to enrich natural feed to an assay of 80%. The rearrangement would be relatively straightforward to accomplish, and the latter option would probably be the method of choice.

The ease with which commercial centrifuge plants could be converted to HEU production facilities has been the source of a good deal of concern. Unlike the two LIS processes, the behavior of centrifuge machines and cascades at high enrichment assays is widely understood and quite predictable.³⁴ Moreover, in view of the small material holdup in individual centrifuges, criticality risks in the cascades are of little concern, even at high assays.

Plant conversion could probably be quite rapid. According to the JNAI review panel, reconfiguration of the cascades could be completed in a matter of a relatively few days if the necessary piping were prepared in advance.³⁵ And no significant preparatory research and development would be required. The equilibrium time for centrifuge cascades producing HEU is quite short: depending on the particular circumstances, on the order of ten or twenty hours, as is illustrated in Appendix I. Once equilibrium is reached, the HEU production rate is high; enough for a single weapon in under five hours, and as many as several thousand critical masses after a year of operation. (See Appendix I.)

The maximum production rates for HEU from the three enrichment facilities are shown for comparison in Table 4.1. It should be emphasized that the estimates for the LIS plants are highly speculative and, almost certainly, HEU production times in these plants will be much longer.

Table 4.1

Estimated maximum production rates for high-enriched uranium in 3000 MTSW/yr commercial enrichment plants*

	AVLIS	MLIS	Gas Centrifuge
Estimated minimum time required for production of enough HEU for one weapon	~2 weeks	~24-36 hours	17-30 hours (+ 'repiping' time)
Estimated maximum annual critical mass production rate	< 65	< 2000	several thousand

* See Appendix I for supporting assumptions and calculations.

4.3.3.2 Covert Diversion of HEU from Safeguarded Commercial Enrichment Plants

While efforts to undertake the complete conversion of a commercial enrichment plant to the production of high-enriched uranium would probably be almost immediately visible to the international community, a would-be proliferator might instead prefer to avoid the possible consequences of detection for as long as possible by attempting to produce and divert HEU from such a plant covertly.³⁶ In this section, we examine some of the opportunities and problems of this approach, again using a gas centrifuge plant as a 'reference'. The focus is on commercial facilities to which

international safeguards are applied; the question of covert HEU production in an undeclared facility is taken up in the following section. Later in this chapter, the issues which will determine whether or not international safeguards will actually be applied to commercial enrichment facilities are dealt with in more detail.

The general objective of International Atomic Energy Agency (IAEA) Safeguards is clearly stated in Agency document INFCIRC/153, "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons":

The Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.

In response to the prospective increase in the number of non-nuclear weapons states engaged in uranium enrichment, the IAEA has been developing safeguards procedures for enrichment facilities since 1972.³⁷ As of this writing, however, enrichment is the only major step in the commercial nuclear fuel cycle for which officially approved Agency safeguards procedures have not yet been established.³⁸

The Agency has apparently mainly concentrated on gas centrifuge technology up to now. So far, no single safeguards strategy has emerged which is applicable to all types of enrichment facilities and, indeed, it may not be possible to develop one. In any case, it is specific facility design information which provides the foundation for Agency safeguards. Thus, since no laser enrichment plant design details are yet available, any assessment of the relative safeguardability of such facilities must be highly speculative. Nevertheless, based on what is known of the likely

safeguarding strategy for centrifuge facilities of the Urenco type,³⁹ together with some of the MLIS and AVLIS plant design considerations that have already been discussed, a few preliminary observations can be made.

A potential constraint on the implementation of all IAEA safeguards, and one which may be of particular significance in the case of enrichment facilities, is the right of the state in which the plant is located to designate parts of it which contain commercially sensitive information as "special material balance areas", to which Agency inspectors would not be allowed access.⁴⁰

For centrifuge plants, it is quite likely that the cascades themselves will be declared 'non-access' areas.⁴¹ It is not yet clear whether any portions of an LIS facility would be subject to similar restrictions, although the areas containing the lasers themselves and the associated optics would seem to be likely candidates. Yet ruling the laser system out of bounds would not necessarily interfere with the ability of the inspectors to verify all stages of material flow into, through, and out of the plant. On the other hand, if no access were permitted to the solids separators in an MLIS plant, or the uranium evaporator system in an AVLIS plant, for example, the effectiveness of safeguards might be significantly impaired; however, at present there is no apparent reason why access to these areas would be prohibited.

In principle, the existence of 'no-access' areas would be of no concern if continuous monitoring and perfectly accurate verification of all inputs and outputs were possible. In practice, of course, safeguards performance will always fall short of this goal, if only because of limits on the accuracy and precision of the instrumentation. The limitations of international safeguards have been discussed by many analysts.⁴²

The task of so-called 'perimeter' safeguards is easier, the fewer points of access for materials and equipment there are. Plants which inherently provide good 'natural' containment of the nuclear material are advantageous in this respect. One virtue that has been claimed for the JNAI AVLIS process is the limited number of points into which material can be introduced.⁴³

Compact plant size may also be an advantage, to the extent that continuous surveillance of the perimeter may be facilitated, and the possibility of undetected movement of materials through unauthorized channels therefore reduced. On the other hand, compactness is advantageous to would-be proliferators intent on the construction of clandestine facilities. Some fairly recent estimates comparing the sizes of various enrichment facilities are shown in Table 4.2.

Table 4.2

Estimated Land Area Requirements for Enrichment Plants

	MLIS	AVLIS	Gas Centrifuge	Gaseous Diffusion
Area (acres)	1 ¹	8 ²	20 ²	60 ² -90 ¹
Capacity (MISW/yr)	9000	3000	3000	9000

- Notes: 1. C. Paul Robinson and J.G. Marinuzzi, "Laser Isotope Separation", paper submitted to Gerald Tsai Forum, New York City, February 3, 1976.
2. Richard Levy, American Physical Society Meeting, New York, February 4, 1976.
-

In general, the limitations of perimeter safeguards are magnified if either of the following conditions are present:

- (i) The plant inventory of fissile isotopes is large. Then, since direct inventory measurement is prohibited, the diversion of a militarily significant quantity of material from the plant could take place undetected.
- (ii) Detection of attempts to rearrange or otherwise physically modify the separating stages or to change the plant operating conditions so as to increase α is prevented by lack of access.

Centrifuge cascade inventories are small. According to the calculations of Appendix I, the inventory in a commercial 3000 MTSW/yr plant would be about 1.5 tons, and the average enrichment of the inventory would be roughly 1%. Recently available data indicate that plant inventories for both AVLIS and MLIS processes will also be low - several hundred kilograms for each, again with a mean enrichment of roughly 1%.⁴⁴ Thus, for none of these technologies is covert diversion of a small fraction of the in-process inventory a possible proliferation scenario.

Lack of access to centrifuge cascades may increase the risk of cascade rearrangement and covert HEU production considerably. For the purposes of illustration, consider the following example. A 3000 MTSW/yr plant would be composed of several hundred thousand centrifuge machines. If only a few hundred of these machines were reconnected to form a small HEU cascade, taking LEU product from the main cascades as feed and discharging a tails stream at 0.711% (natural) assay, say, at least enough high-enriched uranium for a single weapon would be available after a year. Such a diversion strategy would add roughly one tenth of a percent of total plant throughput to the material unaccounted for (MUF), i.e., somewhat

less than the inherent uncertainty of $\pm 0.2\%$ of total throughput that might be achievable in a material balance for a centrifuge plant of this size.⁴⁵ While statistical measurement methods, disaggregated material balance areas, and other accounting techniques can increase the probability of detection, there are nevertheless clear limits to the effectiveness of perimeter safeguards based on the material balance concept.⁴⁶ Even with access, the hundreds of thousands of machines and the vastly intricate array of interconnecting pipework would almost certainly prevent an international inspector from verifying the absence of a small, semi-independent cascade. Yet some additional measure of deterrence would certainly be gained if access were permitted, not only because of the finite chance that an inspector would stumble across a 'rearrangement-in-progress', but also because the probability of detecting undeclared input and output streams to the cascade would be enhanced.

In an AVLIS plant, lack of access might create fewer difficulties for the safeguards system. In the judgement of the JNAI review panel, "significant plant modifications" would be required to increase the separation factor in the JNAI process to the point at which single stage enrichment was possible. If such modifications indeed were to require significantly more equipment, personnel and time to implement them than normal maintenance operations, inspector access to the process modules themselves might be unnecessary in order to detect such an attempt. Moreover, if, as the panel believes would be true of the JNAI process, single stage production of HEU could be achieved with 3% LEU as feed, but not with depleted or natural uranium, routine isotopic assay measurements on the feed uranium would provide a clear indication of a safeguards violation, even if the plant modifications themselves went undetected. Of course, the inspector would

also require assurance that no undeclared feed material was being introduced into the plant.

Another factor which might increase the visibility of a covert attempt to misuse an AVLIS plant for HEU production would be the associated change in the plant's power consumption. Recalling an earlier discussion, lower process densities (and throughput) would conceivably be required for enhanced separation, particularly if the feed enrichment assay was increased. Thus, monitoring the power supplied to the evaporator units could provide an indication of such an attempt. (In contrast, power consumption in centrifuge facilities varies according to factors not directly related to the separative work output, so that power supply monitoring in this case would be less instructive.)

For the MLIS process, it is not known how extensive (and thus how visible) the modifications necessary to achieve a significant increase in the stage separation factor would have to be, although the fact that the Los Alamos group currently expects that staging will be required even to produce LEU provides at least some circumstantial evidence that the changes will not be minor. Criticality considerations arising from the in-process accumulation of solids might add to the conspicuousness of the modifications, and, as noted previously, plant designs which maximize the work that would be necessary to avoid criticality incidents at high enrichments would be desirable. Also, if each stage of the plant consisted of a single module, the possibility of repiping some of the modules to form a long, thin cascade-within-a-cascade would be eliminated.

In general, for both the AVLIS and MLIS processes, the relatively large capacity of the individual separation modules, compared, for example, with individual centrifuge machines, will tend to increase the minimum

feasible scale of covert efforts to misuse the plant for HEU production (where 'scale' here refers to the fraction of the plant that would be involved) and consequently the conspicuousness of such efforts.

4.3.4 Route B - Independent construction of a laser enrichment plant dedicated to the production of HEU for weapons

As in the previous section, three 'attributes' are of principal interest: the time required for materials production; its difficulty; and the probability of detection. The emphasis is different for this scenario, however. The difficulty of the effort is no longer measured in terms of the incremental task of modifying a commercial facility for proliferation purposes, but rather of acquiring a dedicated facility 'from scratch'. Of course, the difficulty is determined both by the nature of the technology itself and by the technological capability of the country in which the effort occurs, and technological generalizations are not possible. A country with a scarcely developed industrial infrastructure and no nuclear capability will be expected to choose differently from an advanced industrial country with a major nuclear industry. Not only will the absolute difficulty of the alternative pathways vary between countries, but the relative attractiveness of different routes will vary depending on the profile of indigenous technological capabilities.

Detectability is also meant in a different sense. The question of international safeguards effectiveness no longer applies, since it is beyond the authority of the IAEA to seek out clandestine or undeclared nuclear facilities. Instead, detectability will depend on indicators of the kind listed in Table 4.3.

Table 4.3

Detectability indicators for undeclared, dedicated nuclear facilities

- Direct observation of construction site, power lines, water supplies, etc.
 - Detection of critical plant items
 - Detection of movement of appropriately skilled foreign personnel into the country
 - Breaches of national security detected/caused by intelligence efforts
 - Monitoring of technical publications in related fields
 - Detection of distinctive plant emissions during operation
-

Again, the probability of detection will depend on the characteristics of the host country as well as the facility itself. For example, in a country with a large laser research and development establishment, the concentration of specialists and the flow of equipment and materials required for an LIS program will obviously be easier to conceal. Moreover, the existence of such an establishment will lessen the need for imports of specialized components and personnel, and thus reduce the risk of detection through monitoring of international trade. (On the other hand, indigenous manufacture may increase the project lead time, with a consequent increase in the probability of detection.) Similar conditions apply to the general level of industrial sophistication.

Detectability will also be influenced by the competence of intelligence organizations and the comprehensiveness and effectiveness of controls on international trade. The latter issue will be dealt with in section 4.5. Here, once again, the emphasis is on the technical aspects of the question. And, once again, the paucity of available data allows only preliminary and speculative observations to be made.

There have been several recent analyses of the proliferation risks presented by other dedicated facilities, e.g., small plutonium production reactors and reprocessing plants,^{47,48} gas centrifuge plants,⁴⁸ and electromagnetic enrichment facilities.⁴⁹ Some of these results are summarized in the next section. Other, classified assessments have also been prepared.

Perhaps the main analytical difficulty in comparing these technologies with the LIS processes is that the comparison must be made at a particular point in time - a point at which the practicality of at least some of the former has been demonstrated, but LIS has not. And yet, for the assessment to have the greatest value, technological trends and developments must be anticipated as far into the future as possible. A fine and elusive balance must be sought between the parallel needs for technological veracity and technological foresight.

4.3.4.1 Other dedicated facilities

Some recent estimates of the costs, personnel and time required to construct dedicated facilities other than LIS are summarized in Table 4.4. The sources from which these data were extracted should be consulted for more detailed information. Since the various authors selected different ground rules and used different guiding assumptions, direct quantitative comparisons are not recommended. Of greater significance are the variations within each technological category, depending on the capabilities of the country making the attempt, and also the qualitative similarities among and differences between the three technologies.

Table 4.4

Resources Required for Production of Weapons Material from Dedicated Facilities

	Plutonium production reactor and plutonium separation facility ^a (~10 kg Pu/year)	Gas Centrifuge Plant ^b (~30 kg 93% U/year)	Electromagnetic separation plant ^c (~15 kg HEU/year)	
			Crude Design	Advanced Design
Cost	Reactor: ~\$13 M (probable max: \$26 M) Separation Facility: ~\$25 M (probable max: \$50 M) <hr/> Total: \$40 - 75 M	Centrifuge development cost: \$40 - 80 M Plant capital cost: \$25 - 45 M Annual operating expense: ~\$ 6 M/yr <hr/> Total: ~\$70 - 130 M	> \$100 M	Development program: Tens of millions Plant capital cost: ~\$15 M
Personnel requirements for design, construction and startup.	~15 professional engineers (maximum) + labour	~100 professionals ~200 skilled tech. ~100 general operators + construction labour	?	Development Program: 20 research scientists Construction: ? Operations: > 600
Time to initial operation	Reactor design: 1 year Reactor construction: ~3 years Separation plant: not specified, but probably similar time frame <hr/> Total: ~4 - 5 years	Rate determining steps: • Centrifuge development program: 3.5 - 4 years • Plant construction: 3.5 - 4 years Total for country with modest industrial capacity and limited nuclear sector: 7 - 8 years (For heavily industrialized country with advanced nuclear expertise) (3 - 4 years) (For country with limited industrial capacity and no nuclear development program) (10 - 15 years)	~4 years	Development program: ~ 5 years Construction: ~ 2 years <hr/> Total: ~ 7 years
Comments ^d	<ul style="list-style-type: none"> Facilities need not be designed from scratch. All essential design parameters are in open literature. High-level research and development personnel not required. All necessary materials and supplies are available on the open market. No exotic, single-purpose items are required. Many small and/or developing countries are capable of such a program. 	<ul style="list-style-type: none"> For countries with on-going centrifuge programs, total project costs could be reduced "by a factor of 5 - 10". (Personnel requirements may be overestimated. In a parallel study of a plutonium production reactor and separation facility, SAI predicted the need for a skilled workforce roughly on order of magnitude greater than Lamarsh's estimate for similar facilities.) (Recent, commercially applicable centrifuge technology is held under strict security, and key components are subject to extensive export controls; however, detailed descriptions of early, non-commercial centrifuge machines are available in the open literature.⁵⁰) 	<ul style="list-style-type: none"> A crude design would require a minimum of development effort, and would involve the maximum use of off-the-shelf items. Nearly all the design features for such a plant have been described in the literature. Some components can be obtained commercially. Nevertheless, construction and operation of such a facility would still require "considerable scientific and industrial resources". 	<ul style="list-style-type: none"> An advanced design would be required to produce enriched uranium at a cost comparable to that of the centrifuge or gaseous diffusion processes. The development effort required "could only be accomplished by industrialized countries with an established scientific and engineering infrastructure."
			<ul style="list-style-type: none"> Batch processing required for such plants is intrinsically labor intensive. 	

Notes

a. Lamarsh (1976)⁴⁷b. Science Applications Inc. (1976)⁴⁸c. Schuette (1977)⁴⁹

d. With the exception of the remarks appearing in parentheses, all of the comments have been extracted from the indicated sources.

4.3.4.2 Dedicated laser enrichment facilities

Here, the key question is whether laser enrichment technologies will provide an avenue to weapons-usable material via dedicated facilities that is qualitatively easier than those currently available. A major shift in the spectrum of proliferation risks will have correspondingly large consequences for current non-proliferation policies.

(1) Atomic Vapour LIS Technology

The single, most persuasive piece of evidence that AVLIS is not a 'garage' technology is not technical at all. It is simply that, despite the existence of two large, independent programs in the U.S., each established for several years and each involving over a hundred personnel, a plant capable of producing enriched uranium even on a small scale (i.e., a few kilograms per year) does not yet exist. Furthermore, both groups anticipate that major additional commitments will be necessary before the technology can be commercially demonstrated. JNAI now expects that it will be 1987-88 at the earliest before this can be achieved,⁵¹ and company officials speculate informally that the total cost of the program to that point will be on the order of a few hundred million dollars. Similarly, AIS program officials at the U.S. Department of Energy suggest privately that the total cost of developing any of the three technologies currently being funded will be several hundred million dollars, up to and including the construction of a 1 million SWU/yr demonstration plant.

While figures of this magnitude are impressive testimony to the formidable technological difficulties in the way of successful development of AVLIS, a few general qualifications are necessary.

First, there are important differences between a program whose objective is to develop a technology to a level at which it can operate

successfully in a highly competitive commercial environment and, on the other hand, a program which is less oriented towards reliability and economic performance goals than to the quickest, cheapest possible production of highly enriched uranium.

A good example is provided by the gas centrifuge process. It has taken the U.S. two decades and at least several hundred million dollars to develop a highly advanced, apparently economically competitive form of the technology, and a commercial plant itself will cost several billion dollars. On the other hand, a small centrifuge facility, annually producing enough HEU for one or a few bombs and using relatively unsophisticated technology, might be constructed by a moderately industrialized nation only a few years after the initial decision was made and at a cost of less than \$100 million. (See Table 4.4.) Similar considerations apply to reprocessing technology.

A second qualification relates to the possible influence on U.S. AVLIS program schedules of constraints only marginally related to technical difficulties. Lower separative work demand than originally anticipated and political and institutional pressures (which are examined in Chapter 5) may have reduced the incentives for rapid development. Once again, centrifuge technology provides a useful analogy. The U.S. centrifuge development program has been paced, to some extent, by the anticipated 'cross-over' point, beyond which the existing gaseous diffusion complex will no longer be capable of meeting the demand for separative work. In contrast, the tripartite Urenco development program in West Europe has been strongly motivated by the drive to reduce the dependence of the participating countries on foreign enrichment supplies. It seems plausible that the greater urgency felt by the Europeans has contributed to their achieving

commercialization several years ahead of the U.S., albeit with apparently less advanced technology.

Both of these factors suggest that a comprehensive analysis of the risks from dedicated AVLIS facilities would usefully extend beyond current U.S. programs to include other, possibly less commercially-oriented research and development programs around the world. (The same applies to MLIS technologies.) A list (not necessarily comprehensive) of foreign LIS programs is shown in Table 4.5. Unfortunately, little information is in the public record concerning these programs, and some preliminary inquiries made by this author failed to yield additional details that would be useful for such an assessment.

A third qualification is necessary. Sometimes a very substantial difference exists between the scientific/technological effort required to develop a process or device and commercialize it initially, and the effort needed to replicate it thereafter. The development and application of solid-state devices is a case in point; the initial scientific and technological effort took years of highly skilled work, but nowadays examples of what would hitherto be called high technology are produced by small enterprises. Another example is the development of radar, and now the ubiquity of microwave ovens. But against these examples it may be argued that large volume production and attendant cost reduction methods led to this simplification; that is very unlikely to be the case with clandestine LIS installations.

Nevertheless, some differences remain, even without mass production. As Willrich and Taylor have noted in a related context:⁵²

Every educated person already knows the single most essential fact about how to make nuclear explosives: they work. . . . The certainty that an idea will work in principle is a large step towards finding ways to carry it out.

Table 4.5

Foreign LIS programs

	<u>Comments</u>
* Soviet Union	mainly MLIS
* France	mainly MLIS
* Germany	MLIS
* England	MLIS
* Japan	AVLIS
Argentina	
Australia	
Belgium	
Brazil	
Canada	
India	
Iran	
Iraq	
Israel	AVLIS
Italy	
South Africa	
Taiwan	
Venezuela	

* Programs involving more than 30 scientists. (Source: Interview at LASL, January 25, 1979.)

In this case, of course, proof of principle has already been demonstrated, but similar considerations apply to other steps in the developmental process. Thus, if the production of kilogram quantities of enriched uranium is demonstrated in a LIS facility, then, even if no details of this work are made available, and even if only LEU has been produced, merely the knowledge that the work has proved fruitful might provide a somewhat more sympathetic environment for future efforts in the same area. *

But while these considerations suggest the need for caution in drawing general conclusions from current U.S. LIS experience, the fact remains that many of the technical problems that have been encountered in these programs would also have to be overcome in any AVLIS development effort, whether commercially oriented or not.

In all cases, successful development will require the integration of several complex technological systems and methods including an advanced laser system and its associated optics, a sophisticated uranium evaporation system meeting difficult specifications, metal vapour handling systems, plasma extraction technology, and advanced atomic spectroscopy. Thus, even if major advances bring one of these areas within easier reach, mastery of the others and a complicated system integration will still be necessary.

Uranium has one of the most complicated of all atomic spectra, as discussed in Chapter 2. For any AVLIS development program, energy levels must be identified and assigned, and frequencies, excited state lifetimes, branching ratios, optical and collision cross-sections, isotope shifts and

* Of course, the greater the difference between LEU and HEU AVLIS facilities in practice, the less convincing this argument becomes.

hyperfine splittings must all be measured. The director of the Livermore AVLIS effort noted some years ago that "(a) major portion of our program over the past two years has been devoted to the investigation of this (uranium) spectroscopy."⁵³

Efforts to keep key spectroscopic data secret may or may not be successful. The information required is relatively easy to transfer, either deliberately or inadvertently. If secrecy is preserved, the question is whether the empirical acquisition of these data will be a serious barrier to the success of an attempt to produce HEU via AVLIS. If not, will the task become significantly easier?

Experimental laser spectroscopic studies of uranium have been reported in detail in the literature,⁵⁴ and while details of the more advanced spectroscopic techniques that have certainly been developed subsequently both by JNAI and at Livermore have been more closely held, there is good reason to believe that the minimum spectroscopic data base required by a would-be proliferator could be assembled without the sophisticated methods used by groups seeking a commercially competitive process. Also, as the field of laser spectroscopy continues to develop, background knowledge of a general nature will tend to accumulate, and techniques used to study other materials (particularly other heavy metals) which could be adapted to uranium seem likely to become increasingly accessible. Furthermore, the necessary spectroscopic studies could be performed well in advance of a decision to construct an AVLIS plant, with a relatively low risk of detection.

Thus, although the need for spectroscopic data will be an important factor in an AVLIS-based proliferation attempt, it seems unlikely to present an insurmountable obstacle even to countries with a fairly modest scientific establishment. Stated differently, a country that found difficulty in

acquiring the necessary spectroscopic data would probably fail in its larger objective, since much more taxing scientific and engineering problems would have to be faced at later stages of the program.

Some general observations on the difficulty of constructing an HEU production facility itself can also be made. Although neither of the two process concepts currently under development are apparently capable of it, there is little doubt that an AVLIS module could be designed to produce HEU from natural feed in a single stage.⁵⁵ On the other hand, it may be easier to construct a lower α module and operate it in a batch recycle mode.

But even with the relaxation of the constraints imposed by commercial competition, the technical difficulties are likely to be severe in either case. Consider the laser system itself. In general, isotope shifts in the uranium spectrum are on the order of 0.1\AA . Thus, for any AVLIS process, frequency stabilization to less than 1 in 10^5 will be necessary for the isotopically selective laser. Also, not only must the laser line width be narrow enough to satisfy the isotope shift constraint, but the output must also be broad enough to cover the hyperfine structure of the U-235 absorption spectrum. Indeed, the latter requirement may be the more difficult to achieve in practice.

Then, irrespective of the scale or separation factor of the process, a laser pulse repetition rate of several kilohertz will still be required. And, while exact values of pulse energy density and pulse duration will depend on the particular spectroscopic transition scheme, currently available evidence suggests that energy densities as high as several millijoules/cm² and pulse durations on the order of tens of nanoseconds may be necessary.

These requirements are compared with the performance characteristics of commercially available pulsed tunable dye lasers in Table 4.6. Even without detailed descriptions of various accoutrements and additional capabilities that might be available (e.g., frequency stabilization, amplitude and synchronization jitter limits, etc.), the Table shows clearly that laser systems for AVLIS are still far from being shelf items.

The Table also illustrates the general tendency of flash-lamp-pumped lasers to provide pulses of higher energy but longer duration than laser-pumped systems. As discussed in Chapter 2, JNAI chose the former, and Livermore is apparently concentrating on the latter.

In either case, a would-be proliferator would require sophisticated optical and electronic timing equipment to synchronize and combine output from lasers emitting at several different frequencies. If the JNAI route were followed, the task would be further complicated by the need to synthesize the 10 kilohertz beam from the output of individual lasers each operating at about 500 herz.

It is possible that either one or even both of these approaches will become more attractive if tunable lasers which could be adapted for LIS become more readily available. In this regard, the JNAI review panel found that:⁵⁶

"the lasers of principal interest in the field of laser-induced chemical reaction have significantly different characteristics from those essential to the JNAI process."

If this is true for the JNAI approach, it is probably also true for the Livermore type lasers.

In any case, it seems certain that, at least for the foreseeable future, the independent development of a laser system and associated optics suitable for use even in a small, non-commercial facility could only be

Table 4.6

Comparison of AVLIS Laser Requirements with
Commercially Available Laser Characteristics *

	Spectral range (micron)	Pulse energy density	Pulse rep.rate (pps)	Pulse length (nanosec.)	Line width (nanometer)	Type
AVLIS requirements	~0.3-0.7	up to millijoules /cm ²	Several kiloherz	tens or less	<0.005	
Sopra (RDLE)	0.217-0.95	0.5 mJ	300	2-5	0.001	N ₂ laser pumped dye
Molelectron (DL14P)	0.217-0.935	?	1-1000	?	0.001	Pulsed N ₂ or YAG pumped dye
Lambda Physik (FL1000TEV)	0.217-0.94	~1 mJ	1-500	2-5	0.005	N ₂ pumped dye
Phase-R (DL-2100D)	0.22-0.96	800 mJ	10	200	0.4-0.01	Coaxial flashlamp pumped
Laser Energy (337-M1)	0.37-0.9	10 mJ	1-120	10	0.01	N ₂ laser pumped dye
Electrophotonics (43)	0.43-0.7	250 mJ	1	500	0.3-0.01	Flashlamp pumped dye

* Source: Laser Focus: '1978 Buyers Guide', March 1978

achieved in a country with a fairly advanced technological capability in this field. Similarly, uranium vapour source and plasma extraction systems in an AVLIS process will also demand a high level of technological competence. The former in particular appears to have required considerable research efforts in the U.S. programs.

Other elements of a dedicated facility, such as chemical processing of the product and tails material, are less difficult; though complicated by criticality considerations, such operations appear no more challenging technologically (and probably less so) than those entailed in reprocessing irradiated nuclear fuel - an activity generally acknowledged to be within the reach of many small or developing countries.⁵⁷ Some of the chemical problems arising in product recovery from the collectors may be similar to those encountered at the equivalent stage of the electromagnetic separation process, which has been described in the literature in some detail.⁵⁸

Detectability: As discussed earlier, the probability of detection of a covert attempt to construct an AVLIS plant can only be assessed with specific reference to the country in which such an attempt occurs, as well as to the technology itself. On this issue, as all others, the JNAI review panel confined its attention to proliferation scenarios involving JNAI technology alone, and did not explicitly address the question of other, perhaps less sophisticated approaches. The panel concluded that "effective means are available for the detection of clandestine construction, and particularly operation, of a JNAI plant".⁵⁹ Detection of construction would rely primarily on monitoring exports of critical components, available only on a limited basis. In the JNAI plant concept, these presumably would include the highly specialized equipment required for the uranium vapor source, including the electron gun drives, the guns themselves, and

the uranium crucible, as well as the lasers, optics, and power supplies. Table 4.7 shows estimates of flows of specialized components to a JNAI-type commercial scale plant. The large concentrations of highly specialized personnel would also contribute to the risk of detection.⁶⁰ Detection of operation can be achieved, according to the panel, by the electronic monitoring of the characteristic electromagnetic signals emitted during pulsed operation of the laser system.

While general considerations of this kind can be expected to apply to any AVLIS plant, the extent to which such indications could be relied on for the purposes of detecting small-scale, dedicated facilities is not immediately clear, and in any case would depend on the design concept that was chosen and the characteristics of the country in question.

(2) Molecular LIS Technology

As in the case of AVLIS, U.S. experience with MLIS research attests to the serious technical difficulties likely to be encountered in any attempt to build a facility dedicated to the production of HEU. Work on MLIS at Los Alamos has been in progress since the beginning of the decade. Now funded at about \$18 million annually, and with a staff of 200, the program is nevertheless not expected to demonstrate commercial applicability for another several years. But, as before, a few provisos are necessary; in particular, the requirements for a dedicated facility may be less demanding than for a commercial plant.

The outstanding technical problem in the U.S. MLIS program appears to be the development of suitable infrared and, especially, ultraviolet lasers. Technology for handling and processing uranium hexafluoride is relatively well known. Indeed, as was shown in Chapter 2, many aspects

Table 4.7

Flow of Specialized Components to a Commercially Sized,
JNAI-type Plant *

<u>Component</u>	<u>Initial Quantity</u>	<u>Annual Quantity</u>
High power thyratrons	80	60
Regular tubes	80	15
HV pulse capacitors	160	100
HV transmission cable	10,000'	3,500'
Flashtubes	160	~40,000
E-beam power supplies	40	
Laser dyes (tons)	4	100

* Source: Interviews with JNAI officials

of the UF_6 flow system in an MLIS plant, including the compressors, seem likely to be very similar to those used in the completely unclassified aerodynamic enrichment process developed in West Germany. Also, the technique of adiabatically expanding a gas through a supersonic nozzle has been studied extensively in connection with the development of gas dynamic lasers and other applications. While the actual manufacture of the compressors, separation nozzles, solids removal systems, etc. would require a quite well-developed industrial capability, the ready availability of relevant technological information would seem to obviate the need for pioneering preparatory research and development work. Again, spectroscopic studies will be an important part of an MLIS program, but, as before, they will probably be at least equalled in difficulty, if not superseded, by subsequent scientific and engineering problems associated with a production facility.

Thus, unlike the AVLIS process, the 'proliferation resistance' of MLIS seems likely to depend primarily on the extent to which suitable laser systems, if and when they are developed, will remain inaccessible to would-be proliferators. As before, the possibility that such lasers may be developed for other, non-nuclear applications has important consequences for the proliferation resistance of MLIS technology; in fact, the issue is probably more important in this case, in view of the relatively greater contribution to proliferation resistance stemming from the complexity of the laser system.

Richard Garwin, who for some time has been optimistic about the prospects for the MLIS process, has addressed this question as follows:⁶¹

Once LIS is perfected and on stream, it will be clear that there are many ways of obtaining ultraviolet lasers. The barrier for gaseous diffusion, still highly classified, has no apparent other uses and so is hardly a matter for research and development in universities or industry. Quite the contrary with lasers.

(In fact, participation in the IASL laser development program is already widespread, as Table 4.8 shows). If Garwin is correct, and if, in addition, suitable 16 micron infrared lasers also become more readily available, then the IASL MLIS scheme could ultimately become a highly attractive route to would-be proliferators.

Garwin's views are not universally shared, however, and IASL officials note that the UV lasers suitable for LIS applications will be highly specialized, thus reducing the risk of functional overlap.

Information available in the public sector is not sufficient to resolve this question; nevertheless, there are several indications which suggest that MLIS process may in time provide significantly less challenging obstacles for HEU production in dedicated facilities than atomic vapour-based methods.

Detectability: MLIS plants will almost certainly be very compact, with low energy requirements, and thus difficult to detect using aerial surveillance techniques.⁶² Monitoring of the electromagnetic signals emitted during pulsed operation of the laser system may provide a useful means of detection, as for AVLIS facilities.

In the unclassified version of a report to the Congressional Office of Technology Assessment prepared by the U.S. Energy Research and Development Administration (ERDA), several activities which, taken together, might give a more or less reliable indication that MLIS work was in progress were identified.⁶³ Among the most important, according to ERDA, would be

Table 4.8

Supporting Laser Research for Los Alamos MLIS Program *

<u>University</u>	<u>National Facilities</u>	<u>Industrial</u>
MIT - Javan, Dewey	MIT Lincoln Laboratory	N. American Rockwell
U. of Illinois - Coleman	MIT National Magnet Labs.	UTRC
USC - Wittig, Louisell	Jet Propulsion Laboratory	AVCO
Texas Tech - Gundersen, Burkes	Naval Research Laboratory	Garrett
Rice - Tittel	Lawrence Berkeley Laboratory	MSNW
Harvard - Bloembergen	Battelle Columbus	INRAD
Brooklyn Polytechnic - Cassedy	Battelle Northwest	II-VI
CUNY - Romn	Mound Laboratories	OCLI
Colorado State - Collins	Aerospace	Cordin
U. of Washington - Hertzberg	Oak Ridge National Lab.	Westinghouse
U. of Alberta - Tulip		Hughes Aircraft
Stanford - Byer, Siegman, Feigleson		Hughes Research Lab.
U. of Rochester - Baumeister		GTE-Sylvania
U. of Utah - Fowles		EG&G
BYU - Thorn		Physics International
Yale - Riley, Wegener		IPC
Drexel - Smith		Tachisto
U. of Mississippi - Bass		Owens-Illinois
U. of Missouri (Rolla) - Nygaard		Laser Analytics
U. of New Mexico - Daub, Paine		Fluidyne
Purdue - Skifstad		Lumonics
		SRI. International
		IIS
		Gentec
		Quanta-Ray
		Sanders Associates

* Source: Interview with Los Alamos Officials

attempts to manufacture, or acquire from overseas, high power ultraviolet or infrared lasers tunable over the spectral range of interest (for IR lasers, 16 μm , and also 7.7 μm , 8.6 μm , 12.1 μm , and for UV lasers 0.2-0.4 μm); optical components suitable for such spectral regions; and contamination-free compressors resistant to fluorine attack. Also mentioned were the electric power supplies to an MLIS facility, and the electrical noise generated during pulsing. Nevertheless, the report also noted that the MLIS process (and, in fact, LIS processes in general) would lend themselves readily to the establishment of a clandestine facility, although there was no indication in the report as to how such facilities would compare in terms of ease of detection with alternatives, for example clandestine gas centrifuge plants. Once again, the probability of detection will depend on the national context, and technological generalizations are not possible.

Notes to Sections 4.1 - 4.3

1. I am grateful to Ian Smart for pointing out this distinction to me with particular clarity.
2. The question was raised, for example, in the landmark study of the proliferation problem by A. Wohlstetter et al, Moving toward life in a nuclear armed crowd?, PH 76-04-389-14. Los Angeles, Calif: Pan Heuristics (1976)
3. For a useful overview of the proliferation resistance literature, see H. Feiverson, "Proliferation Resistant Nuclear Fuel Cycles", in J.M. Hollander et al (eds.), Annual Review of Energy, vol. III, Palo Alto, Calif: Annual Reviews, Inc. (1978). Other discussions of the subject appear in: Marvin Miller, "The Nuclear Dilemma: Power, Proliferation and Development", Technology Review, 81 (6), May 1979, 18-29; R.T. Liner, D.A. Outlaw, and E.A. Straker, "A Methodology for Evaluating the Proliferation Resistance of Alternative Nuclear Power Systems", SAI-78-673-WA, Science Applications, Inc., McClean, Virginia, November 1, 1977; Henry S. Rowen, F. Hoffman and H. Kouts, "Exploring Nuclear Futures: Report of the NASAP/INFCE Summer Study on Alternative Nuclear Systems", Graduate School of Business, Stanford University, Stanford, Calif., November 1978, I-7-9.
4. See, for instance: A. Carnesale, "Nuclear Power and Nuclear Proliferation", in Options for U.S. Energy Policy, Institute for Contemporary Studies, San Francisco, California, 1977, p. 62.

5. See: R.T. Liner et al, op. cit.
6. See: Feiverson, op. cit.
7. See: Pierre Lellouche and Richard K. Lester, "Nuclear Proliferation and the Crisis of Nuclear Energy", Washington Quarterly, 2 (3), (Summer 1979)
8. R.T. Liner et al, op. cit., 10
9. Richard K. Betts, "Paranoids, pygmies, pariahs, and non-proliferation", Foreign Policy, 26, (Spring 1977), 162-163
10. Barry M. Casper, "Laser enrichment: a new path to proliferation?" Bulletin of the Atomic Scientists, January 1977, 28-41
11. Allan S. Krass, "Laser enrichment of uranium: the proliferation connection", Science, 196 (4291), 13 May 1977, 721
12. David Fishlock, "A cottage industry nuclear bomb", Financial Times, 10 May 1978, 21
13. Laser isotope separation: proliferation risks and benefits, Report of the Laser Enrichment Review Panel, (Chairman: T. Keith Glennan) to Jersey Nuclear-Avco Isotopes, Inc., February 27, 1979, vol. I, 41
14. Nuclear Fuel, March 19, 1979, 1
15. For example, in a different scenario, LEU product could be diverted from a commercial LIS plant to a dedicated centrifuge facility, where it would be further enriched to weapons-suitable assays. Alternatively, a nation could attempt to construct independently a commercial

LIS plant designed to produce LEU, and then, if successful, convert it to HEU production at a later date.

In both of these examples, the critical step (or steps) is subsumed from the perspective of proliferation resistance in the two chosen scenarios. In the former case, the feasibility rests on the 'safeguardability' of a commercial LIS plant, an issue addressed in route A above. In the latter example, the conversion step is analysed in route A, and it seems reasonable to assume that a pathway requiring indigenous construction of a commercial LIS facility followed by conversion to HEU production would present at least as many technical challenges as those offered by route B above. (Such an assumption would not necessarily hold, however, if in route B the country felt constrained to act covertly throughout, whereas in the second of the examples here, the country proceeded overtly, and possibly even with some external assistance, at least to the point of conversion.)

16. I.A. Papazoglou, E.P. Gyftopoulos, N.C. Rasmussen, M. Miller and H. Raiffa, "A methodology for the assessment of the proliferation resistance of nuclear power systems", M.I.T. Energy Laboratory Report No. MIT-EL 78-021, September 1978, 29
17. Ibid.
18. See: I.A. Papazoglou, op. cit., 34-46
19. The problems of assembling a HEU weapon might, however, differ in several important respects from those encountered with, say, reactor grade plutonium. For a brief discussion of this question, see:

U.S. Congress, Office of Technology Assessment, Nuclear Proliferation and Safeguards, Washington, D.C. (1977), Chapter VI, 139-143

20. See note 5.
21. A more sophisticated treatment would seek to determine how the probability of detection changes as a function of the fraction of the task of materials acquisition that remains to be completed. See: Papazoglou et al, op. cit., 42
22. See Chapter 2.
23. Report of the Laser Enrichment Review Panel, op. cit., vol. II, App. D
24. Report of the Laser Enrichment Review Panel, op. cit., vol. I, 28
25. Peter L. Auer, "Misuse of Laser Isotope Separation", Report of the Laser Enrichment Review Panel, op. cit., vol. 2, App. F, F-1-8
26. Interview with H.K. Forsen, Exxon Nuclear Company, December 4, 1978
27. Auer, op. cit., F-1-5
28. Auer, op. cit., F-1-13
29. Report of the Laser Enrichment Review Panel, op. cit., vol. I, 29
30. See: NASAP Final Report, Preliminary Draft, Table 4.3:1-2 (Overview of leading enrichment technologies). Here, an α of ~8.4 is mentioned.
31. Interview with H.K. Forsen, Exxon Nuclear Company, December 4, 1978

32. See Chapter 2, section 2.3.4
33. The separation factor of individual centrifuge machines can be increased by reducing the feed rate. The maximum achievable improvement is relatively modest, however, (see: U.S. Congress, Office of Technology Assessment, Nuclear Proliferation and Safeguards, op. cit., vol. II, App. V, 212), and, taken on its own, is not enough to permit HEU to be produced directly from a commercial plant.
34. See, for example: D.R. Olander, "Technical Basis of the Gas Centrifuge", Advances in Nuclear Science and Technology, 6, (New York: Academic Press, 1972)
35. Report of the Laser Enrichment Review Panel, op. cit., vol. I, 27
36. In view of the major modifications to operating conditions, plant equipment, or both that would be required for the former scenario, it seems reasonable to expect that unambiguous signals of the intention to undertake such a conversion would be promptly available even to the most rudimentary of on-site international safeguarding capabilities. If such a plant were unsafeguarded, detection would depend entirely on the effectiveness of national intelligence efforts.
37. See: International Atomic Energy Agency, "Safeguarding Uranium Enrichment Facilities", AG-110, September, 1977
38. See the two Agency safeguards systems: INFCIRC/66/rev. 2 (for non-NPT states) and INFCIRC/153 (for NPT parties).
39. See: IAEA, AG-110, op. cit.

40. See INFCIRC/153, section 46(b) (iv). Also, although this provision is not explicitly stated in the Agency's safeguards system for non-NPT states, INFCIRC/66/rev. 2, such states nevertheless may currently stipulate which areas are prohibited to inspectors in their safeguards agreements with the Agency. If the facility in question has been imported, the safeguards arrangements are normally the subject of a trilateral agreement between the supplier, the importer and the Agency.
41. See: IAEA, AG-110, op. cit., 26. Also, discussions on this issue as it applies to the proposed Portsmouth gas centrifuge plant are currently underway in the U.S., in preparation for the forthcoming U.S./IAEA safeguards agreement. (See: Nucleonics Week, Jan 18, 1979, 2)
42. See, for example: M. Willrich (ed.), International Safeguards and Nuclear Industry, Baltimore: Johns Hopkins (1973), particularly the contributions by V. Gilinsky, E. Kinderman, and L. Scheinman. See also: B. O'Leary, "Critique of IAEA Safeguards", in Export Reorganization Act of 1976, Hearings before the Committee on Government Operations, U.S. Senate, 94th Cong., 2nd sess., (1976), 1452
43. See: Report of the Laser Enrichment Review Panel, op. cit., vol. I, 30
44. See: NASAP Program Report, Preliminary Draft, Table 4.3.1-2
45. See: R. Rometsch et al, "Safeguards - 1975-85", in Safeguarding Nuclear Materials, IAEA-SM-201/103, vol. 1, 3-17, Vienna, October 1975, as noted in IAEA, AG-10, op. cit.

46. Several other diversion scenarios can be postulated for which similar limitations are evident. See, for example: U.S. Congress, Office of Technology Assessment, Nuclear Proliferation and Safeguards, op. cit., vol. II, part I, App. V, 207-219, IAEA, AG-110, 11-17
47. John R. Lamarsh, "On the construction of plutonium-producing reactors by small and/or developing countries", and, "On the extraction of plutonium from reactor fuel by small and/or developing nations", Reports prepared for the Congressional Research Service of the Library of Congress, in: U.S. Congress, House, Subcommittee on International Economic Policy and Trade of the Committee on International Relations, (joint committee print with Senate Committee on Governmental Affairs), Nuclear Proliferation Factbook, 95th Cong., 1st Sess., Washington, D.C., Sep. 23, 1977, 533-585
48. Science Applications, Inc., "Nuclear Proliferation and Safeguards", SAI-76-859-LJ (Draft), McLean, Virginia, November 8, 1976
49. O.F. Schuette, "Electromagnetic separation of isotopes", in: U.S. OTA, Nuclear Proliferation and Safeguards, op. cit., App. VI-C, Volume II, Part Two
50. See, for example: K. Beyerle and W. Groth, "Uranium Isotope Enrichment by Gas Centrifugation, in Proceedings of the International Symposium on Isotope Separation, North-Holland Publishing Company, Amsterdam, 1958, 667; and G. Zippe: "The Development of Short Bowl Ultracentrifuges", U.S. Atomic Energy Commission Report ORO-315, Nov. 1, 1960

51. Press release, "Panel concludes Exxon Nuclear-Avco laser enrichment technique consistent with U.S. non-proliferation objectives", Exxon Nuclear Co., Bellevue, Washington, April 16, 1979
52. Mason Willrich and Theodore B. Taylor, Nuclear Theft: Risks and Safeguards, Ballinger, Cambridge, Mass., 1974, 5
53. James I. Davis and Richard W. Davis, "Some aspects of the laser isotope separation program at Lawrence Livermore Laboratory", UCRL-77981, Lawrence Livermore Laboratory, Livermore, California, 15 November 1976
54. See: G.S. Janes, I. Itzkan, C.T. Pike, R.H. Levy and L. Levin, "Laser isotope separation of atomic uranium: spectroscopic studies of excited state lifetimes, photoionization cross-sections, and separation for isotopically selective two-photon processes", IEEE J. Quantum Elect; QE-12(2), February 1976, 111-120
55. This view was expressed to me most recently in an interview with James I. Davis, director of the Livermore LIS program (March 16, 1979). That single-stage enrichment to high assays could be achieved on a spectroscopic scale has been evident almost from the beginning of LIS research. (See: G.S. Janes et al, IEEE J. Quantum Elect, (1976), op. cit., and Laser Program Annual Report - 1974, Lawrence Livermore Laboratory, UCRL-50021-74 (1975), 491-494.) As the throughput increases, it becomes correspondingly more difficult to sustain the separation factor. It seems likely that an HEU module would operate at lower process densities and with better protection for the collector plates than in LEU designs.

56. Report of the Laser Enrichment Review Panel, op. cit., vol. I, 18
57. See J.R. Lamarsh, op. cit., 582
58. See, for example: J. Koch (ed.), Electromagnetic Isotope Separators and Applications of Electromagnetically Enriched Isotopes, North Holland Publishing Company, Amsterdam, 1958, Chapter X; and, R.H.V.M. Dawton and M.L. Smith, Quarterly Reviews, 9 (1), London: The Chemical Society, 1955. For a detailed discussion of collector design in electromagnetic facilities, see: R.K. Wakerling and A. Guthrie (eds.), "Sources and collectors for use in calutrons", U.S. Atomic Energy Commission Report TID-5218, June 1949 (declassified April 15, 1955)
59. Report of the Laser Enrichment Review Panel, op. cit., vol. I, 33
60. JNAI officials expect that a total of 1000 people (in 4 shifts) will be required to operate the planned demonstration facility. A minimum of 75 of these would be skilled technicians, and 12 highly-trained scientists and engineers would be required. (Interview with D.A. McAlees, Exxon Nuclear Company, December 4, 1978)
61. R. Garwin to Allan S. Krass, October 25, 1976
62. See Table 2.7 in Chapter 2.
63. See: U.S. Congress, Office of Technology Assessment, Nuclear Proliferation and Safeguards, op. cit., Vol. II, Part Two, VI-124

4.4 Historical evaluation of the international uranium enrichment industry:
an analysis of causes and constraints

4.4.1 Introduction

The international enrichment industry is in the midst of a transition. Three decades ago, the only operating enrichment facility in the world was located in the United States. Ten years ago, international enrichment supplies were still essentially monopolized by the United States. Today, several suppliers share the market, and others are planning to enter it. Still others are engaged in sizeable research and development programs, some of which may ultimately culminate in the construction of commercial facilities. (The current and projected enrichment supply situation over the next decade is summarized in Table 3.5 of Chapter 3.)

The conditions under which the new situation has developed and the causes and constraints which have shaped the transition are highly pertinent to the current debate over LIS. Each one of the many available examples of independent enrichment technology development programs or technology transfer arrangements can provide many interesting and useful insights into the manner in which the LIS enrichment technology might be expected to spread in the future. Detailed case studies of all such examples are beyond the scope of this assessment, however. Instead, a brief overview of some of the more notable previous instances of enrichment technology diffusion is presented. ('Notable' here refers to cases in which substantial development efforts have ensued.) The purpose is to distill from the historical record a set of recurring themes which might also be expected to influence the international distribution of enrichment technology, including LIS technology, in the future.

The review is divided chronologically into two parts: from 1945-1960, when enrichment technologies mostly served military purposes; and 1960-1979, during which period the commercial applications of enrichment reached maturity.

4.4.2 Enrichment technology and the nuclear weapons powers: 1945-1960

By the end of World War II, the world's first two enrichment production facilities were in operation in the United States: an electromagnetic separation plant and a gaseous diffusion plant. Both were located at Oak Ridge, Tennessee. The electromagnetic plant was the first to produce kilogram quantities of U-235, but was closed down shortly after the end of the war in favour of the more economic diffusion plant. (In the early years of the Manhattan Project, the gas centrifuge method was also regarded as a possible candidate, but work on this process was discontinued before the end of the war.)¹

As efforts to prevent the spread of nuclear weapons gained momentum after the atomic bombs were dropped on Japan, the guiding principle was established that production of fissile material was the principal obstacle to the acquisition of nuclear weapons, and that containment of the means of production would therefore provide the best hope of success for non-proliferation policy. The design of the weapons themselves, it was felt, would be a less difficult hurdle for a would-be proliferator to overcome.² This view was reflected in the Acheson-Lilienthal plan - the first comprehensive proposal to address the problem of nuclear proliferation. The plan, a modified version of which was presented to the United Nations by Bernard Baruch in 1946, recommended international ownership and control of all strategic materials and of all facilities which could be used for

their production. When the Baruch proposals were rejected by the Soviet Union shortly thereafter, the U.S. government adopted a policy of strict secrecy on all its nuclear activities, both civilian and military.

In 1953, President Eisenhower announced a major change in U.S. nuclear policy, in his famous 'Atoms for Peace' speech to the U.N. At the heart of the new policy was a bargain: the U.S. would be prepared to offer assistance in the development of nuclear technology overseas in return for verified undertakings that the technology would only be used for peaceful purposes. U.S. willingness to cooperate internationally did not extend to the transfer of enrichment technology, however; and when, at the two major conferences on the peaceful uses of atomic energy held in Geneva in 1955 and 1958, a great mass of information was declassified and disseminated by the U.S. and the other leading nuclear nations, gaseous diffusion technology was not included.

U.S. policies imposing secrecy on enrichment technology and excluding the possibility of cooperation with other nations in technology development or facility construction have remained essentially intact until the present day. No other fuel cycle technologies, including reprocessing, which was declassified just prior to the 1958 Geneva conference, have been subject to such restrictions.

Not all enrichment technologies have been treated identically, however. Electromagnetic separation technology was declassified during the 1950s, and not until 1960 was work on centrifuge enrichment removed from public view. On the other hand, the key aspects of gaseous diffusion technology have remained classified to this day, although considerable amounts of information have been presented in the open literature by non-U.S. sources.³¹

A formal explanation for the special treatment afforded enrichment technology in U.S. nuclear policy has never appeared in the public domain, to the knowledge of this author, but a contributing factor has certainly been the highly specialized nature of the technology itself. Unlike reprocessing, which can be accomplished with conventional equipment and materials, uranium isotope separation is a unique physical operation, requiring exotic, special-purpose components, a diverse array of advanced scientific and engineering skills, and large financial resources. In such circumstances, denial of access to key technical information and equipment can be an important factor in ensuring that uranium enrichment will continue to be an unattractive alternative to most would-be proliferators, and beyond the capability of many.

While these features certainly characterized the gaseous diffusion process, electromagnetic separation was quite different. The latter drew on basic physical principles which were well known throughout the world even before the war, and laboratory scale mass-spectrometers, of which the Oak Ridge Calutrons were a scaled-up version, were already in widespread use. In this case, moreover, there was no vital technical 'secret' to hide (such as the diffusion barriers and rotary seals in gaseous diffusion plants). Perhaps more important, it was known that electromagnetic separation was inherently much more expensive than the gaseous diffusion process, and dissemination of the former technology would not threaten the U.S. position at the time as the only supplier of enriched uranium - a position which, as we shall see, served both non-proliferation and commercial purposes. Similarly, classification of centrifuge technology in 1960 took place at a time when both its security implications and its potential economic competitiveness with diffusion were emerging.

Even before President Eisenhower's 1953 speech, however, events were underway which would demonstrate that, while gaseous diffusion technology might not be widely disseminated, neither would the U.S. remain its only guardian.

By the end of the war, or shortly thereafter, the Soviet Union had elected for the plutonium route to nuclear weapons,⁴ but within a very few years, possibly as early as 1947,⁵ a decision was taken to construct a gaseous diffusion plant as well. The first Soviet nuclear explosion, in 1949, was conducted with a plutonium device. Three years later, it is believed, the isotope separation plant was in operation.⁶

Like the Soviet Union, the United Kingdom chose the plutonium route first, and the initial British explosion in 1952 was also a plutonium device. But in 1947 the British, too, decided to construct a gaseous diffusion plant, despite the great expense and technical difficulty involved.

Work on gaseous diffusion had started in the U.K. during the war, and there had been some interchange of information with the U.S. during the preliminary stages of the latter's project. The U.S. subsequently lowered a veil of secrecy over its work, however, and no further communication between the two countries took place on the subject.⁷ The first British gaseous diffusion plant began to operate at Capenhurst in 1953. This facility only produced low enriched uranium, however, and it was several more years before a high-enrichment plant was completed.

The decision to build the high-enrichment plant was taken in 1951. One of the justifications for the decision is of particular interest both in the British context and in its possible relevance for the corresponding decisions taken earlier by the Soviet Union and, subsequently by France.

Margaret Gowing, the official historian of the British nuclear program at this time, has described it as follows:⁸

Britain, having committed herself to an atomic weapons program, was concerned as much with the future types of weapons as with quantities, and recent weapons development suggested that U-235 was going to become more important for bombs not only when mixed with plutonium but also on its own. A high separation plant was an essential part of the atomic energy program of any first class power, it was said, since without it half the field of potential development would be closed.

Whether the "future types of weapons" included the hydrogen bomb, which the U.S. had decided to develop in the previous year and which the British themselves would subsequently acquire, was not disclosed by Gowing.⁹

In both the Soviet Union and the U.K., as in the U.S., military objectives were the dominant driving force during the formative years of the nuclear program, despite the early recognition in all three countries of the promise of civil nuclear power. In contrast, the nuclear strategy of France, the fourth nation to acquire nuclear weapons, was deliberately ambiguous from the outset.¹⁰ Thus, when the choice between plutonium production in natural uranium-fueled reactors and enriched uranium in isotope separation plants was addressed in the first French nuclear five-year plan in 1951-52, both defense and peaceful industrial considerations were involved. In the end, the French opted for natural uranium reactors and plutonium production. Isotope separation plants (presumably the gaseous diffusion process was the only method in serious contention by that time) would require large amounts of electric power and natural uranium, neither of which was available to the French Atomic Energy Commission (CEA) in sufficient quantities at the time. More importantly, the cost was too great.¹¹

But by 1955, isotope separation was again being seriously considered in France. Enriched uranium fuel could be used in civilian power reactors, but also in plutonium production reactors, naval propulsion reactors (at higher assays) and nuclear weapons (especially, perhaps, thermonuclear weapons). French uranium deposits had increased significantly in the intervening years, and, although the embargo on enriched uranium exports from the U.S. that had been in effect in 1952 had since been lifted, U.S. supplies under the new Atoms for Peace program could only be used for peaceful purposes and even then under strict controls, including inspection by American teams.¹²

In spite of the advantages of an indigenous enrichment plant, the cost of independent development remained a serious barrier. Negotiations with the U.K. were started in 1955 for the construction of a gaseous diffusion plant in France by British industry, but the project was not pursued because Anglo-American cooperative agreements prevented the British from providing assistance in a field with military implications.¹³

The cost sharing and lead-time reduction made possible by a joint European enrichment facility were also of interest to France, and a European committee was set up in 1955 to study the prospects.¹⁴ After some debate the other prospective partners indicated a preference for buying enriched uranium from the U.S., which had offered supplies in 1956 at prices only about half those expected from a joint European venture. Also, since these countries had little interest in military applications, the export restrictions imposed by the U.S. were of less concern than they were to France.¹⁵ After these setbacks, and despite a new U.S. offer in 1959 to provide highly enriched uranium for submarine propulsion reactors, the French decided to proceed alone, and a small gaseous diffusion plant was constructed at Pierrelatte. The facility was completed in 1967.

The first two nuclear explosions conducted by China, the fifth member of the nuclear weapons 'club', were enriched uranium devices. It is believed that both gaseous diffusion and electromagnetic separation technology were used to produce the fissile material.¹⁶ (There have also been suggestions that gas centrifuge technology might have been used.)¹⁷ The Chinese gaseous diffusion plant, at Lanchow, is generally thought to have been built with Soviet aid.¹⁸

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The U.S. offer to supply cheap enriched uranium to Europe in 1956 can be regarded as an attempt to prevent the construction of an independent European enrichment plant.¹⁹ In fact, it was one of the earliest manifestations of a long-standing U.S. strategy of complementing its restrictions on the transfer of enrichment technology with efforts to make its own supplies as attractive to foreign customers as possible. While the U.S. desire to retain its monopoly of enrichment supplies to the non-Communist world was motivated in part by non-proliferation concerns, the policy also carried strong commercial overtones, as will be discussed in the next section.

4.4.3 Enrichment technology and the development of the international nuclear power industry: 1960-79

(a) Europe

Already by the early 1960s the demand for enriched uranium from U.S. military programs had started to decline, and the large amounts of surplus enrichment capacity that became available for the low cost production of civilian power reactor fuel would enable the U.S. to dominate the international

enrichment supply picture for many years to come. In fact, the significance of the U.S. enrichment plants in the nuclear power field was felt even earlier.

During the 1950s, the light water reactor, fueled with low enriched uranium, had emerged in the U.S. as a leading contender among the reactor types that might be suitable for commercial electric power generation.

The immediate prospects for economical nuclear power in the U.S. were limited, however. Conventional fuel resources were ample and cheap, and besides, domestic political disputes had hampered the introduction of a reactor demonstration program.²⁰ In contrast, a large market for nuclear power appeared to be developing in West Europe. In their much publicized report to the governments of the European Community, 'A target for Euratom', three influential European figures (the so-called 'Three Wise Men') had recommended that the six countries should install 15000 MW of nuclear capacity by 1967 under the auspices of the just-created European Atomic Energy Community (Euratom). Moreover, the report determined that the American light water reactor design was now as advanced as the relatively well-established gas-graphite natural uranium fueled reactor technology developed in the U.K. and France, and the Three Wise Men urged close technological cooperation with the U.S. in the implementation of this ambitious program. Not surprisingly, Europe was regarded in the American nuclear sector as providing an excellent opportunity for the commercial demonstration of its new technology.²¹

This opportunity had developed against a background of strong U.S. support for Euratom. At that time, the U.S. viewed the political integration of Europe as a vital component of a European defense strategy against the Communist bloc, and Euratom could provide a functional basis

for the larger political goal. Moreover, Euratom was seen as a potentially valuable instrument for achieving U.S. non-proliferation objectives, i.e., preventing the development of an independent military nuclear capability in the Community.

These two objectives for Euratom were not always entirely compatible, as was illustrated by the American opposition to a joint European enrichment plant. On the other hand, American cooperation with Euratom in the implementation of a major power reactor construction program served both objectives, and others besides.

A central role for Euratom in the energy policies of the member states would serve to strengthen the unity of the Community. In addition, since the fuel for the reactors would have to come from the U.S., the only significant supplier of enriched uranium, U.S. control over the direction of European nuclear programs would be strengthened. Finally, the supply of reactors and associated fuel and the prospect of more to come would be of considerable economic benefit to the American nuclear industry and to the nation as a whole.

The enthusiasm of the Three Wise Men for light water reactor technology was not universally shared throughout Europe. Fear of American technological domination, the proven capabilities of the European-developed gas-graphite concept, and the need to rely on foreign supplies of low-enriched uranium all militated against adoption of the American design. While the French were generally the most vocal in their advocacy of European nuclear independence, similar concerns were expressed elsewhere in the Community. In Germany, for example, the first nuclear five year plan - the so-called Eltville 500 MWe Program - stressed the development of natural uranium-fueled reactors in view of uncertainties over the

supply of enriched uranium,²² and the need for dependence on foreign fuel supplies continued to be an issue in the technical orientation of the German program at least until 1963.²³

Nevertheless, by 1958 the U.S. had entered into several bilateral agreements with European nations. More importantly, a major agreement with Euratom had been concluded calling for the joint construction of 6 or 7 power reactors in Europe with a total capacity of 1000 MWe by 1965.²⁴

The American ability to guarantee enriched uranium fuel supplies under attractive conditions and at low prices was a crucial factor in these developments.²⁵ And, of course, this capability rested on the demonstrated effectiveness of U.S. enrichment technology, in the massive form of the gaseous diffusion complex. As has been observed elsewhere:²⁶

While the success in establishing the credibility of the U.S. supply role as an acceptable means for meeting nuclear fuel requirements was heavily dependent on U.S. supply policies and arrangements, and its performance in fulfilling these arrangements, there was also an important technical ingredient in U.S. credibility. This was the U.S. leadership in enrichment technology, reflected in the enormous U.S. enrichment capacity of demonstrated economy and technical reliability.

In fact, the foothold for the American nuclear industry opened by the U.S.-Euratom agreement marked the beginning of a decade-long struggle for commercial supremacy in the European nuclear power reactor market, culminating in the French decision of 1969 to abandon gas-graphite technology in favour of American light water reactor designs.²⁷

As the light water reactor gained ground, the extent of European dependence on U.S. fuel supplies grew correspondingly, and once again the possibility of an enrichment plant for Europe was raised. By the end of the 1960s, the technical foundation for an independent European venture

into the enrichment field was much stronger. With the entry into operation of the Pierrelatte plant in 1967, France had demonstrated its competence with gaseous diffusion technology. Britain, which by this time had moved closer to the rest of the continent politically and economically, and was already engaged in a cooperative reactor development project with several European countries, had of course done likewise in the 1950s.²⁸

In addition, progress had been made in several countries with gas centrifuge technology. Work on gas centrifuge enrichment had been carried out in Germany during World War II, and the development of the centrifuge technique continued there afterwards.²⁹ An important milestone was reached following the repatriation of G. Zippe, a German centrifuge expert who had spent the post-war years in the Soviet Union. A centrifuge machine designed by Zippe was patented in West Germany by the firm of Degussa in 1957.³⁰ The following year, Zippe went to the U.S., where his work at the University of Virginia from 1958 to 1960 in association with Jesse Beams, whose pioneer work in the centrifuge field began in the 1930s, provided an important contribution to the U.S. gas centrifuge program. Centrifuge research was also underway at this time in the Netherlands and the U.K. Indeed, centrifuge studies in Britain had been carried out as early as 1946,³¹ and possibly even earlier. It was at the behest of the British government, which was concerned about the possible application of the centrifuge technique for the production of highly-enriched uranium, that the U.S. classified its program in 1960, and subsequently obtained the agreement of West Germany and the Netherlands to do likewise.³²

One year earlier, work had begun in Germany under the direction of E.W. Becker on a new enrichment process, the so-called 'jet nozzle' or

fixed-walled centrifuge technique.³³ Unlike the gas centrifuge method, jet-nozzle technology was not classified, and much information concerning it has remained in the public domain until the present day, although some details have been withheld for proprietary reasons.

Although the British, Dutch and German gas centrifuge programs were proceeding in secrecy, some contact apparently took place between them during the 1960s.³⁴ In 1968, the three countries began formal negotiations, which culminated two years later in the conclusion of the Treaty of Almelo. The signatories to the Treaty agreed to collaborate in the development and manufacture of centrifuges, and in the commercial production of enriched uranium in centrifuge plants. A tripartite organization, Urenco Centec, was created to carry out these functions. The three countries are represented in Urenco Centec by British, Dutch and French shareholding organizations. Also, the whole organization operates within a framework of intergovernmental agreements which include, inter alia, a joint classification policy, and, generally, joint political control of the centrifuge technology.³⁵

In the cases of both Eurodif and Urenco, the need for a multinational approach was imposed by the nature of the technology. The very large size of commercial gaseous diffusion plants required a capital investment that France could not afford to bear alone, and while the scale economies of gas centrifuge technology allowed a much smaller plant size, the development effort required would be extremely costly for the individual countries concerned. For both projects, moreover, multinational participation provided a means of capturing in advance a larger share of a potentially highly competitive market, with a consequent reduction in investment risk.

The incentives for an independent European enrichment facility were steadily growing. Despite the great efforts made by the U.S. during the 1960s to reassure foreign customers of its reliability as a supplier - efforts which included the adoption of toll enrichment in 1966, long-term contracts with the same attractive terms and conditions and low prices for U.S. and non-U.S. users, and the absence of any commercial restriction on the use of U.S. enriched uranium in reactors not manufactured in the U.S.³⁶ - the European nations grew increasingly concerned over their dependence on a single source of supply for such a crucial commodity. In addition, as Goldschmidt and Kratzer have observed, the Europeans' "natural instincts" to diversify their supply position were reinforced by some of the non-proliferation-related controls that the U.S. placed on its exports.³⁷

A new U.S. policy of transferring the government-owned enrichment industry into the private sector, announced by the Nixon Administration in 1969, added fuel to the fire. In order to put U.S. enrichment operations on a more 'commercial footing', i.e., to make enrichment a more attractive proposition to private industry, prices were to be increased and contract provisions toughened. Simultaneously, of course, U.S. supplies became less attractive to its customers. In addition, by the end of the 1960s, light water nuclear reactor manufacturing industries were emerging in Europe, especially Germany.³⁸ The prospect of competing for reactor sales with American industry while at the same time being obliged to rely on the U.S. to provide the associated enrichment requirements was not an alluring one, particularly since enrichment supplies themselves were now apparently to be provided by the private sector.³⁹ European sensitivities were not soothed during this period by the

recommendation of Craig Hosmer, then the ranking House minority member of the Congressional Joint Committee on Atomic Energy and an influential voice in U.S. nuclear policy, to reverse the long-standing policy of non-discrimination between foreign and domestic enrichment customers by charging higher prices to foreign users whose countries were planning their own enrichment facilities.⁴⁰

The Soviet Union announced its willingness to supply enrichment to the West in 1969 and began contracting four years later.⁴¹ Although this provided an opportunity for supply diversification, the prospect of dependence on the Soviet Union was also not attractive to several West European governments.

All of these factors were instrumental in persuading the Europeans of the need to develop an independent supply capability. An American effort to forestall these initiatives by offering in 1971 to share its gaseous diffusion technology with foreign partners in the construction of a multinational enrichment plant proved to be abortive; indeed, the restrictive conditions of the offer may actually have accelerated the Europeans' own plans.⁴²

After successfully organizing a multinational group to study the possibility of a commercial plant based on French diffusion technology in 1972 (the Eurodif study), France decided to construct such a plant with multinational ownership in the following year.⁴³ The Urenco consortium had developed plans for construction of a commercial centrifuge facility at an earlier date.⁴⁴

(b) Rest of the World

Japan: A major commitment to light water reactors has left Japan totally

dependent on foreign supplies of enriched uranium. The Japanese government is engaged in a program of technology development whose goal is the construction of commercial enrichment facilities sufficient to meet the bulk of its domestic demand, while simultaneously considering participation in multinational enrichment ventures overseas.⁴⁵

The vast bulk of funding in the Japanese enrichment program has been devoted to an independent centrifuge development effort.⁴⁶ Very small pilot plants have been in operation for several years, and a larger one is currently under construction.⁴⁷ A full-sized commercial centrifuge plant is planned for the mid-1980s. Meanwhile, Japan has shown interest in investing in private enrichment ventures in the U.S., and negotiations have been conducted with Australia intermittently for some years concerning the possibility of a joint enrichment facility to be located in the latter country. Under such an agreement, Japan would provide most of the financing and, possibly, the technology, while Australia would provide the feed material. The discussions have apparently been inconclusive until now.⁴⁸

Australia: With no nuclear power plans of her own, Australia's interest in enrichment technology has been stimulated by the prospect of increasing the rent recoverable from her very large uranium resources, by upgrading the value of the uranium to the maximum extent prior to sale. An independent centrifuge development program has been underway since the mid 1960s.⁴⁹ The funding level has been modest, however, and it is recognized that the location of a commercial enrichment plant in Australia would require the supply of both financial capital and proven technology from overseas. Apart from the negotiations with Japan, Australia has also reportedly discussed a possible multinational venture with France,⁵⁰

and West Germany⁵¹ and also apparently with the U.S.A.⁵²

Canada: The Canadians have also shown an interest in acquiring enrichment technology in previous years, again for reasons related primarily to their extensive uranium resources. (Canadian CANDU heavy water power reactors do not require uranium fuel to be enriched.) One of the projects (Canadif) was to have been a joint venture with the French CEA. The proposed site in Quebec province would have access to cheap supplies of electric power. At the present time, none of the Canadian enrichment projects is showing any sign of life, and no significant research and development programs are underway.

Brazil: As part of its major nuclear power agreement with West Germany

in 1975, Brazil will acquire jet nozzle enrichment technology from the Germans, and plans to construct a small demonstration enrichment facility based on this process some time in the 1980s. If the demonstration is successful, a larger, commercial-scale plant may also be built. The Becker jet-nozzle process, whose commercial competitiveness has yet to be demonstrated even in Germany, and which uses more energy per unit of output than other proven enrichment technologies, was apparently not the Brazilians' first choice. Gas centrifuge technology was requested originally, but the transfer was vetoed by the Dutch government, which jointly controls Urenco centrifuge technology with West Germany and Britain under the terms of the Treaty of Almelo.⁵³

This was not the first time that Brazil had sought centrifuge technology from West Germany. A large order for centrifuge machines reportedly had been placed as early as 1953.⁵⁴ On this occasion, the U.S. evidently prevented the sale.⁵⁵ Five years later, Brazil actually did acquire three centrifuge machines, of a design developed by W. Groth et al in West Germany

in the years after the war. The last mention of Brazilian centrifuge studies appeared in the literature in 1964.

Several aspects of the 1975 enrichment technology transfer agreement are of interest.⁵⁶ On the West German side, the major economic benefit from the umbrella agreement was derived from the sale of several large power reactors. The German reactor manufacturer, Kraftwerk Union (KWU) was competing with American firms for power plant sales to Brazil in the period before the agreement between Brazil and West Germany was concluded, and it is generally believed that the German willingness to supply technology for essentially the entire nuclear fuel cycle, including the sensitive enrichment and reprocessing steps, was a vital factor in the defeat of the American concerns, for whom the offer of an equivalent package was precluded by national policy.

For Brazil, implementation of the full agreement would provide an opportunity to move to the front rank of nuclear nations (in both military and civilian senses), a position that would be strongly supportive of her long-standing geopolitical aspirations. Moreover, with her potentially large resources of uranium and German enrichment technology, Brazil could become self-sufficient for nuclear fuel supplies. The value of this goal was underscored by the seemingly deteriorating capability of the U.S. to meet its obligations as a reliable, long-term supplier of enrichment services. The most dramatic manifestation of the U.S. difficulties had occurred in 1974, when the Atomic Energy Commission had been forced to suspend the signing of all new enrichment contracts and to convert many existing ones (including two for Brazilian reactors) to 'conditional' status retroactively. The U.S. cutback in enrichment supplies is regarded by many as having been instrumental in the consummation of the German-Brazilian agreement.⁵⁷

South Africa: South Africa has for some years been developing a fixed wall centrifuge isotope separation process which is believed to be fundamentally very similar to the Becker nozzle process. The South African effort allegedly has received substantial assistance from the West Germans, including, notably, the Essen firm of Steag, which earlier had undertaken the commercial development of the jet nozzle process in cooperation with Becker.⁵⁸ South African officials have stated that their own process has been developed without external assistance, however.⁵⁹

A small pilot plant testing the South African process began operating in 1975, and a decision in principle has been taken to construct a commercial plant by the late 1980s. The pilot plant, at Valindaba, has been the source of speculation as to its ability to produce highly enriched uranium.⁶⁰ The commercial plant would provide enriched uranium for South Africa's small nuclear power program and also, in larger quantities, for export.

* * *

The previous discussion has dealt solely with enrichment programs which have culminated in production-scale facilities, or for which there are plans to do so in the future. There are, in addition, many other countries in which active research in uranium isotope separation has been pursued at relatively low levels. A useful review of these programs has been presented by Levin and Blumkin.⁶¹

Conclusions

1. Enrichment technology has played a central role in the weapons programs of the five nuclear weapons powers. Of the five, only China used

enriched uranium for its first explosion. The U.S. developed enrichment and plutonium production technologies essentially in parallel. The Soviet Union, the United Kingdom, and France all selected the plutonium route first.

2. For the United Kingdom and France, and probably also for the Soviet Union, the plutonium route to nuclear weapons was chosen because it was considered to be easier, cheaper and quicker than the alternative of producing highly enriched uranium. Yet in all three cases, decisions were subsequently taken to construct high-enrichment isotope separation plants. The historical record suggests that uranium enrichment is an essential element of a major nuclear weapons program.
3. Besides nuclear weapons production, the incentives for the acquisition of enrichment technology have also included:
 - (a) a desire to achieve a measure of national autonomy in fuel supplies for commercial light water reactors; these desires have in some cases been strengthened by an erosion of confidence in the reliability of existing supplies;
 - (b) a desire to develop a more economic enrichment process;
 - (c) a desire to maximize the economic rent recoverable from exports of indigenous uranium resources;
 - (d) the availability of large amounts of cheap power that can economically be stored and transported in the form of enriched uranium;
 - (e) the desire of governments or corporations which possess enrichment technology to acquire the various political and/or economic benefits that the transfer of that technology might bring.

4. The principal disincentives or constraints on the spread of enrichment technology and facilities have included:
 - (a) the technical difficulty and cost of the associated development effort;
 - (b) the frequently unfavorable economies of scale and the major investments required in production facilities;
 - (c) the restrictions, motivated by both commercial and security considerations, on the transfer of technology and equipment;
 - (d) the unpredictability of demand over the long lifetime of an enrichment project, and the fear of technological obsolescence;
 - (e) the attractive prices and terms and conditions of existing supplies.
5. There has been a recurrent pattern of multinational cooperation in the development of enrichment technology and the construction of commercial facilities. Out of the seven existing or firmly committed commercial enrichment ventures - U.S., U.S.S.R., Urenco, Eurodif, Japan, Brazil, South Africa - at least three (and almost certainly also a fourth) have involved international transfers of technology.
6. While limitations on the dissemination of information concerning enrichment technology have probably been more stringent than for any other aspect of nuclear technology, with the obvious exception of nuclear weapons themselves, the restrictions have by no means been total. The key aspects of the gaseous diffusion process have remained classified, but electromagnetic separation technology has been largely declassified. Furthermore, important early work on centrifuge development is in the public domain, including the design from which today's commercial machines have evolved, and all aspects of Becker jet-nozzle technology are unclassified.

Notes to Section 4.4

1. Henry D. Smyth, Atomic Energy for Military Purposes, Princeton: Princeton University Press (1945), 169
2. The Atlantic Council of the United States, Nuclear Power and Nuclear Weapons Proliferation, Report of the Atlantic Council's Nuclear Fuels Policy Working Group, Boulder: Westview Press, vol. 1, 58
3. See, for example, S. Villani, Isotope Separation, American Nuclear Society, 1976, Chapter 5
4. Arnold Kramish, Atomic Energy in the Soviet Union, Stanford: Stanford University Press (1959), 108-120
5. Ibid.
6. Bertrand Goldschmidt, The Atomic Adventure, Oxford: Pergamon Press (1964), 67
7. Margaret Gowing, Independence and Deterrence: Britain and Atomic Energy, 1945-1952, vol. 2, 428
8. Ibid., vol. 1, 223
9. In this context, a prominent Indian defense expert has indicated that highly enriched uranium is preferable to plutonium for use in a fission trigger device for thermonuclear weapons. See: K. Subrahmanyam, "The Path to Nuclear Capability", The Institute for Defense Studies and Analyses Journal, 3 (1), July 1970, New Delhi, India, 93

10. For a more detailed discussion of French nuclear policy during this period, see: Laurence Scheinman, Atomic Energy Policy in France under the Fourth Republic, (Princeton: Princeton University Press 1965). See also, Goldschmidt (1964), op. cit. The following paragraphs draw heavily on these two references.
11. Goldschmidt, op. cit., 81
12. Scheinman, op. cit., 176
13. Goldschmidt, op. cit., 100
14. Goldschmidt, op. cit., 111
15. Scheinman, op. cit., 176
16. Walter C. Clemens Jr., The Arms Race and Sino-Soviet Relations, The Hoover Institution, Stanford University, 1968, 23
17. Ibid.
18. Morton Halperin, China and the Bomb, New York: Praeger (1965)
19. Scheinman, op. cit., 177
20. I.C. Bupp and Jean-Claude Derian, Light Water: How the nuclear dream dissolved, Basic Books, New York, 1978, 30-36
21. Ibid., 29
22. Otto Keck, Fast Breeder Development in West Germany: An Analysis of Government Policy, Ph.D. dissertation (unpublished), University of Sussex, 1977, at p. 16 of "Government Policy and Technical Choice in

the West German Reactor Program".

23. Ibid., 39
24. Henry R. Nau, National Politics and International Technology: Nuclear Development in Western Europe, Johns Hopkins University Press, London, (1975), 134
25. Under the supplementary fuel supply agreement of the U.S. - Euratom program, the U.S. would supply 30 tons of enriched uranium initially, with a guarantee to meet additional requirements for a 20-year period. The financial provisions were also attractive. (See Nau, op. cit., 135, footnote 27)
26. Laser Isotope Separation: Proliferation Risks and Benefits, Report of the Laser Enrichment Review Panel to Jersey Nuclear-Avco Isotopes, Inc., February 27, 1979, vol. II, App. B, 5
27. For a detailed account of the developments leading to the adoption of the light water reactor in Europe, see Nau, op. cit., especially pp. 127-156. See also Bupp and Derian, op. cit., for a discussion of French policy during these years.
28. The project in question was the DRAGON high-temperature gas reactor project, which was being conducted under the auspices of the European Nuclear Energy Agency (ENEA), a broader grouping than Euratom.
See Nau, op. cit., 184-211
29. Barbara Rogers and Zdenek Cervanka, The Nuclear Axis, Times Books, New York, 1978, 31-32

30. Ibid., 37
31. Gowing, op. cit., vol. 1, 426
32. M. Mihalka et al, "International arrangements for enrichment",
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33. Rogers and Cervanka, op. cit., 43
34. C. Allday, "Some experiences in formation and operation of multinational uranium-enrichment and fuel-reprocessing organizations", in
A. Chayes and W. Bennett Lewis (eds.), International Arrangements for Nuclear Fuel Reprocessing, Ballinger, Cambridge (1977), 178
35. Ibid., 178
36. B. Goldschmidt and M.B. Kratzer, "Peaceful Nuclear Relations:
A Study of the Creation and the Erosion of Confidence", International
Consultative Group on Nuclear Energy, The Rockefeller Foundation,
New York, 1978, 16
37. Ibid.
38. In 1969, the two principal German reactor manufacturers, Siemens and
AEG, merged their nuclear interests in creating a joint subsidiary,
Kraftwerk Union (KWU). (Nau, op. cit., 151)
39. Nau, op. cit., 154
40. See: Edward F. Wonder, Nuclear Fuel and American Foreign Policy:
Multilateralization for Uranium Enrichment", Westview Press, Boulder,
Colorado, 1977, 12

41. Goldschmidt and Kratzer, op. cit., 18
42. For an analysis of both the 1971 U.S. initiative and a second multi-lateral initiative in 1974, which also failed, see Wonder, op. cit., 11-25, 37-57.
43. Goldschmidt and Kratzer, op. cit., 17. The Eurodif group includes organizations from Spain, Italy, Belgium and Iran, as well as France. However, only French participants have access to the most sensitive aspects of the process. (Wonder, op. cit., 2; see also: J.F. Petit, Proceedings of the International Conference on Nuclear Power and its Fuel Cycle, 2-13 May 1977, IAEA, Vienna, 1977, vol. 3)
44. Nau, op. cit., 154
45. Japan Atomic Energy Commission, "FY 1976 Annual Report on Atomic Energy" (Unofficial translation), March 1977, 23-24
46. Y. Naruse, Japanese Atomic Energy Research Institute, Personal Communication, December 26, 1978
47. Japan Atomic Energy Commission, op. cit., ref. 8
48. Doug Kean, Office of National Assessments, Canberra, Australia. Interview, June 1, 1979.
49. S.A. Levin and S. Blumkin, "Enrichment Supply and Technology Outside the United States", in Proceedings of the Executive Conference on Uranium Fuel Supply, January 23-26, 1977, American Nuclear Society, La Grange, Ill., 1978, 405

50. Nucleonics Week, 27 July, 1978
51. Energy Daily, 21 March 1979
52. D. Kean, op. cit.
53. Norman Gall, "Atoms for Brazil, Dangers for All", Foreign Policy, 23 (Summer 1976), 171
54. Der Spiegel, 31 January 1977, in Rogers and Cervanka, op. cit., 339
55. Ibid.
56. For detailed analyses of the West German-Brazilian nuclear agreement, see Gall, op. cit., and William W. Lowrance, "Nuclear Futures for Sale: To Brazil from West Germany, 1975", International Security, Fall 1976, 147
57. See, for example, the testimony by Myron B. Kratzer, acting assistant secretary, Bureau of Oceans and International Affairs, State Department, U.S. Congress, Senate, Committee on Foreign Relations, International Organization and Security Agreements: Hearings, July 22, 1975, as reported in Gall, op. cit., 163-4
58. Rogers and Cervanka, op. cit.
59. Ibid., 77
60. Jim Hoaglund, "South Africa, with U.S. aid, near A-bomb", Washington Post, 16 February 1977
61. Levin and Blunkin, op. cit.

4.5 LIS Enrichment Export Controls and Restrictions

In the preceding sections, we have identified and analyzed some of the technical issues which seem likely to influence the proliferation risks associated with the development and application of laser isotope separation technologies. We have also discussed the motivations, disincentives and constraints which have affected the spread of enrichment technology and facilities in the past, and which might be expected to continue doing so in the future. In this section, we describe in more detail the existing array of legal and political controls on the international transfer of enrichment technology.

4.5.1 United States controls

Classification policy

All information concerning the production of special nuclear material* is deemed Restricted Data under the Atomic Energy Act of 1954, as amended, unless it has been removed from the Restricted Data category or declassified upon determination that such data could be published "without undue risk to the common defense and security."¹

In 1967, the (then) Atomic Energy Commission declassified all research and development work on any isotope separation method, other than gaseous diffusion and gas centrifugation, until that method shows a reasonable potential for the separation of practical quantities of special nuclear material.² Methods which have demonstrated this potential are classified as Restricted Data. The MLIS process under development at LASL and the AVLIS process developed by LLL have both been deemed to require Restricted

* The definition of "special nuclear material" includes uranium enriched in the isotope U-235 above natural assays. (Sec. 11aa, Atomic Energy Act).

Data classification under this policy,³ and information concerning the JNAI AVLIS process that DOE regards as Restricted Data is treated as such by JNAI, although the latter has not recognized the legal right of DOE to classify its technology as Restricted Data, and stresses the voluntary nature of the JNAI policy in this regard.⁴ DOE classification policy is not to attempt to classify everything about the LIS processes, but rather "to require protection of process details such as unique design and engineering features and operating parameters, which appear critical to achieving a successful process".⁵

Export Controls

Under the present U.S. legislative framework for nuclear export controls, the transfer of certain nuclear technology is controlled by the Department of Energy, while control of equipment and material exports is generally assigned to the Nuclear Regulatory Commission.

Section 57b of the Atomic Energy Act prohibits "persons" (i.e. individuals, corporations or other organizations) under U.S. jurisdiction from directly or indirectly engaging in the production of any special nuclear material outside the U.S., except pursuant to an intergovernmental agreement for cooperation or by a determination of the Secretary of Energy, with the concurrence of the Secretary of State, that such activity will not be inimical to the interests of the U.S.

The implementing regulation for Section 57b is 10 CFR 810, which lists those activities generally prohibited except with the Energy Secretary's specific authorization. To date, Section 57b has always been implemented so as to prohibit the export of enrichment technology.⁶

U.S. policy in this regard was recently affirmed by President Carter, who said in April 1977 that "(We) will continue to embargo the export of equipment or technology that would permit enrichment....."⁷

There are, under Section 57b, other statutory restraints on the transfer of enrichment technology, whose applicability depends on whether the technology in question is deemed Restricted Data or "sensitive" data, i.e., information which is not Restricted Data but which is nevertheless important to the design, construction, fabrication, operation or maintenance of a uranium enrichment facility and which is not available to the public.⁸

Concerning component parts for nuclear facilities, the Nuclear Non-Proliferation Act of 1978 directs the Nuclear Regulatory Commission (NRC), in consultation with the Secretaries of State, Energy and Commerce and the Director of the Arms Control and Disarmament Agency, to determine which items are "especially relevant from the standpoint of export control because of their significance for nuclear explosive properties".⁹ No such item can be exported unless the NRC issues a general or specific license for its export based on a finding that certain specific conditions are met, and further, that the Commission determines (and the executive branch concurs) that the export would not be inimical to the common defense and security.¹⁰

The implementing regulation for this statutory requirement is 10 CFR 110, which includes in the list of items subject to NRC licensing authority "laser isotope separation units", UF₆ corrosion resistant valves, compressors and seals, and "any other equipment or component specially designed or prepared for use in an isotope separation plant".¹¹

Elsewhere in the Act, it is provided that no "major critical component" of any uranium enrichment facility shall be exported under any agreement for cooperation unless such items are specifically designated for export under the agreement.¹² According to the Act, the term

'major critical component' "means any component part or group of component parts which the President determines to be essential to the operation of a complete uranium enrichment, nuclear fuel reprocessing or heavy water production facility".¹³ Significantly, this definition would seem to be more comprehensive than the category of components "specifically designed or prepared for use in an isotope separation plant", and could include so-called 'general purpose' items, which nonetheless are necessary for the operation of the plant. How broadly this definition will be interpreted in practice remains to be seen; in particular, the extent to which it includes components which are readily available elsewhere or whose value to an isotope separation plant rests upon technical modifications made in the importing country is not clear.¹⁴

Related to this question is another provision of the Act, which requires the President to establish procedures by which the Department of Commerce shall control exports which, although not licensed by the Commission, might nevertheless be "of significance for nuclear explosive purposes", if used for purposes other than those for which the export was originally intended.

In sum, current U.S. policy is to embargo the export of enrichment equipment and technology. Existing law provides sufficient authority for the successful implementation of this policy. Moreover, if the export embargo on enrichment should be lifted in the future, existing law vests adequate authority in the relevant agencies of the U.S. Government to monitor effectively the flow overseas of such equipment and technology under future export controls.

4.5.2 International Controls

No matter how effectively they are implemented, unilateral U.S. restrictions on the transfer of enrichment technology and equipment will not be sufficient in themselves to achieve the broader U.S. policy goal of limiting the spread of enrichment facilities. To this end, the U.S. has sought, in the forum of the so-called London Suppliers Group, to persuade other suppliers of nuclear technology to adopt similar controls. Recently, the fifteen members of the Group agreed to a set of 'guidelines' for nuclear transfers, which were published under the auspices of the International Atomic Energy Agency as INFCIRC/254 in February 1978.¹⁵ The guidelines include the following provisions, which are of significance to the transfer of enrichment technology and facilities:

1. A list of items of equipment whose transfer will 'trigger' the application of IAEA safeguards and effective physical protection measures; the 'trigger list' includes equipment "especially designed or prepared for the separation of isotopes of uranium";¹⁶
2. Sensitive facilities (i.e., enrichment, reprocessing and heavy water production facilities) utilizing technology directly transferred by the supplier, or derived from transferred facilities or major critical components of facilities, must also be covered by IAEA safeguards. 'Technology' is defined in the guidelines as "technical data in physical form designated by the supplying country as important to the design, construction, operation, or maintenance of enrichment.... facilities or major critical components thereof, but excluding data available to the public, for example, in published books and periodicals, or that which has been made available internationally without restrictions upon its further dissemination".

3. Replications of enrichment facilities or major critical components thereof, either directly transferred or utilizing transferred technology must also be covered by IAEA safeguards.
4. For the transfer of an enrichment facility or enrichment technology, the recipient should agree that neither the facility, nor any facility based on transferred technology, will produce greater than 20% enriched uranium without the consent of the supplier nation.
5. The suppliers agree to "exercise restraint" on the transfer of sensitive facilities and technology (including enrichment facilities and technology).

The London Suppliers Group guidelines are the outcome of a hitherto unprecedented degree of cooperation among the principal supplier nations against the threat of proliferation, and the impact of the guidelines in general has been to upgrade the effectiveness of international non-proliferation controls on the export of nuclear technology, equipment and materials. Yet for enrichment technology, as for the other technologies and materials falling within their scope, the guidelines are by no means 'watertight', and are considerably less stringent than current U.S. controls. The several reasons for this include:

1. The suppliers have agreed only to exercise "restraint" in the transfer of sensitive technology and facilities rather than to prohibit such transfers completely. The agreement represents a compromise between those countries, including the U.S., which had sought a collective embargo, and others, notably France, which felt in part that an embargo, by encouraging independent, unsafeguarded programs, could ultimately be counterproductive from a non-proliferation perspective.¹⁷

2. The guidelines are not legally binding on the participants under international law. Further, although all the major suppliers have indicated that they will act in accordance with the guidelines, many of them, unlike the U.S., have not passed domestic implementing legislation.¹⁸
3. The London Suppliers Group is deeply resented by recipient nations, particularly in the Third World, who have perceived it as a 'technology cartel'. Partly because of its considerable unpopularity, there have been suggestions that the Group will not convene again. Without the reinforcement provided by continued meetings of the parent body, the guidelines might be expected to exact a progressively declining influence on the export policies of the member states. It is not possible to predict the rate at which such a decline might occur, however.
4. The membership of the Suppliers Group does not extend to countries which may in the future be in a position to engage in significant transfer of nuclear technology and materials. In the enrichment field, South Africa is one country which, although apparently in possession of a demonstrated enrichment technology, has not indicated its willingness to act in accordance with the guidelines.¹⁹ In the laser enrichment field more particularly, the list of non-Suppliers Group nations reportedly engaged in research and development includes Israel, India and Brazil. Whether such efforts will ultimately enable these countries to export technology and equipment significant from a proliferation perspective remains to be seen.
5. The 'trigger list' includes equipment "especially designed or prepared for the separation of isotopes of uranium", but does not extend as far

as U.S. domestic legislation in controlling the export of 'general purpose' items which nevertheless may be essential to the operation of an enrichment plant. In any case, even within the general framework of 'restraint' there may be differing interpretations of what constitutes equipment especially designed or prepared for a laser enrichment plant, particularly if the current lack of specific reference to laser isotope separation equipment and technology is to be a permanent feature of the guidelines.

Notes to Section 4.5

1. The scope of Restricted Data is defined in section 11y of the Atomic Energy Act; the exceptions are given in section 142a.
2. 32 Federal Register 20868
3. See: U.S. Energy Research and Development Administration, "Uranium laser isotope separation and nuclear weapons proliferation", in U.S. Office of Technology Assessment, Nuclear Proliferation and Safeguards, Volume 2, Part 2, App. VI-D, (1977)
4. Report of the Laser Enrichment Review Panel to JNAI, Inc., "Laser isotope separation; proliferation risks and benefits", February 27, 1979, (hereinafter cited as 'JNAI report'), App. J-2
5. OTA report, op. cit., VI-131
6. JNAI report, App. I-2
7. President Carter, Statement on Nuclear Power Policy, April 7, 1977
8. For a discussion of these statutory restraints, see: JNAI report, App. I-2
9. Sec. 109(b) of the Atomic Energy Act of 1954, as amended by Sec. 309(a) of P.L. 95-242, The Nuclear Non-Proliferation Act of 1978
10. Ibid.
11. 10 Code of Federal Regulations 110, Appendix A
12. Sec. 402(b) of P.L. 95-242, The Nuclear Non-Proliferation Act of 1978

13. Ibid.

14. See: Mihalka et al, "International Arrangements for Enrichment",
Rand Report WD-187-DOE (Working Draft), Santa Monica, Ca., May 1979,

25. The authors note that these interpretations will inevitably
depend on the strength of the commitment to non-proliferation within
the relevant government bureaucracies.

15. The Nuclear Suppliers Group consists of the following countries:

Canada, the U.S., the U.S.S.R., France, West Germany, the U.K., Japan,
Belgium, the Netherlands, Italy, Sweden, Switzerland, Poland,
East Germany and Czechoslovakia.

16. The trigger list specifically includes:

- gaseous diffusion barriers
- gaseous diffuser housings
- gas centrifuge assemblies, corrosion resistant to UF_6
- jet nozzle separation units
- vortex separation units
- large UF_6 corrosion-resistant axial or centrifugal
compressors
- special compressor seals for such compressors

No mention is made of laser isotope separation processes. However,
the language indicates that all isotope separation processes are
effectively included in the list.

17. France and Germany, whose 'liberal' nuclear export policies had been
a major source of concern to the U.S. earlier in the 1970s, have both

indicated, outside the context of the London Suppliers Group, that they are banning exports of reprocessing plants and technology until further notice. France announced its decision in December 1976 (see: Pierre Lellouche, "French Nuclear Policy: National Programme, European Dimensions, and Non Proliferation", prepared for the Nuclear Study Group of the Forschungsintitut der Deutschen Gesellschaft fur Auswartigen Politik, Bonn, 23 May 1979), and Germany followed suit in June 1977 (see: Nuclear Engineering International, July 1977, 6). Neither country has adopted a similar ban for enrichment facilities or technology.

18. M. Mihalka et al, op. cit., 25

19. Ibid.

4.6 Implications of Laser Enrichment Technology for Current Non-proliferation

Policies: Conclusions

Based on the analysis presented in the previous two chapters, we conclude that the successful development of laser enrichment technologies will have the following implications for current non-proliferation policies:

First, the development and dissemination of new enrichment technologies may erode existing technical barriers to the acquisition of nuclear weapons material, and may also increase the relative attractiveness of dedicated production facilities compared with the diversion of fissile material from the commercial fuel cycle.

Second, specific conclusions concerning the relative proliferation resistance of laser isotope separation processes are hard to reach given the present dearth of technological information. Nevertheless, the following statements may be made:

- The task of converting a commercial laser enrichment plant of either the atomic or molecular kind to the production of highly enriched uranium is likely to be technically more demanding than the equivalent conversion of a commercial gas centrifuge plant; moreover, covert attempts to divert fissionable material from commercial laser enrichment plants or to produce highly enriched uranium in such plants seem more likely to be detectable by international safeguards techniques than would corresponding attempts made at commercial gas centrifuge facilities.
- There may be substantial differences in difficulty between the effort required on the one hand to develop laser enrichment technology to the point at which it can operate successfully in a highly competitive commercial environment and, on the other hand, to develop

it for the sole purpose of producing highly enriched uranium as quickly and as cheaply as possible. However, at the present time, a dedicated laser enrichment facility of either the atomic or molecular type would be perceived by all nations as a much more difficult route to nuclear weapons material than alternatives such as centrifuge plants, and plutonium production reactors and chemical reprocessing facilities. This situation is unlikely to change in the near future.

- In the longer run, after perhaps a further ten years or more, significant differences between AVLIS and MLIS processes may be perceived by potential proliferators. In whatever form, AVLIS plants will require advanced technological expertise in each of several different areas. Even if major advances bring one of these areas within easier reach, mastery of the others and a complex system integration will still be required. In contrast, MLIS process developments appear to be dominated by a single set of problems concerning the lasers themselves. The balance of plant, while requiring considerable technological skills, and components that are not immediately accessible 'shelf' items, nevertheless probably lies within the capabilities of nations below the first tier of technological and industrial development. Consequently, a breakthrough in laser technology or a new laser system/uranium material combination applicable to MLIS plants conceivably could substantially increase the attractiveness of MLIS processes to potential proliferators.

Third, by improving the efficiency with which existing uranium resources can be utilized, 'tails stripping' laser enrichment facilities can reduce the pressure to introduce uranium-conserving but potentially

proliferation-prone fuel cycles, particularly those involving widespread use of plutonium.

Fourth, the successful development of an economically attractive enrichment process with scale economies favorable to the construction of small commercial facilities will run counter to current efforts to prevent the spread of such facilities. A wider distribution of enrichment plants will tend to reduce the perceived vulnerability of nations to interruptions in low-enriched uranium supplies, and may consequently reduce pressures for the introduction of plutonium as a commercial fuel. On the other hand, any non-proliferation benefits accruing from such developments must be weighed against the increased risks of misuse of commercial enrichment facilities for weapons purposes.

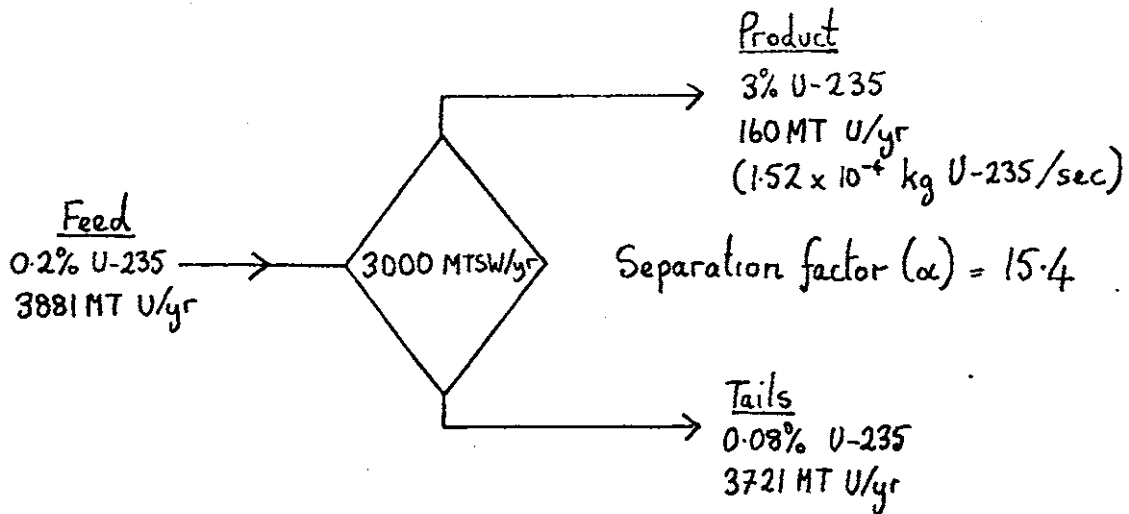
Fifth, the addition of a new, economically highly attractive enrichment process to the list of 'sensitive' technologies which are withheld from international trade will tend to aggravate the already strained and potentially counterproductive relationship between supplier and recipient nations.

How these various considerations can best be integrated with other relevant issues into a coherent U.S. laser enrichment policy is taken up in Chapter 6.

Appendix I: Estimated HEU Production Times in Commercial AVLIS, MLIS and Gas Centrifuge Enrichment Plants

(i) Atomic Vapour LIS Plant

The material balance for a 3000 MTSW/yr depleted feed AVLIS plant operating at the design conditions assumed for this calculation is shown below:



It is assumed further that the separation factor is unaffected by changes in the enrichment feed assay, provided the U-235 ion density (and thus the U-235 throughput of 1.52 x 10⁻⁴ kg/sec) in the extraction zone remains constant. Under these conditions, the increase in enrichment as a function of the number of recycle stages can be determined from a McCabe-Thiele diagram. (See Figure I-1.) Thus, if the initial feed is 3 % enriched material, the first stage product assay will be 31 %; if this material is recycled, the second stage assay will be 87.5 %. If only natural uranium feed is available, the second stage product enrichment will be 63 %. In the following presentation, we assume the availability of 3 % uranium, and base the calculations

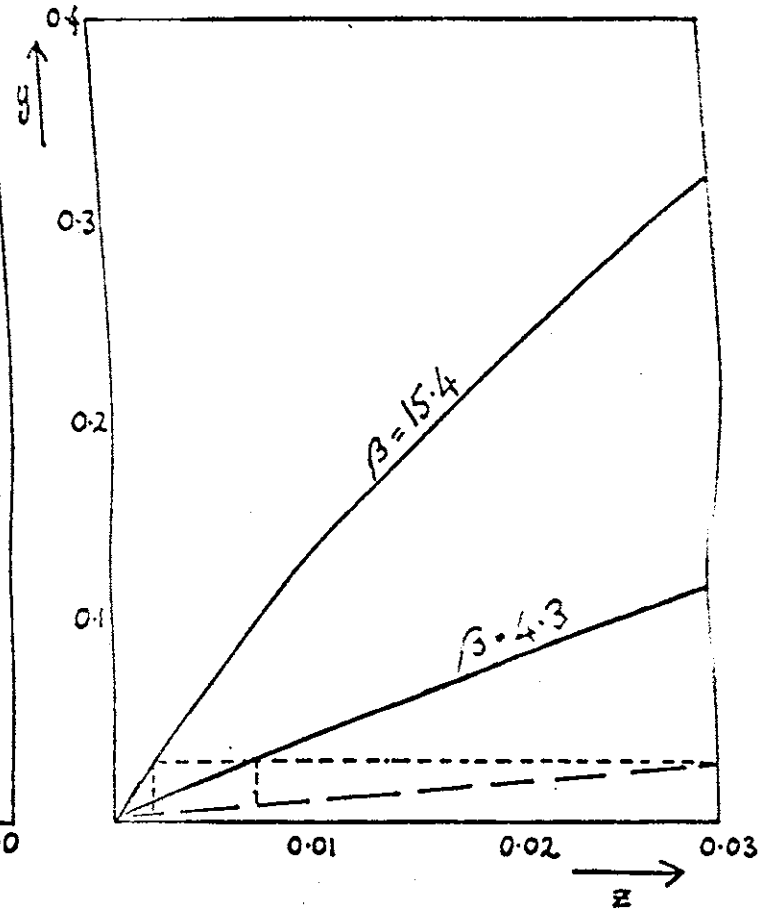
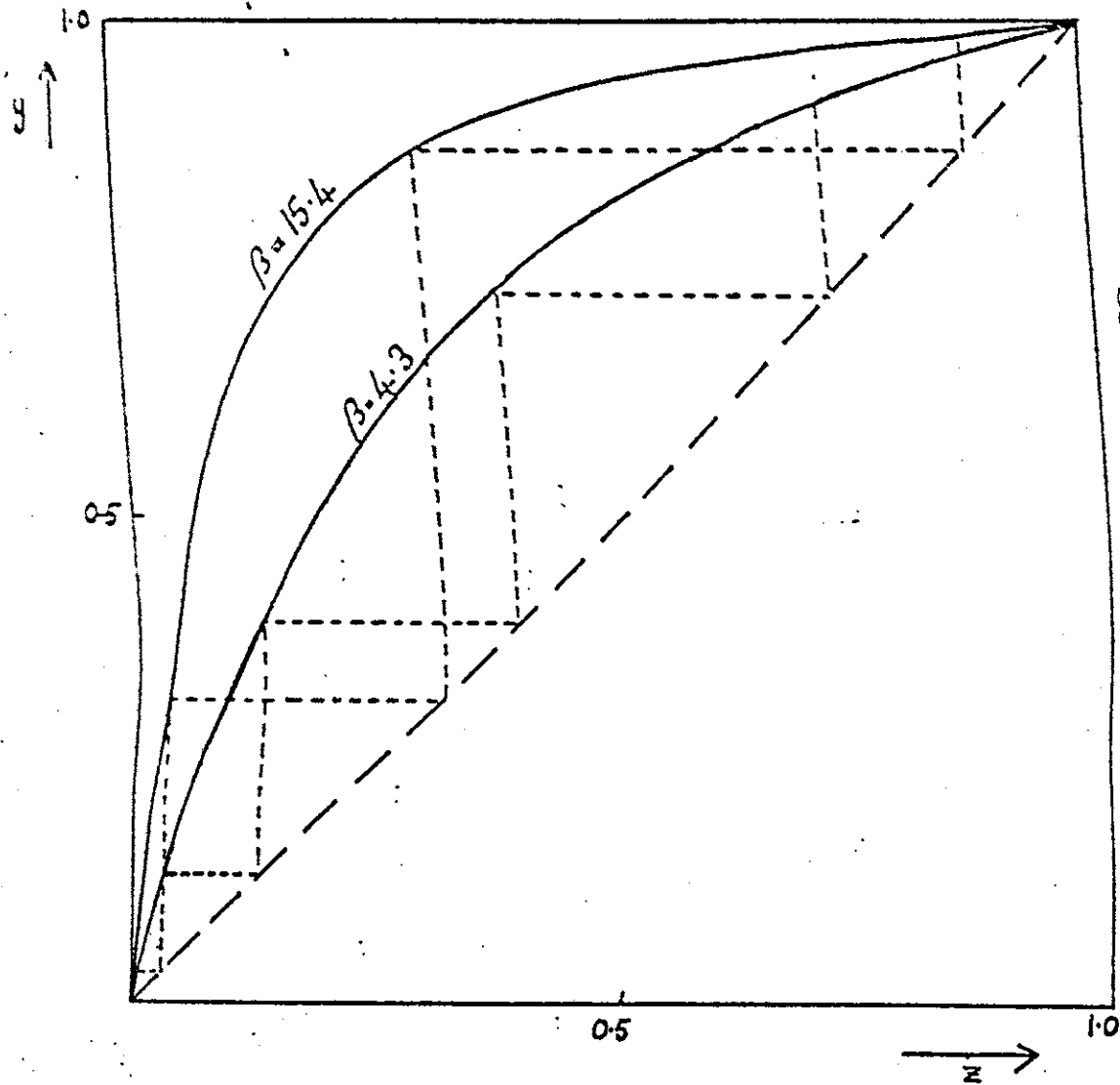


FIG. I.1: MCCABE-THIELE DIAGRAMS FOR DEPLETED FEED ($\beta = 15.4$) AND NATURAL FEED ($\beta = 4.3$) AVLIS PLANTS

on what is known of the JNAI AVLIS process.

From Fig. I - 2 the critical mass of uranium metal enriched to 87.5 % in U-235, with a good neutron reflector, is about 18.3 kg (or roughly 16 kg of U-235). Adding a contingency of 50 % to account for losses during product processing and weapon fabrication, the second stage plant operating time needed to collect the required amount of product is $\frac{16 \times 1.5}{1.52 \times 10^{-4} \times 3600} \sim 44$ hours.

Now, only about 60 % of the U-235 entering the irradiation zone is actually collected on the product plates, and, furthermore, only 50 % of the uranium that is vapourized actually enters the irradiation zone, with the remainder impinging on the shadow shields, or escaping the extractor envelope altogether. Adding a further 5 %, say, for plant start-up losses, the total amount of U-235 (as 31 % uranium) required as feed to the second stage (and thus as product from the first stage) is $\frac{24}{0.6} \times \frac{1}{0.5} \times 1.05 \sim 84$ kg.

If we add a further 30 % margin to account for processing losses incurred during the post-first-stage recycle operations, the first stage plant operating time is $\frac{84 \times 1.3}{1.52 \times 10^{-4} \times 3600} \sim 200$ hours, and the amount of 3 % uranium required as feed to the first stage is

$$\frac{84 \times 1.3}{0.6 \times 0.5} \times \frac{1.05}{0.03} \sim 12.7 \text{ MT. Thus, over ten days of plant operation and}$$

12.7 metric tons of 3 % uranium metal (equivalent to almost half of the annual refueling requirement for a 1000 MWe LWR) are needed to produce enough HEU for a single nuclear weapon.*

* Implicit in this calculation are the additional assumptions that, firstly, there is no minimum threshold quantity for the uranium feed charge below with the plant cannot be operated and, secondly, that all of the uranium in the feed charge can be usefully evaporated.

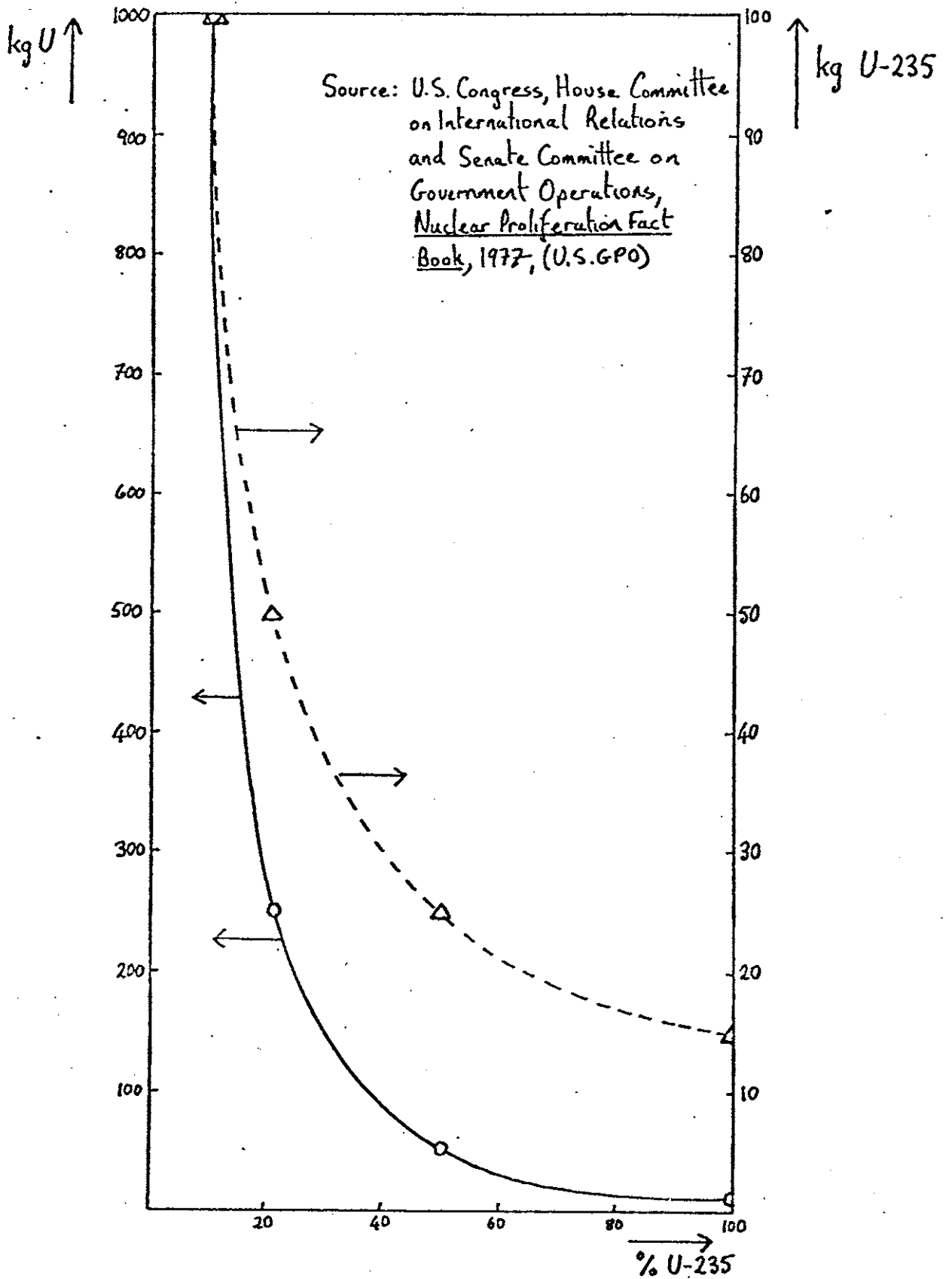


FIG. I. 2 : URANIUM CRITICAL MASSES (METAL WITH REFLECTOR)

Not included in these estimates is the additional time required to make the necessary physical adjustments to the plant at the beginning of each stage and to convert the 31 % uranium deposited on the product plates during the first stage into a form suitable for charging to the second stage. The latter involves several consecutive unit operations. The product collector plates must first be removed from the irradiation modules and transferred to a dissolver. For a 3000 MTSW/yr plant, up to several hundred plates of dimension 1 meter x 5 cm would be involved, and, because of the high pyrophoricity of the uranium deposits even at room temperature, the operation would have to be carried out in an inert atmosphere. Then, after dissolution, the uranyl nitrate solution might be evaporated, calcined, reduced to UO_2 , fluorinated with HF , and the uranium tetrafluoride reduced to the metal by a metallothermic reduction process.

Each of these unit operations would probably be carried out batchwise, with the last being conducted at high temperature and pressure in a steel 'bomb' lined with an insulating refractory layer, and packed with UF_4 and magnesium powder. The uranium metal "biscuit" produced in the 'bomb' would then be broken out of the liner, pickled, washed and then either formed or vacuum melted and recast into a configuration suitable for charging to the AVLIS plant. Criticality precautions would be necessary at each stage.

The total processing time would depend upon the batch size. For maximum speed, several batches might be processed in parallel. A typical reduction time for a 5 kg batch might be 5 hours, with perhaps a further 5 hours required for calcination, reduction, and hydrofluorination. In all, the total time required from product

plate dissolution to the production of uranium metal ingots suitable for charging to the LIS plant would almost certainly not be less than 24 hours, and might easily be twice as long.

A rough schedule of the entire sequence of activities required to produce enough HEU for one bomb from a 3000 MTSW/yr AVLIS plant operated in a batch recycle mode is shown in Table I.1. The Table shows that even for conservative assumptions, it would take a minimum of 2 weeks to produce enough 87.5 % material for one weapon. In practice, the time required would almost certainly be significantly longer.

It should be noted that no allowance has been made in these estimates for any preparatory research and development, component manufacture, and plant testing which might be necessary before introducing higher-enrichment feed material into the plant; the implicit assumption here is that such activities could be undertaken without giving an unambiguous signal of the intention to proliferate, and that they would be completed before the first such signal, the introduction of 3 % feed material into the plant, was sent. In the view of the JNAI research panel, the effort required to undertake these activities would be substantial.⁴

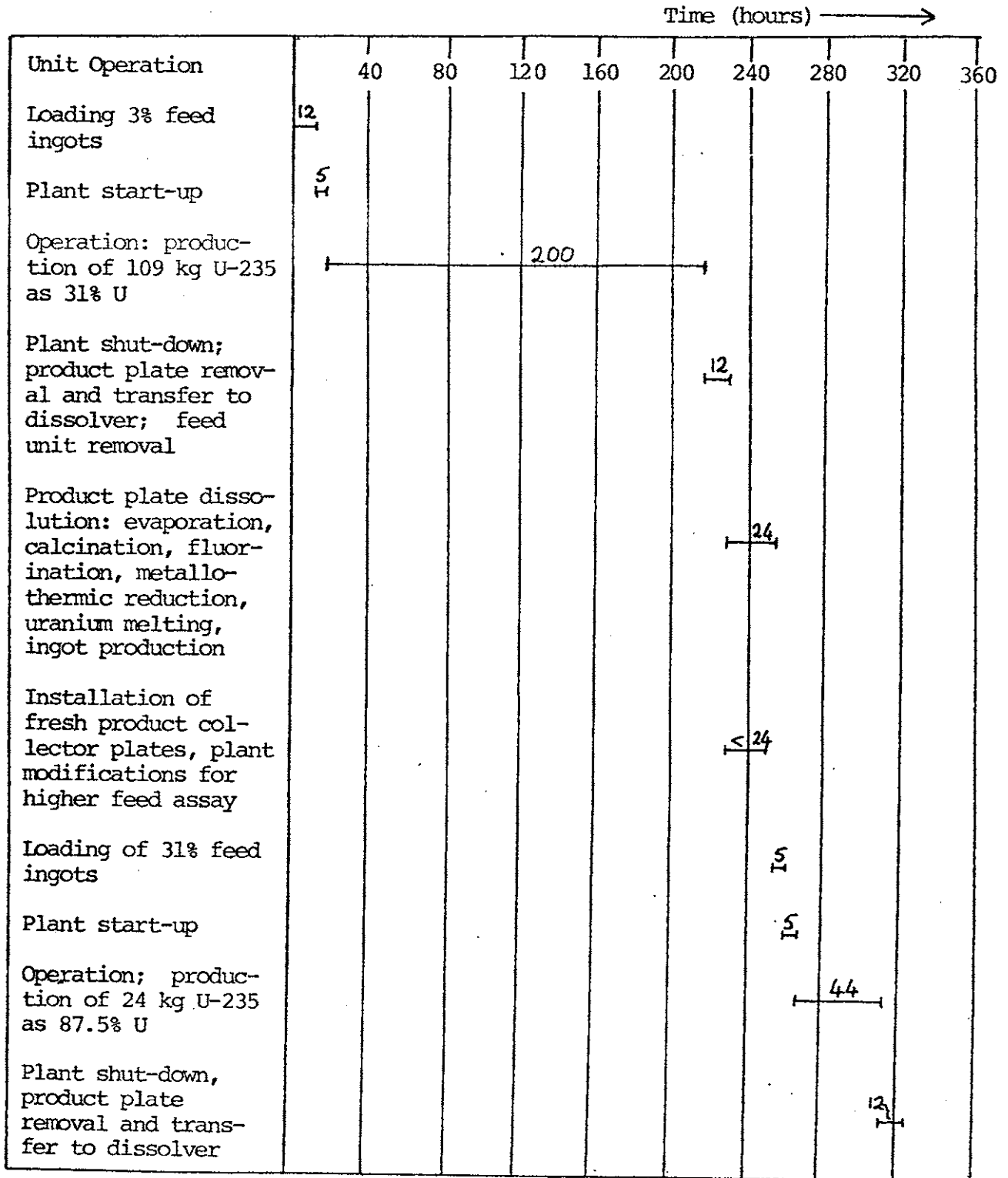
When a similar calculation is made for a 3000 MTSW/yr natural feed plant, for which the separation factor is lower (requiring 3 stages to produce 73.5 % uranium from 3 % feed) but the U-235 throughput is higher, roughly the same minimum time of 2 weeks for the production of enough HEU for one weapon is found.

The "single bomb" scenario is actually highly unlikely once a decision has been taken to dedicate a commercial facility to the production of HEU. Of more practical interest is the rate at which

Table I.1

Operating Schedule for Batch Recycle Production of HEU
Enough for one Bomb in AVLIS Plant

(Basis: 3000 MTSW/yr depleted feed plant capacity)



critical masses can be produced. Considering once again the depleted feed plant, if certain additional conservative assumptions are made (no processing or fabrication losses, 100 % plant availability, etc.) a maximum of 65 weapons could be produced annually.

(ii) MLIS plant

The flowsheet for a 3000 MTSW/yr natural feed ideal MLIS cascade operating under an assumed set of commercial conditions is shown in Fig. I-3. Our purpose is to estimate the minimum time required to produce enough HEU for one nuclear weapon when such a plant is operated in a batch recycle mode.

It is assumed for convenience that the stage separation factor is independent of the stage feed enrichment, and further, that it remains constant over a fairly wide range of stage flowrates. In addition, it is assumed that the cascade is maintained in the ideal, no-mixing condition for each batch. Under these conditions, the number of recycles needed to produce HEU can be determined from the McCabe-Thiele diagram in Fig. I-4; four consecutive cycles are required to produce 85 % uranium from 3 % feed.

Then, if the overall separative work output of the ideal cascade is unaffected by the changes in feed assay, the plant flowsheets for the various cycles are shown in Table I-2. Also shown are the cycle operating times required for the production of enough HEU for one nuclear weapon. A further few hours at the minimum might be required between each cycle to adjust the plant parameters for the new operating conditions and to conduct start-up tests. (If any major plant modifications are required, this period might be much longer.) Thus, a minimum of 24-36 hours might be required to produce enough HEU for a

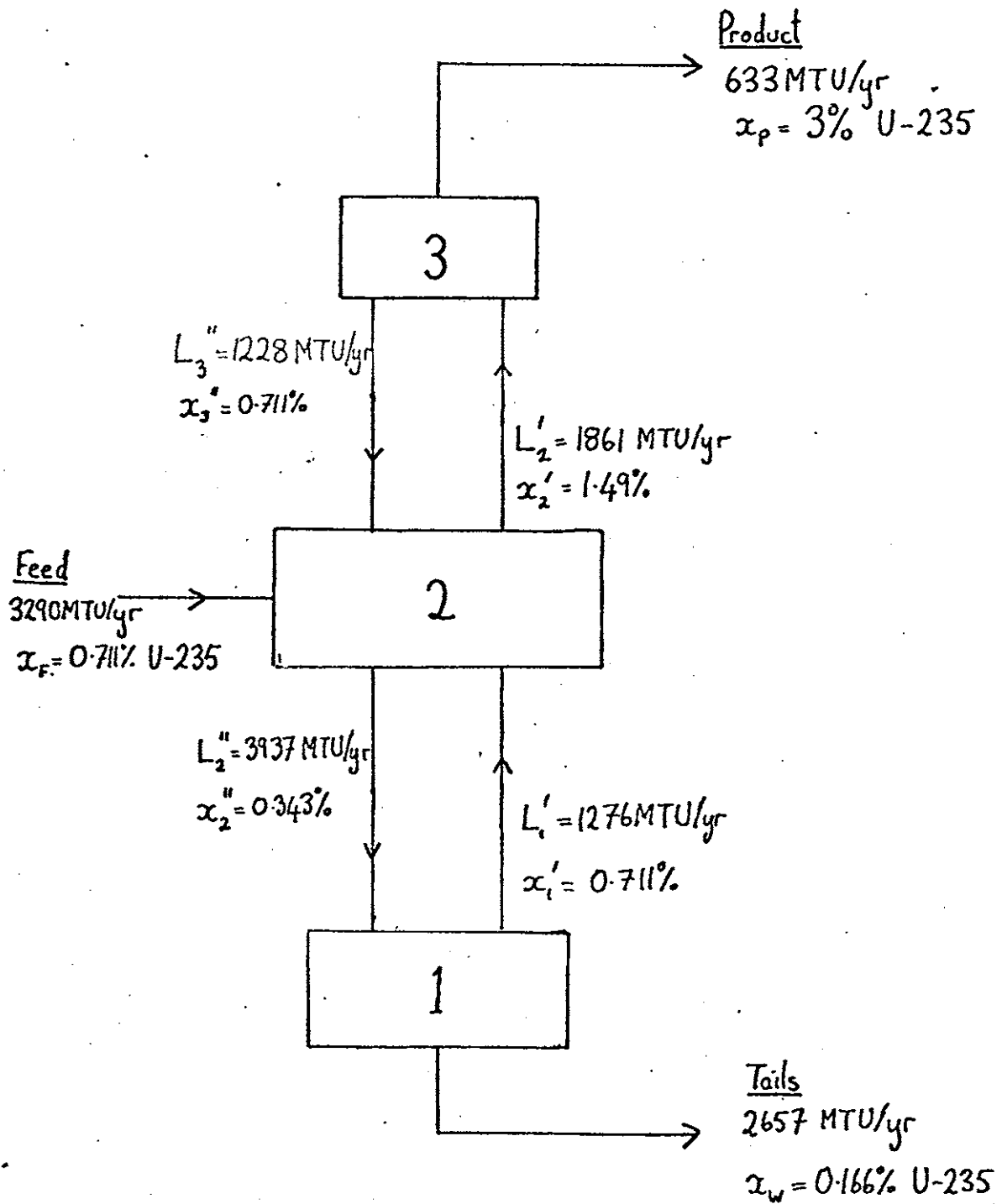


FIG I.3: FLWSHEET FOR 3000 MTW/YR IDEAL MLIS
CASCADE
($\beta = 2.078$)

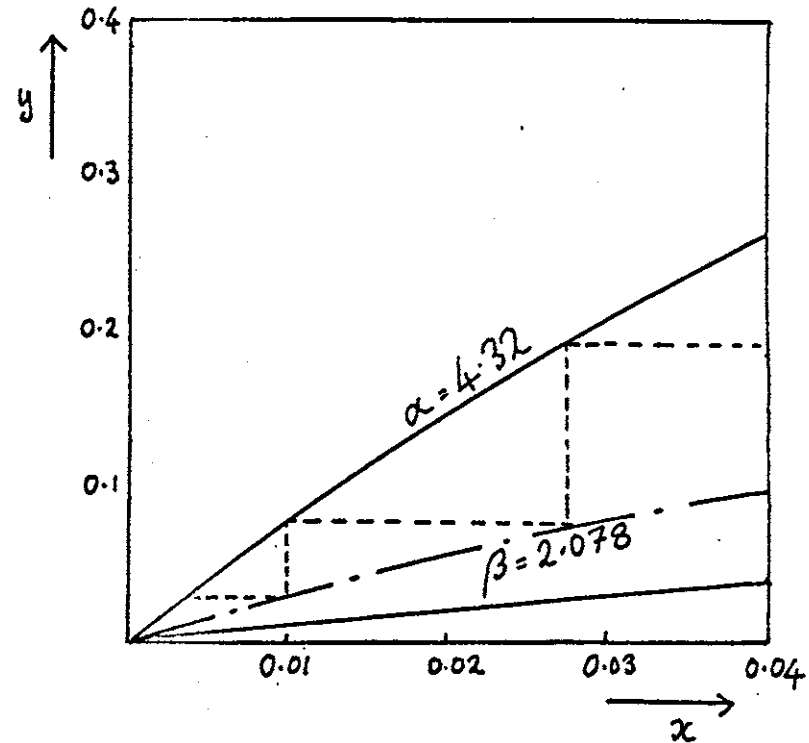
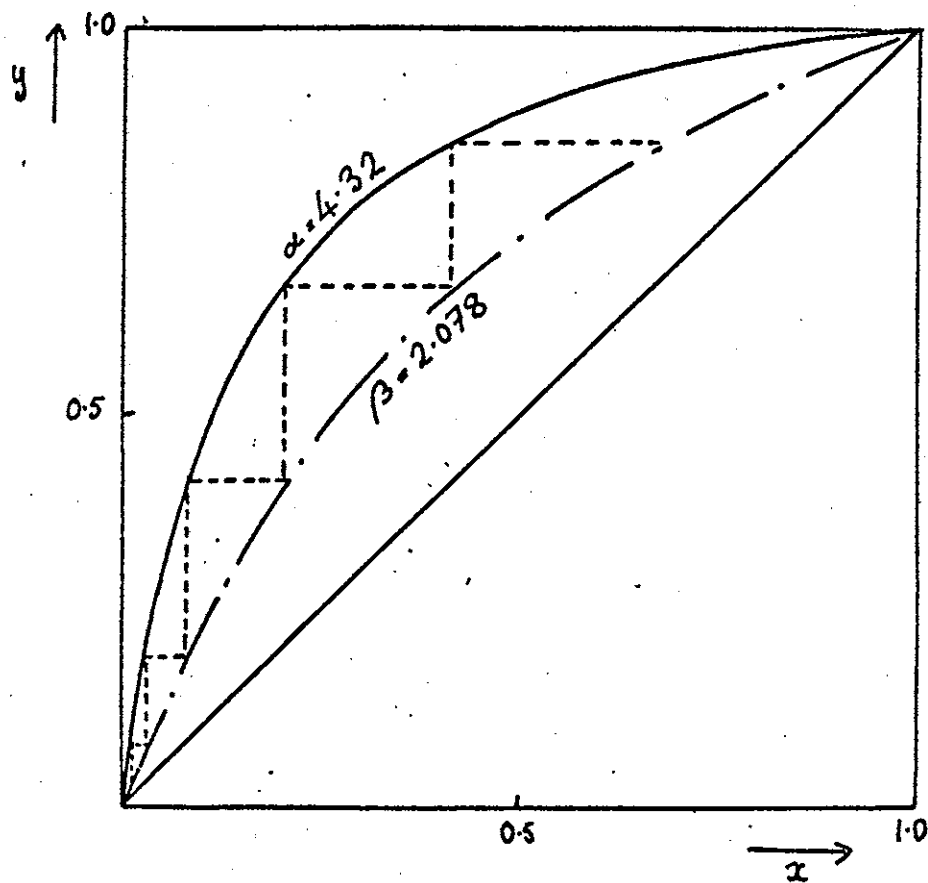


FIG. I.4: MCCABE - THIELE DIAGRAMS FOR MLIS PLANT
 $(\beta = 2.078)$

Table I-2: Material balance flowsheets for 3000 MTSW/yr ideal MLIS
cascade operated in batch recycle mode

(Total separative work output, stage separation factor
 assumed constant)

	Normal Operation	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Feed enrichment, x_f	0.00711	0.03	0.118	0.366	0.714
Product enrichment, x_p	0.03	0.118	0.366	0.714	0.915
Tails enrichment, x_w	0.00166	0.00711	0.03	0.118	0.366
Mass flowrates (MTU/yr):					
Cascade feed	3290	3284	3283	3307	3290
Cascade product	633	678	860	1367	2085
Total feed to stage 1	3940	3890	3700	3200	2480
Total feed to stage 2	5800	5860	5600	5860	5990
Total feed to stage 3	1860	1960	1880	2660	3520
Product required ^{1,2} (kg U)		657	143.1	49.7	26.2
Cycle time (hr)		8.5	1.5	0.32	0.11

Notes:

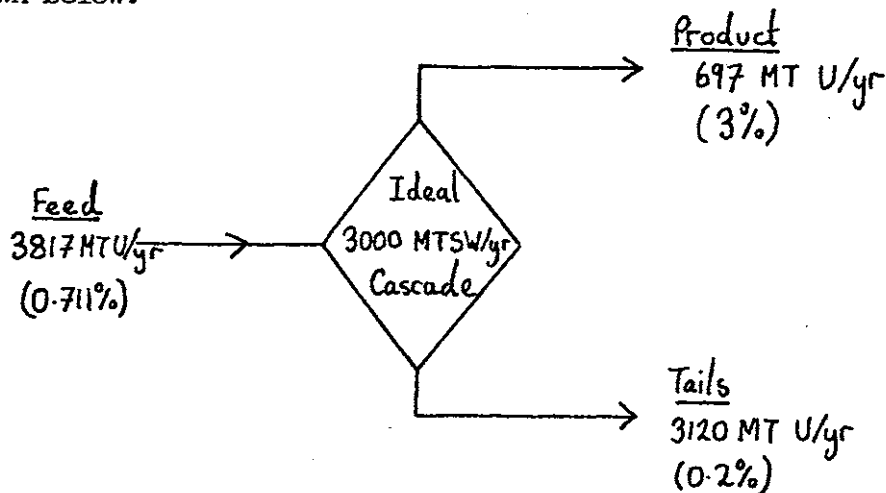
1. Assumes 50 % contingency for losses during processing and weapons fabrication after final cycle, and 20 % processing and start-up contingency for all other cycles.
2. No allowance has been made for start-up plant inventories.

single weapon.

If the plant were operated in the batch recycle mode for a year, this time assuming no inter-cycle processing losses and a plant availability of 100 %, enough HEU for a maximum of about 2000 weapons would be produced.

(iii) Gas centrifuge enrichment plant

The reference plant for this calculation is a 3000 MTSW/yr ideal centrifuge cascade producing 3 % enriched product from natural feed with a tails assay of 0.2 %. The nominal material balance is shown below.



It is assumed that the centrifuge plant is perfectly flexible, that is, it can be rearranged to perform with any combination of feed, product, and tails assays without a loss of overall separative capacity.

If the plant is rearranged so as to eliminate the stripping section, a configuration in which the enriched uranium production rate and the feed requirements are maximized, the performance of the cascade is described by the following equation:⁵

$$\frac{\Delta}{P} = (2x_p - 1) \ln \frac{x_p(1 - x_f)}{x_f(1 - x_p)} + \frac{(x_p - x_f)(1 - 2x_f)}{x_f(1 - x_f)} \quad (1)$$

where Δ is the separative capacity, P the product flowrate, and x_p and x_f are the product and feed assays respectively.

If 87.5 % uranium is to be produced in the cascade, and 3 % material is available for feed, enough HEU for a single weapon (as usual adding a 50 % contingency for processing and fabrication losses) would be produced after only 2.2 hours of equilibrium operation. About 11.5 tons of feed would be required, together with the initial cascade inventory (calculated below). If only natural uranium were available, 8.5 hours of operation would be required. In theory, several thousand critical masses could be produced during the course of a year.

The time required for a centrifuge cascade to reach equilibrium conditions can be estimated from the following approximate expression⁶ for the dynamic behaviour of a close separation cascade:

$$t_p = \frac{8h}{(\alpha - 1)^2} \left[(x_p - 2x_p x_f + x_f) \ln \frac{x_p(1 - x_f)}{x_f(1 - x_p)} - 2 \right] \quad (2)$$

where h is the material holdup time, and α , x_p and x_f are as before.

Benedict and Miller have calculated a holdup time of 44 seconds for a Zippe-type subcritical centrifuge with a separation factor of about 1.15 and a separative capacity of about 3 annual kilograms of separative work.⁷ Such a machine is apparently roughly similar in performance to the first generation Urenco centrifuge. Using these values, the plant equilibrium time would be 15 hours if 3 % feed were available, and about 21 hours for natural feed. Similar times would be expected for larger machines.

The cascade inventory can be estimated from the following exact expression for the total inventory in the enriching section of an ideal close separation cascade:⁸

$$I_E = \frac{8Ph}{(\alpha - 1)^2} (2x_p - 1) \ln \frac{x_p(1 - x_f)}{x_f(1 - x_p)} + \frac{(x_p - x_f)(1 - 2x_p)}{x_f(1 - x_f)^2} \quad (3)$$

where P is the equilibrium product flowrate and the other symbols have their previous meanings. Using the values given above, and for the case of 3 % feed, the cascade inventory would be approximately 1.5 tons of uranium.

Notes to Appendix I

1. Unless otherwise stated, the process information in this section is drawn from: Jersey Nuclear Avco Isotopes, Inc., "Description of JNAI laser isotope separation process," in Laser Isotope Separation: Risks and Benefits, report of the Laser Enrichment Review Panel to JNAI, February 27, 1979, Volume 2, Appendix D.
2. A widely used metallothermic reduction process is based on the work of F.H. Spedding at Iowa State University. For a full description of this method, see: H.A. Wilhelm, Proceedings of the United Nations Conference on the Peaceful Uses of Atomic Energy, United Nations, New York (1956), 8 (162).
3. Processing times for the equivalent unit operations involving a 5 kg batch of plutonium have been given as 5 and 4.5 hours respectively. See: U.S. Congress, Office of Technology Assessment, Nuclear Proliferation and Safeguards, Washington, D.C. (1977), Volume II, Part 1, Appendix V, p. 182.
4. Laser Isotope Separation: Proliferation Risks and Benefits, report of the Laser Enrichment Review Panel, (Chairman, T. Keith Glennan), to Jersey Nuclear Avco Isotopes, Inc., February 27, 1979, p. 29.
5. M. Benedict and T. Pigford, Nuclear Chemical Engineering, New York: McGraw Hill (1957), p. 399.
6. M. Benedict, "Nuclear Chemical Engineering Classnotes," M.I.T. Course 22.76 J, (Fall 1976), eq. 13.203.
7. M. Benedict and M. Miller, "NASAP progress report: September 1, 1977 - January 1, 1978, M.I.T. Energy Laboratory Report, M.I.T. - EL 78-001, February 1978.
8. Benedict, "Classnotes (1976)," op.cit.

CHAPTER 5

INSTITUTIONS, POLICIES AND TECHNOLOGICAL INNOVATION: THE CASE OF LASER
ENRICHMENT

5.1 Introduction

Studies of the relationship between the process of technological innovation* and technology policy usually incline toward one or other of two analytical perspectives. In one, emphasis is placed on the impact of technological developments on policies and institutions and, more broadly, on the political, social, and natural environment. The other focuses on the converse relationship, the effect of pre-existing political and institutional structures on the process of technological innovation.¹ Nau has used the short-hand terms "technical" and "political" to describe these two approaches, reflecting the causal orientation of each.²

While both "technical" and "political" perspectives have figured prominently in retrospective analyses of technological innovations, both general and specific, the "technical" approach has tended to prevail in assessments of new technologies. A widely used definition of technology assessment illustrates this tendency:³

.....a generalized process for the generation of reliable, comprehensive information about the chain of technical, social, economic, environmental, and political consequences of the substantial use of a technology, to enable its effective social management by decision makers.

* Technological innovation is defined here as the process by which an idea or an invention is transformed into a product, process, or service which plays a significant role in the economy.

The emphasis here is on the political and institutional reaction to the effects of a new technology, and on generating the information on which this reaction should properly be based.

But in practice the outcome of technological innovation depends as much on the influence of the political and institutional environment in which the technology is developed and deployed as it does on the intrinsic nature of the technology itself. To be sure, technological developments possess their own inner logic, which determines, for example, what is or is not physically possible, or which of several alternatives is thermodynamically more efficient. . . But the technology is not developed in isolation.* Harvey Brooks, in discussing the parallel development of technologies and their "social supporting systems," has observed that "[s]pecific technological opportunities create interests which influence the behaviour and evolution of the supporting mechanisms, but these mechanisms in turn strongly influence which technological options are selected by society for further development and proliferation."⁴

Thus, if the purpose of technology assessment is to anticipate the outcome of technological innovation, and if the purpose of technology policy formulation based on such assessments is to establish goals for the technology and to devise strategies to attain those goals, then the pre-existing political and institutional environment must be an important element of the assessment, and correspondingly an important target of policy. Technology assessment should properly consist of a synthesis of the technical and political perspectives

* To argue that it would be to fall, inter alia, into all of the potential pitfalls of technological determinism associated with the proliferation resistance assessment methodologies discussed at the beginning of Chapter 4.

identified by Nau.

A very simple conceptual model for such an approach is shown in Figure 5.1.

In the two preceding chapters, we have analysed the potential implications of laser enrichment technology for current nuclear energy and international security policies. In this Chapter, the goal is to analyse the development of LIS from a "political" perspective (as defined by Nau), in which the emphasis will be on the political and institutional antecedents of the innovation, and on how current political and institutional structures might influence its future direction. Thus, Section 5.2 presents a brief review of the highlights of U.S. nuclear policies and institutional developments during the 1970s; the enrichment sector, which has provided the immediate context for LIS development, is given precedence in the review. In Section 5.3, the development of LIS over the last decade is analysed to determine the impact, if any, of these broader political and institutional trends. Chapter 6 examines the implications of the existing political and institutional framework for the future development of LIS.

5.2 Institutional and Political Overview

For two decades following the Atoms for Peace speech of President Eisenhower in December 1953 and the subsequent passage of the Atomic Energy Act of 1954, the United States Government pursued a nuclear energy strategy whose four principal elements remained essentially unchanged:

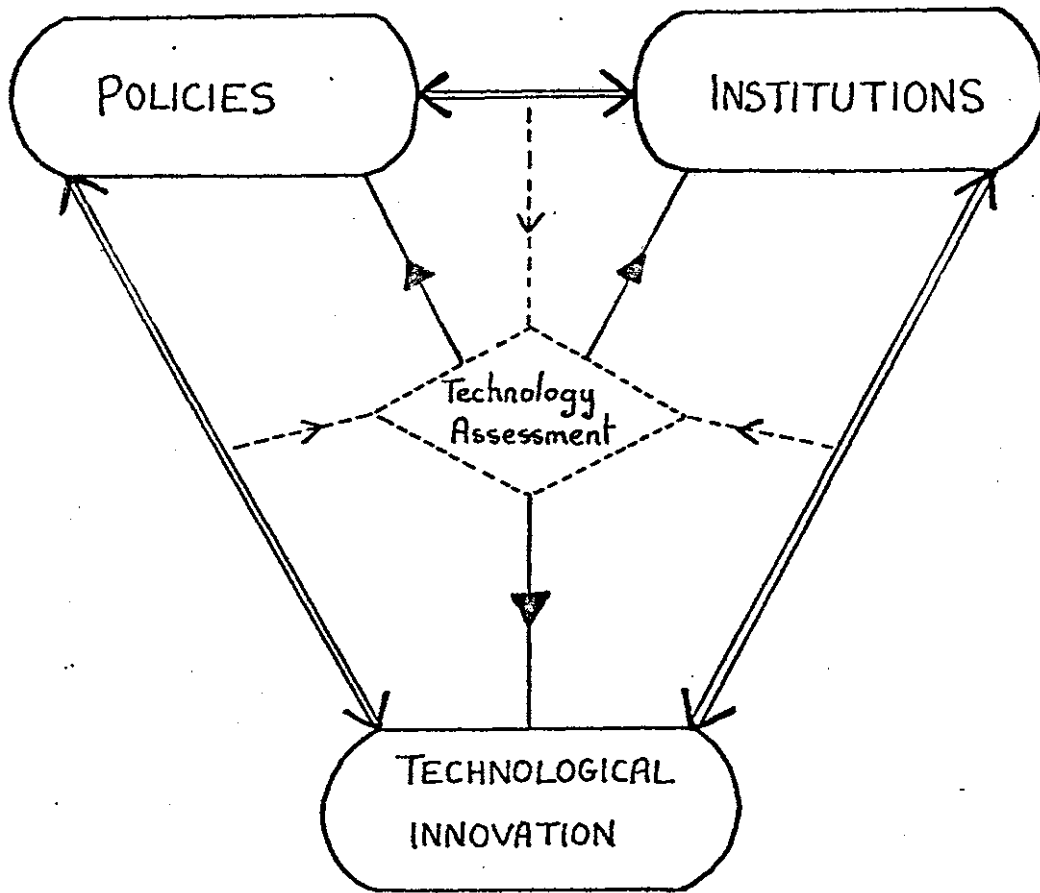


FIG. 5.1: SIMPLE MODEL OF TECHNOLOGY ASSESSMENT

- the promotion of central station nuclear power;
- the promotion of U.S. private enterprise in the nuclear sector, both domestically and overseas;
- less explicitly, but no less importantly, the maintenance of U.S. superiority in all aspects of nuclear technology;
- the prevention of nuclear weapons proliferation (an objective which, of course, extended beyond the nuclear energy sector into the broader realm of U.S. foreign policy).

During this period, several policies played a vital role in the achievement of these objectives. Unquestionably the most important was the massive civilian research and development program funded by the Federal government, the results of which generally were promptly made available to the private sector. In addition, the government's long-term guarantees of low-cost enrichment supplies, its willingness to accept responsibility for the storage of nuclear wastes, and the insurance indemnity provided to the industry by the Price-Anderson Act all were major ingredients of the overall strategy and contributors to its success.

By the beginning of the 1970s, with the domestic utility industry availing itself of the nuclear option with great vigour, and the imminent prospect of rapid growth in the export market for U.S. nuclear technology, political support for the traditional objectives of U.S. nuclear policy was firm. Yet, as the decade has passed, the strength of the government's commitment to the first three goals has gradually declined. Its promotion of nuclear power is no longer so enthusiastic. The two traditional pillars of support, the Joint Committee on Atomic Energy (JCAE) in the Congress and the Atomic Energy Commission in the

Executive branch, have both disappeared. In the Congress, the centralized authority of the JCAE has been divided among several competing Committees, some of which have proved to be considerably less sympathetic towards the nuclear cause than their powerful predecessor. The old AEC was transformed into the Energy Research and Development Administration, which was subsequently incorporated into the much larger Department of Energy, where nuclear interests and issues must compete with many other claimants for attention and budgetary support.

At the same time, government support of the private nuclear industry has ebbed. The long time champion of the industry in Congress, the JCAE, has not been replaced, and, with the formation of the Nuclear Regulatory Commission (NRC), a more explicitly adversary relationship than existed before has developed between the industry and at least one part of the government. More generally, there has been an increasing tendency within certain sections of the government to seek to establish a greater distance between government and industry in the nuclear field.

To be sure, some measure of detachment was to be expected in any case, as private industry matured and the nuclear sector more closely approached the commercial norm.⁵ Also, doubts about the nature of the relationship between government and industry by no means became universal during this period, and there remains a strong residue of political support for nuclear energy and for the nuclear industry within the government. Nevertheless, over the past several years there has been a gradual change in the government's posture towards the industry: the guardian angels have given ground to the watchdogs.

These changes at the governmental level have occurred against a background of mounting public concern over the health and safety risks associated with nuclear power facilities. During the same period, the environmental movement has emerged as a significant political force; and in the nuclear field, as in others, intervenors have mounted increasingly effective court challenges against the nuclear licensing process. More generally, opposition to nuclear power has come to occupy a central position in the ideological and political platforms of groups seeking to respond to a growing sense of disillusionment and frustration with the societal implications of large-scale institutions and technologies.

The third major development during the 1970s has been the re-

appraisal of the principles of international cooperation in the development of the peaceful uses of nuclear energy laid down a quarter of a century ago in the Atoms for Peace program. After a lengthy period during which international security objectives and the goal of furthering the overseas interests of the American nuclear industry were regarded as generally compatible and even mutually supportive, growing concern over the relationship between nuclear energy development and the spread of nuclear weapons has led to the imposition of tighter nonproliferation controls on U.S. exports of nuclear materials, equipment, and technology. Moreover, the increasing importance of security considerations in U.S. nuclear strategy has had major domestic consequences. The decisions taken by the Ford and Carter Administrations to defer nuclear fuel reprocessing and the Carter Administration's efforts to 'restructure' the fast breeder reactor program were each strongly motivated by a desire to avoid the potentially destabilizing consequences of the widespread international use of plutonium as a commercial fuel. Predictably, the American nuclear industry has reacted generally unfavourably, arguing, inter alia, that its commercial opportunities have become intolerably circumscribed as a result, and that what is perceived as the sacrifice of American nuclear technological superiority to the goal of nonproliferation is a misguided and self-defeating strategy.

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An analysis of the causes of these various trends is beyond the scope of the present work. Nevertheless, knowledge of these broader developments is essential to an understanding of the political and institutional evolution of the enrichment sector during

the last decade.

Enrichment

The importance of enrichment supplies in the government's overall strategy for providing a hospitable environment for domestic nuclear power growth has already been noted. And in Chapter 4, the role of enrichment in the achievement of the international nuclear policy objectives of the U.S. was discussed in some depth. These two functions lay at the center of U.S. enrichment policy from the beginning of the nuclear power era. The preservation of U.S. technological superiority in enrichment, in addition to being desirable in its own right, was of course necessary for both sets of objectives.

Towards the end of the 1960s, shortly before the initiation of LIS research in the U.S., several important new issues were added to the enrichment policy agenda.

First, commercial demand for enrichment services was growing rapidly, and would shortly exceed the capacity of the U.S. gaseous diffusion complex to meet it. A decision to construct a new plant would soon have to be made. Second, advances in ultracentrifuge technology were bringing the gas centrifuge process to within competitive range of the proven but highly capital and energy intensive gaseous diffusion technology.

Meanwhile, the U.S. enrichment supply monopoly had begun to erode. As noted in Chapter 4, by 1970 the tripartite Urenco consortium had embarked on its commercial centrifuge project, and the Soviet Union had entered the international enrichment market. Shortly thereafter, France and its partners in the Eurodif group decided to construct a large commercial gaseous diffusion plant.

Finally, a new policy goal for the U.S. enrichment industry was

emerging: the transfer of ownership from the government to the private sector. The chief legal obstacle to private ownership of enrichment plants had actually been removed several years earlier, with the passage of the Private Ownership of Special Nuclear Materials Act of 1964. It was not until the Nixon Administration took office in 1969, however, that enrichment "privatization" was given high priority as a policy goal. By this time, enrichment was the only stage of the light water reactor fuel cycle to remain under government ownership. (Long-term commercial nuclear waste storage facilities would also be government-owned, but none existed at the time.)

The government's privatization strategy included programs to provide private industry with access to classified AEC gaseous diffusion and gas centrifuge technology; in addition, the Commission moved to put its own enrichment operations on a more "business-like" footing, in order to provide market conditions more conducive to private entry. Despite these and other efforts, the strategy was not a success. The focus of political support for privatization was quite narrow. In the government, the initiative came mostly from the White House and the Office of Management and Budget. The JCAE and the AEC were less enthusiastic, as were the utilities and the financial community in the private sector. Faced with a lack of support from the latter, prospective private enrichers, whose own ranks were beginning to be depleted, turned to the government to provide the investment guarantees which they felt were a necessary pre-condition for entry. In legislation submitted to Congress in 1975, the Ford Administration, which had inherited the privatization policy of its predecessor, went a long way towards meeting the demands of the enrichers. Congress failed to

enact the proposed Nuclear Fuel Assurance Act (NFAA), however, and instead instructed the Administration to take responsibility for constructing the next increment of enrichment capacity. A few months later, in April 1977, President Carter announced his choice of centrifuge technology for the next plant.

The main source of Congressional opposition to the proposed Act stemmed not so much from objections to the principle of private ownership, but more to the terms of entry that private industry was demanding. It was felt, in particular, that the government would be assuming an unacceptably high proportion of the commercial risks associated with new enrichment ventures.

Although the privatization strategy was a failure, the attempts to implement it during the first half of the decade proved to have profound consequences for U.S. nuclear policies of the period and beyond. First, the privatization efforts of the government and the lack of enthusiasm of the private sector created great uncertainty in the enrichment sector, where efforts to preserve predictability and continuity of the terms and conditions of supply had previously been a feature of the U.S. policy. Indeed, for a period of over four years, it was not known who would build the next increment of enrichment capacity, when, and with what technology.

Furthermore, the objective of privatization and the related one of preserving U.S. technological and commercial superiority in the enrichment market proved to be decisive obstacles in the way of parallel efforts by the U.S. government in the early 1970s to engage other nations in cooperative multinational commercial enrichment ventures. A key goal of these latter efforts was to avoid what were

regarded as the adverse consequences for international security of the spread of independent national enrichment plants. But the reluctance of the AEC and the Joint Committee to "give away" U.S. technology and markets to potential foreign competitors was a decisive factor in the failure of the multilateral initiatives. Whether, even without such reluctance, these efforts would have been successful in stemming what in retrospect appears to have been an inevitable spread of enrichment capabilities overseas (see Chapter 4) is less important than that the transparency of U.S. commercial objectives created a legacy of distrust among several industrialized nations, to whom continued dependence on U.S. enrichment supplies appeared even less attractive than before. 14

An even more serious cause of international concern over the reliability of U.S. enrichment supplies arose directly from the AEC's policy of shifting some of the commercial "risks" of their own enrichment operations to the customer, in order to create conditions conducive to private entry.* The new contracts introduced by the AEC in 1973 were unattractive to domestic and foreign customers alike, and the impact was aggravated when, in significant part because of these new arrangements, the AEC was obliged to terminate contracting in the following year** and to reassign some existing customers, to whom firm supply commitments had already been made, to "conditional" status. 15

It was against this background of international uncertainty over U.S. policies in the enrichment sector that the Carter Administration

* In fact, the AEC's own risks were low, since by that time the gaseous diffusion plants had been largely amortized under defense programs; enrichment costs were thus almost entirely variable costs, which could be tailored to actual demand.

** It was not until 1978 that the order books were officially reopened.

moved in 1977 to establish nonproliferation as a principal goal of U.S. foreign policy. Ironically, yet inevitably, enrichment would play a central role in the new nonproliferation policy. If the Administration was to be successful in dissuading other countries from using plutonium, a necessary condition would be the restoration of confidence in the reliability of U.S. supplies of enrichment services. At the same time, the Administration and its supporters in Congress sought to apply new political conditions to enrichment exports in an attempt to increase U.S. nonproliferation leverage over the nuclear power programs of foreign nations. The outcome of these potentially contradictory policies remains to be seen.

In sum, the first decade of LIS development has been marked by several important developments in the enrichment industry as a whole:

- (i) Politically, the emphasis on privatization and the preservation of U.S. commercial superiority of the Nixon years has given way to a new focus on nonproliferation objectives.
- (ii) Institutionally, efforts to transfer enrichment into the private sector have faded; the government has retained ownership of the existing plants and has assumed responsibility for building the next one.
- (iii) Technologically, the gas centrifuge process has replaced gaseous diffusion as the technology of choice for commercial plants.
- (iv) Economically, the U.S. enrichment supply monopoly has been broken. New enrichers have entered the market. Over the same period, expectations of demand for enrichment have fallen dramatically.

Finally, throughout much of this period, U.S. enrichment policies have been characterized by a lack of clear direction. As a result, uncertainty has been propagated throughout the nuclear power industry, especially overseas.

5.3 The Impact on U.S. LIS Programs

What, if anything, was the effect of these developments on the direction of LIS research and development programs in the U.S.? We examine three issues in particular: the relative roles of the public and private sectors in LIS development, the evolution of the government's classification and security policies in this area, and the relationships between laser enrichment and gas centrifuge technologies.

Public versus private sector development

A notable feature of the current LIS situation is the parallel development of what appear to be fundamentally similar processes by the Exxon Nuclear-Avco venture in the private sector and by Lawrence Livermore Laboratory, under contract to the government.*

The JNAI program was apparently the first to engage in substantial experimental investigation. The current AVLIS laser enrichment process grew out of a patent filed in 1970 by R.H. Levy and G.S. Janes of the
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Avco Everett Research Laboratory. The patent was issued in late 1973, but already by July 1971 experiments conducted at Avco under the sponsor-

* MLIS development is being undertaken by Los Alamos Scientific Laboratory for the government; a privately-funded MLIS program is underway at Exxon Research and Engineering Labs, New Jersey, but the extent to which this effort is directed at commercial applications is not clear. The plasma separation process is being developed by TRW under contract to DOE.

ship of Exxon Nuclear Company (then Jersey Nuclear) had established scientific proof of principle of the concept. Shortly thereafter, in early 1972, Avco and Exxon Nuclear formed JNAI to develop the process further.

Federally-funded LIS research and development got off to a slightly later start. Indeed, at about the time that the first experiments at Avco were demonstrating scientific feasibility, a panel of experts chaired by Manson Benedict, which had been convened by the AEC to review alternative isotope separation technologies, concluded that, although worthy of limited investigation, photoexcitation processes showed little promise from a commercial standpoint.¹⁷ The panel essentially ruled out atomic processes because of the low volatility of metallic uranium, and noted that no uranium compound had been discovered with a suitable isotopic shift. Significantly, there was no mention in the panel's report of the possibility that lasers might be used as photon sources.

Even before this report was released in 1972, however, a group at Los Alamos had already begun work on laser enrichment, and, in 1973, another program was initiated at Livermore. Both of these efforts were outgrowths of laser fusion research and development programs which had been established at the two laboratories some time earlier.¹⁸

The JNAI venture was launched at the height of the Nixon Administration's drive for privatization, and while commercialization of the new technology was a very remote possibility at that early stage, it seems likely that the positive political developments of the period were considered in the decision to proceed. The new policy would appear to have been particularly relevant for JNAI since, only a few years earlier

(but before the privatization initiative), the Atomic Energy Commission had determined that it was not in the national interest that privately supported work on centrifuge enrichment technology be continued, and had accordingly terminated all such work.¹⁹

For its part, the Livermore program has so far escaped major criticism of its potential for duplicating work underway in the private sector, although in 1976 the JCAE took the opportunity to remind ERDA of the existence of the JNAI project and to note that any such duplication "would not be a justifiable expense of government money."²⁰ In response to the JCAE's comments, ERDA appointed a new panel of experts, this time under the chairmanship of P. Vanstrum, to investigate the question of duplication. The Vanstrum panel's report was classified, but reportedly concluded that although there was some overlap between the two programs, there were also significant differences in both technology and objectives.* The panel's finding apparently convinced the interested sections of the government (including the Office of Management and Budget, whose pro-privatization stance earlier in the decade might have been expected to evolve into an 'anti-duplication' position) because the Livermore budget continued to climb both in absolute terms and relative to the IASL share of the total AIS budget after 1977 (see Table 5.1).

The question of duplication is only one aspect of the broader issue of private ownership of enrichment facilities, whose resolution is still far from clear. This issue is examined in more detail in Chapter 6, section 3.

* A discussion of some of the technical differences can be found in Chapter 2.

Classification and security

The competition between commercial and security goals which was a general feature of enrichment politics throughout the first half of the 1970s proved to have quite far reaching implications for LIS development during that period.

The first issue to be confronted was that of classification. AEC policy on this matter had been clearly laid down in 1967, when the Commission announced that all research and development on new uranium enrichment methods would be declassified until the method showed reasonable potential for separation of "practical" quantities of U-235.²¹

Los Alamos filed its first patent application on MLIS in July 1972.²² In it, the Los Alamos group proposed for the first time to cool UF₆ gas by adiabatic expansion through a supersonic nozzle as a means of overcoming the 'hot band' problem, which had been recognized in the literature as the chief obstacle to isotopically selective infrared excitation of UF₆ molecules.²³ The Los Alamos scheme was clearly an important breakthrough, but at the time that the patent application was filed, the AEC classification staff had not yet determined whether or not it met the criterion for classification; as an interim measure, the application was filed as Confidential Restricted Data. Shortly thereafter, the AEC determined that the disclosures in the patent contained no Restricted Data, and the application was declassified.²⁴ It only remained unclassified for about six weeks, however. (During this period, no publications on the subject appeared in the open literature.) Then, following a meeting between Los Alamos and Oak Ridge technical staff and AEC classification officers, the Division of Classification reversed its earlier decision and upgraded the patent application to Secret Restricted Data.²⁵ The new decision placed important constraints on the patent prospects for the Los Alamos process. In

particular, U.S. law in general prohibits foreign filing of classified patent applications.

Meanwhile, the original (1970) JNAI AVLIS patent application had not been classified, and finally issued in November 1973.* Despite the unclassified nature of its work, few details of the JNAI program were disclosed during this period, reflecting a strict corporate policy of protection of proprietary data.

In contrast with both the JNAI and LASL programs, disclosure of technical results at Livermore in the early 1970s occurred promptly and in some detail. Under the leadership of John L. Emmett, who had arrived from the Naval Research Laboratory in mid-1972, the Livermore Laser Program took the lead in declassification efforts in both the laser fusion and LIS fields. The fact that the JNAI AVLIS work had not been classified probably helped efforts to relax the classification restrictions on the Livermore LIS program. Another factor of probable significance was the strong opposition to secrecy in these fields voiced by Edward Teller, associate director-at-large at Livermore.
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more.

It was also doubtless no coincidence, and probably a reflection of Emmett's personal style, that important releases of information were made on the eve of major conferences. Thus, permission to describe the newly successful spectroscopic demonstration of uranium enrichment via selective photoionization of uranium vapour was obtained just before the eighth biennial International Quantum Electronics Conference of June 1974, where the results that were presented aroused considerable

* JNAI has since filed for and been granted a substantial number of patents both in the U.S. and abroad; many others are pending and the company is generally considered to have established a strong international patent position in the AVLIS field. Reportedly only a small fraction of its patent applications have been classified to date.

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excitement. Although it was known that the JNAI group had obtained similar results some time earlier, it was not until 1976 that a detailed report of these experiments was released, and the 1974 Livermore paper was the first technical account of laser enrichment research in the U.S. to be made public.

The Livermore report also added spice to the traditional rivalry between Livermore and Los Alamos, which had already become a feature of the laser fusion field. The Los Alamos laser enrichment program was labouring under a more restrictive set of classification guidelines, and LASL researchers were obliged to confine their scientific publications to studies of boron and sulfur molecules, and other less interesting materials.

Some resentment was reportedly voiced at Los Alamos following the Livermore announcement, not only because of the less stringent Livermore classification policy which had allowed such a disclosure to take place, but also because it was felt that the newer Livermore group had failed to indicate the true extent of the LASL contribution in the area. In fact, by this time workers at Los Alamos had applied for several patents in laser enrichment; all had been classified.

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The AEC's classification policy towards Los Alamos had already begun to be reassessed in Washington. Some concern was expressed over the effectiveness of classification and its impact on the U.S. government's patent position. Then, in the fall of 1973, LASL was requested by AEC-headquarters to obtain complete patent coverage of all aspects of the LIS program at LASL.

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The request presented several difficulties. Among them was the question of filing patent applications overseas. The Commission had

noted the importance of foreign patent coverage, as had the Joint Committee on Atomic Energy, two leading members of which had stressed the point in a letter to Chairman Dixy Lee Ray of the AEC in early 1974.³⁰ Yet unless the existing LASL patent applications were somehow declassified, foreign filing was impossible. LASL technical staff strongly doubted the feasibility of 'sanitizing' the existing applications so as to be able to file unclassified versions overseas under the current classification guidelines.³¹ Given the time constraints involved, only one practical alternative remained: declassify the basic concepts of the LASL LIS process.

The dilemma was clear. Would U.S. government interests best be served by declassification and strong domestic and foreign patent protection, or by continued classification?

By March 1974, the AEC's Division of Classification (DOC) was ready to conclude that continued classification would not be effective for long.³² It noted that the key concept of adiabatic cooling involved well-known, basic physics, and that the remaining concepts of selective laser excitation and photodissociation were already in the public domain. In view of the worldwide interest in LIS, it would thus only be a matter of time before independent discoveries of the LASL process occurred. Indeed, there were already several indications that other groups were moving in this direction.³³ Based on these considerations and what it recognized as the importance of protecting the U.S. patent position, DOC recommended that certain aspects of the LASL LIS process be declassified, and that patent applications should then promptly be filed both domestically and abroad.

The Los Alamos staff certainly agreed with this view, and,

judging by the strength of its recommendation to Chairman Ray to seek maximum patent protection, so did the Joint Committee. The latter had, of course, already made its views on the importance of protecting U.S. technological and commercial superiority in enrichment quite clear during the 1971 debate on the U.S. multilateralization initiative. While "giveaways" of government technology were not at issue on this occasion, continuation of the existing classification policy would threaten the U.S. technological lead in this potentially highly attractive new area.

The DOC position was by no means unanimously supported, however; not even within the AEC. The Division of Military Applications, for one, had reservations regarding the proposed declassification.³⁴ Apparently so, too, did the State Department. A major concern was the effect of declassification on the risk of proliferation. After all, the IASL staff itself had indicated that once the adiabatic cooling technique became generally known, it would not be long before numerous foreign countries would achieve a laser enrichment capability.³⁵ The position taken by the Department of Defense is not known for certain. It had been informed of developments at IASL as early as November, 1972, however,³⁶ and it maintained direct influence over the resolution of issues such as the declassification of the LASL LIS process through its Military Liason Committee to the AEC, before which all proposals of a militarily significant nature had to pass. The Pentagon was generally concerned about proliferation, and had demonstrated both its concern and the strength of its influence in 1971, when it adopted a hard-line (and ultimately successful) stance against the proposals to share U.S. enrichment technology with other nations.³⁷ It thus

seems reasonable to suppose that the Pentagon at the very least did not view the prospect of MLIS declassification and the subsequent filing of patent applications overseas with enthusiasm.

The debate on declassification and patent strategy continued throughout the summer and on into the fall. Finally, in late 1974, the Commission decided not to declassify.³⁸

The Commission's decision can be interpreted in various ways. In general terms, it reflected the gradual shift in priority from protectionist to non-proliferation objectives that characterized U.S. nuclear policy during the 1970s. In technological terms, the decision would necessarily seem to have been based on a judgement that continued classification would be a significant obstacle to the further spread of the IASL concept.

Finally, there had been important changes in the bureaucratic lineup since the multilateralization debate three years before. For the technological 'protectionists', the Joint Committee's position remained generally unchanged. But the AEC was no longer such an effective advocate of the need to preserve U.S. technological and commercial superiority. The powerful Production Division, which was responsible for the gaseous diffusion plants and technology and which had played a central role in the protectionists' success in 1971, was less closely involved in the development of the new laser technologies, and did not play such a prominent part in the later debate. In contrast, the Division of Military Applications, which provided most of the funding for the still predominantly weapon-oriented Los Alamos Laboratory, was a more active participant than before; and, predictably, its views of the issue were closer to those of the Pentagon.

In addition, the State Department, which in 1971 had been ineffective in espousing the need for technology sharing and multi-

lateralization as a means of reducing the proliferation risks of independent enrichment facilities, had in the meantime, under the active leadership of Secretary Kissinger, become a somewhat more potent nonproliferation advocate, in this case arguing against declassification. Lastly, the Pentagon (through the Military Liaison Committee) had reversed its bureaucratic links while continuing to be motivated by its concern over proliferation. In 1971 it had sided with the Joint Committee and elements of the AEC against the enrichment technology transfer proposals of the State Department, but in 1974 it was apparently arguing with the State Department for continued classification and against the Joint Committee and parts of the AEC, for whom complete patent coverage was the more important goal.

As events turned out, those who had argued that classification of the basic concepts of the LASL 'mainline' process would be ineffective were rapidly shown to be right. Indeed, just as the Commission was reaching its decision not to declassify in late 1974, two MLIS patent applications were filed in West Germany which both featured the key concept of adiabatic expansion of UF_6 ; one of them, due to Jetter et al, disclosed and claimed subject matter essentially identical to the earlier LASL 'mainline' process patent applications.³⁹ (The original LASL patent of 1972 which described the basic concepts of the mainline process had been updated in August 1973.)⁴⁰

In the absence of competition from the LASL applications, which would have had chronological priority had they been filed overseas, the German interests succeeded in gaining a strong international patent position in MLIS.* Indeed, to the consternation of the LASL staff, the Jetter patent even

* While under U.S. law patent rights are established on the basis of who invented the device or process first, in other countries the criterion is who files first. The latter criterion is followed in international patency. Because of the logistical impossibility of simultaneous filing in many countries, an International Patent Convention exists under which

issued into the open literature in the U.S. in May 1977,⁴¹ while classification restrictions had prevented the almost identical IASL patent from issuing, despite its clear priority over Jetter in the U.S. There were reportedly other examples of IASL classified patent applications being rejected by the Patent Office at the same time that unclassified private applications covering very similar material were issuing.⁴² The August 1973 IASL application was subsequently declassified, and Jetter et al conceded priority to it in the U.S. in February 1979.⁴³ The fate of the other IASL patent applications is not clear.

Meanwhile, the foreign fortunes of the IASL patent applications were proving to be even gloomier. A patent specially tailored for the purposes of foreign filing had been filed in the U.S. in late 1975, and was declassified shortly thereafter.⁴⁴ (In retrospect, the principal difference between the declassified patent and earlier IASL patents which remained classified - but which have since also been declassified - was that the former omitted any reference to the potential application of LIS techniques to plutonium isotope separation. Such

(contd.)

a patent application filed in a signatory country may be filed at any time during the next twelve months in other signatory countries and still be assigned the original filing date for the purpose of establishing priority. Thus, as a hypothetical example, had a IASL patent application covering the same material as the Jetter patent been filed domestically in April 1974, and then filed in Germany in March 1975, months after the Jetter patent application was filed there (actually in December 1974) it could still receive priority in Germany because of its earlier U.S. filing date. If foreign filing does not take place within 12 months, however, the original 'convention date' is lost. A result of the AEC's classification policy was that convention dates for several IASL patents were lost, because filing overseas within the stipulated twelve month period was prevented.

a 'sanitization' would surely not have exceeded the ingenuity of the IASL staff two years earlier, when the latter had argued that foreign filing of unclassified patents under the classification guidelines of the day would probably be impossible. Thus the AEC's guidelines had apparently become less restrictive in the meantime.)

The declassified application was then filed in several countries, including France, the U.K., Canada, West Germany and Israel, and is reportedly now being generally rejected. Its patent convention date fell, of course, about a year after those of the two German patents filed in West Germany in late 1974.

Clearly, therefore, the classification policies followed by the U.S. government failed in their objective of preventing the spread of key concepts associated with the IASL mainline MLIS process. At the same time, implementation of these policies cost the U.S. a strong international patent position in the MLIS field. Indeed, there can be little doubt that the inability to acquire foreign patents has left the U.S. in a potentially very vulnerable position if the favorable commercial prospects for MLIS are ultimately realized.

The episode certainly provided a graphic illustration of the widely held view that fundamental scientific principles, and concepts based on such principles, cannot be effectively contained by secrecy measures. However, there is nothing in these events to support the broader contention that classification in general will always be similarly ineffective. What was not generally recognized at the time was that an understanding of the basic concepts required for a successful MLIS process was just the first step in a long and difficult technological task. The subsequent steps (for example, the development of

suitable lasers) require much in addition to basic principles of physics. Technological expertise, sophisticated equipment, prolonged and complex experimentation: all are essential. In this context, classification may play a more effective role. Of course, in all such situations, only a limited amount of time can be gained by the imposition of secrecy. But the delay that can be achieved varies and the experience with MLIS in the mid-1970s, although commercially costly, should not be regarded as a general indictment of classification policies in this field.

The Department of Energy certainly did not interpret it in this way. By about 1976, the relatively open atmosphere which had characterized the earliest years of the Livermore LIS program had given way to a more restrictive climate. To what extent this trend was a reflection of the growing importance attached to security considerations in the government is not clear. One factor which certainly contributed was the well-established DOE policy of tightening classification controls as a new isotope separation method was brought closer to practice; there had been ample evidence in the preceding years that significant progress was being made at Livermore. Moreover, in this case, the conflict between patent coverage and classification which had arisen with the IASL process was less significant; by then JNAI was holding most of the patents for AVLIS.

The JNAI program itself has posed special problems for the government with regard to classification. For several years, from its beginnings in 1970-71, the program remained generally unclassified. The company naturally sought to protect its technology for proprietary reasons. Over the same period, nevertheless, a significant number

of patents covering various aspects of its process issued into the public literature in the U.S. and overseas. As the potential of the process for producing 'practical quantities' of enriched uranium became increasingly apparent, ERDA (as it then was), on the basis of information voluntarily provided by JNAI, concluded that certain aspects of the latter's program now fell into the 'Restricted Data' category, as defined in the Atomic Energy Act. For its part, JNAI was concerned about the impact of governmental classification and security controls on its technological lead and its rights to the process; indeed, a government contractor, Livermore, was developing a very similar process, and would certainly benefit greatly from access to information developed by JNAI. In addition, JNAI had major reservations as to the legality of an attempt by the government to impose classification and security controls on information developed independently by JNAI, without government assistance of any kind.

It is possible that JNAI's concern was heightened by the dissipation of government support for privatization that had occurred in the previous few years. There were certainly anxious recollections of the government's virtual takeover of private centrifuge programs in the 'pre-privatization' era a decade earlier.⁴⁵ And there had been a dramatic example of the government's willingness and ability to preempt private nuclear investments very recently, when Allied General Nuclear Services had been forced to terminate work on its half-completed commercial reprocessing plant at Barnwell, S.C., because of a government decision to defer domestic civilian reprocessing indefinitely.

A compromise was reached between JNAI and the government in a classification and security agreement concluded in September 1977. Under the agreement, JNAI program information is to be treated as if it were Restricted

Data, where the classification is determined according to guidelines established for the process by DOE. The agreement does not give DOE any property rights to the JNAI technology, and the Department has guaranteed to protect JNAI proprietary information from anyone other than designated personnel; the latter does not include DOE contractors. The agreement applied retroactively to all material generated subsequent to January 1976.

It is noteworthy that JNAI has not agreed that its information actually is Restricted Data in the legal sense, but only that it should be treated as such. (DOE apparently chose not to press this point.) Furthermore, JNAI has reserved the right to challenge DOE's authority to control the dissemination of its data at some future time. The agreement thus reflects a continuing tension in the relationship between the two parties, and a residue of uncertainty remains within JNAI as to whether the government will at some later date attempt to halt or otherwise intervene in its development program on national security grounds.⁴⁶ Indeed, this concern was probably a major motivation for JNAI's decision in 1978 to appoint a panel of independent experts to assess the proliferation risks of its process. The panel's report was discussed in Chapter 4.

LIS and gas centrifugation: competitors or companions

The third development in the enrichment sector which significantly affected the course of LIS programs during the 1970s was the emergence in 1977 of the gas centrifuge process as the technology of choice for the next increment of U.S. enrichment capacity. Throughout the preceding several years, the question of whether the gas centrifuge process or the proven gaseous diffusion technology would be chosen had been debated in parallel with the debate over privatization. In fact, the two issues were linked by the concern voiced in the private

sector over the risk of technological obsolescence. With initial investments running into billions of dollars and payback periods on the order of 25 years or more, anything that might jeopardize future market prospects, including the risk of obsolescence, was naturally a source of worry for prospective private enrichers.

Thus questions about the competitive threat from gas centrifuge and LIS were raised in connection with a private consortium's proposal to construct a large commercial gaseous diffusion plant.⁴⁷ And the ranking House minority member of the JCAE warned in 1974 of the possibility that LIS could make both gaseous diffusion and gas centrifuge technology economically obsolete.⁴⁸ In hindsight, the fear of technological obsolescence was without doubt one of the factors responsible for the failure of the privatization initiative, since the private sector's reaction, a request for increased government investment guarantees, contributed to Congress's lack of enthusiasm for the NFAA.

After President Carter's 1977 decision to select the gas centrifuge process, the obsolescence question narrowed to whether the new choice would be rendered obsolete prematurely by one or more of the advanced isotope separation technologies. But the groundrules had also changed: it was now the government which was to own the new gas centrifuge plant, and it was of course also the government which was funding most of the research and development work on the advanced isotope separation technologies.

The JCAE had foreseen what might happen in such a situation a year earlier:⁴

The objectives of the Advanced Isotope Separation Technology Program are to develop low cost and less energy-intensive processes for uranium enrichment, to develop techniques for

plutonium isotope recovery, and to develop new solutions to waste management problems.

The Joint Committee notes the major economic gains that will result if this program meets its objectives and understands that there may be a tendency within ERDA to stretch out or delay this program in order not to adversely affect on-going programs which utilize present uranium enrichment technology. (emphasis added)

It was perhaps predictable, therefore, that a decision would be taken by DOE in the summer of 1977, just a few weeks after the President's April policy statement, to redirect the AIS program towards the development of a 'tails stripping' process, capable of enriching tails uranium from conventional enrichment plants up to 0.7%, and producing its own tails material with an assay of 0.1 % or less. In this mode of operation, it will be recalled, AIS plants would function as adjuncts to conventional enrichment capacity, rather than substitutes.

(See Chapter 3, Figure 3.1.) DOE statements at the time stressed the 'companion system' relationship of the new technologies with the gas centrifuge plant to be built at Portsmouth.

The AIS schedule has also been delayed. In early 1977, the program anticipated choosing which of the three technologies would be scaled up for evaluation in a demonstration facility in 1979; the first production from a commercial-scale plant was expected in 1989. By early 1979, selection among the three technologies had been deferred until the latter half of 1981; construction of the first production plant was not expected to begin until 1989, with the first production scheduled for 1995.

The budget figures reflect this decision. After four years of rapid growth, funds have leveled off since 1977. Indeed, in real terms expenditures have probably dropped during the past three

years.*

Several factors may have contributed to the new AIS policy. The Carter Administration was espousing a philosophy of fiscal conservatism; balancing the budget by 1980 was a major political goal. Also, its overall support for nuclear fission technology has remained fairly constant in the three energy budgets submitted since 1977. ⁵⁴ While not necessarily directly responsible, both of these factors are at least consistent with the trend in the AIS budget.

More specifically, the Administration's concern over the proliferation risks of the new AIS technologies may have acted as a constraint on funding. ⁵⁵ Such concerns had not inhibited spending on the centrifuge, but in that case there were clearly identifiable risks associated with not going ahead, i.e.; confidence in U.S. fuel supply assurances would be eroded still further. In the case of the AIS program, no such consequences would ensue, at least directly.

Finally, there was the effect of the centrifuge decision itself. Seen from one perspective, the new AIS policy was a sound and logical response to this decision. The Portsmouth 'add-on' plant would postpone the need for additional enrichment capacity until the early 1990s. In the meantime, it made sense to focus on tails-stripping processes; the existing tails stockpile was large, and could be enriched to 0.7 % without reducing the demand for separative work from the new enrichment plant. Tails stripping was thus clearly the first target of commercial opportunity for the AIS processes, and would be the only

* The trend is even more pronounced for the two LIS programs; since 1977 they have had to share the total AIS budget with the TRW plasma separation process, whose allocation, despite the general cutback, has continued to grow rapidly. (See Table 5.1)

target for some time, given the slower growth in enrichment demand.

In another context, the new AIS policy could be (and was) interpreted as an attempt to preserve the viability of the centrifuge project in the face of a potentially eroding economic advantage. After the failure of the privatization initiative, the government had in effect assumed responsibility for creating, by contract, a new industry to design and construct the (1978) \$ 4-5 billion Portsmouth facility. A key task was the creation of a competitive centrifuge manufacturing industry, and a necessary condition for achieving such an objective was that the demand for machines would be large enough to provide several suppliers with enough business to maintain profit margins at attractive levels.

While projections of separative work demand at the time were still high enough to rule out any chance that one or other of the AIS technologies could be developed in time to compete with the initial increments of the Portsmouth plant, the projections were consistently being revised downward, and the gradually emerging possibility that the later stages of the plant might be abandoned in favor of a new enrichment process would tend to reduce the number of interested suppliers, and consequently the level of competition among them. In addition, the Portsmouth project, as originally planned, would provide up to 5000 construction-related jobs in South-East Ohio,⁵⁶ and naturally there were regional political and economic incentives to preserve them.

By reorienting the AIS program towards tails stripping, and by delaying it, not only were the "realities" of the President's decision to proceed with the Portsmouth plant being acknowledged, but the possibility that the economic viability of the plant might subsequently be threatened was also eliminated.

The extent to which these considerations actually influenced DOE's AIS policy cannot be gauged accurately at this stage. Nonetheless, several officials, both in and out of the government, and with substantial knowledge of the events leading up to the policy shift, have suggested privately that their influence was indeed considerable.⁵⁷

The technical foundation for the policy emphasis on tails stripping was never very clear. DOE officials noted that the AIS technologies could provide an economic means of enriching conventional tails material to 0.7%. Presumably, 'natural' uranium produced from depleted feed-stock in AIS plants would be cheaper than either performing the same task in gas centrifuge or gaseous diffusion plants or purchasing the real thing. But there was no indication as to whether or not the new technologies were also expected to produce reactor grade uranium from natural feed more economically than the conventional processes.* Given the background to the new AIS policy, this omission not surprisingly generated some scepticism within the technical community.**

The emphasis on tails stripping has become more questionable since 1977, as the projected demand for separative work has declined and the Portsmouth schedule has slipped. It was shown in Chapter 3 that there is

* See Chapter 3, section 2, for a fuller discussion of this issue.

** DOE's policy shift was subsequently echoed by JNAI, whose officials have also recently been stressing the potential of their technology for tails stripping.⁵⁸ The economic motivation for this is clear, given the government's intention of proceeding with the Portsmouth plant, and JNAI claims that its process is more economical in the tails stripping mode than for natural uranium enrichment. But in addition, de-emphasizing the JNAI process's potential for competing directly with the centrifuge technology appears to be a politically prudent course to follow, in view of the vulnerability of the firm's position as the lone prospective private enricher in the U.S.

a plausible range of scenarios under which one or other of the AIS technologies may be in a position to compete with the centrifuge for the next increment of enrichment capacity. That there is a useful role for AIS technologies as tails strippers remains in no doubt, but the often implied corollary that the same technologies have no near-term role as natural uranium enrichers has become increasingly dubious.⁵⁹

Resolution of this issue is only one of several tasks now awaiting policy-makers in the enrichment sector. In Chapter 6 we present the policy problem in its entirety, and examine various alternative approaches to dealing with it.

Table 5.1

Federal R&D Expenditures on Advanced Isotope Separation Technologies

(Dollars in Thousands)

	1974	1975	1976	1977	1978	1979
1 TOTAL	4,5 3,514	6 24,009	6 32,650	8 47,000	8 52,000	8 54,200
Livermore	1,344 ⁴	5,500 ⁷	8,700 ⁷	10,100 ⁹	11,900 ⁹	15,500 ¹⁰
Los Alamos	1,949 ⁴	n.a.	n.a.	16,600 ⁹	19,900 ⁹	20,300 ¹⁰
2 Oak Ridge	n.a.	n.a.	n.a.	4,400 ⁹	6,000 ⁹	4,500 ¹⁰
3 TRW	0	0	0	5,800 ⁹	8,300 ⁹	11,200 ¹⁰

Notes to Table 5.1

1. Total includes expenditures on all advanced isotope separation processes, and is not limited to LIS or the TRW process. However, other methods (e.g., chemi-ionization, chemical exchange, aerodynamic separation etc.) have accounted for only a few percent of total expenditure.
2. The Union Carbide Corporation at Oak Ridge is carrying out supporting studies for the programs at IASL, Livermore and TRW. The Oak Ridge work is oriented primarily towards the development of experiments necessary for transition from the laboratory to the industrial phase.
3. TRW is developing a laserless process under contract to DOE.
4. Source: U.S. Congress, Joint Committee on Atomic Energy, ERDA Authorizing Legislation: FY 1976, Hearings, February 4, 1975,

94th Cong., 1st Sess., Part I, 724.

5. In a press release issued on November 28, 1973 (as reported in Nuclear Industry, January 1974, 21, No. 1), the AEC announced that its funding of LIS research and development would amount to about \$1.5 million in FY74.
6. Source: U.S. Congress, Joint Committee on Atomic Energy, ERDA Authorizing Legislation: FY 1977, Hearings, January 21, 1976, 94th Cong., 2nd Sess., Part I, Vol. II, 1014.
7. Source: Lawrence Livermore Laboratory, "Laser Program Annual Report - 1976," University of California, Livermore, UCRL-50021-76, Table 1-1.
8. Source: U.S. Congress, House. Subcommittee on Fossil and Nuclear Energy Research, Development and Demonstration, Committee on Science and Technology, Department of Energy Authorization Legislation: FY 1979, Hearings, February 1978, 95th Cong., 2nd Sess., Vol. III, 27
9. Laser Focus, September 1977, 4
10. Norton Haberman, Office of Advanced Isotope Separation, U.S. Department of Energy, interview, April 4, 1979

Notes to Chapter 5

1. Henry R. Nau, National Politics and International Technology, Baltimore: Johns Hopkins University Press, 1974
2. Ibid.
3. "Science Policy: A Working Glossary," prepared for the Subcommittee on Science and Astronautics, House of Representatives, U.S. Congress, July 1973.
4. Harvey Brooks, "Technology Assessment as a Process", International Social Science Journal, XXV: No. 3, pp. 247-256 (1973)
5. Indeed, the AEC was already extracting itself from light water reactor development and turning to the next generation of nuclear reactor technology, the breeder, in the mid-1960s, even before the LWR achieved significant commercial success. See: I.C. Bupp and Jean-Claude Derian, "Light Water: How the Nuclear Dream Dissolved", (New York: Basic Books, Inc., 1978), 50-53
6. For a discussion of the underlying motivations and causes of the Carter Administration's non-proliferation policy, see: David J. Rose and Richard K. Lester, "Nuclear Power, Nuclear Weapons and International Stability", Scientific American, April 1978, 45
7. For details of the AEC's technology access programs, see: U.S. Congress, Hearings Before the Joint Committee on Atomic Energy, Future Structure of the Uranium Enrichment Industry, 93rd Cong., 1st Sess., 1973, Part 1, Phase I, 129. (Washington, D.C.: Government Printing Office,

1974), hereafter referred to as Enrichment Industry Hearings.

"Business-like" is a quote from a speech by James Schlesinger, then Chairman of the AEC, as reported in E. Wonder, Nuclear Fuel and American Foreign Policy, (Boulder: Westview Press, 1977), 33

8. For a comprehensive account of the debate over privatization, see Enrichment Industry Hearings, Parts 1 - 3, (1973-74)
9. Both General Electric Company and Westinghouse withdrew from enrichment plant feasibility studies in 1974; in so doing each noted the large investments required and the uncertain and deferred returns.
See: Nuclear News, November 1974, 67
10. See: U.S. Congress, Hearings before the Joint Committee on Atomic Energy, S.2035 and H.R. 8401: Nuclear Fuel Assurance Act of 1975, 94th Cong., 2nd sess., 1975, (Washington D.C.: Government Printing Office, 1975), hereinafter referred to as NFAA Hearings.
11. Fact Sheet, "The President's Energy Program", Office of the White House Press Secretary, April 20, 1977.
12. A critical appraisal of the proposals contained in the NFAA can be found in a report by the U.S. General Accounting Office, Evaluation of the Administration's Proposal for Government Assistance to Private Uranium Enrichment Groups, Report to the Joint Committee on Atomic Energy, RED-76-36, October 31, 1975
13. For a full account of the two 'multilateralization' initiatives of the U.S. Government in 1971 and 1974, and the influence of domestic privatization objectives on their outcome, see: Wonder, Nuclear Fuel and American Foreign Policy, op. cit.

14. Ibid.
15. For an analysis of how the new Long-Term Fixed Commitment (LTFC) contracts contributed to an artificially high demand for enrichment, which in turn forced the AEC to cease contracting earlier than was actually necessary, see: Vince Taylor, How the U.S. Government Created the Uranium Crisis (and the Coming Uranium Bust), Pan Heuristics, Los Angeles, June 1977 (Preliminary), 25-37
16. R.H. Levy and G.S. Janes, U.S. Patent 3,772,519 to Jersey Nuclear Avco Isotopes, Inc. (Nov. 13, 1973)
17. M. Benedict et al, "Report of the Uranium Isotope Separation Review Ad Hoc Committee", U.S. Atomic Energy Commission, ORO-694, June 2, 1972.
18. Indeed, the different directions taken by the laser enrichment programs can be attributed in part to the different laser technologies that had been developed for the parent fusion programs.
19. Enrichment Industry Hearings, Part 2, Phase 2, 217. At the time, five companies, including General Electric and Allied Chemical, were engaged in centrifuge research and development. Another factor which might have influenced the JNAI decision was the above-mentioned conclusion of the Benedict report, from which it could certainly have been inferred that the Government was not about to fund a significant program of its own.
20. U.S. Congress, House, Authorizing Appropriations for the Energy Research and Development Administration for Fiscal Year 1977, Report of the JCAE,

94th Cong., 2 sess., 33, (Washington, D.C.: Government Printing Office, 1976)

21. See Chapter 4, Section 5
22. N.R. Greiner, R.J. Jensen, C. Paul Robinson, T.P. Cotter and K. Boyer, "Isotope separation by laser means", S.N. 270,800, filed July 7, 1972.
23. See, for example, R.L. Farrar, Jr., and D.F. Smith, "Photochemical Isotope Separation as Applied to Uranium", Oak Ridge Gaseous Diffusion Plant, K-L-3054 (Rev 1), March 15, 1972.
24. C.L. Marshall, Director, Division of Classification, AEC, letter to R.D. Krohn, LASL, September 20, 1972.
25. E.C. Walterscheid, LASL, letter to R.A. Anderson, AEC, February 15, 1973
26. See, for example, Teller's letter in Laser Focus, November 1974.
27. S.A. Tuccio, et al, "Two-step selective photoionization of U²⁵ in uranium vapour", IEEE J. Quant. Elect. QE-10, 790 (1974) A similar coup had been engineered two years before, when some important laser fusion work performed at Livermore was declassified just in time to be presented at the 1972 IQEC conference.
28. Laser Focus, August 1974, 10
29. Memo from Philip Belcher, LASL Legal Officer to Harold M. Agnew, Laboratory Director, October 30, 1973
30. Melvin Price and Craig Hosmer, respectively Chairman and Ranking Minority Member of the JCAE, letter to D.L. Ray, Chairman, AEC, February 1, 1974

31. Reported in letter from Edward Walterscheid, LASL, to James E. Denny, Office of General Counsel, AEC, March 8, 1974.
32. C.C. Marshall, Division of Classification, TWX to H.M. Agnew, LASL, March 8, 1974, as reported in a letter from E.W. Walterscheid to the author, February 22, 1979
33. For contemporary published works which referred in more or less detail to the opportunities for molecular spectroscopy offered by supersonic gas streams, see: T.A. Milne and F.T. Green in H. Eyring (ed.), Advances in high temperature chemistry, vol. 2 (New York: Academic Press, 1969); D.I. Kateev and A.A. Mal'tsev, JETP 37 (1973), 772; M.P. Sinha, A. Schultz and R.N. Zare, J. Chem. Phys. 58 (2), 549 (1973); P.E. Smalley, B.L. Ramakrishna, D.H. Levy, and L. Wharton, J. Chem. Phys. 61, 4363 (1974); In addition, adiabatic expansion of gases in supersonic nozzles had already been widely applied in the related field of gas-dynamic lasers. See, for example, E. Vallach, A. Zeevi, E. Greenfield, and S. Yatsiv, Appl. Phys. Lett., 20(10), 15 May 1972
34. F.C. Gilbert, Division of Military Applications, AEC, TWX to H.M. Agnew, LASL, March 27, 1974, as reported in a letter from E.W. Walterscheid to the author, February 22, 1979.
35. E.C. Walterscheid, LASL, Letter to R.A. Anderson, AEC, May 18, 1973.
36. Keith Boyer, LASL, letter to Major B. Stafford, Military Liaison Committee to the AEC, Department of Defense, November 29, 1972.
37. Wonder, Nuclear Fuel and American Foreign Policy, 18

38. E.C. Walterscheid, letter to the author, February 22, 1979.
39. The patent application which more closely resembled the LASL 'main-line' process had been filed in Germany by H. Jetter, K. Gurs and W. Englisch of the Julich firm of Uranit-GmbH on December 11, 1974. Even earlier, on October 7, 1974, K. Gregorius and K. Janner of KWU had filed another application which featured adiabatic cooling of a mixture of UF_6 and a chemical reactant and isotopically selective laser excitation of the UF_6 . Separation was achieved by selective photochemical reaction, rather than photodissociation, as LASL and Jetter et al were proposing.
40. In August 1973, the LASL investigators filed an improved version (a so-called 'continuation-in-part') of the original S.N. 270,800 which was then abandoned. The new application, S.N. 387,859 was, of course, also classified.
41. H. Jetter, K. Gurs, and W. Englisch, U.S. Patent 4,025,790 to Uranit-GmbH (May 24, 1977)
42. The inconsistencies that had permitted this situation to arise were a source of particular concern to LASL, whose director, H.M. Agnew, advised DOE headquarters in January 1978 of specific procedural irregularities at the U.S. Office of Patents and Trademarks which had contributed to the problem. Agnew also highlighted several other difficulties arising from DOE policies on the relationship between classification and patenting. (Harold M. Agnew, LASL, letter to A.L. Alm, Assistant Secretary for Policy and Evaluation, U.S. Department of Energy, January 11, 1978.) As a result of Agnew's inquiries,

both the AEC and the Patent Office introduced procedural changes designed to avoid a repetition of the problem. (D.M. Kerr, Acting Assistant Administrator for Defense Programs, DOE, letters to H.M. Agnew, LASL, March 10 and April 14, 1978; R.D. Tegtmeyer, Assistant Commissioner for Patents, U.S. Patent and Trademark Office, letter to J.E. Denny, Office of General Counsel, U.S. DOE, October 11, 1978)

43. Jetter et al v. Robinson et al, Interference No. 100,012 in the United States Patent and Trademark Office, February 8, 1979
44. C. Paul Robinson, R.J. Jensen, T.P. Cotter, K. Boyer, N.R. Greiner, "Laser Isotope Separation", patent application S.N. 636,343, filed 26 November 1975, (declassified 29 January 1976). According to a DOE patent attorney, a key incentive for filing overseas at the time was to generate some bargaining strength against the possibility of foreign patents issuing in the U.S.
45. The 'specter' of the government's takeover of the centrifuge technology was recently raised in public by Exxon Nuclear's general counsel. See Nuclear Fuel, February 19, 1979, 13.
46. The information presented in the preceding four paragraphs was mostly obtained from an interview with H.K. Forsen, Vice-President, Exxon Nuclear Co.
47. NFAA Hearings, 368
48. Nuclear Industry, January 1974, vol. 21, no. 1. In the previous year General Electric, which at the time was considering entering the

centrifuge enrichment business, had requested information pertaining to all LIS work then being funded by the AEC. (E.C. Walterscheid, IASL, letter to J.A. Horan, USAEC, August 22, 1973)

49. U.S. Congress, House, Authorizing Appropriations for the Energy Research and Development Administration for Fiscal Year 1977, Report by the Joint Committee on Atomic Energy, 33 (Washington, D.C.: Government Printing Office, 1976)
50. The new policy was announced by a DOE official at a conference in February 1978; the announcement was reported in Laser Focus, April 1978, 4.
51. Nuclear Industry, February 1978, vol. 25, no. 2, 6
52. "Evaluation and Selection Plan for Advanced Isotope Separation Processes", Division of Nuclear Research and Applications, Energy Research and Development Administration, TID-27641, July 1, 1977.
53. "Environmental Development Plan for the Advanced Isotope Separation Program (Rev. 1): 1979", U.S. DOE, March 1979
54. See Nuclear News, March 1978 and April 1979
55. Senator Frank Church indicated his concern over this issue during Congressional hearings in early 1978: "It does not seem to me it would be wise at this time to start spending money on simplifying and further reducing the costs of enriching uranium. That is where the whole nuclear weapons problem begins, with the enrichment of uranium".
Nuclear Industry, February 1978, 6

56. Nuclear News, February 1978, 43
57. According to one such official, the policy was presented to the AIS teams in the form of an ultimatum, which apparently was referred to by some as the 'Godfather proposition': "concentrate on tails stripping, or lose your funding altogether".
58. See, for example, the Exxon Nuclear press release, "Exxon Nuclear and Avco announce formation of laser enrichment review panel", November 13, 1978
59. The tails stripping policy has received no public endorsement from EOE headquarters in recent months, and recent conversations with Los Alamos LIS officials suggest that there, at least, the process is being developed on a more flexible basis.

CHAPTER 6

POLICY SYNTHESIS

In the preceding chapters of this work, we have presented a technical overview of LIS processes based on information available in the open literature and on our own personal study; we have analysed the potential economic and security implications of these technologies; and we have examined the impact of existing political and institutional structures on their course of development until now.

Taken together, these various elements provide an essential foundation for the development and evaluation of laser enrichment policy. The purpose of this chapter is to perform the synthesis required actually to formulate such policy. We address, in particular, three policy questions:

- Should existing LIS development programs be continued?
- If so, under what schedule, and with what objectives?
- What are the appropriate roles for the private sector and the government in the development of these technologies, and in their potential demonstration and commercial operation?

Of course, these questions can only be answered in the broader context of U.S. enrichment policy and, even more generally, in the context of the entire range of domestic and international nuclear policies of the U.S. The array of relationships linking the various items and levels of policy is conveniently represented by the schematic diagram in Figure 6.1.

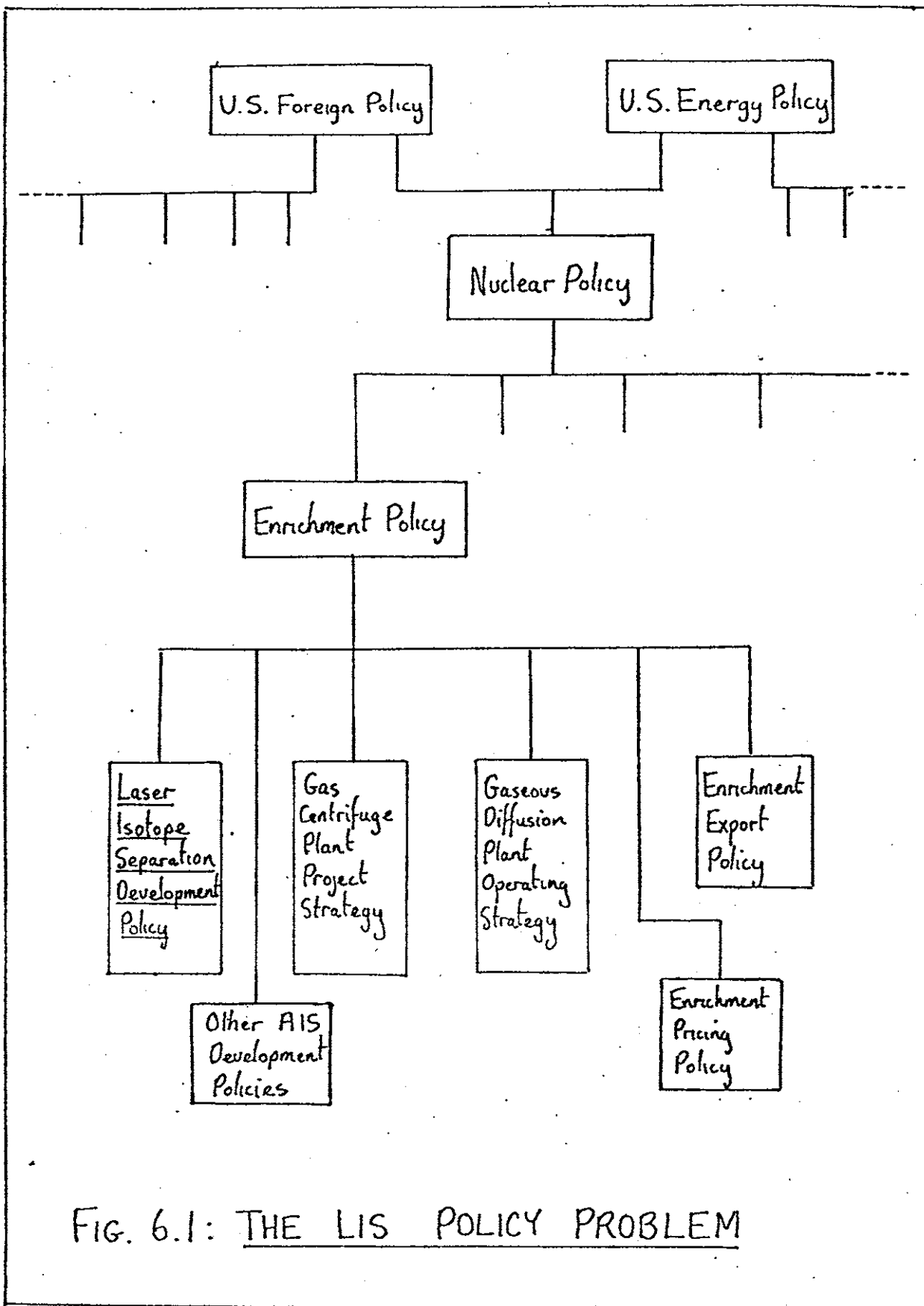


FIG. 6.1: THE LIS POLICY PROBLEM

6.1 Should LIS Development Programs be Continued?*

There are two possible incentives for terminating or postponing current LIS development programs in the U.S. First, if the potential economic benefits accruing from the effort are likely to be outweighed by the costs of development and commercialization, then the programs obviously could not be justified. At present, this seems not to be the case. The total cost of developing one or other of the technologies to the point of commercialization is expected to be less than \$1 billion. Separative work cost estimates for AVLIS and MLIS facilities are consistently at least 50% lower than current gaseous diffusion or gas centrifuge enrichment costs. If this projected cost differential materializes, then to a crude approximation the development expenditures could be recouped in the form of fuel cost savings after less than 200 GWe-years of LWR operation (or about 3 years of operation for the current U.S. LWR population.) Furthermore, the great sensitivity of gaseous diffusion enrichment costs to the cost of electricity suggests that the comparative advantage of low-energy enrichment processes is likely to increase rather than decrease in the future. Of course, it is possible that the future world demand for enrichment services may be so low that the investment in LIS development might not be recoverable. For the moment, however, even with the precipitous decline in projections of nuclear power growth, investment in LIS development appears to be a sound economic proposition.

The other reason not to proceed with LIS development at this time is its potentially adverse impact on international security and, in particular, on U.S. nonproliferation policy goals. Several such

* We address this question in a general U.S. context, and make no attempt at this stage to account for differences between government and private sector programs. The question of the appropriate role for the private sector is dealt with subsequently, in Section 6.3.

impacts can be readily imagined:

- Continued development could result in a process (or processes) which would be much easier technically to adapt to the production of weapons grade uranium than any method now available, and further, the processes might be more difficult to control by classification and security measures; continued U.S. development could thus unleash a particularly dangerous and unmanageable technological genie.
- Continued development in the U.S. could stimulate parallel development efforts in other countries. Such efforts could result in a general reduction of barriers to proliferation. And even if the outcome was not a radically simpler way of producing highly enriched uranium, by its own efforts the U.S. would have encouraged the addition of a new technological pathway to the existing set of routes to nuclear weapons.
- Continued U.S. development could result in an economically attractive process with scale economies favorable for the construction of small commercial facilities (with a capacity suitable for serving, say, a few 1 GWe LWRs). If so, one of the key barriers to the spread of commercial enrichment plants in the past will have been removed. The spread of such facilities to additional nations would inevitably increase the risk of misuse or replication for the purposes of nuclear explosives acquisition. Yet the addition of a new, economically attractive, and 'appropriate' enrichment process to the list of sensitive technologies that the U.S. currently withholds from international trade would tend to aggravate already strained and potentially counterproductive

relationships between the U.S. and other nations in the nuclear field. Only if U.S. AIS development is halted can this dilemma be avoided. Also, by halting now, when the commercial prospects are potentially attractive, but not proven, (and if possible persuading other countries engaged in AIS development to stop too, or at least to abandon any plans for commercial application), the effect would be ambiguous: did development cease because it was commercially infeasible, or because it was dangerous? The ambiguity would cause countries which might otherwise have launched an independent development effort to hesitate; for those interested mostly in the commercial applications, the prospect would appear less inviting, and for those more interested in the military potential but seeking to conceal it under a cloak of legitimate civilian aspirations, the camouflage might seem flimsier.

- Finally, continued aggressive U.S. development of AIS processes could undermine parallel U.S. initiatives to prevent the international spread of other 'sensitive' fuel cycle technologies.

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Taken together, do these arguments provide a convincing rationale for halting current AIS development programs in the U.S.? The first question concerns the direct impact of LIS development in the U.S. on existing technical barriers to proliferation. Under present U.S. policy, all information developed in domestic LIS programs is subject to classification and security restrictions, and the export of any enrichment technology is foreclosed. Thus, the question really can be reduced

to the following: How closely can existing restrictions approach their objective of preventing the transfer of any significant information or equipment to another country? If the objective can be closely approached, or, at least, if the information that is transferred as a result of imperfect controls is relatively insignificant compared with what can be obtained independently or from other (non-U.S.) sources, then on this limited basis there is no justification for halting the U.S. development programs.

It is beyond the scope of the present work to assess the efficacy of the U.S. classification and security controls. It is generally known, of course, that such controls are not foolproof.¹ But to the knowledge of the author there has never been an occasion on which a sensitive development has been stopped purely because of doubts about the ability to keep it secret. Similarly, export controls have not worked perfectly in the past, but, as was shown in Chapter 4, the authority vested in the U.S. government is sufficiently broad, in principle, to prevent all exports of equipment or transfers of technology that might be useful for the construction of LIS facilities overseas.

The second question concerns the risk of U.S. programs stimulating similar commercially-oriented efforts overseas, even in the absence of any technology transfer, deliberate or otherwise. Here there are actually two questions: To what extent would other countries be influenced by American domestic policy decisions? And if U.S. programs did stimulate others to proceed, would the consequence be a significant reduction in the technical barriers to proliferation?

The analysis in Chapter 4 attempted to answer the latter question, on the basis of unclassified information. Many important issues necessarily

went unexplored, and no definted conclusions were possible. At the present time, and probably for the next several years, LIS technology will not offer an easier route to the acquisition of nuclear weapons material than other methods now available. This situation may not persist in the future, however. But is the risk that it will not persist a sufficient basis on which to terminate U.S. development efforts?

Chapter 4 showed that there are likely to be significant differences in difficulty between alternative approaches even within the field of LIS. For example, while AVLIS processes might always present a more difficult technical challenge than, say, gas centrifuge technology for any country, regardless of its stage of development, in future years MLIS processes may become easier than both. Should U.S. policy try to account for such differences by enforcing only a selective moratorium? Drawing strict lines in a continuum of technological opportunity might be absurd. On the other hand, imposing a ban on all types of LIS development because of the potential dangers of one can lead to other logical fatuities.

The relevance of these questions depends upon the extent to which other countries would be influenced by domestic U.S. policy. There is no doubt that large-scale development of LIS technologies in the U.S. will provide both justifications and incentives for similar programs in other countries. But the impact of a unilateral U.S. decision to cease development is less clear. Other countries with growing LIS programs have substantial national economic and energy independence incentives to develop new enrichment technologies irrespective of U.S. actions. To the extent that development is driven by the forces of international competition, the withdrawal of the leading competitor (which the U.S. now appears to be) might dampen the fires. But even

so the effect would only be temporary. The other incentives to proceed would remain; in time someone else would seize the opportunity to fill the vacuum, and a new leader would emerge. The process would be renewed, but this time without U.S. technological leadership. And the ability of the U.S. to influence the development of future international arrangements for the control of the new technologies would be weakened as a result.

Not surprisingly, these arguments bear an uncanny resemblance to those that erupted following the decisions taken by the Ford and Carter Administrations to defer domestic reprocessing. And indeed the two issues have many structural similarities. Supporters and opponents of the reprocessing decision (and its accompanying objective of persuading other countries to defer too) naturally draw different conclusions as to its impact. The former point, with some justification, to the clear evidence that the international commitment to plutonium as a commercial fuel has faltered in the intervening two years. The latter note the continuing determination of countries such as France to proceed with plutonium use, and deplore both the resulting loss of U.S. technological leadership and the corrosive and possibly counter-productive effect of U.S. policies on its relations with other countries.

While the net effect of U.S. reprocessing policies on decisions taken elsewhere is a matter best left to the historians, it is quite clear that the general economic prospects for reprocessing and the particular domestic and international political and economic circumstances of the country in question have played a key role in decision making. So it will certainly be with decisions taken on advanced enrichment technologies. No amount of generalizing can obscure the fact that such decisions will be taken on a national basis, and the direction of U.S.

domestic policy will only be one of many influences.

The analogy should not be extended too far, nevertheless, since the costs and benefits to the U.S. of deferral, both economically and with regard to nonproliferation, are quite different for the two cases.

Commercial and technological leadership in the enrichment sector has always been a central element of U.S. nonproliferation policy, and its importance has increased of late as a consequence of the U.S. stand against widespread reprocessing and plutonium use. Thus a conscious decision by the U.S. to abandon its leadership role in the development of the next generation of enrichment technology would arguably represent a more fundamental discontinuity in nonproliferation policy than did the antiplutonium strategy, even though the impact on the domestic nuclear power program would be much less noticeable.

The world enrichment market during the next decade will be characterized by a much higher level of international competition than before. This may continue to be the case even after the anticipated enrichment 'glut' subsides (probably in the early 1990s), if only because the number of suppliers will have increased. In such a market, a supplier's position will be determined largely by the price that it can offer; the relative importance of fuel assurance guarantees will decrease as the diversity of supply sources increases. If the potential savings offered by LIS technologies can be reduced to commercial practice, then the U.S. will be in a stronger position to recapture a substantial fraction of the international market, or at least to retain its existing share. Without a significant commercial edge over its competitors, the nonproliferation leverage derived by the U.S. from its enrichment exports may erode even further, particularly if other

suppliers are not persuaded to follow the U.S. lead in terminating LIS development.

Alternatively, if, whether in reaction to the glutted market of the next several years or for any other reason, there should be a trend towards greater international cooperation in the planning and implementation of commercial enrichment ventures, the U.S. would be better placed to play a major role in such arrangements with a leadership position in the next generation of enrichment technologies. Such a role would again be to the advantage of U.S. nonproliferation goals.

More generally, the spectacle of the U.S. abandoning the development of a potentially cheaper, more resource-efficient technology just as the world is becoming even more acutely aware of the magnitude of its energy problem would almost certainly damage still further the already badly tarnished image of the U.S. as a responsible participant in world energy affairs. The overall significance of the incremental effect may be slight, but the impact on U.S. efforts to engage other nations in cooperative programs to find more proliferation resistant alternatives to the plutonium fuel cycle might not be.

Even apart from the political advantages that successful development of AIS technologies might bring to the U.S., and the disadvantages that might follow from its abandonment, we have already shown in Chapter 3 that commercialization of AIS processes can promote a significant reduction in uranium consumption, particularly in conjunction with other fuel conservation measures; the increased availability of uranium and the easing of upward pressures on uranium price would be expected to reduce the economic attractiveness of alternative fuel cycles involving plutonium. A similar effect would arise if a substantial reduction in

the cost of enrichment services were achieved.

Conclusion

Technological leadership is a form of capital. It may be exercised through spending, once. Alternatively, if preserved, it can provide a continuing source of benefit.

One or other of the LIS processes may be the technology of choice for the next generation of commercial enrichment facilities. In addition, one or more of them may eventually provide a much simpler way of producing highly enriched uranium than any method now known, or they may not.

On balance, U.S. nonproliferation interests would not now be served by a decision to abandon current LIS development programs. The potential benefits seem small, and while it is possible that little would be lost as a result, it is more likely that an important opportunity to influence the future evolution of the international nuclear fuel supply system would be foregone. LIS development should therefore be pursued vigorously.

6.2 What is the Optimal Development Strategy for the AIS Technologies?*

Future planning of the AIS program must be done in conjunction with gas centrifuge enrichment plant (GCEP) project scheduling and operational management and planning for the gaseous diffusion plants, since all are interdependent.

A recurring theme in the preceding chapters has been the influence of GCEP policy on the AIS program. In Chapter 5, the reorientation and

* Although the preceding section dealt only with the LIS technologies,
(continued)

delay of the AIS program following the Carter Administration's 1977 decision to proceed with the centrifuge plant at Portsmouth was noted. And Chapter 3 underlined the emerging possibility that the next increment of commercial enrichment capacity will not be required until the 1990s, which in turn reopens the question of whether gas centrifuge technology might ultimately become obsolete before it even enters commercial operation.

Current policy does not recognize this possibility, and must be modified accordingly. We concentrate here on the Government's programs. The issues facing JNAI corporate planners are somewhat different, and we examine the implications of these for national policy in the next section.

Present Policy:

-- At present, DOE's plan is to have "pre-prototype models" for the three AIS processes now under development in operation by FY 1981; by the end of that fiscal year, one of the three will be chosen to be scaled up for testing in an engineering demonstration facility. The demonstration plant should be operational by 1987, and, based in part on the experience with that plant, a decision will subsequently be made as to whether a commercial tails stripping plant should be built.

in the remainder of this chapter the scope of the discussion is broadened to include the entire range of AIS technologies, including the TRW plasma process. It is possible that an analysis corresponding to the one presented in the preceding chapters for the LIS processes would lead to a different conclusion as to the desirability of proceeding with development of the TRW technology. It is assumed here that this is not the case. However, the conclusions of the next two sections, which are presented as being generally applicable to the next generation of enrichment technologies, would not be invalidated for the LIS processes if this assumption is incorrect.

Current plans suggest that construction work on the production plant would then begin in 1989, with the first production² anticipated in 1995.

- The first 2.2 MSWU increment of the Portsmouth centrifuge plant is scheduled to enter operation by 1988, with subsequent increments being added sequentially until about 1993, when the full 8.8 MSWU of capacity should be completed. Major construction expenditures have already begun, as Table 6.1 shows.
- The gaseous diffusion complex will be operated at substantially less than available capacity until 1985. As shown in Figure 6.2 (a reproduction of Figure 3.13), however, the DOE stockpile of enriched uranium is expected to grow for at least another six years and probably for longer. The tails assay will be maintained at 0.2 % for as long as possible, and probably at least until the end of the decade.

* * *

The task of modifying these plans to cope with recent developments can be formally defined in terms of a dynamic, multi-variable decision problem with multiple (and sometimes conflicting) objectives and multiple uncertainties. The respective elements of the problem are presented in Figure 6.3. We do not attempt to 'solve' this problem in a numerical sense. There is no unique solution, and in any case the problem must be continually reworked and sometimes also reformulated in response to changing conditions.

Nevertheless, it is now apparent that DOE's enrichment operations have reached a crossroads. Two general directions are available, each of which holds quite different consequences for the AIS program. In

Table 6.1

Construction Schedule and Expenditures for the PortsmouthGas Centrifuge Plant*

(All expenditures in 1978 dollars)

<u>Fiscal Year</u>	<u>Construction funds (\$ millions)</u>	<u>Operating expenses (\$ millions)</u>	<u>Capacity available (MSWU)</u>
pre - 1978	21	}	--
1978	46		21.6
1979	150		--
1980	200	1.6	--
1981	330	4	--
1982	300	5	--
1983	400	6	--
1984	370	8	--
1985	340	11.8	--
1986	380	19.3	--
1987	530	29.9	1.1
1988	490	49.5	2.2
1989	450	80.2	3.3
1990	420	112	4.4
1991	345	141.7	6.6
1992	260	168	7.7
1993	68	192.1	8.8

* Source: Roger Gagney, Uranium Resources and Enrichment Division, U.S. Department of Energy, July 29, 1979

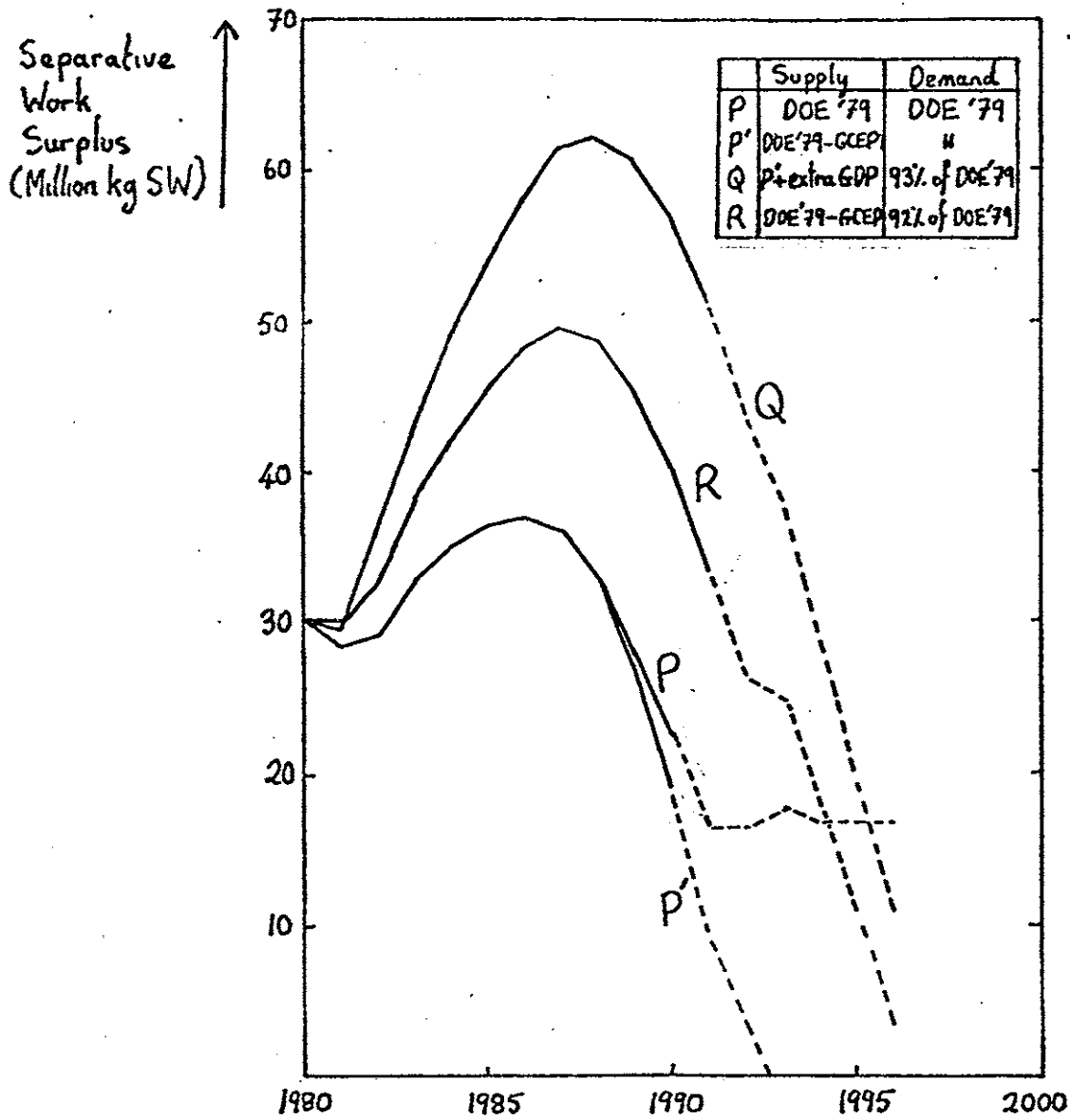


FIG. 6.2 : U.S. DOE SEPARATIVE WORK STOCKPILE PROJECTIONS, 1980-96

(Basis: 0.25% assay)

Time →

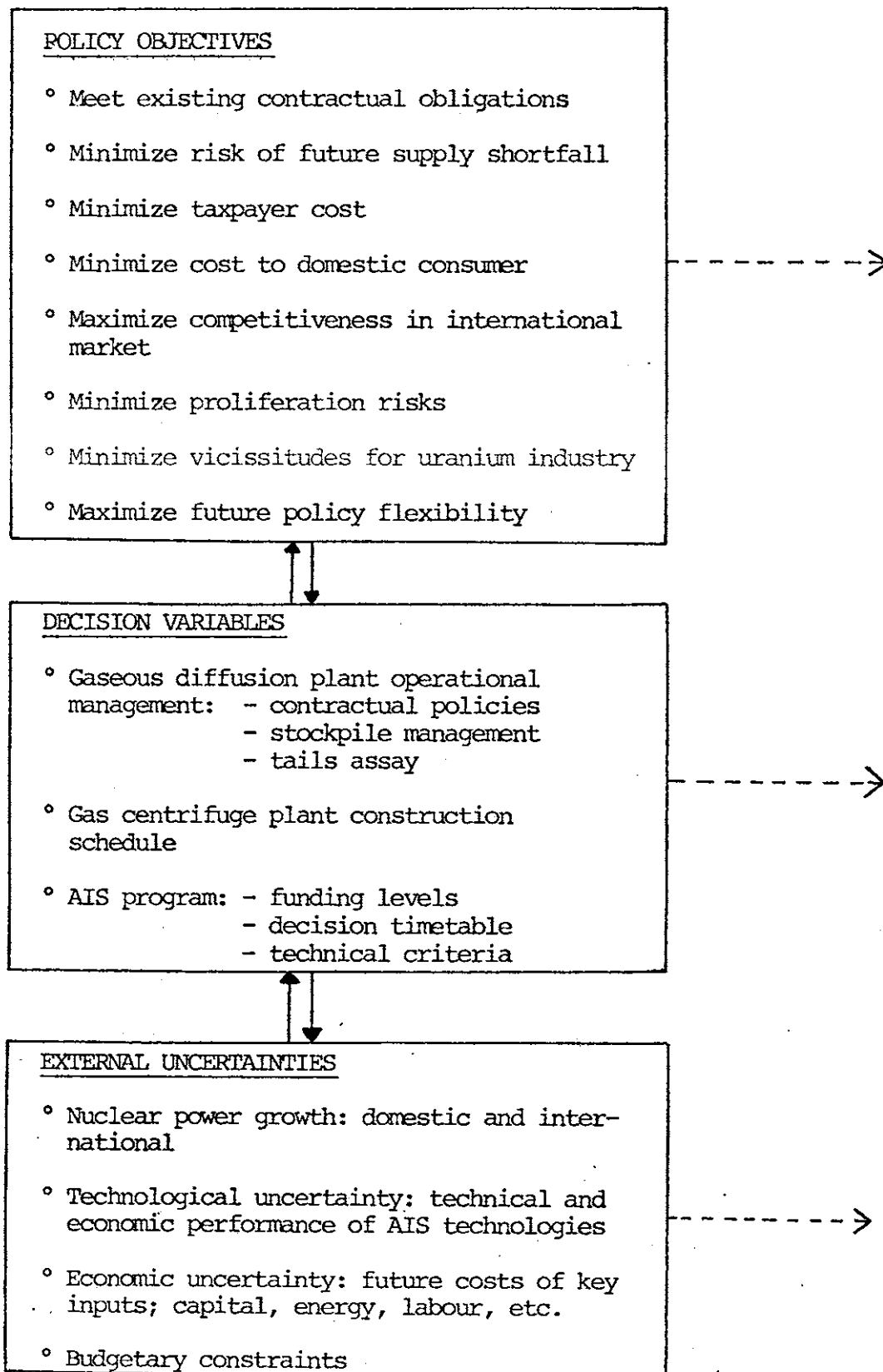


FIGURE 6.3: THE ENRICHMENT MANAGEMENT PROBLEM

one, the current schedule for the Portsmouth centrifuge plant is maintained, with the first increment coming on line in 1988. Meanwhile, during the next few years production from the gaseous diffusion complex is reduced even below currently planned levels, so as to match demand more closely and to avoid the accumulation of an overly large stockpile of separative work in the latter half of the 1980s. Finally, the AIS program is maintained on its current course, with commercial production targeted for the mid 1990s.

In the alternative path, any further major construction expenditures for the centrifuge plant are deferred for a few years. Funding is limited to that which is necessary to maintain project continuity and for further design improvements. Production from the gaseous diffusion plants is maintained at projected levels, or even increased. A larger stockpile is thus accumulated, and can be drawn down as demand increases in the early 1990s in order to delay the need for additional capacity increments. In parallel with the deferral of the centrifuge project, the AIS program is accelerated. The target date for commercialization is brought forward slightly, but more significantly, the program is reoriented so that the goal is to develop a process (or processes) capable of competing directly with the later modules of the centrifuge plant. As part of this reorientation, it may no longer be appropriate to focus the program on a single process so early in the development phase; increased benefits may flow from a more prolonged period of technological competition among the three (unless of course one or other of them is quickly shown to have no commercial prospects). Under this plan, the future of the centrifuge plant would be continuously reassessed during the next few years, with a firm decision taken by a set date (i.e., the deferral would not be "indefinite" as in the case

of the recent reprocessing decision).

The broad outlines of these two alternative strategies, respectively referred to for convenience as the 'GCEP preservation' and 'GCEP deferral' plans, are summarized for convenience in Table 6.2. A qualitative discussion of their relative merits follows.

Table 6.2

Alternative Approaches to U.S. Enrichment Operations Management

"GCEP Preservation"

- Reduce GDP production to follow demand over short term
- Maintain current GCEP construction schedule
- Maintain current AIS program plan

"GCEP Deferral"

- Maintain GDP production at anticipated levels; build separative work stockpile
- Defer further major expenditures on GCEP until mid-1980s
- Accelerate AIS program; pursue technologies in parallel

(a) GCEP Preservation Strategy

- A continued commitment to the centrifuge facility will reinforce domestic and international perceptions of the strength of U.S. fuel supply assurances, and will generally reduce concerns over the adequacy of supplies in the 1990s.
- A cutback in production from the gaseous diffusion plants so as to approach separative work demand more closely will ease the pressure on regional electricity supplies. For example, if separative work output were reduced from currently planned levels to a level corresponding to an estimate of future demand

made last year (which is itself almost certainly overstated), during the next six years roughly 1000 MWe of power would be freed for other uses.

- Furthermore, a cutback in production would also avoid further growth of the stockpile of enriched uranium, whose costs ultimately must be borne by the consumer.
- The GCEP preservation strategy essentially substitutes gas centrifuge swus for gaseous diffusion swus. Since the latter are approximately twenty times as energy intensive, a substantial amount of energy can be saved. (Per unit of electricity produced by LWRs, however, the saving provided by the GCEP substitution only amounts to about 4%.)

On the other hand:

- Gaseous diffusion swus produced today from the existing, largely depreciated gaseous diffusion complex are cheaper than gas centrifuge swus (in constant dollars), and in this respect the substitution is uneconomic.
- At a time of general fiscal restraint, major Federal expenditures (well over \$1 billion during the next four years) are being allocated to a project which could reasonably be deferred. While the Treasury (and the taxpayers) will be reimbursed in the long run by the revenues paid by DOE enrichment customers (and thus ultimately by electricity consumers) for GCEP swus, the net impact in the short term is to increase the Federal appropriations burden while relieving consumers of the burden of financing a growing stockpile of enriched uranium that the gaseous diffusion plants would otherwise be called on to produce.

(b) GCEP Deferral Strategy

- Deferral of the gas centrifuge plant at this stage will provide further opportunities for improvement in the technology, and will reduce the risk of a premature commitment to a particular centrifuge machine design.
- Acceleration of the AIS program coupled with the GCEP delay will provide an opportunity to reduce uncertainty associated with the risk that the centrifuge plant will rapidly become obsolete; moreover, if indeed one or other of the AIS technologies turns out to be economically superior to the gas centrifuge, it will be available for commercialization before the later increments of the Portsmouth plant are added.
- Deferral of the GCEP at this stage, rather than later (if it then is deemed necessary owing to subsequent demand reductions), will result in lower interest payments during the construction period, and thus a lower overall plant cost.
- A portion of the deferred GCEP plant budget can be used for the acceleration and broadening of the AIS program.

On the other hand:

- A delay in construction of the GCEP will increase the effect of inflation on the overall plant cost.
- The psychological damage wrought by deferring one of the few remaining 'viable' nuclear projects in the U.S. would be considerable, particularly coming at a time of deep depression in the nuclear industry after the Three Mile Island accident.
- More practically, a delay at this stage might inflict irreparable damage on the efficiency of project implementation; con-

tinuity and momentum will be lost at a crucial stage, and it may be difficult to retain key personnel. Project costs may increase as a result.

- Similarly, delay may reduce the number of centrifuge machine suppliers involved in the project, particularly if there is a real possibility that the later modules may never be built. As the number of actual and potential contractors declines, the competition among them, which is generally considered to be an important factor in holding costs down, may also diminish.³ In addition, the stimulus for technological innovation, whose results might otherwise have been utilized in later modules and possibly later plants, may also decline.
- Further delay in the Portsmouth project might aggravate the already seriously eroded image of the U.S. as a reliable supplier of fuel, at a time when restoration of this image is considered to be of paramount importance to the success of its nonproliferation policy. (On the other hand, a decline in demand, a growing enriched uranium stockpile, and a new urgency in the AIS program would all tend to act against these perceptions.)

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The description of these alternative strategies was deliberately qualitative, and no attempt was made to evaluate their comparative merits in quantitative terms. To do so would require, among other things, a detailed knowledge of the structure and dynamics of the Portsmouth centrifuge plant construction project, which is beyond the scope of the present work. In addition, present uncertainties, especially (but not only) those concerning future separative work demand, prevent precise quantification.

Nevertheless, a rough calculation was performed to compare the impacts of two specific examples of the above strategies on electricity consumer costs during the 15-year period from 1980-95. While little importance should be attached to the absolute magnitude of the results in view of the coarseness of the underlying assumptions, the calculation clearly showed, as would be expected, that the attractiveness of the 'GCEP deferral' case increases relative to the 'GCEP preservation' case as cumulative demand during the period declines.* Of course, as Figure 6.3 illustrates, the cost to the consumer is only one of several criteria that must be weighed in evaluating the alternatives.

Like all policy problems, the characteristics, priorities and uncertainties associated with the problem presented in Figure 6.3 will not be perceived identically by the various individuals and bureaucratic entities influencing the decision process. And, as always, policy will ultimately be determined through a process of

* The 'GCEP deferral' strategy assumed that the centrifuge plant would begin operation in 1992, and would be completed in 1995 (i.e. no credit was taken for the possibility that a more economical process might be available to substitute for the later stages of the centrifuge plant.) It was also assumed that escalation of all factor inputs, including capital, energy, and labor, would occur at the same annual rate, and that the cost of the GCEP plant would be otherwise unaffected by delay. A discount rate 5%/year greater than the escalation rate was chosen. With demand at the level assumed for Case R in Figure 6.2, the 'GCEP deferral' strategy would cost consumers about \$1.5 billion more (in constant 1980 dollars) during the period from 1980-95 than the 'GCEP preservation' strategy. For reference, this is equivalent to an average surcharge of about \$6/swu on enrichment costs during that period. If demand slipped a year, however, the cost increase associated with the 'GCEP deferral' strategy would fall to about \$900 million (\$1980), or equivalently about \$4/swu. At a discount rate of 10% the trend is the same, but the 'GCEP deferral' strategy would be less attractive, resulting in surcharges of \$8.5/swu for Case R and \$5/swu if demand slipped a year. As noted above, the absolute magnitude of these results is less important than the underlying trends.

political adjustment among competing interest groups, in which issues functionally unrelated to the problem at hand may play a significant role. For this reason too, the objective of finding an optimized strategy, the elements of which are spelt out precisely and in detail, should not be overemphasized. A more useful goal is to fashion a common frame of reference for the policy debate, in which differences in underlying assumptions and perspectives are necessarily brought to the surface. That is the significance of the two broad strategies presented above.

In conclusion, we note that many of the arguments against the "GCEP deferral" strategy lose strength as demand growth continues to slip. At the same time, an important element of any overall strategy for the foreseeable future will be to preserve the capability to build commercial centrifuge plants to meet future increases in demand on a timely basis. The demand picture will become somewhat clearer after September 30, 1979, when customer response to DOE's new enrichment contracts will be complete; a policy decision must be taken very shortly thereafter, otherwise much of the flexibility now available will be eroded.

6.3 What are the Appropriate Roles for the Private Sector and the Government in the Development of AIS Technologies, Their Demonstration and Commercial Operation?

This question is particularly apropos in light of JNAI's current role as a leading developer of AVLIS technologies, but it is also of concern regarding plans for the further development and possible commercialization of the government-developed advanced enrich-

ment technologies. The general question of private ownership of course received a great deal of attention during the 'privatization' debate of the first half of the 1970s. A brief summary of that debate provides a useful introduction to the present one.

At that time, the major arguments advanced in favour of private ownership included the following:

- (i) The Government (through the AEC) has a statutory responsibility under the Atomic Energy Act to encourage the development of the civilian nuclear power industry. According to that Act, "the development, use and control of atomic energy shall be directed so as tostrengthen free competition in private enterprise."
- (ii) Safeguards, technology protection and other security measures could be implemented equally well whether enrichment technology and facilities were owned by the Government or by private industry.
- (iii) Private industry would be both technically capable and willing to enter the enrichment sector. Private ownership would eliminate a large appropriations burden from the Federal budget (and as enrichment requirements grew the burden would become much larger). In any case, enrichment was fundamentally a commercial operation in which it was inappropriate for the Federal government to be involved. The annual budget and appropriations process is an obstacle to the businesslike conduct of enrichment operations; enrichment activities compete for funds with the entire spectrum of Government programs, and decisions on allocations involve considerations other than cost minimization.

- (iv) Private sector competition would generate more efficient, productive and reliable technology than a government monopoly.
- (v) Profit-oriented, private entrepreneurs in a competitive market would set prices more efficiently than legislative mandating of price by the government. Also, competition would bring a diversity of marketing approaches, and lower prices and greater diversity would increase the U.S. share of foreign markets.
- (vi) Continued Federal monopoly ownership of the enrichment sector would lead to an unprecedented degree of control over the nation's electrical energy supply system.

Opposed to these arguments were others which generally pertained more to the process of privatization than to the principle of private ownership:

- (i) Technology which had been developed at the taxpayer's expense would be acquired by private industry without adequate compensation. Moreover, the Federal guarantees requested by private industry as a condition of its entry would effectively transfer most of the commercial risks to the government, and thus to the taxpayer.
- (ii) Because of the long payback times associated with commercial enrichment facilities, private owners would tend to protect themselves against technological obsolescence by 'locking in' customers under long-term contracts with heavy termination charges. In such a situation, the opportunities for genuine competition would be greatly reduced.
- (iii) The number of potential private entrants would be quite small, owing to economies of scale favouring relatively large plants.

Again, competitive pressures would be low in such a situation.

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While some of the arguments on both sides of the issue still apply today, the situation has undergone two significant changes. First, neither the Administration nor any other branch of government is openly advocating privatization any longer. With the decision to build the next increment of capacity under public ownership, the Government effectively withdrew its support for private entry into the enrichment industry, at least for the time being. But the issue was only deferred, not resolved; the Government currently has no policy on the question of private entry after the Portsmouth plant.

The second major difference is that there is now a private venture, JNAI, which is contemplating entry into the enrichment sector with a technology developed quite independent of any government assistance, financial or technical. JNAI points out that there are no formal legal barriers to private entry (although any privately owned enrichment facility would of course have to obtain licensing approval from the NRC); nevertheless, corporate officials are admittedly uneasy about the present policy vacuum, especially with the uncomfortable precedent of the AGNS reprocessing facility at Barnwell hanging over the situation.

We make no attempt here to debate the merits and problems of private ownership of enrichment in broad philosophical terms. Our concern is more narrowly with the question of how private participation in AIS technology development and utilization might affect existing and future U.S. policies in the enrichment field. Even more specifically, the analysis deals primarily with the security implications of private ownership. To the extent that economic issues enter the security debate, they will be taken up here. But other economic dimensions of the problem

are not discussed; for example, antitrust issues, which occupied a substantial portion of the earlier privatization debate, are not dealt with here.

* * *

The development and/or commercialization of AIS technologies by the private sector will inevitably reduce the degree of government influence over the direction of the innovation. The question is whether this replacement of Government with private interests will adversely affect the prospects for U.S. nonproliferation policies.

It is important to note that the potential harm is of two kinds: first, the accession of private interests may introduce new policy conflicts or aggravate existing ones, thus making nonproliferation goals harder to attain; second, private ownership, merely by diluting the strength of government influence (and not necessarily by opposing it), may nevertheless hinder the coherent and consistent implementation of U.S. nonproliferation policies.

What would be the extent of Government influence over privately owned AIS technology, and how might it be lacking?

-- Privately owned enrichment facilities would be subject to regulatory review and licensing approval by the Nuclear Regulatory Commission (NRC). National defense and security issues would lie within the scope of the NRC's regulatory authority. Although the NRC has not yet been called upon to license enrichment facilities (the existing gaseous diffusion plants are self-regulated by DOE), and does not now have a comprehensive body of regulation for the task, it is generally agreed that NRC licensing, inspection and enforcement will result in

safeguards and physical security protection of special nuclear material produced by the plant, and protection of the plant itself, at least as effective as the protection provided by DOE for its own plants.⁴

- DOE has responsibility for security measures for protecting classified enrichment technology, whether privately or publicly owned; these measures would be substantially the same for each case.*
- In general, the export of privately-owned enrichment technology and equipment and enriched uranium produced in privately-owned plants is subject to export controls at least as stringent as those applying to government-owned technology and facilities.

Thus in a strictly regulatory sense (and subject to continuing agreement between JNAI and DOE on the question of Restricted Data), private ownership of laser enrichment technology would not be inconsistent with U.S. nonproliferation goals.

Nonproliferation policy involves more than the implementation of formal controls, however, and it may enter into management decisions concerning research and development programs or commercial operations which private interests, if left to themselves, might approach in

* The situation with respect to JNAI is less straightforward. As described in Chapter 5, JNAI has not recognized the right of the government to classify technology developed independently of any government relationship, and has agreed only to subject information that DOE regards as Restricted Data to security safeguards that are equivalent to DOE's requirements for such data. A situation could arise in future in which security protection of JNAI technology was less stringent than DOE requirements for Restricted Data, but in practice this could only occur either with the acquiescence of DOE or following a legal ruling that JNAI's privately developed information

(continued)

largely commercial terms.

With respect to research and development, key decisions affecting the rate or the technological orientation of LIS development might be perceived and resolved differently by the private sector and the government, in part because of the different weights attached to non-proliferation goals in their respective decision-making processes. One such example was raised in Chapter 4, where the adaptability of the JNAI process to the production of highly-enriched uranium was discussed. Resolution of this question would require a substantial experimental effort. The outcome would have little commercial value to JNAI, and the cost would probably provide a positive disincentive for the investigation. By contrast, in a government program the temptation to explore all interesting avenues, not just commercially relevant ones, might be greater, and the budgetary constraints less. In addition, to the extent that uncertainties about process performance at high enrichment levels might themselves contribute to the perceived proliferation resistance of the technology, JNAI might be understandably reluctant to invest a great deal of its own time and funds in eliminating them. On the other hand, from a government perspective the resulting information might have considerable significance for policy. This difference in institutional perspective would be heightened, furthermore, if JNAI was less sanguine about the efficacy of classification restrictions than the government.

(Contd.)

is not Restricted Data and need not be treated as such. Whether JNAI would be prepared to engage in legal proceedings on this issue is not clear. In the case of government-developed LIS technologies that are subsequently turned over to private ownership, this question does not arise.

If, from a non-proliferation viewpoint, there is a value attached to the preservation of uncertainty and another value to its removal, where is the investigative line to be drawn? Intuitively it might be expected that decision-makers responsible for government LIS programs and JNAI corporate managers might differ on the answer, although it is not immediately clear in this case where the advantage would lie for the purposes of non-proliferation.

Other differences seem probable in the sphere of commercial operations. Twice in the past decade the U.S. government has offered to share its enrichment technology with other nations in an attempt to achieve its non-proliferation goal of preventing the spread of national enrichment facilities. On the second of these occasions, Secretary of

State Kissinger sought additionally to use the transfer of U.S. enrichment technology as a diplomatic instrument in securing a greater degree of cooperation on a broad range of energy issues among the industrialized nations.⁵ With private ownership, the government's freedom to use enrichment technology as a diplomatic instrument would be circumscribed. Private industry would have to play a large role in technology transfer arrangements, but would clearly be reluctant to do so if it was required to give up its technology to potential competitors.

(Ironically, it has been suggested that foreign enrichment interests might be more willing to cooperate with private U.S. enrichers than with DOE, whose decisions would be constrained by the annual budget process, legislative oversight, and other political influences.)

Of course, there are other kinds of international cooperative arrangements, falling short of technology transfer, for which private ownership in the U.S. might be no disadvantage at all. These include international rationalization of plans for future enrichment capacity expansions, exchanges of information on markets and investment opportunities, back-up supply plans for new facilities, and internationally coordinated plans for supply emergencies, including joint stockpiles. To the extent that these measures are successful in reducing the centrifugal tendencies in the international enrichment industry, U.S. nonproliferation interests would be served, and private industry would be expected to participate in them just as readily as DOE, since clear commercial benefits would be involved.

More substantially, private ownership of AIS technology could generate nonproliferation benefits if it were to enhance the competitive position of the U.S. in the international enrichment market through more

efficient pricing and a greater variety of contractual arrangements. While the direct influence of the government over U.S. commercial enriching operations would be reduced, the nonproliferation 'leverage' provided by its export controls could be strengthened if the U.S. market share was to grow.

In this sense, the private ownership issue adds yet another variation to a familiar tension in U.S. enrichment politics: will U.S. competitiveness in the international market (which might be reinforced by private ownership) or U.S. offers to share its technology with other nations (which private ownership might obstruct) be the more effective instruments in the conduct of U.S. nonproliferation policy?

The question is clearly an oversimplification of the problem, but in its simplism it brings to the fore a difficulty which has plagued previous debates of the privatization issue. Private ownership is an institutional state, and may be discussed as such, but what is at least as important as the state itself is the process of achieving it. The transition will take time, and will itself become part of the policy environment. In particular, the nature of the transition will color views of the desirability of the final outcome, just as it did earlier, when private sector demands for government financial and other guarantees to negotiate the transition helped to undermine political support for the privatization goal.

Thus a general examination of the merits and disadvantages of private ownership, even within the narrow context of the advanced enrichment technologies, must be supplemented with an analysis of how the transition might be accomplished. For this purpose, the JNAI issue should be separated from the question of the appropriate institutional

structure for commercialization of the government-developed technologies. The distinction is made not because of technical differences between government and private sector programs, but rather because the two issues raise quite different policy problems.

JNAI: There is no apparent reason why the JNAI LIS program should be prevented from proceeding on non-proliferation policy grounds.

Politically, such a step would be difficult to justify if similar government programs were permitted to continue, and in the first section it was argued that U.S. non-proliferation interests would not now be served by a decision to terminate LIS development programs generally.

More concretely, there is nothing in the previous analysis to suggest that the continuation of the JNAI program would be necessarily prejudicial to U.A. non-proliferation objectives.

First, it was noted above that there may be instances in which JNAI would not generate non-proliferation related process information on its own initiative that would be of interest to the government. Such information might, for example, be useful to the government in its efforts to achieve international agreement on export controls to be applied to enrichment technology and equipment. (As noted in Chapter 4, the London Suppliers Group guidelines currently contain no specific reference to laser enrichment technology.) Preventing further private sector development on these grounds would be an unnecessarily drastic response, however. Institutional arrangements could be devised which would permit the development and communication of this information on a basis acceptable to both the government and JNAI. For example, the government could pay JNAI to develop the information, which could then be classified, thereby protecting JNAI's proprietary interests. Such arrangements might be implemented as a supplement to one or other of the existing

channels between the two, i.e., involving the Division of Classification and Security of DOE or the NRC. Alternatively, a new institutional link might be established. In either case, concern expressed by JNAI over the consequences of greater Federal involvement in its program would be tempered by the knowledge that the increased flexibility of government action would be better matched to its requirements and goals, and would thus reduce the risk that the government would be constrained by the limited range of its policy instruments to react excessively harshly towards JNAI in the future.

Second, as shown previously, government safeguards, security, and export controls for JNAI-owned enrichment facilities and the material produced in them would be essentially no less broad in scope and no less stringent than the equivalent controls for government-owned plants. To be sure, the operators of privately-owned plants might be expected to have greater incentives to evade these controls than government contractors, but the penalties for violation might correspondingly provide stronger disincentives. In any case, the inherent effectiveness of the controls would be unchanged. And a decision to withdraw the rights of JNAI to develop its technology independently on the presumption that the company would act illegally in the future seems far-fetched and would certainly be difficult to justify.

Third, although the fact that the JNAI process is being developed in the private sector and not by the government reduces the likelihood that it would be featured in international technology transfer arrangements, the government is developing its own technology which could be applied to such ends. The freedom of the government to enter into these arrangements would not appear to be significantly constrained by the

existence of the JNAI process in the private sector, (although if AVLIS technology were selected by the government for this purpose, JNAI's strong patent position might entitle it to substantial royalties from the international enterprise.) In general, the ability of the government to initiate or participate in international cooperative arrangements in the enrichment sector would be largely unimpaired by the successful commercial operation of JNAI technology in the private sector.

Thus, on the basis of national security and non-proliferation policy considerations, there appear to be no outstanding reasons why the JNAI AVLIS program should not be allowed to proceed.*

Government AIS Program: At present, the government has no clear policy on the appropriate institutional arrangements for commercialization of the advanced enrichment technologies whose development it is now supporting. Several alternatives are possible: at one end of the spectrum is the existing organizational structure, in which technology development and commercial plant design, construction and day-to-day operation are performed by private firms under contract to DOE, with the latter retaining responsibility for management policy, subject to Congressional approval. Alternatively, the technology could be completely turned over to private ownership prior to commercialization, and the private sector would be fully responsible for all phases of the design, construction and operation of commercial facilities. Several intermediate possibilities have been suggested in the past, including a government corporation of the TVA type.⁶

* Of course, a JNAI-owned commercial enrichment facility would also have to satisfy a wide range of other Federal requirements, none of which are considered here. We make no attempt to evaluate, for example, the antitrust implications of a single private venture operating in parallel with the government enrichment complex.

The national security and non-proliferation policy implications of private ownership discussed here are in fact only a few of the many factors having to do with economic feasibility and political acceptability that will together determine which of these various approaches is ultimately chosen. Moreover, the choice may be made as part of a comprehensive new institutional strategy for the entire DOE enrichment operation, including the existing plants. (And even without such a strategy, the chosen approach for the advanced enrichment technologies must be compatible with the existing institutional structure.)

As the previous discussion has shown, from a strictly regulatory perspective, the transfer of government advanced enrichment technology into the private sector would not be expected to damage U.S. non-proliferation interests, given current laws and policies concerning safeguards, security and export controls. Moreover, as before, institutional arrangements could be devised under which the government could request the development and/or communication of technical information useful for its non-proliferation policy function, provided proprietary information could be protected satisfactorily. Thirdly, the economic competition stimulated by privatization could increase U.S. control over the international enrichment market.

In these respects, therefore, privatization of government AIS technology would not be prejudicial to U.S. non-proliferation goals, and could conceivably support them. In other respects, however, privatization could be harmful.

Assignment of the rights to the technology to the private sector might constrain the ability of the government to use U.S. technological pre-eminence as an incentive to persuade other governments to engage in multinational enrichment ventures rather than constructing indigenous

facilities. To be sure, enrichment technology transfer would run counter to the current U.S. embargo on such exports, but whether that policy will still be in effect in a decade, when one or other of the advanced enrichment processes might be available for such purposes, is unclear. On two previous occasions, enrichment technology transfer initiatives by the U.S. government have been unsuccessful, in part because of parallel attempts to implement privatization policies. There are inherent tensions between the goal of privatization and the use of enrichment technology as an instrument of foreign policy, but it is not now possible to predict whether the latter will be a sufficiently important element of U.S. non-proliferation policy in future years to justify retaining the technology under government ownership.*

Another reason for not seeking privatization would be if, as a consequence, the security of supplies to existing enrichment customers was threatened. We have observed earlier that fuel supply security concerns will probably be permanently alleviated to a degree with the emergence of several major enrichment suppliers around the world. Nevertheless, hesitation in implementing privatization policies (caused, for example, by the reluctance of private industry to commit the necessary funds) would be damaging to the U.S. position in the international market, and under certain circumstances could generate more widespread instabilities even in the more diversified market of the future; for example, if the privately owned advanced enrichment plant(s) were to take the place of just-retired gaseous diffusion capacity. A resurgence of market instability could once again strengthen incentives to acquire independent national enrichment facilities.

* However, a successful example of a joint multinational¹ venture involving private and public ownership is provided by Intelsat.⁷

Conclusion

The question of private ownership of enrichment technologies was dealt with here only in the context of its implications for national security and non-proliferation. A great many other issues of importance thus went unexplored. Furthermore, there was no attempt to approach the question from the perspective of JNAI corporate planners.

Even within this narrow context it was concluded that the dynamics of the transition to private ownership are at least as important as the implications of the final state itself. It is necessary, therefore, to separate the question of the future role for the JNAI AVLIS program from the question of the appropriate institutional structure for commercialization of the government-developed advanced enrichment technologies.

Based on national security and non-proliferation policy considerations alone, there are no outstanding reasons why the JNAI AVLIS program should not be allowed to proceed to commercialization, provided that mutually satisfactory provisions for information transfers between the firm and the government can be made.

The government currently has no policy on the appropriate institutional arrangements for the commercialization of its advanced enrichment technologies. While transfer of its technology to the private sector would not necessarily be inconsistent with current U.S. non-proliferation policies, under certain circumstances such a process could be prejudicial to U.S. non-proliferation interests. These circumstances include an increased emphasis in future U.S. non-proliferation policy on enrichment technology sharing arrangements with other nations, and a delay in construction of new enrichment facilities owing to the reluctance of private industry to invest the necessary funds.

6.4 Summary of conclusions

In the preceding chapter we have addressed three policy questions:

- Should existing LIS development programs be continued?
- What is the optimal development strategy for the LIS technologies?
- What are the appropriate roles for the private sector and the government in the development of these technologies, and in their potential demonstration and commercial operation?

The following conclusions have been reached:

LIS development in the U.S. should be pursued vigorously.

U.S. non-proliferation goals would not now be served by a decision to halt LIS development. The reduction in international availability of the technology that could be expected from such a step seems marginal, whereas a potentially important new opportunity for the U.S. to influence the future evolution of the international nuclear fuel supply system would be foregone as a result. Furthermore, the successful commercialization of laser enrichment technologies in concert with other uranium-conserving modifications to the once-through fuel cycle would ease significantly the pressure on world uranium supplies, and the strength of international incentives to establish commercial plutonium fuel cycles might therefore be reduced. Finally, quite apart from the implications for international security, there are presently strong economic incentives for proceeding with LIS development. For all these reasons, U.S. LIS programs should be pursued vigorously.

The recent emphasis on tails stripping as the primary goal of U.S. AIS development programs should be modified. There is a growing possibility of direct economic competition between the later stages of the Portsmouth

gas centrifuge plant and the advanced enrichment technologies. This possibility should be recognized explicitly in U.S. enrichment policy.

Recent reductions in the expected demand for separative work suggest that a further delay in the construction schedule for the Portsmouth gas centrifuge plant (GCEP) may be warranted. At the same time, the possibility that one or more of the advanced enrichment technologies may compete with the later modules of the GCEP (or conceivably the whole plant) has increased. The current U.S. AIS program should be reoriented so as to give higher priority to developing a process (or processes) capable of competing directly with the centrifuge technology. A longer period of technological competition between the three AIS processes may also be appropriate. In general, AIS program planning should be more closely integrated with the other elements of U.S. enrichment policy. A premature commitment to the Portsmouth centrifuge plant should be avoided, although the capability to build commercial centrifuge plants to meet future demand increases on a timely basis should be preserved.

Private ownership of advanced enrichment technology and plants would not be fundamentally inconsistent with U.S. non-proliferation policy goals.

At present, the government has no clear policy on the question of private investment in the enrichment sector beyond its own commitment to construct the next increment of U.S. capacity. Policies must be formulated with regard both to the JNAI venture and to the institutional arrangements for the further development and possible commercialization of the government-developed advanced enrichment technologies. Non-proliferation considerations are an important, although not a unique determinant of these policies. Based on national security and

non-proliferation grounds alone, there are no outstanding reasons why the JNAI AVLIS program should not be allowed to proceed to commercialization, provided that mutually satisfactory provisions for the transfer of technical information between the firm and the government can be made. Transfer of government advanced enrichment technology to the private sector would also not necessarily be inconsistent with current U.S. non-proliferation policies, although under certain circumstances such a process could be prejudicial to U.S. non-proliferation interests. These circumstances include an increased emphasis in U.S. policy on enrichment technology sharing arrangements with other nations, and a delay in the construction of new enrichment facilities owing to the reluctance of private industry to invest the necessary funds.

Notes to Chapter 6

1. See, for example, the recent controversy surrounding the attempted publication by the Progressive magazine of an article disclosing supposedly classified details of thermonuclear weapons design. For a review of the legal issues underlying the Progressive case, see: Anthony Lewis, "New Hearing, New Wrinkles in Appeals on H-Bomb Case", The New York Times, Sunday, 16 September 1979, 20E
2. W.N. Thomasson and A.P. Litman, "Environmental Development Plan for the Advanced Isotope Separation Program (Revision 1)," U.S. Department of Energy, March 1979.
3. For some time, there have only been four prospective centrifuge suppliers for the Portsmouth project. Very recently, the number dropped to three, when a contract proposal by Exxon Nuclear Company was turned down by DOE. (See Energy Daily, August 7, 1979.)
4. See, for example, U.S. General Accounting Office, "Evaluation of the Administration's Proposal for Government Assistance to Private Uranium Enrichment Groups", Report to the Joint Committee on Atomic Energy, RED-76-36, (Washington, D.C.: Government Printing Office, 1975.)
5. For a discussion of these technology transfer initiatives, see E. Wonder, Nuclear Fuel and American Foreign Policy, (Boulder, Colorado: Westview Press, 1977).
6. See the U.S. GAO report cited in note 4.

7. Eugene B. Skolnikoff, The International Imperatives of Technology,
Research Series no. 16, Institute of International Studies,
University of California, Berkeley, 1972

CHAPTER 7

AFTERWORD

The preceding assessment has focused quite narrowly on a particular class of technologies. Nevertheless, it has touched upon several issues and problems whose significance extends far beyond the realm of laser enrichment policy. These include, for example:

- (i) the general problem of managing long lead-time technological innovations under rapidly changing and unpredictable economic, political and institutional conditions;
- (ii) more specifically, the impact of the especially volatile political climate for nuclear energy on decision-making in all sectors and phases of the nuclear power industry, from uranium production to nuclear waste management, and from exploratory research to commercial operation;
- (iii) the question of 'institutional choice' with respect to research and development in the United States, and in particular the appropriate roles for Government laboratories and private industry;
- (iv) policy conflicts among nations over the relative priorities to be attached to the desire for nuclear fuel supply autonomy and the fear of an uncontrolled spread of nuclear weapons capabilities, if not of weapons themselves;
- (v) the relative weight to be given to technical and institutional nuclear fuel cycle 'fixes' on the one hand and political measures on the other in the development of non-proliferation policy;
- (vi) more generally, the balance to be struck between short-term efforts to shore up the existing non-proliferation regime and longer-term,

more radical measures directed towards the underlying causes of conflict within and among nations;

- (vii) and more generally still, conflicting perceptions of the fundamental nature of technology, as an instrument of social progress or a source of social ills.

As a postscript to this assessment, we briefly address two such issues, which, although diverse, are nevertheless linked by much more than just the question of laser enrichment technologies. First, we take up the general question of the evolving U.S. role in the development and application of civil nuclear energy throughout the world. Second, we attempt to extract from the preceding assessment some modest insights into the general process of technology assessment.

7.1 The United States and the International Nuclear Order

The first phase of LIS technology development in the U.S. has coincided with a period marked by rapid changes, an erosion of confidence, and sometimes outright confrontation in relations between nations concerning the peaceful uses of nuclear energy. Many of the tensions can be traced, at least in part, to the emergence of new foci of technological and industrial capabilities in the nuclear field. After a quarter of a century of largely unchallenged U.S. dominance, the international nuclear order within the last ten years has come to be characterized by a much greater degree of multipolarity. As a result, U.S. nuclear policy has entered a period of uncomfortable reassessment, and the U.S. government is now groping its way towards a new role in international nuclear affairs.

The success of this process will depend on the ability of U.S. policymakers to gauge the extent and the limits of U.S. power and influence in the international nuclear field. In turn, the success of this task will depend heavily on a clear recognition of the importance of foreign percep-

tions of U.S. policies and actions, and an understanding of how these perceptions are shaped. By now almost a cliché, it is nonetheless still true that perceptions acquire their own reality. And, of course, the reality becomes more important as the ability to act upon it increases.

Historically, U.S. influence over the direction of technological innovation and industrial development in nuclear energy overseas has been motivated by three underlying goals: simply stated, the pursuit of commercial gains to the U.S. nuclear industry and of economic benefits to the nation as a whole; the prevention of nuclear proliferation; and the maintenance and strengthening of U.S. prestige abroad.

Several kinds of policy instruments have been applied to the pursuit of these goals, including a variety of measures not directly related to nuclear energy. In the nuclear field, domestic technological and industrial strengths and financing capabilities have enabled the U.S. to provide vital strategic support to the nuclear power development programs of other nations, often with major benefits to domestic industry. In addition, export controls and conditions of assistance have served U.S. security and economic interests. And in recent years, the U.S. has sought to influence the nuclear policies of other nations through national technological abstentions, most notably in the area of nuclear fuel reprocessing.

The relative emphasis given to these various instruments of U.S. policy has not always remained the same. The pendulum has swung from near-total secrecy and exclusion in the immediate post-war years to the enthusiastic promotion of international cooperation and technology transfer in peaceful nuclear applications sparked by the Atoms for Peace program of 1954, and then back to a more restrictive set of nuclear policies in the last five years.

A long-running domestic political debate has focused, with fluctuating strength, on the question of where the pendulum ought properly to be. In recent years, as first the Ford and then the Carter Administrations, aided and sometimes led by Congress, have sought to augment U.S. export controls and generally to strengthen the barriers against nuclear weapons proliferation, the debate has intensified. Proponents of the new policies have stressed the need for U.S. leadership in developing new, more stringent non-proliferation controls on international nuclear commerce and in bringing about a deferral (and preferably, for some, an abandonment) of the transition to plutonium fuel cycles, while opponents have argued that U.S. power to influence the nuclear policies of other nations is limited, that the new policies of the U.S. are overly repressive, that at best they will fail and at worst they will catalyze the developments that they were designed to avert, and that cooperation in development rather than restriction or confrontation is the best way to realize U.S. objectives, in both the non-proliferation and economic spheres. An often-used and not inappropriate metaphor for the controversy has been that of carrots and sticks, with the latter faction urging that more nuclear carrots are necessary, and the former favouring greater use of the stick.

This debate, and its predecessors over the last 25 years, have all rested on a foundation of U.S. technological supremacy and industrial strength in peaceful nuclear applications. Without this pre-eminence, such debates would have been largely irrelevant: international cooperation in the development of nuclear energy would have been an ineffective policy instrument because the U.S. would have had little to offer in return for its insistence on adherence to non-proliferation controls; on the other hand, the effect of imposing more stringent export controls would also have been inconsequential, since the flow of U.S. nuclear goods and services overseas would have been small in any case.

The importance of U.S. technological and industrial power to its international nuclear policies has been acknowledged so often during the last 25 years that it long ago became almost too obvious to mention in policy debates, an unchanging part of the policy scenery, as it were. It is perhaps for this reason that its dissipation, actual and potential, has failed to attract the attention that a process of such importance undoubtedly deserves. For in the last several years a combination of two separate, powerful forces has gradually and with little fanfare undermined U.S. leadership in civil nuclear power to the point at which, almost without warning, the whole foundation of traditional U.S. international nuclear policies has been thrown into question.

First, it has already been noted that the growth of national nuclear technological and industrial capabilities overseas has ended the era of virtual monopoly power for the U.S. and led to an increasingly polycentric international nuclear order. These developments have also aggravated long-standing tensions in U.S. policy to the point of incoherence - the incoherence, as Stanley Hoffman has observed, of unilateralism versus internationalism.¹ While on the one hand the U.S. has sought to cooperate with the other advanced nuclear nations in the development of new non-proliferation controls (in the London Suppliers Group forum) and with all other nations in developing new international technical and institutional arrangements for the future development of nuclear power (in INFCE, the International Nuclear Fuel Cycle Evaluation), on the other hand the Nuclear Non-Proliferation Act of 1978 contains unilateralist export controls of unprecedented stringency. The Act has already taken its toll on U.S. relations with many of the countries with which it is trying to cooperate, including the nations of the European

Community, Japan, and India. And more difficulties arising from this legislation are certain to follow.*

But apart from the diffusion of nuclear technological capabilities to many nations, and the rise to nuclear industrial power of some, an even more fundamental threat to the traditional conduct of U.S. international nuclear policy is coming from within. The once commanding partnership of government and industry which established and reinforced the position of the United States in the vanguard of international nuclear developments has fallen into disarray, and is in retreat on several fronts. For the government, other energy sources have begun to compete increasingly vigorously with the nuclear program for Federal research and development funds, a trend which has emerged in a time of wider fiscal restraint, while more generally a position of overt support for the domestic nuclear option is now perceived as being too costly politically to be worthwhile; under the Carter Administration, ambivalence towards nuclear power has effectively become institutionalized. The nuclear industry, deprived of traditional government support and facing what appears to be an increasingly hostile public, is less willing to make long-term investments; indeed, firms in several sectors of the industry are re-evaluating their nuclear-related activities with a view to reducing their scope, or even withdrawing from

* Future historians may very well identify the Nuclear Non-Proliferation Act as the swansong of the era of unilateralism in U.S. nuclear policy. Although it is still too early to be certain, the Act seems likely to accelerate the erosion of unilateral U.S. control over the nuclear fuel cycle practices of other nations that it was actually intended to strengthen.

them altogether. And for similar reasons the utilities, whose commitment to nuclear power was the sine qua non for the development of the U.S. nuclear industry, has virtually ceased ordering new power plants. How long this de facto moratorium will last is presently highly uncertain. But the stark fact remains that without a dynamic domestic nuclear power sector, the whole basis of traditional U.S. international nuclear policy, in its various shades and ramifications, is undermined. In the long run, the significance of the Ford-Carter decisions to defer domestic spent fuel reprocessing may be less that they established a precedent for allowing domestic nuclear power policy to be determined by external non-proliferation objectives than that they marked formally the onset of a period of nuclear technological retrenchment in the United States, a retreat from what has increasingly come to be perceived in domestic political terms as the treadmill of world technological and industrial leadership in civil nuclear energy.

Interestingly, the coalition between the environmentalists and the arms-control community which proved to be so effective in the debate over domestic U.S. reprocessing in the mid-1970s may prove to be quite short-lived. Indeed, there are already some signs of divergence (although not of dispute). Earlier, important support for the restrictive and abstentionist elements of U.S. non-proliferation policies had come from domestic anti-nuclear groups, which saw such actions as strengthening anti-nuclear factions in foreign nations, and thus bringing about a change in their policies of increased reliance on nuclear power. Now, while many environmental groups are concentrating on limiting the lifetime of the nuclear power option in the United States, non-proliferation advocates have become immersed in the intricacies of export controls and international institutional arrangements, with U.S. policy officials seeking room for manoeuvre in a highly constrained

environment, bounded by the rigours of the Nuclear Non-Proliferation Act on one side, the announced policies of other nations on another, and the declining power and influence of the U.S. on a third.

But the stratification of the domestic and foreign policy debates masks a crucial fact: that recent and expected future developments in the domestic nuclear sector of necessity will shift the locus of U.S. non-proliferation policies away from the present emphasis on nuclear fuel cycle controls, a shift which, ironically, many of those opposed to the current U.S. strategy have been attempting to obtain all along.

Possible new directions seem to be in short supply. With a few small exceptions the Carter Administration's initial attempts to find and promote economically attractive, more proliferation-resistant new fuel cycle systems as alternatives to the conventional plutonium cycle have largely petered out. On closer inspection, most of the alternatives have few advantages from a non-proliferation point of view, and many economic disadvantages; moreover, even had the search been successful, the preceding discussion suggests strongly that the U.S. nuclear industry, in its present torpid state, would have been either unwilling or incapable of undertaking the substantial development efforts required to achieve commercial feasibility.

In principle, the U.S. could exert influence over foreign nuclear programs by offering attractive new non-nuclear energy technologies, and in the long run this could conceivably occur. As a source of influence in the near term, however, the opportunities seem very limited; indeed, the most graphic example currently offered by the U.S. to the rest of the world in the non-nuclear energy sector is its vast consumption of scarce fossil fuel resources, an example that other countries will do well to avoid, and

which is generating increasing hostility towards the U.S. throughout both the developed and developing worlds, with U.S. demands on the world petroleum market increasingly perceived as the primary source of the current world energy crisis.

Nevertheless, at least as far as proliferation is concerned, it is in areas outside the nuclear power field that the U.S. will probably draw most of its influence. Security guarantees; mutual defense pacts; conventional military assistance; concerted superpower pre-emptive action; to the extent that they are practical, these are the kinds of policy measures upon which the success of U.S. non-proliferation policy will increasingly come to depend. And if, in the present period of declining confidence in the reliability of American security guarantees and of what is perceived overseas as a growing reluctance on the part of the United States to act decisively in regional conflicts, this seems a frail thread on which to hang such momentous goals, it also underlines the need for new, internationalist approaches to the problem of proliferation. As the unilateral power of the United States fades, the need for a strengthened international consensus against the spread of nuclear weapons grows. There, too, the U.S. role is circumscribed, but this time by its status as a nuclear superpower. Just as domestic political disputes have interfered with the ability of the U.S. to retain its leadership role in civil nuclear power, its massive and growing nuclear armament will surely inhibit its role in efforts to build an international consensus against nuclear proliferation. A strong and sustainable international consensus will be impossible unless it is based on a commonly held set of values opposed to the existence of nuclear weapons. But the sharing of such values by the United States is fundamentally untenable, and will be regarded

as such by the rest of the world. U.S. non-proliferation policy is a prisoner of the U.S. role as a superpower. Stripped of its moralistic overtones, U.S. non-proliferation policy boils down, in practice and in overseas perception, to an attempt to preserve existing power structures, to preserve the international status quo. Yet in the long run, the success of efforts to prevent the further spread of nuclear weapons will ride on the very antithesis of U.S. motivations; stated differently, and with apologies to H. Alfven, nuclear non-proliferation and nuclear disarmament are Siamese twins. It is in this paradox that the ultimate source of the limits of U.S. influence is to be found.

7.2 The process of technology assessment

Taking a cue from an authoritative early study of the process of technology assessment by the National Academy of Sciences,² it must first be noted that the preceding assessment started out from one particular point, out of several possibilities. That is, the assessment began with a cluster of related new technologies and sought to explore the political and economic consequences of their continued development. The Academy study noted that in addition to such a technological focus, alternative starting points for assessments include the environment (or some segment thereof), society (a social system or relationship, for example), and the individual. In the end, the NAS study opted for a mixed approach, with several focal points. To the extent that the present assessment had too narrow a technical focus, the conclusions presented here will have a correspondingly limited application.

First, the observation made at the outset, in Chapter 1, can be confirmed in retrospect: there can be no useful prescriptions for tech-

nology assessment. To be sure, certain themes and objectives must be common to all assessments: for example, the need for broader perspectives; the emphasis on the preservation of future options; the need to deal with the problem of decision under uncertainty; the proper degree of public participation. But to prescribe in further detail is not useful. The structure of this assessment was determined by the nature of the particular set of problems in question, not by a pre-determined methodology. The same will be true of any innovation which raises more than the most insubstantial set of problems.

The second conclusion relates to the timing of assessments. Here there is always a trade-off. The earlier in the process of technological innovation that the assessment is undertaken, the greater is the uncertainty, and the greater the likelihood that the results will be misunderstood, distorted, or simply ignored. On the other hand, beyond a certain point, the assessment will come too late; interests associated with various aspects of the innovation will become entrenched, and the political or economic costs of changing direction will become too great.* On balance, the dangers of the latter outweigh the risks of the former. There is always a chance that misunderstandings and distortions can be cleared up, and that apathy can be cured; but the consequences of delay are frequently irreversible. Moreover, delay in undertaking detached assessments leaves the field open to the already committed. As the Academy study warns, "only the contending interests of those who already recognise their stake

* A variation of this problem was encountered in the present study. Here, one of the dangers is that by delaying the assessment of LIS technologies (and advanced enrichment technologies in general) for too long, the commitment to the Portsmouth gas centrifuge plant could become effectively irreversible, and an important area of policy flexibility would then be lost.

in the technology and are prepared to enter the public arena to defend their position find their way into the legislative and appropriations processes."³ The result is frequently a debate that is polarized from the start, a debate in which the contribution of assessments whose goal is to be as objective and neutral as possible may be lost from view completely. For all of these reasons, therefore, assessments of new technologies should be undertaken as early in the innovation process as is reasonably achievable.

Like the innovation process itself, the process of assessment is a process of successive approximation. Indeed, the process of assessment should properly be considered as an integral ingredient of the innovation process. During the course of an innovation, not only will more technological information become available, but the external environment will evolve: uncertainties will be resolved and new ones will appear; the economic climate may change, and new policies may be implemented; political and economic relations between nations may be altered; underlying social values may be transformed. Clearly, no single assessment can provide the last word. Continuous assessment is necessary to ensure that all such developments are properly accounted for in the innovation process, and in the evolution of the associated institutional supporting structure.

A third issue, which is linked to the question of timing, concerns the problem of uncertainty, and how to deal with it in assessments, and in the policy derived therefrom. The problem of uncertainty becomes more acute when, as is the case in the present assessment, the innovation is a large technological system, with large investments required for research and development, long lead-times for commercialization, and an extensive

institutional supporting structure. For such innovations, the institutional supporting systems tend to be monolithic, almost by definition; frequently the government plays the dominant role. Here, a heterogeneous mix of views of the future, which might otherwise provide an implicit mechanism for accounting for uncertainty, is often not a natural or a feasible characteristic of the decision process. On the contrary, monolithic supporting systems foster an internal uniformity of view. With survival and continuity of development funding frequently the primary objectives of those with immediate responsibility for the technology, diversity and flexibility of assumption are not encouraged; internal consistency becomes a more highly valued asset, and there is a tendency on the part of decision-makers to seek to shape the external environment so as to coincide with their own views of what it should be, rather than vice versa.

These institutional tendencies add significantly to the inherent rigidity of large-scale technological innovations, and to their vulnerability in periods of rapid external change. There is thus an important role for the assessment function in ensuring that real uncertainties which might otherwise be assumed away or ignored are introduced explicitly into the decision process.

The present assessment focused mostly on two kinds of uncertainty which, despite being very closely related, nevertheless enter into the decision process in quite different ways. The first kind included those uncertainties associated with the level of future demand for enrichment services; as was shown, a reduction in the expected demand could have major consequences for the direction of U.S. enrichment policy, but many uncertainties currently obscure the demand picture.

The second class of uncertainties included those that external actors perceive to be associated with U.S. government actions and policies; the significance of these uncertainties is in how they affect the behaviour of these actors - individuals, corporations, nations, international organizations - and what the consequences of their reactions are for U.S. policies. Thus, for example, we have shown how indecisiveness and a lack of clear priorities have caused other nations to lose confidence in the reliability of the U.S. as a supplier of nuclear fuel; how the possibility of future unpredictabilities in U.S. policies and actions is currently a source of concern both domestically (to JNAI) and overseas (to actual and potential enrichment customers); and how basic U.S. policy goals have suffered in the past and may suffer in the future as a result.

These various uncertainties feed upon each other and upon the larger set of uncertainties which currently surround the nuclear option in the U.S. No amount of assessment will resolve any of them completely. But in this respect two limited goals of the present assessment are worth emphasizing: one was to place realistic bounds on the uncertainties flowing into the decision process (such as, for example, the demand for separative work); and the other was to gain a clearer understanding of the impact of uncertainties flowing outward from it. In certain circumstances, inherent uncertainties may be aggravated by policy decisions and actions rather than alleviated by them. To use a simple physical analogy, technology assessments should help to ensure that technology policies dampen rather than amplify the instabilities in the system arising from uncertainty.

The problem of how to deal with uncertainty is closely related to the principle of preserving future options to the greatest possible

extent. Aside from the inherent appeal of this principle, it is clearly a logical response to present uncertainties. For a technology still in the development phase which is suspected of possibly deleterious secondary and tertiary consequences, one of these future options is, of course, not to deploy it widely. Once again, however, complications arise from the nature of the institutional supporting systems for large-scale technologies. In this case, there is an increased risk that political and institutional momentum will accumulate prematurely to the point of irreversibility. Thus, another important role for the assessment function is to identify in advance points of potential irreversibility in the innovation process, and the characteristics of the institutional supporting system which might be responsible. One such example that emerged in the present assessment was the possibility that an irreversible commitment to building the Portsmouth centrifuge plant could be made before it was either prudent or necessary to do so.

This discussion is consistent with a more general point which emerged during the present assessment and which the Academy study articulated ten years earlier. The nature of the institutional supporting system, as well as the technology itself, is an essential element of technology assessments, and frequently the principal target of policy.

The penultimate conclusion concerns the question of the appropriate scope for assessments. As with the issue of timing, there is a trade-off: here, it is that of breadth versus depth, or, in more pejorative terms, superficiality versus narrow-mindedness. The exact dimensions of this trade-off obviously will depend on the resources available for the assessment, and prescriptions here, as elsewhere, are impractical. Nevertheless, on balance, the evidence provided by the present assessment points to the

need for an emphasis on breadth, even if some superficiality is unavoidable. It is easier to add more detail to an existing framework at a later date than it is to graft on whole new facets of the problem. To the extent that technology assessments serve fundamentally as catalysts for policy debate and formation rather than as substitutes for it, holism more than precision must be the primary goal. As a corollary, assessments which do focus only on certain facets of the overall problem, for whatever reason, should be accompanied by statements defining the limits of inquiry as clearly as possible.

There is also another side to the question of scope. In addition to seeking the maximum feasible breadth of analysis, it is also desirable to compare the innovation in question with other technologies and supporting systems, with a view to identifying similarities and differences in policies and consequences.

The final point concerns the proper degree of public participation in the assessment process when, as in the present case, information concerning the technology in question is subject to classification restrictions. We make no judgements on the need for classification or its efficacy in this case or any other. We note, however, that even in the case of laser enrichment, where most technological data are closely held, it has proved to be possible to discuss several issues of considerable importance for national policy in some depth on a wholly unclassified basis. The government itself has made no significant effort to conduct an unclassified assessment of these issues, and has not sought a public debate on the subject. This is not surprising, since in this case, as in others, those with access to the information are generally those who are identified with existing policies, and for them there can be few incentives and probably positive disincentives

to encourage broader debate. But as we have argued in the Introduction and also here, there is a clear need for such debate, beginning as early in the development process as possible. The stimulus will generally have to come from outside the government (or at least those parts of the government most closely involved in the development). What the present assessment has sought to demonstrate, in this broader context, is that such efforts are not only necessary to stimulate debate, but can also contribute materially to its progress. The present assessment in part was stimulated by and benefited considerably from earlier assessments of the same subject, and it is the author's hope that the future assessments that will certainly be required in this field will be served by the present one in the same way.

Notes to Chapter 7

1. Stanley Hoffman, "The Perils of Incoherence", Foreign Affairs: America and the World 1978, 57 (3), (1979), 476
2. Report of the National Academy of Sciences, Technology: Processes of Assessment and Choice, Committee on Science and Astronautics, U.S. House of Representatives, July, 1969, 8
3. Ibid., 25