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ISSUES IN FEDERALLY SUPPORTED RESEARCH ON ADVANCED AUTOMOTIVE POWER SYSTEMS

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Preface and Acknowledgments

This report is the result of an effort conducted at the MIT Energy Laboratory over the period January to December, 1977. It is based upon research supported by the National Science Foundation under Grant No. PRA-7681015. It follows two reports from a previous grant on similar topics at the MIT Energy Laboratory, over the period June 1974 to March 1976; the relationship of this report to those previously published is discussed in Chapter 1. The Principal Investigator on the present effort was Lawrence H. Linden, a member of the research staff of the MIT Energy Laboratory and a Lecturer in Mechanical Engineering and Management. Subramanyam Kumar and Paul R. Samuelson are graduate students in Mechanical Engineering and Management, respectively, and were responsible for research assistance and much of the writing of Chapters 3 and 4, respectively.

Many individuals from government and industry contributed their time and ideas in discussions with the authors; we gratefully acknowledge their assistance, but retain for ourselves responsibility for any errors. We have also benefited from the sympathetic monitoring of this project by Dr. Ronald M. Powell at the National Science Foundation.

Table of Contents

1. INTRODUCTION

Issues in Energy Conservation R&D

Large scale federal support for research and development (R&D) on energy conservation technologies seems now to be one of the few features of national energy policy upon which there is wide popular support. From fiscal years 1975 to 1978 the federal energy conservation R&D budget increased by a factor of 9, a tremendous rise even by comparison to all energy R&D, which slightly more than doubled (1-1, p. 33). Yet there remain important conceptual and analytical issues which raise serious questions about government policy in this area. This report addresses a number of these questions as they arise with respect to one particular set of energy conservation technologies: advanced automotive power systems.

Some of the key policy questions are the following:

(1) Is energy conservation R&D a reasonable target for expenditure of taxpayers' dollars at all? If our private market system is working efficiently, then, aside from those in fundamental research areas, most worthwhile R&D projects on technologies likely to be utilized within the economic and regulatory environment of the future will be supported by private firms. Thus government funding would either be spent on technologies not likely ever to be introduced into the marketplace, or it would serve principally to merely substitute public dollars for private ones. In the case of alternative automotive powerplants, the vast technical and financial resources of three of the nation's largest dozen firms are potentially available for R&D, and in fact the pace of technology change in the automotive sector is more rapid now than at any time since the introduction of the Ford Model T.

(2) If our economic system is failing to provide sufficient incentives for energy conservation R&D because it is failing to provide sufficient incentives for energy conservation, how should R&D be planned? Federally supported R&D cannot change the behavior of buyers in the marketplace for a new product. However, other government policy measures can. Should federal support go to products whose ultimate acceptance is contingent upon some change in a related price or product regulation which is not under the control of R&D planners? In the automotive case, petroleum product price controls and air pollutant emissions control regulations may be crucial in determining the future viability of some powerplants.

(3) How should energy conservation technologies be valued? Much of present American social attitudes and political behavior with respect to energy policy can be described as attaching an implicit value to energy which is higher than its market price. If this is truly the case, then somehow this social value of energy must be estimated and used in analyses of energy conservation technologies. In the automotive case the value of automobile fuel economy increases should be based on some concept of the social value of automotive fuels.

(4) How should problems of the process of adjusting to new technologies be analyzed and dealt with? Very often technology analysis focuses on the value of a new technology in place in some long-run equilibrium. The technology itself and the related parts of the economic structure are assumed to have materially adjusted to take maximum advantages of the features of the new technology. Whether the system could or would in fact adapt and attain this equilibrium is not

considered. Substantively, the R&D program itself generally does not address the transition problem. In the automotive case, new socially desirable powerplants may be economic only if new fuels and new vehicle structures accompany them into the transport system. But the behavior of the automotive and petroleum industries in providing these important accompaniments is difficult to analyze, at best. Further it is not clear how a federally supported R&D program might deal with this transition problem, or whether it should attempt to.

(5) How can the government arrange its contractual arrangements with industry in order to avoid merely substituting its own dollars for private industry's? Most attractive energy conservation R&D projects will be related to technologies which have at least some market value and thus the R&D itself will be at least somewhat attractive to the relevant private firms. Very often these technologies will be controlled by one or a small number of firms through patents or to barriers to entry. Cost-sharing R&D agreements between the government and the firm will be the logical and mutually desirable outcome in such cases. Two problems will arise. First, only the firm will know with certainty what R&D activities it would undertake without government help. Second, the firm will have better information than the government about the potential future value of the technology. The government will thus be at a substantial disadvantage at the bargaining table. In the automotive powerplant case these problems are quite apparent.

This is hardly a complete set of the important policy analysis issues arising with respect to federally supported energy conservation, but it describes some of the most difficult. The case of federally supported R&D on advanced automotive power systems is in some ways a representative case, and in some ways it is unique. Each of these issues is addressed in this report for that case. The depth of treatment varies from strictly descriptive to somewhat formal analysis, depending on the tractability and importance of the issue.

Contents of This Report and Relation to Previous Work

Over the period June 1974 to March 1976, the MIT Energy Laboratory conducted a study, for the National Science Foundation's Office of Energy R&D Policy, entitled "The Role for Federal R&D on Alternative Automotive Power Systems." The study was conducted in two phases. In Phase I the critical issues were laid out and discussed, the key features of the relevant technologies were described, the various possible objectives for federally supported R&D were analyzed, and the present government and industry programs and policies were discussed and evaluated (1-2).

In Phase II, federal support with the explicit objective of advancing the relevant technology was addressed. This is the most expensive, controversial, and difficult to analyze, of the four possible objectives identified in Phase I. The analysis of the resulting report, "Federal Support for the Development of Alternative Automotive Power Systems," ("Federal Support," 1-3), proceeded as follows. First, the process by which major technological product changes are made in the automobile industry was examined. The general aspects of the federal R&D decision were then addressed, including the question of whether or not federal support is justified at all, and the issues of project choice and program design. A forecast of the advances to be expected in the internal combustion engine (ICE) was made. Finally, the potential federal role in advancing three of the possible alternative power systems -- the Stirling, diesel, and electric systems -- was analyzed (1-3).

The present report builds on and extends the previous efforts in three areas. Each has been made desirable by events and trends occurring over the past two years.

In Chapter 2 below we examine the impact of two changes in the structure of federal regulation on the incentives that the automotive industry has for R&D in this area. The first occurred in December 1975. This was the passage, and signature into law, of the Energy Policy and Conservation Act, which mandates fleet-wide fuel economy standards for the automobile manufacturers. This significantly affects the incentives to the manufacturers to invest in R&D on alternative powerplants. Just how, though, is not immediately obvious. The passage of the Act took place too late to be incorporated into the previous effort. The second was in August 1977, when the Clean Air Act was amended once again, and a new schedule of emission standards became law. The Clean Air Act is one of the major determinants of the extent and direction of R&D in automotive power systems.

In Federal Support (1-3, Sect. 3.2) a detailed analysis concluded that there was solid ground for government support for R&D on alternative automotive power systems due, in significant measure, to the unintended effects of government regulations. They result in a disparity between the social and private benefits of long-range R&D due to: (1) the disparity between the value of automotive fuels and their market price, caused principally by a national goal for security from dependence on foreign supplies not reflected in the market price and government price controls which hold the market price of automotive fuel well below its value to the nation, and (2) the Clean Air Act, which forces the industry to focus its R&D resources on technology available in the very near term, thus reinforcing its natural predilection toward small and evolutionary changes, and which adds risk to long-term investments due to uncertainties in the standards of the regulated air pollutants, the possibility and unpredictable level of standards for presently unregulated air pollutants, and possible government response to the availability of new technology.

The second area of extension in the present report is an examination of federally supported R&D on the automotive gas turbine. In August 1975, the Jet Propulsion Laboratory (JPL) published its comprehensive analysis of the alternative engine technologies (1-4). It recommended a major national effort to develop two "advanced" automotive powerplants, the gas turbine and Stirling systems, with the goal of bringing one or both of them into production by the mid-1980s. Similarly, over the last year, the Department of Energy has begun to focus its attention on these two systems as the most promising for government support. This is consistent with the results of Federal Support (1-3, Chap. 5), which recommended government funding for the Stirling engine, but that study did not examine the gas turbine. Due to project funding limitations, the Stirling engine was chosen to represent the general class of advanced heat engines. In Chapter Three of this report, the previous work is extended to the gas turbine system. In contrast to the JPL analysis, which is principally technological, the MIT analysis focuses on economic, public policy, and organizational issues.

A framework similar to that used for the analysis of the Stirling engine is presented in Chapter 3 for examining the gas turbine. The

Stirling engine work proceeded in the following manner. First, the state of the technology and present R&D programs were examined. Then a simple social cost-benefit analysis for government investment in Stirling R&D was performed. This required simple models of the operating economics of Stirling-powered vehicles, the change of the engine's attributes during the R&D process and the impact of increased investment on the probability of R&D success. The principal conclusions of the social economic analysis were that: (1) the uncertainty in the maximum allowable premium of engine cost over the ICE (for positive total social operating benefits), the engine attribute on which R&D efforts are focused, is about as large as its likely level -- up to 50% or so; (2) the magnitude of the likely total social operating benefits is similarly uncertain, up to several tenths of a cent per mile, thus making cost-benefit calculations extremely tenuous; (3) the status of present R&D programs is such that the incremental impact of government funding on the probability of R&D success is significant; and finally (4) that an investment of several hundred million dollars over five to ten years is likely to be a very good gamble. Next the process by which the Stirling engine would be introduced into commercial utilization was examined; an analysis of the disparities between the economics when examined socially and privately indicated how a socially beneficial engine might not meet private decision criteria, and the implications of this for the government programs were discussed. Finally, the proposal by the Ford Motor Company for support of their Stirling R&D effort was considered and it was concluded that such a shared-cost program was likely to be a good framework for the support of Stirling engine R&D.

The differences in the technological status, and the direction and rate of change of that status, between the Stirling and gas turbine are significant enough that neither the framework nor the conclusion would carry over directly. For example, in contrast to the Stirling, the gas turbine offers a substantial improvement in power density over the ICE. This would seem to indicate that a special vehicle body would have to be developed and produced to take advantage of this property. However, this is not consistent with the normal process of technology development and production in the automotive industry (1-3, Chap. 2). It has implications for the ultimate commercialization of the gas turbine, and is incorporated into the analysis reported here.

Finally, in Chapter 4 below we examine the set of issues of federal research strategy. The previous MIT analysis focused on the issue of whether or not the government should support the development of these systems. Resources were not available for detailed study at a lower hierarchical level of "strategic" decisions -- the number of different types of engines to be supported, the number of different firms to be involved, etc. This set of questions is defined and examined in Chapter 4.

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2. INCENTIVES FOR R&D IN THE AUTOMOTIVE INDUSTRY[1]

As in most other areas of the private economy, the traditional pattern in our society has been to leave to private industry the task of researching and developing new product lines for sale in commercial markets. So long as markets function well, this pattern is rarely questioned, and indeed the great bulk of the R&D carried out in the United States takes place quite outside the direct concern of the Federal Government. However, problems arise when markets do not function properly — when markets "fail." In the most general terms, this "failure" occurs when the social evaluation of the costs and benefits of a particular action are not fully reflected in the private costs and benefits to which corporations and individual consumers respond, i.e. there are "externalities" involved. Where the incentives to private behavior are judged socially undesirable or inadequate, intervention by the government, as the agent of society as a whole, may be called for to correct the imbalance.

It is relatively easy to find some sort of failure in most any market, and there are good arguments (discussed below) as to why the private incentives for the performance of R&D are always inadequate. There is a tendency to cite them in passing and proceed to "justify" government investment in R&D, without examining the government's other, sometimes extensive interventions in a given market and their impact on the incentives for R&D. In this section we therefore undertake an

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[1] In order to provide a presentation here which is fairly complete, some material from Federal Support (2-1, Section 3.2) is repeated.

examination of the possible disparities between the social and private incentives for R&D in the automotive market, including the government interventions presently extant. We will attempt to confine ourselves to those features of the market which are related to R&D on alternative powerplants; e.g., we will not look at other issues such as safety, damagability, support of road construction, etc.

First we will discuss the economies of R&D from the traditional approach of welfare economics. Next, problems of market structure will be examined. However, as important as are the traditional economic arguments under competitive markets or the special circumstances in oligopolistic markets, there is in the automotive case a host of non-market forces that are introduced by government regulation. Three areas of present government regulation are significantly affecting the incentives for R&D in alternative automotive powerplants, and each is examined in turn.

Traditional Economic Arguments

One set of conditions that justifies government intervention in the process of technology development occurs when various "failures" arise in the performance of economic markets, even when those markets are perfectly competitive. For example, certain types of technical developments may have the character of a "public good" where the knowledge, once developed, costs nothing for others to use. Very often in such cases the benefits of such knowledge are "inappropriable," i.e., competitors, or consumers, receive the benefits, and there is insufficient advantage to any one competitor to expend the funds to carry out the technical development. Much of basic research -- which is devoted to the increase of human knowledge rather than the development of specific technological procedures -- has this character, and it is for this reason that a great deal of basic research is justifiably carried out with some involvement of public funds. (It should be emphasized, of course, that a great deal of basic research is supported by private corporations as well). At some level this argument holds for all markets and technologies, and might be cited to support, for example, research on less expensive washing machines. A unique feature of the automotive market, however, is its vast economic size, so that very small changes in automotive technology make very large differences in social welfare when used over the roughly one trillion miles driven annually by the American passenger car fleet. Thus the "public good" argument applies with particular quantitative strength in the automotive case.

The case of advanced automotive power systems offers, we believe, a potentially important case of appropriability difficulties. They are associated with the development of ceramics for use in advanced heat engines. Ceramics have the potential to replace metallic superalloys where a material is required to endure and resist a load at high temperature. If the peak cycle temperature of a heat engine can be raised, it can be made more efficient. Furthermore, ceramic components may be less expensive than their superalloy counterparts. Below in Chapter 3 we will discuss at some length the potentially large benefits of the availability of ceramic components for the advanced automotive engine. However, they will have important and often unforseeable effects in many areas of modern mechanical technology. It seems very unlikely that a significant fraction of the benefits of the availability of high-temperature load-bearing ceramic components can be captured by any present economic decision-making unit short of the nation as a whole. Research on basic ceramics processing, and possibly the development of the related automotive engine technology as well, may be suffering under the usual economic incentives.

Another circumstance that may call for government intervention arises when there are "externalities" of one type or another. An externality occurs when an economic decision-maker -- be he a supplier or consumer -- is not faced with the full costs (or does not receive the full benefits) of the actions he takes. That is, market prices fail to reflect the full range of impacts of a particular decision. A clear example is automotive air pollution, where the operating costs of an "uncontrolled" vehicle did not reflect the damage being done to others through tailpipe emissions; thus clearly justifying some sort of regulatory performance standards, such as those of the Clean Air Act. These regulations deal directly with the pollution externality. They may, or may not, provide an incentive to manufacturers to carry out needed R&D. In the case of the Clean Air Act, the regulations have brought both dramatic reductions in emissions from present automotive systems. However, they have turned out to be very crude instruments from the standpoint of spurring the development of new technology to reduce the externalities. Thus, in spite of the regulation, a sound reason may exist for the involvement of public bodies in research to find ways to reduce the external affects; this will be addressed in more detail below.

Another externality of automotive operation, though less obvious than that involved with air pollutant emissions, is that the present high level of consumption of gasoline (and all other petroleum products) exposes the nation to pressure by the Arab oil producers. That is, there is a value to the reduction of petroleum imports that is higher than the avoided cost of the petroleum itself. Thus the price of automotive fuel is too low by (at least) a "national security premium." One rationale for estimating this premium is suggested in Section 3.4 below. The premium is estimated at 4% of the value of crude oil, or about 1.5¢/gal. Even given that this is an extremely crude approximation, we can conclude that the national security premium is not quantitatively significant.

Still another example of a market failure, though more controversial than the ones above, is that which occurs when the relevant private decision-maker has a degree of risk aversion which is significantly different from that of the society at large. In essence, the government is capable of spreading the risk of particular technological experiments over a very large pool of alternative activity. A private corporation, on the other hand, may be limited in its ability to diversify the risk of a large investment (say in a new technology) even in the corporation's estimate of the expected value of the investment is the same as that of the government.

Now, of course it is argued that a variety of financial measures exist within our market system to allow a private corporation (or individual stockholders) to diversify risks of this kind, and therefore that the risk aversion of the private corporation should be no different than that of a public body. But once again these arguments depend on the efficient working of financial markets, and to the extent these markets "fail" in one way or another, the private and public perceptions of risk may be different. This will happen, for example, when the formation of various types of risk pools is retarded by various government restrictions on the market, such as are imposed by the antitrust laws.

Thus it might very well be the case that an expensive venture on the part of Ford or General Motors may involve a degree of risk to the corporation which mitigates against its adoption, while at the same time the society as a whole could well afford to bear the risk given its capacity to spread risk over the body politic as a whole. In these circumstances there is a justification for govenment involvement in carrying out such experiments. In fact, on the basis of a 1969 consent decree between the automobile manufacturers and the U.S. Justice Department, the manufacturers are specifically forbidden from collaborating on R&D related to air pollution control. There is a trade-off here between the ability to form risk-bearing consortia and the need to maintain competition that is beyond the scope of this discussion. The fact remains, however, that, with ventures of the size involved in the development and introduction of an alternative powerplant, the risk as perceived by a manufacturer and its management may well be much larger than when calculated socially.

Problems of Market Structure

Another circumstance which also leads to a concern for government involvement in technological development concerns the structure of the automobile industry itself. All of the previous arguments in this chapter hold when the market is made up of large numbers of sellers and buyers. However, the supply of automobiles to the American market is dominated by the "Big Three," with a fringe consisting of one "independent" and a number of importers. In such a circumstance there are good reasons to suspect that the full play of competitive forces is not brought to bear. There are really two questons here: the large scale necessary for the economic mass production of motor vehicles through the extensive use of automated machinery; and the small number of sellers that has resulted from the development of firms probably beyond the size required for these economies. The former may result in a more than optimal degree of sluggishness to technological change. The latter may reduce the degree of competition, but, on the other hand, the existence of such huge industrial organizations and their associated financial power gives opportunities for R&D that might not exist were the industry made up of much smaller units.

So therefore, on balance, it is not easy to argue whether more or less R&D on new technical options takes place under current market structure or some alternative. Debate on this issue has been hot and heavy, both within the academic community (on the general topic) and among those involved in automotive policy. It is impossible to resolve this issue as it bears on government support of alternative powerplant R&D.

Petroleum Price Controls

Present federal price controls hold the price of automotive fuels well below their marginal cost. The legal price of gasoline (and all other petroleum products) is based on an "average" cost of crude oil, where the average includes imports at a price determined by the Organization of Petroleum Exporting Countries (OPEC) cartel, "old" domestic oil at a much lower price, presumably related to its old "cost," and "new" domestic oil, at an intermediate price. The problem is that production of domestic crude is relatively fixed, so that any gallon of crude that is not consumed results (roughly speaking) in a gallon of crude not imported. But, because price controls hold the cost of automotive fuels well below their cost based on the cost of imported crude (i.e., their marginal cost), the savings privately received in not consuming a gallon of automotive fuel are substantially lower than the savings received by the nation as a whole in not having to import the extra unit of expensive international crude oil. This will be discussed further in the following chapter, but as long as petroleum price controls are continued, then (as in the case of the "security premium" discussed above), all investment in fuel-conserving technology will be undervalued in private decisions; specifically, this includes investment in R&D on alternative automotive powerplants which consume less fuel than the ICE. Quantitative estimates of the importance of this effect on the valuation of automotive gas turbine engines are presented in Section 3.4 below. At this writing the Congress is considering a tax program (the "Crude Oil Equalization Tax") for raising the average domestic price of crude oil to the international price, eliminating this source of government-induced market failure.

Air Pollutant Emissions Regulation

The second important regulatory program in this category is the Clean Air Act, which, in its structure, and its history and administration, has in the past biased investments in R&D on technology to control air pollution -- away from major technological changes (such as alternative powerplants) and towards smaller, "evolutionary" technological changes. The history and basic structure of the Clean Air Act and its implementation will not be repeated here; rather the impact of its key features on the incentives for alternative powerplant R&D will be addressed.

Before proceeding, however, it is worthwhile summarizing the effects of the Act as we perceived them before the passage of the latest amendments in August of this year. Several features of the Act and its administration have been important. The standards of the Clean Air Act, in spite of the tough language of the Act, have had to be adjusted several times to levels that could be met by the ICE without drastic performance degradation or cost increase, or increase in emissions of unregulated pollutants. There has therefore been little advantage to a manufacturer in introducing a powerplant which offers lower emissions at a cost premium. Thus the social benefits of reduced emissions had not been effectively internalized and provide a limited incentive to alternative powerplant R&D.

The uncertainties inherent in the administration of the Act have inhibited investments in alternative powerplants by making them riskier. For example, the long-term standard for oxides of nitrogen has never been well known, due to the number of credible alternatives to the former statutory 0.4 gm/mi standard. The underlying problem is the lack of a solid technical justification. A similar problem has arisen with respect to standards for emissions of a number of presently unregulated pollutants which are emitted by some of the alternative powerplants. For example, an emission standard for particulates would probably be imposed if the diesel engine were to become widely used. The standard might result in significant costs added to the diesel vehicle, or it might not, but the uncertainty inhibits private investment in the system.

The requirement that each of the vehicles produced in any one year must meet the same standard means that there is no mechanism whereby a vehicle with an advanced engine, whose emissions are superior to those of the ICE, can be gradually introduced, providing a significant obstacle to any major technological change. This feature of the law reflects the industry's traditional annual model change, and it encourages exactly the type of innovations made in the model change, namely, incremental ones. Major technological innovations take much longer than one year to diffuse across the industry's product lines.

Finally, the year-by-year approach for strengthening, then postponing, the standards, has forced the manufacturers to concentrate their resources on short-term modificatons which can be rapidly introduced. It has consistently been the case that only one to three years into the future at any given time were standards that were generally conceded to be impossible to attain at acceptable levels of cost or quality degradation with known technology. Uncertainty over the levels that actually would obtain has been the case. This type of uncertainty is totally inconsistent with the type of planning necessary in capital-intensive industries, and again inhibits investments in long-range emissions-related R&D.

In summary the Clean Air Act and its history and administraton, as the results of Congress' desire for haste in reducing air pollution levels, has significantly biased the industry away from major technological changes such as some of the potential alternative powerplants toward control technologies which could be more rapidly and certainly implemented.

It now appears that the automotive emission regulatory situation has stabilized somewhat. In August, 1977, the Congress passed the Clean Air Amendments of 1977. The most important feature of the Amendments is a further postponement of the original "statutory 1975" standards for hydrocarbons and carbon monoxide (0.41/3.4 gm/mi HC/CO) from model year 1978 to model year 1980 for hydrocarbons and 1981 for carbon monoxide. The original "statutory 1976" standard for oxides of nitrogen (0.4 gm/mi) is dropped as a statutory vehicle requirement and changed to a "research objective;" the new minimum requirement is set for 1981 (at 1.0 gm/mi). The passage of these Amendments was accompanied by the usual Congressional pronouncements that at last there was an emission standard schedule that the automobile industry could live with and would.

This time, however, the claim seems considerably more plausible than in the past. One indication is that the automobile industry has been less vehement than before in its objections to the timing and level of the new statutory 1981 requirements. This is due to two factors. First, the alleviation of the ultimate oxides of nitrogen standard mitigates what has always been the most contentious single regulation. Second, the technological advances which have taken place over the past decade, during which automotive emissions have been a major national issue, have made it possible to produce cars which will meet the 1981 standards with more reasonable cost, fuel economy, and quality losses than has ever been the case in the past. Technologies very similar to those which will be used are now being tested on some sales models, and it appears that these techniques will be ready for fleetwide use in 1981. They are of course incremental adaptions to the ICE, and the cost and fuel economy penalties they involve are by no means negligible (see Sections 3.2 and 3.4 below), but they are reasonably effective and reliable.

There are two possibilities for renewed contention embedded within the Clean Air Amendments of 1977. First, there is a mandatory study to be performed by the Administrator of the Environmental Protection Agency, of the costs and benefits associated with the formerly mandatory 0.4 gm/mi goal for oxides of nitrogen emissions. Recommendations are to be submitted to the Congress with the report on the results of the study no later than July 1, 1980. Second, there is provision for a waiver for up to two years for the most stringent carbon monoxide standard. These provisions, or other non-legislative possibilities for disruption of the new schedule of standards, weigh against the view of increased stability.

However, it does seem that the inhibitory effect of the Clean Air Act on advanced power system R&D has now been somewhat mitigated. A reasonably stable set of standards seems in sight, so the future competitive environment for an alternative is less uncertain. The cost increase and fuel economy penalty associated with the 1981 controls will probably be realized by ICE-powered vehicles and this will make alternative systems appear more attractive (as shown in Section 3.4 below). A significant source of disparity between social and private valuation of automotive power systems will in this case have been eliminated.

Fuel Economy Regulation

On the other hand, a whole new regulatory regime has been added in the automotive sector. This is the set of fleetwide fuel economy standards imposed by the Energy Policy and Conservation Act. The details of the standards will not be described here. They consist of a gradually tightening schedule of minimum new car fleetwide average fuel economies that must be met by each manufacturer. The incentives these standards provide for the behavior of the automotive industry are extremely complex and not well understood.[1] Because the standards are imposed on the fleetwide average rather than each vehicle, the manufacturers have substantial flexibility in meeting the limit, especially as between actions affecting various weight classes of vehicles offered.

As with the Clean Air Act, the Energy Policy and Conservation Act is without question affecting short-run behavior in the intended direction. That is, the manufacturers are pouring tremendous development resources into modifying present vehicles to meet the tightening standards. Off-the-shelf technology is being introduced now -- especially vehicle redesign to reduce weight while maintaining volume and comfort ("downsizing"). Extensive planning is under way within the firms to introduce known technology to make changes as needed to meet the standards.

However, as has been the case with the Clean Air Act, efforts to develop new technology are being focused on innovations which would be available for introduction by the time they are needed, i.e., when present technology will not suffice. Planning within the industry, and analysis outside it, indicate that this "crunch" will occur approximately in the early 1980s.[1] Therefore major engine development efforts are

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[1] See Jacobs and Linden (2-2, Chapter 3) for a description and behavioral analysis of the standards.

under way, but they are aimed at modifications to, and closely related replacements for, the ICE (especially the diesel and stratified charge engines). As formerly under the Clean Air Act, advanced systems such as the gas turbine and Stirling engines would not be available in time to help the manufacturers avoid violations of the standards. This is true independent of the fact that advanced systems might be more desirable methods of improving fuel economy in the long run.

Thus the impact of the fuel economy standards on the incentives for R&D on advanced power systems is mixed. It raises the value of vehicle fuel economy, as a vehicle attribute, in the long run. But it simultaneously forces the manufacturers to pour their engine development resources into alternatives that would be available with less delay and more certainty.

Summary

In this chapter we set out to analyze the adequacy of the incentives faced by the automotive manufacturers for R&D on advanced automotive power systems. Two years ago, we reached the following conclusion:

> In summary, it is very likely...that the automotive industry will under-invest in alternative powerplant R&D, relative to the level which would be socially desirable. This provides a solid but very general justification for government support of alternative powerplant R&D. (2-1, p. 68)

This situation now seems less clear. The incentives described above are extremely complex and difficult to sort out. We now find it hard to

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[1] See H. Kahn (2-3) for a survey of submissions by the automobile manufacturers to the Department of Transportation and the Congress describing their strategies for meeting the standards through technical changes and their indications that they do not believe these changes to be adequate.

argue that the net effect of all these considerations goes one way or the other with respect to advanced systems. One area where there is an important exception to this conclusion is the area of ceramic components, which was mentioned above and will be analyzed at some length in the following chapter.

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3. THE AUTOMOTIVE GAS TURBINE: THE FEDERAL ROLE

3.1 Introduction

In this chapter we address government policy with respect to a single automotive power system: the gas turbine. This system offers the potential to provide automobiles with substantially higher fuel economy, lower air pollutant emissions, and superior levels of noise, durability, reliability, etc., than today's ICE-powered passenger cars. This potential, however, remains only that: the high fuel economy levels have not been demonstrated in any actual vehicle. The cost of the gas turbine engine is even more uncertain than its potential. Furthermore, the fuel economy of ICE-powered vehicles is improving rapidly, and the diesel and stratified charge engines are also improving the available and foreseeable passenger car technology. Thus while the benefits potentially available from the gas turbine engine are large, they are very uncertain.

The gas turbine is not a new technology. The major automotive manufacturers, domestic and foreign, have supported gas turbine engine development, and even vehicle demonstrations, intermittently over the last two decades. A substantial part of this effort has been aimed at the heavy duty application. Over the past five years a great deal of the American gas turbine effort for passenger cars has been subsidized by the federal government. At first the focus was reduced emissions; more recently, it is improved fuel consumption.

The policy issue, now, is what, if any, continuing role for government support of automotive gas turbine technology is reasonable. At one extreme is no federal support whatsoever; funding could be terminated when the effort which has been the centerpiece of the federal government's program for the past five years -- development and demonstration by Chrysler of the latest system technology -- is completed in mid-1978. Taxpayer dollars could be spent elsewhere or not collected. Within the alternative of continuing support there are choices of the technical focus of the development effort, the number of firms to be supported, the choice of supporting whole new engine systems or advanced individual components, and several others. Here we address principally the question of whether there should be a continuing role, and what its technical focus should be. In the course of the analysis we raise a number of subordinate issues which the gas turbine system, and thus any federal R&D program directed at it, may face.

We offer no original technical analysis. Our effort is centered on the economic analysis of the technology and the resulting policy implications. The technical data we use has been obtained from interviews and the open literature, and tempered by our own judgment.

This chapter may be considered a companion piece to the three case studies reported in Federal Support (3-1, Chaps. 5, 6 and 7). It follows most closely the analysis of the Stirling engine reported there; repetition of the analytical framework will be avoided where possible. While much of the analysis is similar, it is extended in two directions. First, a number of appealing simplifications in the economic analysis of the Stirling are not available here, due to the greater disparity in certain key attributes of the gas turbine from those of the ICE. Second, we have been forced to be less reticent in projecting the properties of advanced systems -- those involving ceramics -- than in the Stirling case, for here the choice of materials technology is a central policy issue; the Stirling engine has not yet reached this stage.

The analysis proceeds as follows. First, in Section 3.2, the technology and its key components and subsystems are discussed. The institutional history is described and reviewed, and the nature and content of the past gas turbine efforts of industry and government are briefly described. The technology is then classified into distinct levels and the potential attributes of the system at each level are compared with those of the present ICE. A brief analysis of the evolution of the ICE and related systems is undertaken to enable comparisons of the gas turbine and the baseline of the future.

Next the analytical framework for our economic evaluation of the gas turbine is motivated and described, in Section 3.3. The style of our methodology is explained, in the context of our goals and compared with the approaches taken by others. Our simple vehicle total operating cost model is laid out.

Sections 3.4 and 3.5 then present economic calculations of the value of the automotive gas turbine from three differing perspectives. In Section 3.4 the perspective is the social one, that is, we calculate the value of the system to society, at each of its levels of technical advancement. The social calculations use social prices to value fuel and capital. The sensitivity of these value calculations, to both engine attributes and price levels, is explored. The framework is a static one, in that it is assumed that the vehicle body and fuel logistics system have been jointly optimized in a long-run equilibrium with the gas turbine engine.

In Section 3.5 the value calculations are repeated from a private perspective. First, the static calculations framework is repeated, only with private prices. Next, the transition process is analyzed, as the valuation is made on the assumption that the vehicle body and fuel logistics systems have not adjusted.

Finally, in Section 3.6, the results are summarized, and our conclusions presented. Our focus is on the place of ceramics in gas turbine technology and in the federal government's role in supporting R&D in ceramic-based engines.

3.2 Status of the Technology and Current R&D Programs

In this section we will first briefly describe the gas turbine engine and the present status of its key components, and also touch upon the important materials and manufacturing issues. We shall then summarize quickly the history and present status of R&D programs on the engine. We shall then discuss the probable attributes of the automotive gas turbine engine at various levels of development relative to the present internal combustion engine (ICE).

We subsequently consider in this section the movement of the baseline ICE from the present through the mid-1980s time frame, which is seen as the earliest plausible time frame for the introduction of a gas-turbine-powered automobile.

3.2.1 Modern Automotive Gas Turbine Technology[1]

The automotive gas turbine engine is a heat engine operating on the open Brayton cycle. It is conceptually distinct from the ICE on three major points. First, it operates on a different thermodynamic cycle; in the Brayton cycle heat addition and rejection take place at constant pressure whereas in the Otto cycle, used by the ICE, heat addition and rejection take place at constant volume. Second, the gas turbine utilizes steady flow processes of compression, heat addition, and expansion, which permit better control and flexibility of operation. Third, compression and expansion are effected by aerodynamic machinery in contrast to the positive displacement action of the ICE.

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[1] Fuller treatment of the contents of this section may be found in (3-2, p. 5-2), (3-3), (3-4, pp. 1-162).

The key components of the gas turbine engine are: the compressor, which raises the pressure of the incoming air; the combustor, in which fuel is introduced and burned with the compressed air; and the turbine, which, powered by the hot expanding combustion products, delivers work. Part of the work drives the compressor; the remainder is available as motive power. The addition of a regenerator enables the transfer of heat from the turbine exhaust to the compressed air prior to combustion, serving to raise the efficiency of the engine.

The attractiveness of the gas turbine engine as an alternate automotive powerplant is due chiefly to: simplicity - fewer moving parts than the ICE; potential for higher specific power (maximum horsepower available per pound of engine weight); smooth and vibrationless power delivery - a consequence of rotary work processes in contrast to the reciprocating action of the ICE; low emissions - due to the isolation of the combustion process, permitting better control; easy cold starting; potential for reduced maintenance requirements; improved life expectancy, and potential for improved fuel economy. Weighing against these advantages are its relatively exotic material and manufacturing requirements -- which lead to a high initial cost; and the engine's inherently constant speed characteristic which is inconsistent with the highly variable load demand of an automobile.

More than one system configuration exists for the modern automotive gas-turbine engine. Thermodynamically, the cycle may be "simple" or "regenerated," as mentioned earlier. A further distinction can be made based on the coupling between the engine and the drivetrain: the single-shaft configuration employs a single expander turbine to drive both compressor and drivetrain on a common "engine" shaft.

Alternatively, a second, "power" turbine, mounted on a separate shaft, can provide motive power to the wheels via the transmission. This is the free- (or twin-) shaft configuration. The latter is at present the better developed, by far, of the two.

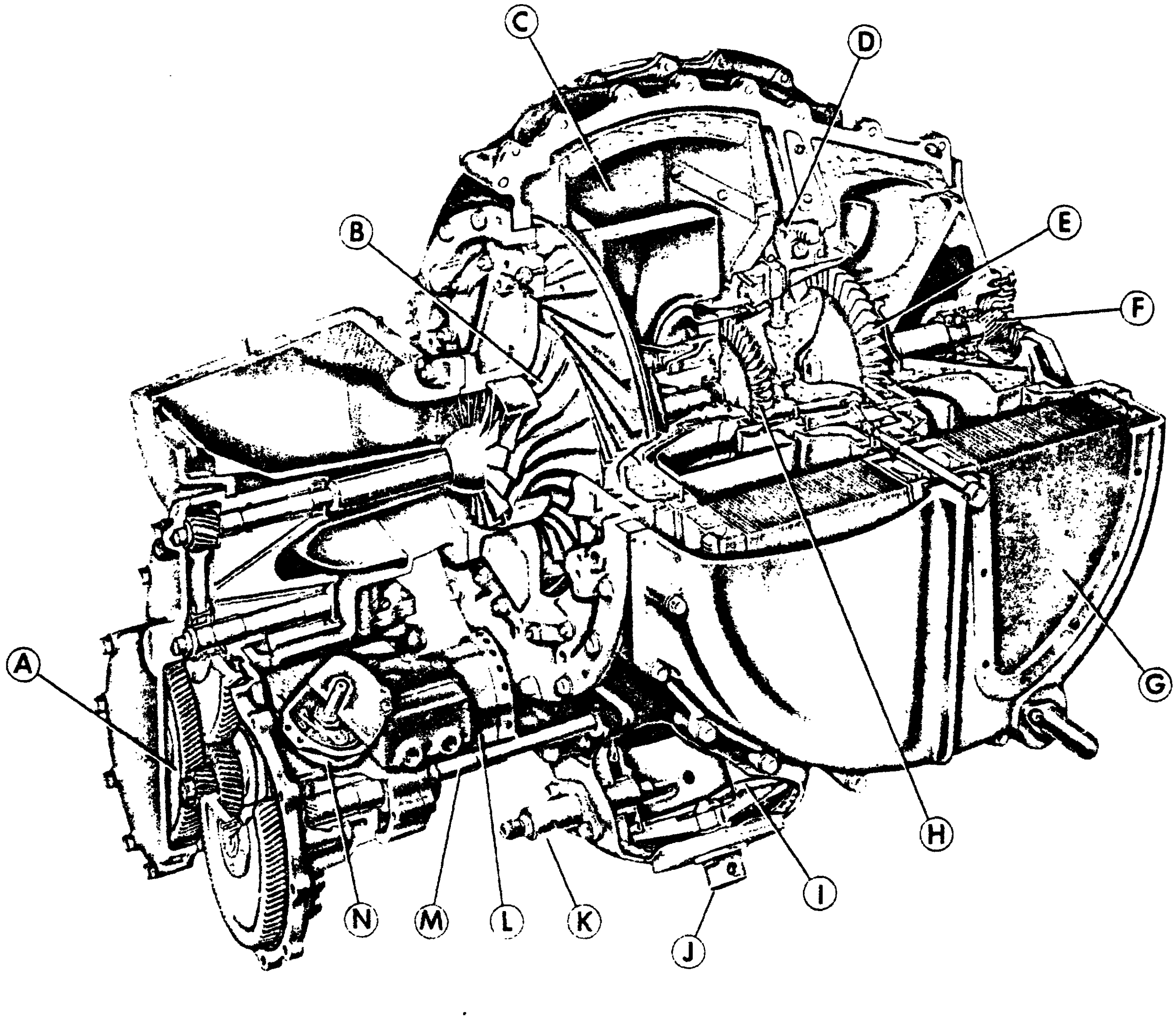
Numerous automotive gas turbine prototypes have been built to date. Hardware details are highly specific to each prototype. Some common elements may, however, be identified. Here we will outline the status of these major components and subassemblies.

A cutaway view of a representative (free-shaft) modern automotive gas turbine engine is shown in Figure 3.1. We will subsequently discuss the principal differences between the free-shaft and single-shaft configurations. The principal structural member of the engine is the main housing supporting the major subassemblies and providing connected flow passages. The housing plays an important role in providing air flow guidance and bearing bases for the shafts. It must have adequate strength to contain the high-pressure gas flow without the distortion that might lead to misalignment of the working components. The housing may be a one-piece casting or may be a fabricated multiple-piece structure. The former is preferable, since it can be more easily and quickly mass-produced.

The major subassemblies are: the "gasifier" section (compressor, "gasifier" turbine and gasifier shaft), the power turbine section (including the nozzle assembly), combustor, regenerator, and reduction gearing. Accessories may be driven either off the gasifier or the power turbine shafts; the former arrangement adds to the inertia of the gasifier section, affecting acceleration response, while the latter

Figure 3.1

CUTAWAY VIEW OF CHRYSLER FOURTH GENERATION GAS TURBINE



MAIN COMPONENTS OF THE TWIN-REGENERATOR GAS TURBINE: (A) accessory drive; (B) compressor; (C) right regenerator (D) variable nozzle unit; (E) power turbine; (F) reduction gear; (G) left regenerator; (H) compressor turbine; (I) burner; (J) fuel nozzle; (K) igniter; (L) starter-generator; (M) regenerator drive shaft; (N) ignition unit.

necessitates the use of a clutch between power shaft and drivetrain to keep the accessories running when the vehicle is stationary.

Modern automotive gas turbines use centrifugal (radial) compressors exclusively, in preference to axial designs; ruggedness, compactness and the ability to provide high pressure ratios in a single stage make radial compressors the natural choice. Variable inlet guide vanes on the compressor (not shown in the engine in Figure 3.1) help improve response and part-load fuel economy at the cost of additional complexity.

Pressurized air from the compressor is routed through the rotary regenerator(s),[1] where it picks up residual heat from the hot exhaust gases of the power turbine. The regenerator consists of a rotating heat transfer matrix shaped like a drum or disc, which is alternately exposed to the hot and cold gas streams; the pressure differential between them necessitates sealing to prevent leakage of the compressed air to the low pressure side. Crucial problems, aside from sealing, are the durability and reliability of the matrix under prolonged operation.

The compressed and preheated air from the regenerator is then ducted to the combustor. Isolated combustion is the key to controlling emissions from the gas turbine engine, since it permits control of the combustion process independent of the power generation process. The continuous nature of the combustion process also eliminates the noise generated in the intermittent explosive combustion process of the ICE. Combustor design is complicated by conflict between HC & CO emissions on the one hand and NO_x on the other. Further, higher temperatures, necessary for higher efficiencies, aggravate NO_x emissions. Careful

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[1] The engine shown in Fig. 3.1 features twin regenerators. This is not characteristic of present day design practice.

compromise between these factors is necessary. Variable inlet geometry offers one way of solving the problem but involves greater hardware complexity and, consequently, increased cost.

The combustion products are ducted to the first-stage (gasifier) turbine, which runs the compressor. The axial turbine has thus far predominated in this application, but the radial turbine holds several advantages over the former, especially in the single-shaft configuration, and is a likely candidate for future designs.

Turbine inlet temperature is crucial in determining engine power output and efficiency; it is desirable to maintain it as high as possible under all operating conditions. Metallic turbine technology is close to the limit of development - an upper limit of about 1900°F is imposed by uncooled superalloy turbine rotors. Turbine blade cooling as a means of raising inlet temperature is not considered practical or cost-effective for the relatively small-size turbines used in automotive practice, although its use makes temperatures on the order of 2200°F or higher possible in aircraft turbines (3-5). The second approach is to find a material (such as ceramics), having properties that will enable it to withstand higher operating temperatures.

There is no mechanical connection between the first and second stage (power) turbines -- coupling is aerodynamic, giving the engine its flexibility. The axial design is preferred for the power turbine from packaging considerations. Variable geometry inlet nozzles (see Figure 3.1) on the power turbine are an established feature of most modern gas-turbine engines; they help improve part-load fuel economy and response and provide engine-assisted braking for the vehicle.

The technology associated with the aerodynamics of the rotary components (compressor and turbine(s)) is close to the limit of its development. While the overall cycle efficiency is sensitive to improvements in aerodynamic component efficiencies (3-2, Figure 5-3, p. 5-35) only marginal improvements (of the order of a few percent) in the efficiency of these components may be expected (3-6). Minimization of the inertia of the rotating parts (of which the aerodynamic components are the most important) is a necessary requirement for fast acceleration response.

Finally, mention must be made of the control system. Control of the gas turbine engine involves greater complexity than the ICE. It represents one of the largest cost components of the engine. Essential functions of the control system include limiting of turbine inlet temperature, fuel metering and start-up sequence control from ignition to idle. Control operation may be hydromechanical or electronic. The latter offers increased versatility at greater cost.

The alternative to the free-shaft configuration is, as mentioned earlier, the single-shaft version. By permitting the elimination of the power turbine used in the free-shaft turbine, the single-shaft configuration realizes several advantages: i) greater mechanical simplicity; ii) less weight; iii) better efficiency; iv) lower cost. However, the flexibility of operation offered by a separate power turbine in the free-shaft version is lost. This makes the single-shaft turbine incapable, as such, of meeting the highly variable operating conditions

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[1] The engine shown in Figure 3.1 features twin regenerators. This is not characteristic of present-day prototypes.

characterizing passenger car utilization. This inherently constant speed characteristic of the single-shaft turbine presents difficult transmission problems in automotive applications. It is also important to mention that the radial turbine is preferable for use on single-shaft designs, principally because it can accommodate a higher pressure drop per stage. At the cost of some increase in inertia, it gives higher efficiencies over a wider operating range and is more rugged.

The single-shaft system cannot utilize conventional passenger car transmissions; development of a suitable transmission is a necessity for the single-shaft gas turbine to be a viable passenger car engine. While a variety of candidate transmission designs exist or have been proposed, we shall briefly discuss only those that have emerged from past studies and development efforts (3-7 through 3-10) as being the most promising. It is generally believed that a continuously variable transmission (CVT), which permits a continuous variation in the ratio of vehicle speed to engine speed, will be required. Two designs appear attractive: the hydromechanical and the traction systems. In the former, the power is split between a conventional mechanical gear train and a speed-changing component consisting of a variable displacement pump and motor. Design studies claim that this transmission has potential for good overall efficiency in comparison to the conventional automatic, with no significant weight or volume penalty (3-9, 10), but these are yet to be realized in present prototypes for passenger car application. Further, noise generation remains a crucial problem area.

Among the traction transmissions, the principal candidate is the rolling element type, in which the radii of points of contact on power rollers operating between toroidal output and input discs is varied to give a continuously variable speed ratio (3-9). The most critical problem is one of durability, due to wear and fatigue at the highly loaded contact points.

Final mention may be made of the variable-angle stator vane torque converter (3-11) concept, which in combination with a conventional automatic transmission, appears to be a potential transmission candidate for the single-shaft engine.

It has been clear for some time that they key to achieving a breakthrough in the status of the gas turbine relative to the ICE is to employ ceramic materials which make higher turbine inlet temperatures (as mentioned earlier), higher hot-flow-path-component service temperatures, and more efficient heat exchangers possible, all of which contribute to substantially improved engine efficiency. In addition, ceramic material costs are lower (by about an order of magnitude) than the expensive inputs to the superalloys used in state-of-the-art gas turbines. Thus ceramics could substantially lower the cost of the gas turbine engine in volume production. Finally, ceramics in addition to being only about 40% (or less) as dense as ferrous metals (or superalloys) offer outstanding resistance to corrosion, abrasion, and wear. Thus it is important to consider the status and prognosis for ceramic materials development.

Ceramics materials for turbines fall into two classes: heat exchanger ceramics, used in the regenerator, and structural ceramics for the other hot flow path components, which are required to withstand high mechanical stresses at high temperatures.

The principal requirements of heat exchanger ceramics (aside from being able to operate at the highest possible temperature levels)are durability under thermal cycling and resistance to chemical attack, rather than the ability to withstand heavy mechanical stresses. Ceramic materials in the regenerator offer potential for lower cost, reduced weight, and easier sealing (due to their low thermal expansion characteristics). Within the past several years heat exchangers using ceramics have been satisfactorily tested at suitable conditions and lifetimes and they now seem a well-developed technology, on a par with metallic components elsewhere in the engine.

The status of structural ceramics for the hot flow path components, in comparison, is not as encouraging. Among these, the stationary components that experience lower stresses but high temperatures are relatively better developed. These include the turbine shroud rings and nozzles, combustor lining and scroll, insulating liners on the inside housing, and hot flow path ducting.

The ceramic turbine rotor, which could most dramatically affect the status of the gas turbine by raising the allowable turbine inlet temperature to 2500°F or more, is also the key development bottleneck: this component has to effectively tolerate the highest stress at about the highest temperatures in the engine. Consequently, a breakthrough in ceramic rotor technology would almost certainly be accompanied, if not preceded, by successful development of structural ceramics for the other hot parts. Currently, the most viable concept is the duo-density rotor, which utilizes a high-strength, hot-pressed silicon nitride hub, diffusion bonded to a temperature-resistant, reaction-sintered silicon nitride blade ring.

Mention must also be made, for completeness, of the hybrid rotor concept which utilizes a superalloy hub forged around ceramic blade roots. Apart from stress problems at the metallic-ceramic junctions, this concept is still subject to the cost of the superalloy hub.

A focus on ceramic components, however, must be tempered by an awareness of the status of the basic understanding of ceramics as a material.[1] The basic properties of ceramics are quite different from those of metals, and they present relatively unique design problems. These problems are most acute in the area of structural ceramics. Although they possess high strength comparable to superalloys, they are brittle and susceptible to the thermal shock imposed during engine transients. This brittleness leads ceramics to crack or shatter at points of contact or high stress, rather than yield and flow as do ductile metals. These properties result in an extreme sensitivity of ceramic component strength to the purity, fineness, and uniformity of particle size in the powdered raw material and the number of pores in the finished article. In the past few years, various types of silicon nitrides and silicon carbides have been developed that seem to offer the best combination of properties and potential for significant improvement.

Advances in structural ceramics technology need to be made in the following three areas (3-13). First, suitable mass production techniques must be develdoped, especialy for the turbine rotor. Sinterable silicon nitride appears to have the best potential for volume production, and development efforts are needed in this direction. Second, durability testing is necessary to obtain presently scarce mechanical property data to verify the long-term integrity of the hot-flow path compononents under

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[1] A detailed assessment by the Army Materials and Mechanics Research Center may be found in (3-12) as cited by Katz, R.N., in "Ceramic Rotors for Small Automotive Gas Turbine Engines," presented at ERDA Automotive Power Systems, Contractors Coordination Meeting, Ann Arbor, Michigan, May 1975. Descriptions of key development tasks identified from this assessment may be found in (3-13) and the current status of these development efforts is reviewed in (3-14).

thermal cycling at temperatures up to 2500°F, and the long-term effects of environmental extremes. Third, there must be development of economic proof testing methods to predict ceramic component life and reliability, given the influence of impurities in the material, the considerable variability exhibited in mechanical behavior, and the brittle fracture characteristics, which combine to make a statistical approach mandatory to account for these uncertainties. Finally, it must also be realized that a ceramic gas turbine engine will call for an integrated design effort and not just a simple subsitution of ceramic parts for metals parts in view of their vastly different materials characteristics.

Finally, it is important to recognize that the unique set of properties of ceramic materials extends their potential application to areas far beyond just the gas turbine, or even heat egines in general. First, structural ceramics have potential uses in the hot parts of the ICE, and the diesel engine, including piston heads and rings, insulating liners for the combustion chamber, etc. It has been proposed that replacement of the water cooling system in the diesel engine by a ceramic-based one could result in substantial improvements in fuel economy and specific power (3-15). Ceramics also have potential applications in bearings, sensors and control devices, exhaust ducting, etc.

Going further afield, ceramics have potential to replace heat exchanger tubing in chemical and metallurgical process industries, especially where corrosion resistance is an important requirement, if the technology for producing large flaw-free ceramic parts can be developed. Ceramics also have potential application in large industrial gas turbines in the same areas as in automotive size turbines: this could have significant impact on electric power utilities, if their high reliability standards can be met. Further, with the incentives to convert to the more abrasive and corrosive coal-derived fuels, the resistant properties of ceramics make them look attractive.

The impact of ceramics could extend as far as magnetohydrodynamics, fusion power, and fuel cell technologies in the long term.

The materials problem is closely coupled with the manufacturing issues relating to the gas turbine engine. High-volume production of automotive gas-turbine engines would require major new handling, machinery, and transfer equipment. Further, superalloy components are harder to machine than the lower-alloy-content ICE parts, but the fewer number of parts in the turbine relative to the ICE should offset this to some extent. It is also likely that the metallic gas turbine would require an appreciable number of complex and expensive investment casting processes, whereas the piston engine uses none.[1]

Ceramic materials, as mentioned earlier, are far from the mass production stage, having yet to demonstrate adequate properties on the test bed. The feasibility and cost of mass-producing ceramic materials are presently unknown. It is therefore not clear what fraction of the raw material cost advantage associated with ceramics relative to superalloys would be reflected in the final production versions of the engines.

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[1] For a detailed treatment of the mass-production potential of the metallic turbine, see (3-16).

3.2.2 Review of History and Present Status of R&D Programs on the Automotive Gas Turbine Engine[1]

The history of R&D on automotive gas turbines is long and has involved numerous participants. Beginning with the demonstration of the first gas-turbine-powered car by the Rover Company of England in 1950 (3-17), various organizations both within and outside of the automotive industry on both sides of the Atlantic have contributed to the development of the gas turbine engine. The Big Three in particular have had a long-standing, substantial and continuing involvement in gas turbine research.

The pace of R&D on the gas turbine picked up considerably in the U.S. through intensive federal support of such work in the wake of the Clean Air Amendments of the 1970s, and, as a consequence, the major advances in gas-turbine technology have since been made in this country. During this period, various groups were involved with various aspects of gas turbine development. The list includes (aside from the Big Three) AiResearch Manufacturing Company of Arizona; Corning Glass Corporation; General Electric Company; GTE Sylvania; Mechnical Technology Incorporated of New York; Owens-Illinois, Pratt and Whitney Aircraft of Florida; Sunstrand Aviation of Illinois; and Williams Research Corporation of Michigan. We shall focus briefly on the involvement of the Big Three in the following pages and then subsequently review quickly the history of federally supported R&D on the gas turbine.

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[1] See (3-4) for a detailed description of gas turbine development programs through 1975.

The first important advances in automotive gas-turbine development in the U.S. were made by the Chrysler Corporation.[1] Active research on gas turbine powerplants for automobiles began at Chrysler in late 1947. The first gas-turbine-powered passenger car in the U.S. was demonstrated by Chrysler in 1954. Six "generations" of development followed in the years 1954-1966. The Chrysler engine prototypes were all free-shaft designs and were installed in conventional vehicle test beds, apparently reflecting Chrysler's manifest aim to eventually mass-produce turbine cars.

Chrysler's second-generation engine was operated in 1958; a third-generation prototype followed in 1960. This period saw considerable component development work, as well as materials research. In addition to gains in component efficiency, a substantial amount of data was gathered on regenerator design and consistent improvements were made in reducing the acceleration lag of the vehicle. The third-generation prototype also featured variable turbine nozzles, aimed at improving fuel economy. Chrysler's fourth-generation engine holds an important place in the history of gas-turbine development. Fifty such engines were installed in two-door passenger vehicle chasses. From 1963 to 1965 these "turbine cars" were distributed to typical drivers across the U.S. on a rotating basis. This program represents the only major organized effort to date to generate consumer response to the gas turbine passenger vehicle and to evaluate these cars under actual in-service conditions. A total of more than a million vehicle miles was logged by

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[1] For a detailed description of Chrysler's early involvement with the gas turbine, see (3-18, 19).

more than 200 users. User reaction typically was especially favorable on the smooth and vibrationless operation of the engine and its reliable starting ability. Some dissatisfaction with acceleration lag and fuel economy was recorded. Chrysler's service operations apparently had to face no major maintenance problems. Technically, this engine was essentially similar to its predecessor, except that it had twin metal regenerators instead of the single unit in the previous model. The engine was rated at 130 b.h.p.

In 1966, however, the focus of research at Chrysler shifted towards emissions control for the ICE. Despite this, the Chrysler gas turbine was carried through two more generations of development through the early 1970s.

In 1972, in the wake of the Clean Air Amendments of 1970, gas-turbine research at Chrysler gained impetus under a contract with the Advanced Automotive Power Systems Division of the U.S. Environmental Protection Agency. Three 1973 intermediate-size passenger vehicles were fitted with the Chrysler sixth-generation engines forming a "baseline" configuration, and component improvement programs were begun. The baseline proved capable of meeting the original statutory 1975 emissions standards (0.41/3.4 HC/CO gm/mi) but displayed poor fuel economy (8-9 mpg over the urban Federal Driving Cycle). In the subsequent phase of the program, the technological advances made under related contracts were incorporated into the "upgraded" engine. The latter is roughly the best available respresentative of the state-of-the-art gas-turbine technology. The Chrysler gas turbine program is continuing under government support and further details of this work are discussed below.

Early gas turbine research at General Motors was done in the Research Laboratories; later, with the shift towards commercial vehicle applications, it was transferred to the Allison Division. Over the period 1953 through 1958 GM built and demonstrated three gas-turbine-powered cars, named respectively, Firebird I, II, and III. In general, these prototypes reflect unconventional and complex design approaches. The vehicles were overpowered; consequently their performance was good but fuel economy was poor.

In 1958, the thrust of research shifted to military and, subsequently, to heavy-duty commercial vehicle applications, under the Allison Division. A major contribution to the technology -- the power transfer system -- came about at this time. This is a coupling device for the free-shaft gas turbine which improves part-load fuel economy and provides engine-assisted braking, without variable turbine geometry. Until 1970, Allison continued to design gas-turbine engines for commercial vehicles on its own. Several vehicle installations were made and road-tested.

Following the merger of Allison with the Detroit Diesel Division in 1970, GM announced its intention to produce turbine-powered, heavy-duty vehicles on a pilot basis. However, even though a new prototype engine, the "GT-404", was built expressly for the purpose, the program has not yet materialized.

In 1971, under a new office called the Passenger Car Turbine Development Group, at the GM Engineering Staff, and in close collaboration with the Research Laboratories, some very intensive combustion studies were initiated to evaluate the emissions potential of the gas turbine. An experimental test-bed engine, the "GT-225," was built to evaluate these concepts (3-20). This engine, using complex control concepts and variable geometry, was able to meet the original statutory 1978 emissions standards (0.41/3.4/0.4 HC/CO/NO_x gm/mi) in dynamometer tests.

In the latest development, Detroit Diesel Allison has contracted, starting in 1976, for an ERDA-funded program to improve the fuel economy of GM's advanced industrial gas turbine, the "404/505," by 20% (3-21). The program goal is targeted for 1981 using ceramic parts on a staged basis. Further details of this work are discussed below.

The Ford Motor Company began active turbine development about the same time as its Big Three competitors. The first Ford gas turbine engine was built in 1955 following four years of intensive component development. In 1957, following a full program reappraisal, the thrust of research shifted to engines for commercial road vehicles.

Ford made an important step forward with the "707" prototype, demonstrated in 1966, which featured twin glass-ceramic regenerators. Following successful road tests, Ford began planning for full-scale production of turbines in its Toledo, Ohio plant. A modified version of their previous engine was developed and 36 such engines were placed in trial service by 1972. However, they had to be recalled due to problems involving corrosion and disintegration of the ceramic regenerator cores, and the operation was terminated.

In mid-1971, Ford's ongoing work on ceramic components for turbines was accelerated under a five-year contract with the Advanced Research Projects Agency (ARPA) of the Department of Defense, under the supervision of the Army Materials and Mechanics Research Center. Further details of government-supported work at Ford are discussed below.

Several non-automotive organizations have also been involved in automotive gas turbine system development. Foremost domestically among these has been Williams Research Corporation, a manufacturer of small gas turbines. Their most significant efforts to date have been the design, construction, and vehicle installation of gas turbine engines for Volkswagen and the City of New York under separate contracts.

The main thrusts of government involvement in automotive gas turbine technology, beginning in the aftermath of the Clean Air Amendments of 1970, have been made through: 1) the "Baseline Gas Turbine Development Program" with Chrysler as principal contractor; 2) the "Brittle Materials Design Program" with Ford as prime contractor; and 3) the "Ford Regenerator Design and Reliability Program," again with Ford as principal contractor.[1]

The "Baseline Gas Turbine Development Program" actually consists of two phases. In the first phase, originally under contract, starting November 1972, from the Advanced Automotive Power Systems Division of the Environmental Protection Agency (management was transferred to the Energy Research and Development Administration (ERDA), Division of Transportation Energy Conservation, upon formation of that agency in January 1975), the "baseline engine" (namely, Chrysler's sixth-generation engine as described earlier) was built, installed in intermediate size vehicles, and tested. The results highlighted the need to improve NO_x emissions and the fuel economy of the engine, and helped establish the priorities to be addressed in the next "upgraded" phase. Various improvement concepts generated from the preceding program were

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[1] A detailed description of government-supported automotive gas turbine R&D may be found in (3-22).

incorporated in the "Upgraded Engine." The upgraded engine modifications include a backward bladed impeller and variable inlet guide vanes for the compressor, replacement of twin regenerators by a single ceramic one, accessory drive from the power shaft instead of the gasifier shaft, slightly higher turbine inlet temperature, etc. Initial running of the upgraded engine took place on July 13, 1976; the engine was found to be 43% deficient in power (3-23). A corrective development effort was begun to effect (principally) major aerodynamic redesign of the engine. This effort has been extended through mid-1978 to attempt to eliminate the current power shortfall of 25% (3-24). Further efforts are also needed to meet the efficiency goals.

Concurrent with and backing up the baseline program, ERDA-funded & NASA Lewis Research Center-monitored contracts were awarded to Corning Glass Corporation and Owens-Illinois, among others, to develop and supply ceramic regenerator core materials to Chrysler; the most significant outcome of these programs was the identification of metal aluminum silicates as promising candidate ceramic materials for regenerator cores. The Baseline Program (i.e., the baseline and upgraded engine phases together) has served most importantly to bring together and establish the status of the metallic gas turbine as a complete system, at close to the limit of its development. Major advances are now contingent on the successful incorporation of ceramic materials for the hot parts.

The second principal focus of government involvement has been through support of ceramic component research at Ford Motor Company, through two major programs.

The "Brittle Materials Design Program" which has been supported in part by ARPA since 1972, has served as the principal focus of ceramic hot-parts development to date (3-25). A number of stationary, hot-flowpath components have succesfully completed the goal of a 200-hour durability test at temperature levels of 2500°F. The principal conclusions to emerge were: 1) for combustors, reaction bonded silicon carbide was adjudged a leading candidate material; 2) injection-molded, reaction-sintered silicon nitride was identified as a promising candidate material for nose cones; 3) stators were adjudged approximately in the same stage of development as rotors; 4) silicon nitride rotor tip shrouds survived more than 200 hours at 1930°F, remaining in excellent condition; 5) the leading candidate for a ceramic turbine wheel emerged as the duo-density rotor. This concept essentially involves diffusion bonding a reaction-sintered silicon nitride blade ring to a hot-pressed silicon nitride hub of higher density, hence higher strength, but less temperature resistance.

Work on the Ford "duo-density" ceramic rotor concept is ongoing and test runs at steady 2500°F temperature levels for about 25 hours have recently been made (3-26). When viewed against the perspective of the order of a 3500-hour lifetime endurance requirement for automotive gas turbines with the order of 20,000 startups and shutdowns, these advances are seen to be quite modest. Further, there are other major unanswered questions, in particular about the reliability of brittle-material component designs, and the manufacturing feasibility and cost of ceramic components. Plans are under way to continue this effort through FY 1978 under NASA, Lewis Research Center, supervision (3-27).

Since 1973, Ford had been working on new chemically resistant ceramic materials to replace the lithium aluminum silicate materials then prevalent (3-28). In 1974, EPA joined Ford in the "Ford Regenerator Design and Reliability Program" and the program was transferred to ERDA in 1975 and is now under the technical direction of, and partly supported by, NASA. The ceramic regenerator matrix suppliers participating in the Ford program include Corning Glass, GTE Sylvania, and others. Considerable and encouraging progress has been made: two new promising materials, aluminum silicate and magnesium aluminum silicate, have been identified; the former, especially, shows excellent durability characteristics.

Present and planned support of gas turbine research by the Department of Energy will continue under the technical supervision of NASA, Lewis Research Center, in three principal directions: (i) "Improved gas turbine" development to provide the industry with the option of initiating production engineering development of improved gas turbine systems by 1983. The improved turbine by definition, "incorporates near-term technology and has at least a twenty percent gain in fuel economy over a 1976 spark-ignition engine, and compares favorably with respect to emission, driveability, reliability, and life-cycle cost to various alternative engines." (ii) Definition of an "advanced gas turbine" system by 1983, described as "one which incorporates significant advances in technology, has a fifty to sixty percent gain in fuel economy over a 1976 spark-ignition engine, and, like the improved engine, compares favorably with respect to emissions, driveability, reliability, and life-cycle costs to various alternative engines." (iii) To "develop the technology required for advanced systems in a timely manner, so that production of these systems is possible in the 1990s" (37-27).

Project organization and approach to attain these goals contain several elements. First is the completion of the development of the Chysler upgraded engine in 1978. Second, conceptual design studies for improved passenger-car gas-turbine systems are planned with several contractors. These comprise GM (Detroit Diesel Allison Division in combination with the Pontiac Division), Chrysler, Ford in collaboration with AiResearch Company, and finally, Williams Research Corporation teamed with American Motors Corporation; the results of the initial design studies are expected in early summer of 1978, after which further development work through 1983 is expected to continue (3-29). Third, the work on ceramics at Ford will continue through FY 1978, as will the program to incorporate ceramic components into the Detroit Diesel Allison 404 engine; the study program concerning potential improvements to the engine is now complete (3-21).

In the advanced systems definition area, a variable geometry, single-shaft engine prototype will be characterized, probably at GM (3-29). Related in-house studies are also planned within NASA-Lewis.

In the supporting research and technology effort, most importantly, development of a hydromechanical continuously variable transmission (crucial to the success of the single-shaft turbine engine) is continuing at Orshansky Transmission Corporation (3-30), aimed at better packaging and noise and weight reductions. Also, Mechnical Technology Incorporated is working in coordination with the current development effort at Chrysler on the upgraded engine, to continue testing and to verify their hydromechanical transmission concept (3-23). Development of the hydromechanical transmission CVT has also been carried out by General Electric (as described by Wright [3-8]) and by Sundstrand Corporation (3-9), the latter for commercial heavy duty vehicles.

We will conclude this discussion with a brief review of the future plans of the Big Three vis-a-vis gas turbine research. The main focus of gas turbine research at GM is at the Detroit Diesel Allison Division, in the area of heavy-duty commercial vehicles, under joint government support. While GM appears more optimistic (reflected in their level of internal interest and funding for this effort) about the prospects of the gas turbine in commercial applications, the emphasis on passenger-car gas-turbine research is relatively low. They appear, however, to be willing to enter into government-supported research in this area (see above). The passenger-car turbine is seen as requiring major efforts in all areas, especially cost, durability, and fuel economy (3-31).

At Ford, the major emphasis has been on ceramic component development and will continue to be so under cost-sharing agreements with the government. Total system development appears to have been relegated to second place, behind the drive for improvements realizable from ceramics. At Ford, the single-shaft engine is seen as the likely advanced configuration (3-11).

The consensus at Chrysler that appears to have emerged from the Baseline Engine Program to date is that the metallic engine is not a viable alternative candidate to the ICE. A major step to advanced turbine engines (i.e., with ceramic rotors) seems to be favored (3-32).

The Big Three in general, believe that the potential gains achievable by the ICE and the other engines (such as the diesel) now in the automotive market make the potential value of the gas turbine an open question; however, they all seem to be in favor of entering into cost-sharing programs with the government to investigate this potential further.

3.2.3 Attributes of Future Automotive Gas Turbine Engines

This section will focus on the attributes of the future automotive gas turbine. While it is clear that the attributes of the vehicle as a whole are of ultimate interest, the relationship between engine and vehicle systems is complex and will be taken up in Section 3.3.

We delineate the technology according to degree of development as follows: first, the state-of-the-art gas turbine -- defined as employing metallic parts except for the ceramic regenerator; second, we define an "intermediate" gas turbine technology, stipulated to employ ceramic components for all or some of the stationary hot-section parts of the engine -- i.e., excluding the turbine rotor(s); and finally, the advanced engine -- defined as incorporating ceramics for all hot-section parts, including the turbine rotor.

It is important that no temporal framework has been explicitly associated with this delineation of the technology -- the focus is exclusively on the technology itself. The state-of-the-art metallic engine, perhaps, comes closest to such an association -- by definition, it represents the best of the available technology, and the available (metallic) technology is very close to its peak of development. The intermediate and advanced technologies, on the other hand, are presently so inchoate as to preclude a meaningful forecast of the timing of their availability for an introduction decision.

In addition to the preceding classification based on the stage of development, we also identify technological options within each class, based on the choice of engine configuration -- single-shaft or free-shaft.

Ostensibly, this leaves us with six different engine types to consider; however, the number may be reduced to four in view of the following considerations. First, no state-of-the-art metallic, single-shaft automotive turbine prototypes are extant. Any single-shaft prototypes that are built and developed to a level adequate for introduction into the market will almost cerainly incorporate some ceramic hot parts at least. This conclusion precludes us from considering a metallic single-shaft configuration as we have defined it.

Second, we also neglect the advanced free-shaft technology, based on consensus from industry (3-11 and 3-31, 32) and our own judgment; the successful development of an advanced engine requires a major, risky, and protracted effort to develop ceramic hot running parts, i.e. the turbine rotor. The magnitude of this effort is probably much greater and less certain than that needed to successfully develop the single-shaft turbine configuration with a CVT. If and when an advanced single-shaft configuration (with CVT) is developed it will certainly show advantages over a comparable free-shaft engine on the important attributes as indicated by Table 3.1. We therefore consider the single-shaft engine as the only (or almost certainly so) viable advanced configuration.

Prior to consideration of the engine attributes, the technology delineations made above will be described more precisely. We will limit the description to the major components, those which it is felt largely determine engine attributes. The metallic engine, as mentioned earlier, is a free-shaft design; it incorporates: (1) all-metal technology, except for the ceramic regenerator; (2) a radial compressor with variable inlet guide vanes and backward-bladed impeller; (3) a fixed (possibly variable) geometry combustor using premix/prevaporization combustion techniques; (4) axial (possibly radial) flow superalloy turbine, and (5) axial-flow superalloy power turbine with variable inlet nozzles. This configuration corresponds roughly to the Chrysler upgraded engine.

Table 3.1

AUTOMOTIVE GAS TURBINE ATTRIBUTE STATUS

		FREE SHAFT		SINGLE SHAFT		
ATTRIBUTE	ROLE	METALLIC	INTERMEDIATE	INTERMEDIATE	ADVANCED	REMARKS
Initial Cost	Crucial for consumer acceptance	2 to 3 times cost of present ICE of comparable power.	Uncertain.	Uncertain.	Cost may be 1-2 times cost of ICE of comparable power.	Wide spread in cost estimates within technologies. Relative cost dependent on size.
Brake Efficiency	Key to fuel economy	About the same as the (present) ICE.	About the same as metallic engine, or marginally higher.	About 10% better than intermediate free shaft.	Very uncertain. Anywhere from 30% to 60% better than metallic turbine.	Crude efficiencies given. Relative part load efficiencies are lower.
Specific Weight (Weight per design horsepower)	Key to cost and fuel economy	About 10%-20% better than (present) ICE.	Marginally higher than metallic engine.	About 10% better than intermediate shaft.	Roughly 30-40% better than metallic free shaft.	Relative values vary with size. Values given are therefore roughly representative.
Power-speed Characteristic	Determines transmission requirements	Excellent characteristics. Conventional automatic transmission adequate.		Highly unsuitable characteristics make use of CVT imperative.		CVT development likely to benefit all engine technologies.

Table 3.1 (continued)

ATTRIBUTE	ROLE	FREE SHAFT METALLIC	FREE SHAFT INTERMEDIATE	SINGLE SHAFT INTERMEDIATE	SINGLE SHAFT ADVANCED	REMARKS
Packageability	Determines extent of vehicle modification necessary.	No problem with fit of engine proper in conventional chassis Large ducting may require vehicle body and seating modifications.	Same characteristics as metallic expected.	More compact than comparable free shaft. Same ducting problems apply.		
Emissions	Legislated standards to be met.	Attainment of 0.4 gm/mile NOx limit a continuing problem, appears solvable, maybe with variable geometry. Other emissions (HC, CO) no problem.		Same basic characteristics as comparable free shaft. Better fuel economy may help lower NOx emissions.	NOx emissions aggravated at higher temperatures.	NOx may impose an inherent limit of about 3000°F on maximum cycle temperature.
Driveability	Crucial consumer requirement	Reliable cold starting. Standing start acceleration slightly sluggish but not crucial. Response under cruising speed comparable to ICE.		Standing start response poorer than comparable free shaft.		Appears quite satisfactory in general.
Scaleability	Important for long-run production cost.	In comparison to ICE, scalibility may be a major problem, due to loss of efficiency with decreasing size.		Like free shaft		Characteristics of gas turbine (specific power, acceleration, fuel economy, etc.) worsen with decreasing size. So does relative cost.

Table 3.1 (continued)

		FREE SHAFT		SINGLE SHAFT		
ATTRIBUTE	ROLE	METALLIC	INTERMEDIATE	INTERMEDIATE	ADVANCED	REMARKS
Noise	Consumer and socially appreciated attribute.	Different noise characteristics from ICE--high audio frequency range--but easier to insulate.		Like free shaft.		
Vibration	Consumer requirement	Smooth and vibrationless performance, much better than ICE.		Like free shaft.		
Safety	Consumer and legal requirement	No major problems expected.		Like free shaft.		Aircraft and power station gas turbine practice show excellent safety record.
Durability	Consumer requirement	Unproven.		Like free shaft.		
Maintenance	Crucial consumer	Compared to ICE, the free shaft turbine has about 2/3 as many moving parts. Possibility of significantly reduced service needs. Ceramics likely to call for training of service-personnel to handle brittle materials.		General improvement over free shaft expected due to increased simplicity and reduced number of components.		

The intermediate gas turbine engine is defined as one that employs ceramics for some or all hot-section stationary parts. Successful stationary ceramic hot parts development is expected to precede ceramic turbine rotor development to a degree sufficient to make this a distinct technological configuration. Potential replacements of ceramics for metal parts would include the turbine shroud rings, combustor lining and scroll, gas generator turbine nozzle, variable power turbine nozzle blades, and transition ducting (3-25). The switch to ceramic parts is, however, likely to call for major design changes rather than just simple replacement.

The advanced gas turbine engine is defined as employing ceramics for all hot-section parts, including the turbine rotor. This will certainly lead to major mechanical design changes and attribute differences.

Having characterized the technology in this fashion, we may proceed to examine the attribute status of the various engine configurations. We will begin with the attributes of the metallic turbine engine and then proceed to examine the attributes of the others, focusing principally on the potential of these engines to deal with the shortcomings of the metallic engine. Table 3.1 summarizes the attribute status of the various gas-turbine configurations with the present ICE as reference.

First, we consider the efficiency of the metallic engine. By efficiency, we mean brake efficiency measured at the output of the transmission. A single, unqualified, numerical value for this attribute is of little validity. Brake efficiency is dependent on numerous factors, namely: (i) turbine inlet temperature; (ii) component efficiencies; (iii) engine operating point (or engine and transmission operating characteristics) to name only a few. The estimates given in

Table 3.1 may be taken as a crude bracketing of the efficiency of the turbine relative to the present ICE. The deterioration of efficiency with part-load is generally worse for the gas turbine than for the ICE and this is, in fact, a major drawback of the turbine, leading to poor fuel economy under the part-load conditions prevalent in normal driving patterns. The efficiency of the metallic engine, roughly representative of the (yet unattained) goals of the Chyrsler Upgraded Engine, is about the same as the present ICE but could be slightly better or worse. It is important to remember that we compare a laboratory turbine engine with a production ICE. It is unclear how a production version of the turbine would compare with the ICE.

Specific weight is a function of engine size or overall scale. hence a single specific weight value cannot be truly representative of the entire size range. The interpretation of numerical values given for these attributes in Table 3.1 must be tempered accordingly. The specific role of the efficiency and specific power attributes are brought out in more detail in the discussion of the vehicle-engine interaction in the next section. The specific weight of the metallic engine (based on the Chrysler upgraded engine) is somewhat better than the present ICE. However, it is possible that an actual production version could realize some marginal improvements in specific weight.

Attributes such as driveability, noise, vibration, and safety, compare satisfactorily with the ICE, if not actually better. The best evidence for this stems perhaps from the consumer reactions to the Chrysler and Ford pilot gas turbine vehicle introduction programs (see Section 3.2.2): while some dissatisfaction with standing start response was recorded, the low-noise and vibrationless characteristics of the turbine seemed especially to be appreciated. As for response, the indications are that this has since improved substantially, in the Chrysler Upgraded Engine.

One of the imporant factors favoring the gas turbine engine is its excellent emissions characteristics. The legislated research goal 0.4 gm/mile NO_x limit remains largely elusive. However it is not viewed as being critical: first, because the problem appears to be solveable, although perhaps at some penalty in cost and combustor complexity; second, fuel economy improvements will help alleviate the problem since emissions per mile vary inversely with fuel economy; and finally, the legislated NO_x standard can be expected to reflect the capabilities of the ICE, for which the problem of NO_x control is much more acute.

To sum up then, the status of the above attributes[1] appears satisfactory; any deficiences that may exist are dwarfed by the high initial cost. The actual cost of the metallic engine is very difficult to estimate. There are numerous unavoidable sources of uncertainty -- the new and as yet unoptimized (for production) engine technology, poor knowledge of mass-production methods, especially for gas turbine superalloy components, disagreement as to the appropriate costing methodology, etc. The initial cost data shown are compiled from available studies both within and without the automotive industry and the wide spread may be viewed as a consequence of the different ways in which the various groups have coped with these uncertainties. Very roughly, the cost of the metallic engine varies from 2 to 3 times the cost of an ICE of comparable power. We do not deal here with the initial cost

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[1] Not referring to efficiency and specific weight, discussed earlier.

comparison for engines with comparable vehicle performance, but will choose to address this in detail in Sections 3.3 and 3.4. Note also that these cost comparisons depend strongly on overall scale and assumed production levels for the gas turbine.

We will now consider the key attributes (efficiency, specific weight, initial cost) of the intermediate and advanced engines. Our approach will be to examine how these advanced technologies are likely to differ in these attributes from the metallic engine. Almost no estimates of the efficiency and specific power of the intermediate engine can be uncovered from the literature, and we have had to resort to engineering judgments. The efficiency is most importantly affected by turbine inlet temperature; since the latter is subject to the materials limit of the metallic turbine rotor, which is common to both metallic and intermediate configurations by definition, the efficiency is not likely to be much better. Schultz (3-25) estimates on the order of ten percentage points improvement in efficiency due to stationary ceramic hot parts. The potential for weight reduction from the sustitution of ceramics for the metallic hot-section parts is also unclear. There is some indication that the scope for improvement is small (3-33). Specific weight is not likely to improve substantially.

The attributes of the intermediate single-shaft engine are equally uncertain, but we have made crude estimates based on comparisons between metallic single-shaft and free-shaft configurations (3-2). Roughly, improvements of the order of 10% over the intermediate free-shaft engine in efficiency and specific weight are estimated.

The efficiency as well as the specific weight of the advanced engine have the potential to be substanially better -- a consequence of the higher operating temperatures permitted by a ceramic rotor -- but this potential is very uncertain. The scalability of the advanced engine, especially in sizes below about 100 hp, is a major issue (3-34). The decrease in size with higher operating temperatures could negate much of the efficiency improvement arising fom such temperatures, principally because of increased aerodynamic losses. On the other hand, efficiency of the gas turbine is also dependent on the ambient temperature, which affects the density of the intake air. Most available technology studies assume ambient temperatures (about 75-100°F) that are considerably higher than the national average ambient temperature, around 56°F. Since the performance of the gas turbine improves with decreasing ambient temperature, some credit must be attributed to the gas turbine on this score. The improvement in efficiency has been estimated to be of the order of 5% (3-21, p. 34). Although this estimate applies to heavy-duty engines for commercial use, it is sufficient to convey the magnitude of the improvement involved. The efficiency improvement of the advanced turbine over the metallic turbine could be from roughly 30% to 60%. The specific weight improvement is also uncertain, but could be around 30% less than the metallic turbine.

Emissions control of the advanced engine will become more difficult with the higher operating temperatures, which aggravate NO_x emissions. On the other hand, combustor design may be expected to advance, hopefully coping with this problem. The ceramic turbine rotors, lighter than their superalloy counterparts, may be expected to contribute to improved acceleration response.

The initial cost decrease realizable from ceramics (whether in the context of the intermediate or advanced engines) is extremely uncertain at this stage. The already formidable task of initial cost estimation for the metallic engine is compounded by the embryonic nature of ceramics technology. So far, only the material cost of ceramics exists as conrete data: ceramics are at least an order of magnitude cheaper than the expensive superalloys they will replace; and what is more important, but less clearly quantifiable in terms of benefits, available domestically in abundance. However, the extent to which this cost reduction will be reflected in the finished component in production stituations is unclear.

We will now quickly summarize the status of the gas turbine engine, beginning with the metallic turbine. Apart from the key attributes of initial cost and efficiency, the engine appears satisfactory, if not better, on all other counts. The initial cost is considerably higher and the engine efficiency is uncertain, but close to that of the present ICE. The intermediate, free-shaft engine is likely to have values of all attributes (except efficiency, which may be somewhat higher) about the same as the metallic engine. The intermediate, single-shaft engine is likely to have some improvement over the intermediate free-shaft in specific weight and efficiency and also in initial cost, contingent on the availability of a continuously variable transmission (CVT). The advanced single-shaft engine has uncertain potential for substantial improvement in the key attributes of initial cost, efficiency, and specific power; it may have a problem with controlling NO_x emissions to the 0.4 gm/mi statutory "research goal;" but has satisfactory values of other attributes.

3.2.4 The ICE Baseline

In the preceding sections we have explored at some length the status of gas turbine technology at various levels of development. The attributes were assessed relative to the present, or contemporary ICE: the status of the latter is well known and provides a sound basis for comparison. In this subsection, we shall deal briefly with the character and dynamics of the baseline. A more detailed but somewhat dated treatment of this subject may be found in Federal Support (3-1, Chap. 4).

The ICE has been the globally dominant automotive powerplant since the early 1900s, supported by a vast, well established and sophisticated production, distribution, and service infrastructure. Further, the industry has maintained an impressive and continuing record of improvements in almost all aspects of the technology.

Two critical impediments now raise concern over the future of the baseline technology: emissions standards and fuel economy goals. Uncertainty regarding the future levels of these standards compounds the situation. Since the alternative automotive powerplants are unlikely to be in mass production before the mid-1980s, it is evident that a realistic evaluation of the gas turbine must be based on the available ICE in this future time frame. This forces us to consider the movement of the baseline from the present through this future.

The tremendous development resources available for the ICE, coupled with intensive ongoing efforts to adapt the ICE to the perceived needs of the 1980s make substantial improvements in the conventional automobile likely, with the main thrusts directed toward improving emissions and fuel economy. Unfortunately for the ICE, these are conflicting goals. A full discussion of the various technological devices and concepts under development to improve emissions and fuel economy can be found in Federal Support (3-1, Chap. 4) and elsewhere. Our aim here will be to focus on areas of improvement in the engine alone that can lead to increased engine efficiency and to roughly quantify the magnitude of this improvement.

The need for isolating potential improvements in the engine alone is clear: vehicle fuel economy gains are likely to be realized through improvements, in the ICE design and also unrelated to the ICE. Unrelated effects include changes in vehicle aerodynamic characteristics, weight, tire design, etc. However, improvements in vehicle fuel economy due to these effects would apply equally to a vehicle powered by a gas turbine as to one powered by an ICE. It is principally improvements in vehicle fuel economy due to changes in the ICE alone that will affect the relative value of the engines.

A breakdown of the possible engine changes leading to improved fuel economy without any emissions penalty is given in Federal Support (3-1, Table 4.2). A similar, more recent cataloging of possible engine changes leading to improved fuel economy by Withrow and Franceschina (3-35) includes combustion chamber development providing for more efficient combustion, more compression-induced turbulence, variable valve timing, intake manifold improvements, use of electronically controlled fuel injection systems, optimizing of engine controls such as air-fuel ratio, EGR, and spark timing under all operating conditions, etc.

As mentioned earlier, improvements in fuel economy realizable from engine modifications have to be traded off against losses due to tighter emissions standards. Any estimates of fuel economy gains carry implicit assumptions about emissions levels. The emissions levels that will obtain in the mid-1980s time frame are not known with certainty. We will assume that the legislated 1981 standards (0.41/3.4/1 HC/CO/NO_x gm/mi) will carry over into this period. The actual emissions levels will probably be at least as tight as these, so that the fuel economy gains for the ICE predicated on these standards might be somewhat on the optimistic side. A crude estimate of the potential fuel economy changes due to engine improvements by 1985 at the assumed emissions levels can be obtained from Federal Support (3-1, Fig. 4.1., p. 111). The 1981 emissions levels are not represented, but relative to the 1977 ICE, a fuel economy penalty ranging from 5% to 15% can be interpolated. We now believe this to have been overly pessimistic by approximately 10%, so that the 1985 ICE may be from 5% inferior to 5% superior to the 1977 ICE, in efficiency, at 1981 and 1977 emission standards, respectively. This is roughly consistent with the predictions of Withrow and Franceschina (3-35), and others.

We have made the point in Section 3.2.3 that the continuously variable transmission (CVT) is required for the single-shaft engine. It is also important to recognize that this could result in major improvements in the efficiency of the ICE powerplant (3-30) and consequently, fuel economy. The impact of the CVT on the other attributes of the baseline engine is uncertain, but the indications are that there will be no significant increase in weight compared to the conventional automotive transmission and the cost increment, although uncertain, is probably not considerable. Our focus on CVTs will be confined mainly to the realization that advantages of the development of a CVT for a single-shaft turbine will also apply to the ICE.

3.3 Analytical Framework for Economic Analysis of the Gas Turbine Engine

3.3.1 Conceptual Background

In Section 3.3.2 following we develop a simple, quantitative model for comparing automotive powerplants. In later sections (3.4 and 3.5) we apply it to a comparison of the gas turbine and the ICE under various circumstances. Our goal here is to develop a framework which is as simple as possible, which captures the important effects of the differences in attributes between the gas turbine and the ICE, and yet which is no more detailed than is justified by the uncertainties in the available input data -- especially the forecasts of the attributes of the two systems and the other key exogenous parameters (in particular, fuel prices). The purpose of the framework is not a conclusive comparison of the two systems -- for as we shall see, this is impossible -- but rather it is for analyzing the reasonable extent and direction of the government's role in supporting R&D in this area.

The basic methodological issues in comparing automotive powerplants are discussed adequately in Federal Support (3-1, Sects. 3.3, 3.5 and 5.3) and will not be reviewed in detail here. The work by MIT (3-1), JPL (3-2), and Rand (3-36) remain the important contributions in this area; little of methodological interest has been published since these three works were published one and one-half to two and one-half years ago. In the present effort we continue the basic approach previously used in those three efforts. This may be summarized as a comparison of life-cycle costs of vehicles using different engines, where the following key vehicle parameters are held constant at exogenously specified levels: internal compartment volume, acceleration, and emissions. Vehicle structure (i.e., weight), engine design power, and fuel type are allowed to vary across engines. Cost minimization is especially appropriate for the present study as it constitutes a reasonable normative goal for government-supported R&D programs (3-1, Sect. 3.5). As discussed in Federal Support (3-1, Sect. 5.3.1), vehicle acceleration and emissions should properly be calculated endogenously, as they in fact result from something approaching optimizing behavior and their marginal costs are quite different between engines; however, lack of data on the demand (marginal value) side makes this impossible at present.

The model used here is an extension in substance and style of that used in the previous MIT effort on the Stirling engine. That powerplant could reasonably be assumed to have approximately the same specific weight (engine weight per unit of power) as the ICE and a similar power-speed characteristic; thus equal vehicle performance implied equal engine power, so that vehicle cost difference equalled engine cost difference, and the ratio of vehicle fuel economies was the ratio of engine efficiencies. An extremely simple vehicle cost model was therefore acceptable.

Here we extend that basic model, but in the simplest possible manner, to account for the gas turbine's advantage in specific weight and in power-speed characteristic relative to the ICE as they affect the engine/vehicle system configuration. The economic value of the gas-turbine, relative to the ICE, is calculated for an individual vehicle. It is a function principally of the extensive properties of the fixed "baseline" vehicle (weight and fuel consumption), the intensive attributes of the ICE and the gas-turbine engines (efficiency, power-specific weight, power-specific initial cost, and a parameter characterizing the power-speed characteristic), and fuel prices (gasoline price, social premium on fuel, price difference between baseline and gas-turbine fuels).

As will be apparent, our model makes drastic simplifications for the preservation of computational simplicity and analytical clarity. However, it will be seen that, for the purpose at hand, the model exploits the data available to us to the maximum extent justifiable. The results establish the rough range of the possible benefits of the availability of the gas turbine engine, and the factors upon which those benefits are dependent. Where detailed guidance for project management is the goal, then original and detailed technical analysis is appropriate; our goals are quite different.

A major continuing difficulty in this (and other) powerplant analyses is the choice of a "baseline," or the system against which all new engines must compete, at least analytically. With the recent introduction of the diesel into the passenger car marketplace by General Motors, and the serious consideration of a similar move with the open chamber stratified charge system by Ford, it is no longer adequate to just attempt to forecast the future attributes of the ICE. Further, we will be examining the potential role of gas turbine engines using ceramics for hot parts, and thus our time horizon extends beyond the mid-1980s. Nevertheless we will compare future gas turbines with our estimate of the mid-1980s ICE. We do this because it is not clear whether beyond that time there is much to be gained by the ICE or similar systems (the diesel or stratified charge). In this sense we use the same 1985 baseline to refer more generally to the ICE or similar systems at even more distant dates. To the extent that this is incorrect, we have erred in favor of the gas turbine. Thus, accompanying the following calculations there is an implicit case where the "baseline" system makes much greater improvements than we admit in our presented results, and which thereby makes the gas turbine valueless under all circumstances. We consider this an unlikely occurrence.

Difficulties in dealing with emissions as an engine attribute are essentially related to the baseline. It remains the case that the "original 1976" statutory emissions goals (.41/3.4/.4 HC/CO/NO_x gm/mi), are the most stringent in sight, that the gas turbine can meet them fairly readily, and the ICE can meet them only with sacrifices in cost and efficiency. At the present time the most stringent legislated goals are .41/3.4/1.0 for model year 1981 and thereafter, and indications are that these standards will be attained by ICE-powered vehicles (see Chapter 2 above). Thus there will likely be little difference in emissions between future powerplants. We have incorporated the efficiency loss and initial cost increase due to these standards in our ICE baseline projections. The lower NO_x emissions of the gas turbine have no measurable health impact (3-37, p. 16), so no credit will be given for this in the social economic calculations to follow.

Continuous combustion systems have the desirable property of being able to burn almost any liquid or gaseous fuel (and possibly even pulverized coal). This seems a desirable attribute in light of the foreseeable evolution of the energy system, as conventional petroleum becomes depleted and synthetics take its place in uses where liquids are especially highly valued, as in transportation. However, whatever the ultimate source of the liquid fuels used by transport systems, it is unlikely to be the case that any given vehicle will operate during its lifetime on more than one type of fuel (or, at worst, a gas turbine or other flexible system would be modified once during its lifetime to accommodate a change in fuels). The highly refined gasoline required by the ICE can be produced from almost any of the potential synthetic crude oils. Thus the value of fuel flexibility is nothing more, or less, than the value of the ability to burn a fuel which is less expensive than gasoline. This is accounted for in the simple model below.

In consonance with the basic style of our analysis, we will perform our economic calculations for a single vehicle size only. We have chosen a compact class vehicle representative of those likely to dominate the American automotive fleet of the future. Consideration of the diverse range of vehicle classes, or of the diversity of driving patterns, would add little substance to our results.

3.3.2 A Simple Vehicle Total Operating Model

A simple calculation procedure (model) is developed here for comparing the "total lifetime operating cost" (defined here to include initial outlay minus scrap recovery and direct operating costs) of a vehicle equipped with an alternative power plant to one having a conventional ("baseline") Internal Combustion Engine (ICE). Although the model developed here is similar in basic approach to the one developed in Federal Support (3-1, Section 5.3.1.2) it is more general, being applicable to any powerplant given quantitative values of the relevant engine attributes (to be identified below). The model is somewhat more versatile, bringing out more clearly the role of these key attributes in determining total operating costs, and allows us to investigate trade-offs other than just those between initial powerplant cost and efficiency attributes as in the original study. First, the physical configurations of the alternative powerplant and ICE vehicle systems are established with the ICE-powered vehicle, and with what are considered to be appropriate consumer acceptance criteria as a starting point. Second, an equation for determining the total lifetime operating cost associated with these configurations is formulated.

As discussed above, the style of our analysis will be one of drastic simplification. The purpose of this model is to crudely estimate in economic terms the benefits available from an alternative powerplant, and the key dependencies and uncertainties of those benefits. Detail is retained in the model only as necessary to adequately meet this purpose.

System Configuration

First, we will establish a consistent basis for comparison of engine technologies by defining "powerplants" to include the engine and all auxiliaries such as fans, radiator, generator, battery, cooling systems, emission controls (if any) and transmission. Thus all elements of the automobile exogenous to the powerplant are common to all technologies.[1]

Before attempting to estimate the total operating costs and benefits associated with alternative powerplants, it is necessary to establish the total powerplant-vehicle system configuration; we limit our description of system configuration to the principal extensive powerplant attributes -- power and weight, and the major vehicle attribute -- weight. The

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[1] Note that we may subsequently sometimes loosely use the term "engine" (as we have done previously in Section 3.2.3) but in the same sense as the powerplant defined above.

comparison between the ICE and alternative powerplant cannot be made arbitrarily; configurational differences will be determined on vehicles with comparable acceleration performance.

The first two of the inputs to the analysis will be the following intensive powerplant attributes: (i) power-speed characteristic and (ii) specific weight (powerplant weight per design horsepower). From these two attributes, powerplant configuration will first be established. The vehicle configuration will then follow by the weight-propagation effect.

There is more than one way to characterize vehicle performance, and none does so completely. Quantitatively, the performance is variously described in terms of distance covered from standing start in a given time, time taken to attain a specified velocity from standing start, or time (distance) to go from a highway cruising speed to passing speed. We shall opt here (although it is not entirely clear that this is the best option) to use the most common measure of performance, namely 0 - 60 mph acceleration time. The performance criterion can then be specified abstractly in terms of the parameter pair -- (V_o, t_o) -- where V_o is the final velocity at the end of the acceleration mode and t_o is the time duration of this mode.

We now attempt to determine roughly the relation between engine power and vehicle weight. The major components of the load on the engine are inertia load, rolling friction, and aerodynamic drag. Aerodynamic drag power is a cubic function of vehicle velocity and thus is most significant at higher speeds. We choose to neglect it during the 0 - 60 mph acceleration mode to preserve analytical simplicity. A simple correction for this nontrivial, but not crucial, effect will be introduced below.

The power required during the acceleration mode is

$$P_i = (WV/g)(dV/dt) + \alpha WV \qquad (1)$$

where

P_i = total instantaneous power demand (hp)

W = inertial vehicle weight (lb)

V = instantaneous vehicle velocity (mph)

t = time from standing start (s)

α = tire coefficient (hp/lb-mph)

g = acceleration due to gravity (ft/s^2)

The above differential equation sums up the inertial and rolling friction power requirements in the acceleration mode. In order to confine ourselves to a closed form solution, we replace dV/dt by the time--averaged acceleration V_o/t_o, which is expected to be most closely representative of the instantaneous acceleration at the midpoint of the acceleration period; we further assume the velocity to be about its average value ($V_o/2$) at this time so that an "average" power, P_a, can be estimated as

$$P_a = (W/2)\ (V_o^2/gt_o + \alpha V_o)$$

or

$$P_a/W = K_a \qquad (2)$$

where

$$K_a = (V_o/2)\ (\ V_o/gt_o + \alpha\ ) \qquad (2a)$$

The quantity K_a can be regarded as an "acceleration parameter," crudely summarizing the dynamics of the acceleration mode.

The discussion so far has been concerned strictly with the power required by the vehicle. We now turn to the power available from the engine and its relationship to vehicle kinematics. This relationship plays a significant role in determining the design horsepower of the engine, as JPL (3-2, p. 10-4) has demonstrated.

The power that the engine[1] can deliver at a certain vehicle road speed is determined by two factors: (i) the power that the engine can deliver at a certain engine rpm, and (ii) the manner in wich the transmission and drivetrain system relates engine rpm to vehicle road speed. The first of these factors depends on engine design and is also specific to engine type. The second factor is a characteristic of the transmission and drivetrain system, and insofar as all engines are constrained to have the same transmission, is independent of engine type (the single-shaft gas turbine, which requires a continuously variable transmission is an important exception and we shall deal explicitly with it in Section 3.4). For the purpose of establishing powerplant and vehicle configuration from acceleration performance criteria, we deal with the maximum power that the engine can deliver at any given engine-rpm.

A complete representation of the two distinct (i.e., (i) engine and (ii) transmission and drivetrain) characteristics would take the form of

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[1] Strictly speaking, and confined only to this discussion of the power-speed characteristics, we refer to "engine" excluding the transmission, and to engine rpm before the transmission, while we refer to the powerplant as defined earlier, that is, including the transmission.

functional relationships. However, consistent with the very limited level of detail we wish to retain in this analysis we will make a gross simplification which will, however, capture in a rough sense, the importance of these characteristics.

First, recall that in equation (2) we estimated an "average" power during the acceleration mode at an average velocity (for our assumed 0-60 mph acceleration mode, this average value is 30 mph). For a conventional 3-speed automatic transmission, the engine rpm is about 65% of the rpm corresponding to peak or design horsepower, Rand (3-36, p. 12). We can also estimate, from available curves of normalized[1] engine horsepower versus normalized engine rpm, a value for the ratio of the design horsepower to that at 65% of design speed. A "power-speed" parameter ϕ is defined accordingly, as given below:

$$\phi = 1/P^* \tag{3}$$

where P* is the normalized horsepower at a normalized engine rpm value of 0.65. The parameter ϕ is the first intensive engine attribute input to our model, and since its definition is consistent with the conditions underlying our earlier estimate of an "average" power from equation (2), we may combine equations (2) and (3) as follows

$$P_a/P \simeq P^*$$

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[1] "Normalized" implies that the relevant quantity (such as horsepower, or rpm) is expressed relative to its design value.

where P is the design horsepower. Then,

$$P/W = \phi K_a \tag{4}$$

Thus, the acceleration parameter K_a and the power-speed parameter, ϕ , combine to determine the design power-to-weight ratio. This equation in its present form is inadequate, even given the assumptions and simplifications that led up to it. It diverges from reality in several respects. Not only is the actual relationship a more complicated one, but each key simplification tends to result in an underestimate of design horsepower. To attempt to characterize these effects rigorously would vastly increase the complexity of the analysis; our approach, therefore will be to estimate the import of these factors, listed below. These estimates will be used to roughly correct the value of P from equation (4) and are roughly consistent with similar estimates given by Hurter ((3-38, p. 5); also refer to (3-39 through 3-44)).

First, inefficiencies in the transmission and drivetrain will reduce power availability -- a loss of 10% to 15% of design power is typical; second, auxiliary and accessory power requirements -- a 10% to 15% margin is estimated on this account; third, and finally, aerodynamic drag and grade effects are assigned a 10% to 15% margin. The above effects add up to roughly 40% of the design power. An overall factor, $\xi = 0.6$ is used to upgrade our estimate of design power from (4).[1] ξ may be recognized

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[1] It is also recognized that ξ should vary with engine type, but probably not significantly, so that we elect to use the same value for all engines.

as the fraction of design power reaching the wheels. Then, from equation (4):

$$P/W = (1/\xi)\,\phi\,K_a \tag{5}$$

It may be mentioned that the calculations of powerplant configuration that follow in Section 3.4 roughly validate this formulation by giving us power-to-weight ratios for the ICE that agree with those for current ICE automobiles (3-45, p. 7).

Equation (5) is the first of our equations for establishing the (extensive) engine-vehicle configuration. We now turn to the role of another engine attribute, specific weight, in determining this configuration. We seek to relate powerplant weight to engine design horsepower. Available studies do this in various ways; both linear as well as nonlinear relationships have been used. For our purposes, a simple proportionality constant is judged adequate:

$$W_p = wP \tag{6}$$

where

W_p = powerplant weight (lb)
w = specific weight (lb/hp).

It is recognized that changes in powerplant weight due to any reason whatsoever (from modifications within engine type to entire replacement with a different engine type) should be reflected in the weight of the nonpropulsive (i.e., excluding the powerplant) vehicle, which is consistent with the fact that the vehicle provides structural support for the powerplant. The weight propagation factor quantifies the change in the total vehicle weight resulting from a unit change in powerplant weight. JPL (3-2, p. 10-3) has accounted for the effect of differing engine specific weights (across engine types) on the weight propagation factor. However, a preliminary analysis indicates that this effect is well within the error limits of our analysis. We therefore adopt a weight propagation factor that is independent of engine type, defined as:

$$dW/dWp = k$$

or

$$W = kWp + K_W \qquad (7)$$

where k is the weight propagation factor.[1] The constant K_W is independent of engine type, has the dimension of weight, and may be determined from relatively well-established baseline data.[2,3]

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[1] See Wright (3-46, p. 858) for a similar treatment of, and JPL (3-2, p. 10-3) for a more detailed approach to, weight propagation.

[2] This actually assumes that the baseline ICE is optimal in the sense that there is no needless weight or power. It is seen as a fairly reasonable assumption, in view of the long evolutionary development of the baseline.

[3] In Section 3.5.2, we shall also adapt the model to conditions where no weight propagation might result.

Equations (5), (6), and (7) form the basis for the determination of powerplant configuration; from these it is possible to obtain very easily the following equations expressing system configuration in terms of intensive engine attributes:

$$W = K_W/(1 - k\phi K_a\ w/\xi) \qquad (8)$$

$$P = K_W(\phi K_a/\xi)/(1 - k\phi K_a\ w/\xi) \qquad (9)$$

$$W_p = K_W(\phi K_a\ w/\xi)/(1 - k\phi K_a\ w/\xi) \qquad (10)$$

It may be noted that the quantity $(\phi K_a\ w/\xi)$ represents the ratio of powerplant to vehicle weight.

Initial Cost

The initial cost comparison between the alternative powerplant and the ICE must necessarily be made on a vehicle basis. On the other hand, our ultimate objective is to focus on powerplant attributes -- which, in this case, means the initial cost of the powerplant alone. To start with, the total vehicle initial cost is expressed as follows:

$$I = I_v + I_p \qquad (11)$$

where

I_p = initial cost of the powerplant,

I_v = initial cost associated with the rest of the vehicle (nonpropulsive vehicle), and

I = initial cost of the entire vehicle.

It is possible to crudely estimate I_v as being proportional to the weight of the nonpropulsive portion of the vehicle. This allows us to focus conveniently on the initial cost of the powerplant itself. Thus:

$$I_v = c_v(W' - W_p) \tag{12}$$

where c_v is the cost per pound of nonpropulsive vehicle. W' is the curb weight, taken to be inertial weight W, less 300 lbs.

At this stage we introduce the intensive engine attribute, "i," the power-specific initial cost of the power plant. Thus,

$$i = I_p/P \tag{13}$$

Equations (12) and (13) allow us to express the total initial cost of the entire vehicle entirely in terms of intensive engine attributes.

At this stage, however, we shall not introduce all the intensive attributes, but express the initial cost in a simpler form, using the extensive attributes W, P, and W_p (recalling that these are expressible explicitly in terms of the intensive attributes according to equations (8) through (10)). Combining (11), (12), and (13),

$$I = iP + c_v(W' - W_p) \tag{14}$$

Further, the initial cost difference between the alternative powerplant and the baseline ICE may be expressed as

$$\Delta I = \Delta(iP) + c_v\Delta(W - W_p) \tag{15}$$

where $\Delta x = x - x_o$, where x stands for alternative powerplant attribute and the zero subscript indicates the corresponding baseline attribute, here, and in all subsequent discussions.

Using equation (7)

$$\Delta I = \Delta(iP) + (1 - 1/k)c_v\Delta W \tag{16}$$

Finally, we also define a comparative measure of specific initial cost relative to the baseline:

$$r_i = i/i_o \tag{17}$$

We choose to deal with specific initial cost, since it allows us to ignore scale effects for not too large variations in scale.

Fuel Economy

Fuel economy (or its reciprocal, fuel consumption) is an attribute of the engine-vehicle system. Engine attributes, system configuration, vehicle dynamics (dependent on driving cycle), and controlled design parameters (air fuel ratio or compression ratio, for instance), even ambient conditions, all affect fuel economy. The interrelationships between these factors are very complex. There is, however, no doubt that the single intensive engine characteristic that most directly determines fuel economy is the engine brake specific fuel consumption (BSFC) characteristic, which expresses the fuel consumption rate per unit power output at any point in the operating range of the engine. The BSFC is a direct measure of engine brake efficiency, according to a reciprocal relationship.

Apart from this engine attribute, a second crucial factor affecting fuel economy is the extensive system configuration, most conveniently expressed as vehicle weight (3-47). The fuel economy appears to vary more or less proportionately with vehicle weight, other factors remaining unaltered (3-45, 47) -- a conclusion supported analytically.

We will consider these two factors within the simple framework of our approach. We are specifically interested in the effect of engine efficiency and in the effect of weight changes (due to the differing specific weight and power-speed characteristic of the alternative powerplants) on fuel economy. We thus construct the following simple relation

$$F \simeq K_F \, (W/\epsilon) \qquad (18)$$

where

F = fuel consumption (gallons per mile)

ϵ = a crude average efficiency estimate over the Federal Composite Driving Cycle

K_F = a (dimensional) constant that includes the effect of those factors other than total vehicle weight and efficiency, such as the particular driving cycle, aerodynamic drag, tire friction, etc. which affect fuel economy.

The factors embodied in K_F may be assumed largely independent of powerplant type. Consequent on this assumption, it is expedient to factor out the constant K_F and deal only with fuel-economy ratios as represented below.

$$\eta = F_o/F = r_\epsilon\ (W_o/W) \qquad (19)$$

where

η = ratio of fuel economy of alternative-powerplant-powered vehicle to that of the ICE vehicle of comparable performance, and

r_ϵ = ratio of the average efficiency of the alternative powerplant to that of the ICE.

It must be realized that this treatment is a very crude simplification. The effect of the numerous engine-vehicle design variables that affect engine efficiency are not considered -- but it is nonetheless consistent with our initial assumption that we consider only optimally designed engines; here, we may interpret this to mean that these design parameters are controlled to provide the best possible engine BSFC characteristic and consequently, optimum efficiency.

Vehicle Total Operating Costs

We choose a representative vehicle class and compute the total operating costs for this class. An equation for the average total cost per mile was developed in Federal Support (3-1, pp. 154-155). We will present the equation below with this brief note. The total cost is averaged through the vehicle's life using a single average vehicle lifetime and an average annual vehicle mileage assumed invariant over time (for comparisons in the future). Thus

$$C = T/M = (A/M)I + pF + V \qquad (20)$$

where

T = total annual average vehicle operating cost (¢)

I = initial vehicle purchase price (¢)

A = annualized fraction of capital cost

V = vehicle total operating cost other than fuel and capital costs, i.e., maintenance, insurance, oil, etc., all calculated on a per-mile basis (¢/mi).

p = price of fuel (¢/gal)

F = vehicle fuel consumption (gal/mile)

M = average annual vehicle miles traveled

C = total operating cost (¢/mi).

The annualized fraction of capital cost, A, is defined below.

$$A = r((1 + r)^L - \gamma)/((1 + r)^L - 1) \tag{21}$$

where

r = relevant interest rate; and

γ = fraction of initial value received for salvage at the end of the vehicle life.

Equation (20) is applicable to any automobile in general, independent of powerplant type. We now introduce powerplant-vehicle system characteristics, using equations (14) and (18).

$$C = (A/M)(iP) + (A/M)c_v(W' - W_p) + p(K_F\, W/\epsilon) + V \tag{22}$$

where, once again, it may be recalled that the extensive system attributes W, P, and W_p are expressible in terms of the intensive powerplant attributes according to equations (8) through (10).

The first term in the above equation constitutes the amortized fraction of powerplant cost; the second, the amortized fraction of nonpropulsive vehicle costs; the third, fuel costs; and finally, the other operating costs per mile. This last is a very uncertain quantity for the alternative powerplants; service experience with them is virtually nonexistent. The indications are, however, that the maintenance requirements will, at worst, be the same as those for the ICE.

It is evident that the status of the alternative powerplants is meaningful only in comparison to that of the ICE. This highlights the importance of the economic benefit associated with the alternative powerplant over the ICE, if any. A positive benefit may be said to accrue when the total operating cost for the alternative powerplant is less than that for the baseline. The total operating benefit, "B," may be defined on this basis:

$$B = C_o - C = -\Delta C \qquad (23)$$

This benefit may also be expressed as follows (via equation (20))

$$B = -(A/M)\Delta I - \Delta(pF) - \Delta V \qquad (24)$$

Thus it is composed of an initial cost difference, a fuel-consumption benefit, and a maintenance benefit. In accordance with our earlier discussion with respect to "V," the associated benefit is (conservatively) set to zero. Thus

$$B = -(A/M)\Delta I - \Delta(pF) \qquad (25)$$

Before proceeding further, we shall quickly summarize the factors that determine the benefits. These benefits are a function of (i) the intensive technical engine attributes (of both the alternative powerplant and baseline ICE) namely, the power-speed characteristic, specific weight, efficiency, and specific initial cost; (ii) the extensive baseline system configuration chosen as a reference, represented by the vehicle inertial weight and fuel economy (note: the comparable alternative system configurations are incrementally derived from the baseline reference, using the intensive attributes listed in (i)); (ii) economic inputs, namely fuel prices, interest rate on initial cost, and cost per pound of nonpropulsive vehicle, and finally, (iv) exogenous factors such as annual average vehicle miles traveled and vehicle lifetime.

The total operating benefits may this be expressed by the following equation, using equations (16), (17), and (19) in (25)

$$\begin{aligned} B = \; & (A/M)i_o P_o(1 - r_i(P/P_o)) \\ & + (A/M)c_v(1 - 1/k)W_o(1 - W/W_o) \\ & + P_o F_o(1 - (1/r_\epsilon)(W/W_o)) \\ & + F_o \Delta p(1/r_\epsilon)(W/W_o) \end{aligned} \qquad (26)$$

where, from equation (8),

$$W/W_o = (1 - kK_a \phi_o w_o/\xi)/(1 - kK_a \phi w/\xi) \qquad (27)$$

and, from equation (9)

$$\frac{P}{P_o} = \left(\frac{\phi}{\phi_o}\right)\left(\frac{1 - kK_a\phi_o w_o/\xi}{1 - kK_a \phi w/\xi}\right) \qquad (28)$$

The first term in the the benefits equation is the difference in amortized powerplant costs. The second is the amortized cost difference associated with differences in nonpropulsive vehicle weight. The last two terms constitute the fuel economy benefit. The expression of the possible alternative powerplant fuel price advantage as a difference in fuel price (Δp)[1] rather than as a fractional value of the gasoline price (p_o x fraction) is because the difference would be attributable to refining cost differences, while movements in the price of both gasoline and the fuel used by the alternative powerplant would be expected to occur principally due to changes in the cost of crude oil. Thus the two factors are clearly distinguished by this form of expression of the fuel price advantage.

Because the initial cost of the gas turbine engine remains the single most uncertain engine attribute, in the following economic analysis we will treat it as the "residual" attribute. The net benefits (equation 26) are linear in relative specific initial cost, r_i. We will focus our discussion on the two intercepts of the line obtained when B is plotted against r_i. The vertical intercept (B @ $r_i = 1$) is a rough indication of the maximum obtainable benefits from a gas turbine

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[1] The fuel difference Δp, is defined as $(p_o - p)$ so that a positive value would mean positive benefits associated with the alternative powerplant.

system defined by all the attributes other than initial cost; we have taken it to occur where the specific initial cost of gas turbine is equal to that of the ICE. The horizontal intercept (r_{BE}) indicates the maximum socially acceptable initial specific cost, relative to the ICE, of a given configuration; that is, it is the relative specific initial cost at which the gas turbine "breaks even."

Finally, it is necessary to include the effect of the different energy densities of gasoline (or whatever fuel is used by the ICE) and the fuel used by the alternative powerplant. We shall do this by adjusting the price "p" of the alternative fuel to gasoline-equivalent gallons (in terms of equal energy content) as follows:

> p (in cents per gasoline-equivalent gallons) = p (in cents per gallon of alternative fuel) x (energy content per gallon of gasoline/energy content per gallon of alternative fuel).

In calculating the total benefits, we shall use the price of the fuel used by the alternative powerplant in cents per gasoline-equivalent gallon. We shall also use (roughly) constant 1977 dollars and real interest rates.

3.4 The Social Value of the Gas Turbine Engine

The total operating cost model developed in the previous section will now be used to investigate the potential operating benefits associated with a gas-turbine-powered automobile, relative to the ICE-powered vehicle of comparable performance. We consider four different classes of gas turbine powerplants, as defined in Section 3.2, -- (i) the mature metallic free-shaft turbine (MMFST), (ii) the intermediate free-shaft turbine (INFST), (iii) the intermediate single-shaft turbine (INSST), and (iv) the advanced single-shaft turbine (ADSST). The baseline is held fixed at the mid-1980s level, as previously discussed. We also include at this point the ICE baseline equipped with a continuously variable trasmission (ICE-CVT) for reasons explained below. For the purpose of examining the gross desirability of the gas turbine engine, calculations across the range of vehicle sizes are not necessary. Extrapolating data on average inertia weight class for automobile sales by GM (3-48, p. 12a) in model years 1974 through 1977, the average automobile inertia weight in 1985 is close to 3,500 lbs which corresponds to a "compact" class vehicle; we shall use this inertia weight for our baseline ICE-powered automobile of 1985.

In this subsection we estimate the potential social benefits of the gas turbine engine, on an individual vehicle basis. That is, we estimate the economic benefits using social prices for fuel and for capital. Furthermore, the calculations are made for an optimal vehicle-engine-fuel configuration, i.e., the superior specific weight and power-speed characteristic of the gas turbine engine are given full credit in the vehicle design, and the use of a distillate fuel is assumed for the gas turbine vehicle.

At the outset a "base case" is defined for each class of gas turbine technology. This base case represents the conservative end of the available spectrum of technology projections. Table 3.2 summarizes the range of available estimates for the gas turbine attributes. The values in the table are adapted from the available data (displayed in Table 3.9 in Appendix A) consistent with the attribute definitions in our model (see Section 3.3). In addition to the base case, we will also compute the benefits for a number of other cases, some examining the impact of uncertainties in a single, key parameter or attribute, and some reflecting combinations of these. The magnitude of the variations roughly reflects the spread of available projections for that parameter, where applicable. The benefits will be calculated, in every case, as a function of the relative initial specific cost of the gas turbine, which remains the most uncertain key engine attribute.

The parameter and attribute values used in the base case are listed in Table 3.3. For the most part, little explanation is required beyond that presented in the table. The discount rate and the fuel prices explicitly reflect the considerations involved in computing the social benefits. The baseline fuel price is fixed at the 1977 (retail) market level, but a social premium is added. The social premium, however, is assumed not to affect the fuel price differential between gasoline and the distillate fuel used by the gas turbine (calculated from first quarter 1977 gasoline and diesel fuel prices), following our earlier argument that the changes in baseline fuel price are likely to be distinct from changes in the fuel price differential. The tax on fuel is included as part of the fuel price, since the tax revenues for the most

Table 3.2

RANGE OF TECHNICAL ATTRIBUTE VALUES DERIVED FROM LITERATURE (1)

POWER-PLANT	ATTRIBUTES			
	Power-Speed Parameter	Specific Weight (lb/hp)	Average Efficiency (Ratio relative to to 1985 ICE) (3)	Specific Initial Cost ($/hp)
ICE	1.22-1.32	4.6-6	1	11-13
ICE-CVT	1.0 (2)	Roughly same as baseline ICE	About 20% improvement over baseline ICE	About 10% higher than baseline ICE
MMFST	1.08-1.14	4.0-4.5	1.0	-
INFST	Same as MMFST	Same as MMFST	1.05-1.15	-
INSST	1.00 (2)	Roughly 10% improved over INFST	Roughly 10%-15% improved over INFST	-
ADSST	1.00 (2)	2.2-3.2	1.3-1.6	

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(1) Where available data (see Table 3.9) are not directly applicable, the attribute values were estimated according to the definitions in Section 3.3.2.

(2) Dependent on assumption of a continuously variable transmission.

(3) Our economic model explicitly requires only relative values of efficiency. The baseline efficiency is implicit in the baseline fuel economy given in Table 3.3. Note that for the single-shaft engines, in actually calculating the benefits as shown in Tables 3.5 through 3.8, relative efficiencies with respect to the ICE-CVT are used (see text).

Table 3.3

PARAMETER AND ATTRIBUTE VALUES USED IN GAS TURBINE BENEFITS ANALYSIS

I Parameter Values Used in All Cases (1)

PARAMETER	VALUE	COMMENT
M	10,000	(3-49, p. 44)
L	10 years	(3-50, p. 3-11)
γ	0.07	(3-36, p. 17)
c_v	1.15 \$/lb	Retail cost of nonpropulsive vehicle from JPL (3-2, p. 20-5) adjusted roughly to 1977 dollars
V_o, t_o	60 mph, 13.5 sec	Prevailing performance level for compact class vehicle
α	.018 hp/lb-mph	Estimated from (3-36, p. 13)
W_o	3500 lbs	Compact class baseline vehicle material weight (1)
F_o	0.043 gal/mi (23 mi/gal)	Estimate of 1985 baseline vehicle fuel economy (see text) (1)
i_o	12 \$/hp	Estimate from Table 3.2 (1)

II Parameter Values Used in Social Base Case (SBC)

PARAMETER	VALUE	COMMENT
P_o	65.7 ¢/gal	Calculated using national average (regular gasoline, full and self-service, over first quarter, 1977) retail gasoline price of 59.3¢/gal (3-51) plus social premium calculated using average (over first quarter 1977) imported crude oil price of 14.4 \$/bbl and a composite average domestic crude oil price of 14.4 \$/bbl with 4% social real interest rate for one year (See text for discussion of methodology; figures taken from (3-51))

Table 3.3 (continued)

PARAMETER	VALUE	COMMENT
Δp	8.7 ¢/gal	Assuming gas turbine operates on diesel fuel. Fuel price differential based on retail diesel fuel price of 55.8 ¢/gal averaged over first quarter 1977 (3-51) and adjusted to gasoline-equivalent gallons, using 116,800 Btu/ gal for gasoline, and 127,600 Btu/gal for diesel fuel (3-52)
r	4% annual	Social real discount rate (range 3-5%)
k	1.22	Taken from JPL (3-2, p. 104)

III Powerplant Attribute Values Used in Social Base Case (SBC)

POWERPLANT	ATTRIBUTE	VALUE	COMMENT
ICE	ϕ	1.25	Likely values for 1985 ICE based on data in Table 3.2
	w (lb/hp)	5.0	
	i ($/hp)	12	
ICE-CVT	ϕ	1.0	Likely values for 1985 ICE equipped with a CVT from data in Table 3.2.
	w	5.0	
	r_ϵ	1.2	
	i	13	
MMFST	ϕ	1.14	Conservative figures from the ranges given in Table 3.2
	w	4.5	
	r_ϵ	0.95	
INFST	ϕ	1.14	As above
	w	4.5	As above
	r_ϵ	1.05	As above
INSST	ϕ	1.0	As above
	w	4.0	As above
	r_ϵ	1.15	As above
ADSST	ϕ	1.0	As above
	w	3.2	As above
	r_ϵ	1.3	As above

Table 3.3 (continued)

IV Parameter and Attribute Values Used in MMFST Cases

CASE	PARAMETER OR ATTRIBUTE DIFFERING FROM SBC	VALUE	COMMENT
SM1a	r_ϵ	1.05	Stricter NO_x standard or optimistic gas turbine efficiency
SM1b	w (lb/hp)	4.0	Optimistic specific weight
SM1c	ϕ	1.08	Optimistic power-speed characteristic
SM1d	all of above		Optimistic technology case
SM2	P_o (¢/gal)	99.7	Doubling of imported crude oil price. Approximate long run cost of synthetic crude oil
SM3	all of above		Most favorable reasonable case

V Parameter and Attribute Values Used in ADSST Cases

CASE	PARAMETER OR ATTRIBUTE DIFFERING FROM SBC	VALUE	COMMENT
SA1a	r_ϵ	1.5	Optimistic efficiency
SA1b	w (lb/hp)	2.2	Optimistic specific weight
SA1c	both of above		Optimistic technology
SA2	P_o (¢/gal)	99.7	Doubling of imported crude oil price. Approximate long run cost of synthetic crude oil
SA3	all of above		Most favorable reasonable case

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(1) The values of W_o, F_o, and i_o shown above were not used in computing the benefits associated with the single-shaft turbines; the ICE-CVT was used as the "basleine" for these engines and the values of W_o and F_o used are those corresponding to the ICE-CVT in Table 3.4; the value of i_o for the ICE-CVT is shown above in Section III of this table.

part go to road maintenance and construction and represent, as such, a real part of the social cost of automobile operation. We have taken the present differential between the prices of gasoline and diesel fuel to be indicative of the future differential between gasoline and a distillate fuel of some sort which would require less refining than gasoline and be suitable for the gas turbine. Inasmuch as we have not attempted to distinguish between the differing tax rates between gasoline and diesel fuel, the fuel price differential does not reflect the difference in taxes. However, the error involved is small, since the difference between average tax rates (1976), state plus federal, for motor gasoline and diesel fuel (3-53) is of the order of a tenth of a cent per gallon compared to the total fuel price differential on the order of ten cents. It is important to note that the adjustment of the retail price of diesel fuel to gasoline equivalent (in terms of energy content) gallons accounts for as much as 60% of the price differential.

The social premium on automotive fuel is a matter worth some discussion. We have used the following extremely simple approach. The value of crude oil in the United States is set by its marginal cost, which is the price of imported crude oil plus a national security premium to account for the national security costs associated with importing crude oil from insecure foreign sources. Thus the social value of gasoline is taken to be the retail price, plus the difference between the average domestic and the imported costs of crude oil,[1] plus the national security premium.

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[1] We ignore the fact that one gallon of crude oil is not converted to fully one gallon of refined products.

A simple measure for the national security premium is the cost of the crude oil stockpile necessary to mitigate or deter an embargo, thus voiding any possibility of international blackmail. If the cost of a stockpile is principally the cost of holding the crude oil, and if the stockpile is sized to supply the nation with N years of imported oil, then the national security premium is simply the cost of storing each imported barrel for N years. In terms of a fractional increase in the value of the imported crude, it is N times the relevant interest rate.

The difficulty of predicting the fuel economy of the 1985 baseline ICE is compounded by the minimum fuel economy standards through 1985 and by the effect of changing emissions standards. We have assumed earlier, in Section 3.2.4, that the mandated 1981 emissions standards (0.41/3.4/1.0 HC/CO/NO_x gm/mi) will carry over through 1985. At these standards we have estimated, based on the JPL (3-2, p. 3-17) estimate for their "mature Otto engine" and from estimates by GM (3-48, p. 17c) that the fuel economy of the compact baseline ICE will be roughly 23 mpg.

For computing the benefits associated with the single-shaft engines (both intermediate and advanced) on a technologically consistent basis, the ICE-CVT was used as the baseline. The incorporation of a CVT in the ICE brings about fuel economy improvements as well as powerplant size and vehicle weight reductions (see Table 3.4). The extensive system configuration shown in Table 3.4 is used as a baseline against which the benefits for the single-shaft turbines are evaluated.

The gas turbine attribute values used in the social base case are reasonably conservative projections for the respective technology classes, as comparison between Tables 3.2 and 3.3 will indicate. The two sets of sensitivity calculations then address more optimistic technology

Table 3.4

BASE CASE SYSTEM CONFIGURATIONS

POWERPLANT	DESIGN POWER (hp)	POWERPLANT WEIGHT (1) (lb)	VEHICLE INERTIA WEIGHT(1) (lb)	FUEL ECONOMY (mpg) (2)
ICE	128	640	3500	23.0
ICE-CVT	97	480	3310	29.2
MMFST	111	500	3330	23.0
INFST	111	500	3330	25.4
INSST	93	370	3170	29.2
ADSST	90	290	3070	34.1

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(1) Rounded to nearest 10 pounds.

(2) Gallons are energy-content equivalent to gasoline.

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projections, as well as the impact of a doubling of the cost of crude oil, for both the metallic and advanced systems. The impact of optimistic values of each relevant attribute is tested separately, an overall technologically optimistic case is presented, and a combined favorable technological and economic case. The doubled cost may be taken to represent a rough upper limit on crude oil prices for the next several decades, because it is roughly the cost at which a synthetic crude oil can be obtained from coal or oil shale.

Table 3.4 shows the standardized (with respect to acceleration performance) base case configurations which result. These results are preliminary to calculating the total operating benefits. It may be noted that the intermediate and mature metallic free-shaft configurations are alike. This results from our model in that the efficiency does not affect system design; for engines satisfying the same acceleration criterion, the power-speed characteristic and specific weight together determine the vehicle configuration. The intermediate single-shaft turbine and the metallic turbine, when compared with the corresponding compact class JPL configurations (3-2, p. 10-5) are calculated to have around 10 to 25% larger design horsepower. Within the limitations of our analysis, these results reflect the somewhat more conservative nature of our base-case assumptions for the gas turbine.

The results in Table 3.4 also show the dramatic impact of the availability of a CVT for use with the conventional ICE. This will have significant implications for the economic value of the single-shaft systems, which require its availability.

Table 3.5 summarizes the results of the social benefits calculations. The social base case benefits across technologies are illustrated in Figure 3.2 while the variants from the base case are illustrated (only for the metallic free-shaft case) in Figure 3.3. We shall focus our discussion on the two intercepts of the lines shown in Figures 3.2 and 3.3.

The results show that the "maximum" benefits for the metallic turbine range from 0.66 to 1.31 ¢/mile. The spread due to uncertainty in attributes and prices is therefore about 100% of the base case benefit. However, it must also be recognized that these benefits are a somewhat arbitrarily defined maximum -- it is defined to occur at equal powerplant specific initial cost. Given the manufacturing problems associated with the gas turbine, as discussed in Section 3.2 above, this is a reasonable upper expectation.

The breakdown of the maximum benefits for the metallic turbine in Table 3.6 indicates that they result almost entirely from the ability to burn a less expensive fuel and from the smaller engine allowed by the superior power-speed characteristic. The savings in non-engine initial cost is small; the benefit due to reduced fuel consumption is zero.

Reasonable variations in each important non-cost attribute (efficiency, power-speed parameter, and specific weight) have significant effects on the potential benefits of the metallic turbine engine, at any initial cost. Fuel price has no impact because, as seen in Table 3.4, the fuel economy of the metallic gas turbine is the same as that of the baseline (the effect of the improved specific weight and power-speed curve is eactly cancelled out by the lower efficiency). Further, it is

Table 3.5

SUMMARY OF GAS TURBINE TOTAL SOCIAL OPERATING BENEFIT CALCULATIONS

I. Social Base Case (SBC)

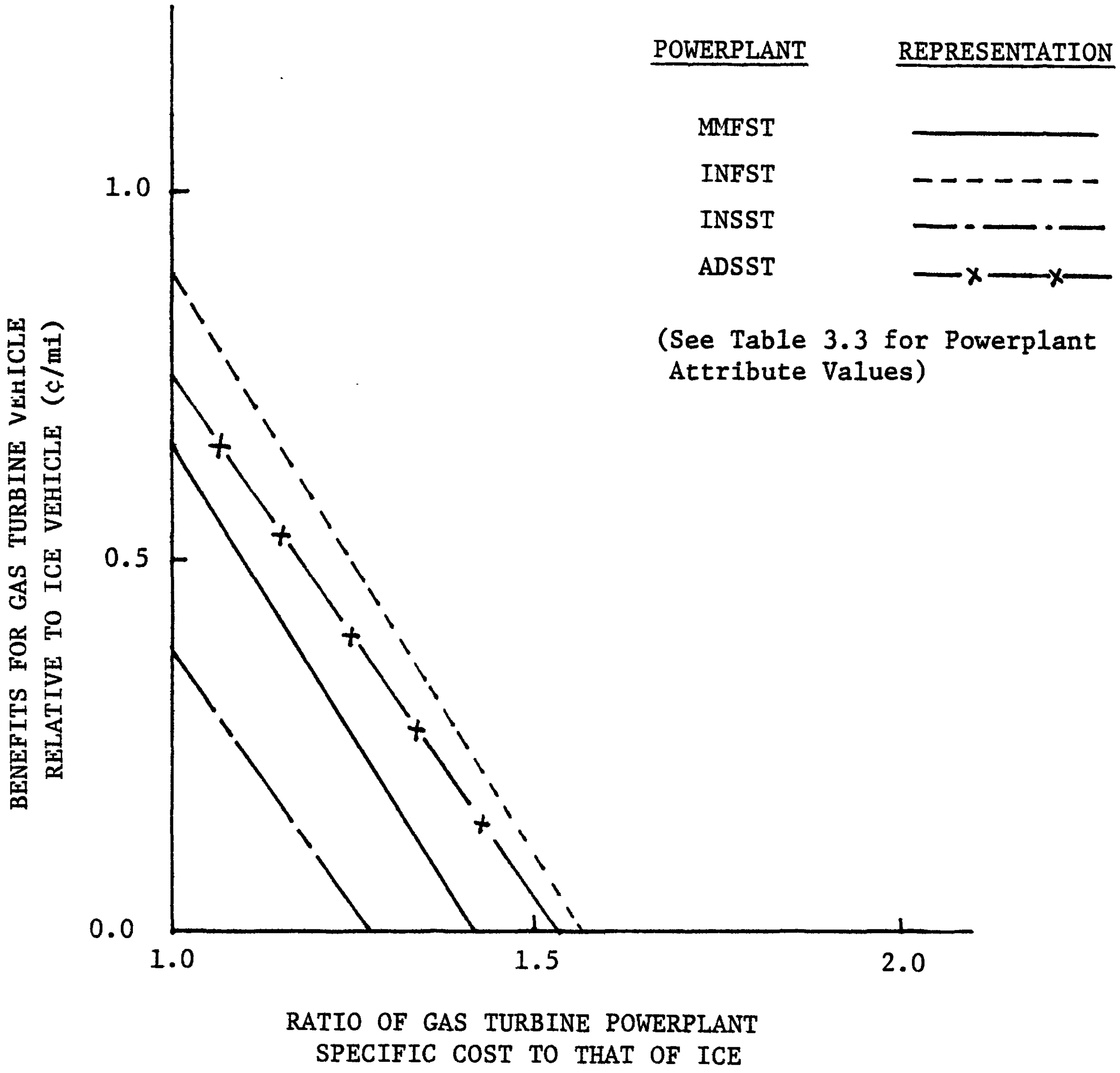
POWERPLANT	RELATIVE BREAK-EVEN SPECIFIC INITIAL COST (r_{BE})	MAXIMUM SOCIAL BENEFIT (¢/mi) (B @ $r_i = 1$)
MMFST	1.42	0.66
INFST	1.57	0.89
(ICE-CVT)	(2.02)	(1.39)
INSST	1.27	0.39
ADSST	1.54	0.75

II. MMFST Sensitivity Cases

CASE	PARAMETER OR ATTRIBUTE AS CHANGED FROM BASE CASE	RELATIVE BREAK-EVEN SPECIFIC COST (r_{BE})	MAXIMUM SOCIAL BENEFIT (¢/mi) (B @ $r_i = 1$)
SM1a	$r_\epsilon = 1.05$	1.57	0.89
SM1b	$w = 4.0$ lb/hp	1.51	0.77
SM1c	$\phi = 1.08$	1.54	0.79
SM1d	all of the above	1.79	1.13
SM2	$P_o = 99.7$ ¢/gal	1.42	0.66
SM3	all of the above	1.92	1.31

III. ADSST Sensitivity Cases

CASE	PARAMETER OR ATTRIBUTE AS CHANGED FROM BASE CASE	RELATIVE BREAK-EVEN SPECIFIC COST (r_{BE})	MAXIMUM SOCIAL BENEFIT (¢/mi) (B @ $r_i = 1$)
SA1a	$r_\epsilon = 1.6$	1.76	1.05
SA1b	$w = 2.2$ lb/hp	1.67	0.89
SA1c	both of above	1.89	1.19
SA2	$P_o = 99.7$ ¢/gal	1.66	0.91
SA3	all of the above	2.18	1.58



(See Table 3.3 for Powerplant Attribute Values)

Figure 3.2

SOCIAL BASE CASE BENEFITS ASSOCIATED WITH VARIOUS CLASSES OF GAS TURBINES AS A FUNCTION OF GAS TURBINE POWERPLANT SPECIFIC INITIAL COST RELATIVE TO BASELINE ICE (FOR THE SINGLE-SHAFT TURBINES, RELATIVE TO THE ICE-CVT).

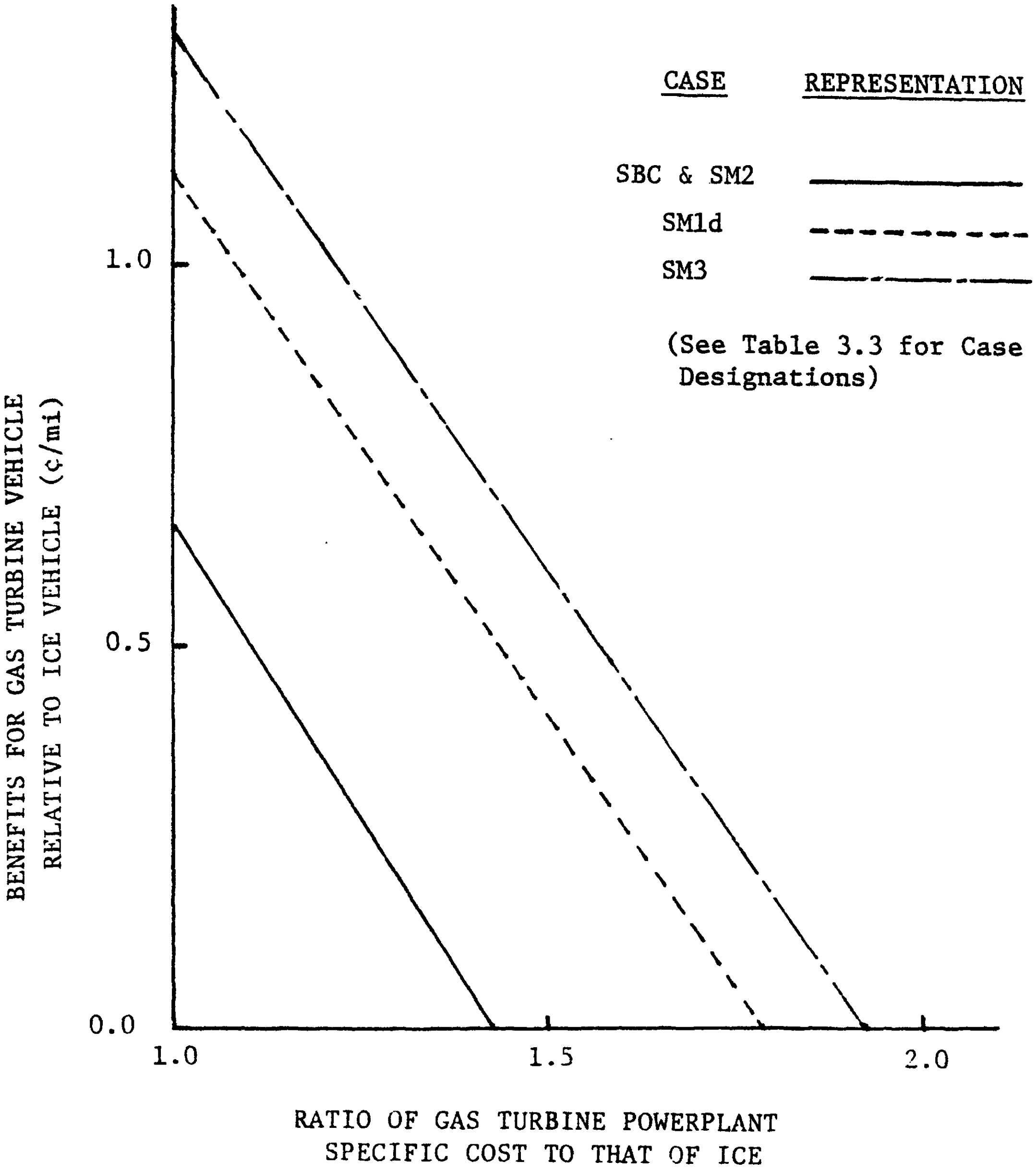


Figure 3.3

SOCIAL BENEFITS OF THE MATURE METALLIC GAS TURBINE FOR VARIATIONS IN PARAMETERS AND ATTRIBUTES AS A FUNCTION OF GAS TURBINE POWERPLANT SPECIFIC INITIAL COST RELATIVE TO BASELINE ICE.

Table 3.6

BREAKDOWN OF MAXIMUM BENEFITS FOR AUTOMOTIVE GAS TURBINE

COMPONENT (1,2)	BENEFIT (¢/mi) (3)	
	MMFST	ADSST
Engine Total Initial Cost Difference	0.24	0.11
Non-Engine Total Initial Cost Difference	0.04	0.06
Fuel Economy Improvement	0.00	0.32
Fuel Price Advantage	0.38	0.26
Total	0.66	0.75

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(1) The components in order are the terms in equation (26).

(2) Base case values of all parameters are used, with $r_i = 1$.

(3) Rounded to two decimal places.

also evident that these (admittedly uncertain) benefits cannot be realized at all unless the specific initial cost of the metallic turbine powerplant is brought down to within 40% to 90% above that of the ICE of equal horsepower.

It is necessary therefore to compare these breakeven costs (crude as they are) with available estimates (even though evaluated on somewhat differing bases) of the relative specific cost of the turbine powerplant. A recent Volkswagen study (3-54) estimates the relative production cost of engines of the same horsepower (bracketing engines of 100 to 150 hp). As indicated in Table 3.9, their estimate is for a specific initial cost of 2 to 2.6 that of the ICE. This clearly is not likely to result in a socially beneficial engine. The JPL (3-2, p. 11-12) estimates, on the other hand, put the specific initial cost of the "mature" metallic turbine powerplant at about 50% more than that of the ICE. While this appears to make the turbine look barely attractive, judging by our breakeven criteria, there is considerable doubt (3-55) as to whether these projections are realizable. The set of available estimates is, however, meager.

Included for comparison in Table 3.5 are the calculated value indicators for the ICE-CVT. At any given relative specific initial cost it is clearly more valuable than either of the free-shaft configurations using conventional transmissions. That is, the relative break-even cost and its maximum benefits are higher. Further, its cost is better known than those of the gas turbines; at the value $r_i = 1.1$ which we have assumed the ICE-CVT gives benefits relative to the ICE of 1.3 ¢/mi. Of course the CVT would benefit the free-shaft gas turbines as well as the ICE. Therefore the relatively higher economic value of the ICE-CVT as compared to the free-shaft turbines does not imply that it should be developed in place of them. The high value of the CVT does, however, have important implications for the value of the single-shaft systems relative to the free-shaft systems, as our analysis implicitly assumes the CVT in the single-shaft calculations but not in those for the free-shaft.

At the other technological extreme, the advanced single-shaft turbine might offer benefits ranging from 0.8 to 1.6¢/mile at specific initial costs equal to the ICE-CVT. Breakeven specific cost ranges from about 50% to 120% above that of the ICE-CVT. The social base case values of the advanced single-shaft turbine relative to the ICE-CVT are seen to be less than those of the intermediate free-shaft turbine relative to the baseline ICE. Thus, inasmuch as the single-shaft engines require the existence of a CVT, which can also be applied with great benefit to the ICE, their own incremental value is reduced. Nevertheless, their value beyond the ICE-CVT is still potentially large.

The specific initial cost of the advanced single-shaft powerplant has been estimated by Volkswagen (3-54) at 40% to 100% above that of the baseline ICE. The margin relative to r_{BE} in this case is sufficient to realize possible benefits for the advanced single-shaft turbine relative to the 1985 ICE. However, the degree of uncertainty associated with advanced technology predictions is of course much higher than those for the metallic systems. As discussed in Section 3.2, it is well known that the materials costs of ceramics are low, far lower than those of superalloys, however the primitive state of the process technology leaves only the vaguest knowledge of the costs of processing this material into engine components.

Our level of analysis does not allow any significant discrimination of the intermediate gas turbine as against the metallic or advanced; the benefits are in fact at intermediate levels (given either that the CVT exists or it does not), and there are few data on potential costs.

Another important conclusion from Table 3.5 is that the effects of uncertainty in prediction of gas turbine technology status are much greater than the effect of the uncertainty in the fuel prices. This further compounds estimation of the social value of the gas turbine. We can only conclude that the order of uncertainty in benefits matches the order of the likely benefits. These arguments hold equally well for the advanced technologies.

Finally, it is worth considering the possibility that ceramics technology might develop more rapidly than anticipated, or that CVT technology might develop more slowly, so that an advanced gas turbine engine was possible but no CVT had been developed. In this case an advanced free-shaft engine would be an extremely desirable system, giving benefits on the order of .5¢/mi more than the intermediate free shaft, at any given initial cost.

In summary, then, this simple economic analysis reveals the following. First, only a technologically optimistic estimation of the performance and cost attributes of the metallic gas turbine lead to the belief that social benefits of much more than a tenth of a cent per mile or so are available. Second, while the attributes of the advanced gas turbine are even less well known, it appears that benefits on the order of a cent per mile are possible. Third, both of these extremely crude estimations are subject to great uncertainty. Even given a value of specific initial cost, the most uncertain of the attributes, variations of the performance attributes or of fuel price significantly affect social value calculations.

How important are social benefits of .1 to 1¢/mile? One perspective on the benefits might be gained by considering them in relation to the total baseline operating cost. Corresponding to a value of about 15¢/mile for the latter, the maximum benefits range from 5% to 10% of the total baseline operating cost, for the metallic free shaft, as well as for the advanced single shaft. For specific costs greater than those of the ICE, the fractional cost reduction is of course much lower. However, as discussed in Federal Support (3-1), the discounted present value of the aggregate benefits resulting from single-vehicle benefits of the order of several tenths of a cent per mile, for reasonable values of vehicle miles traveled, conversion engine dates, etc. are easily $1 billion and more. Thus the amount of dollars our nation should be willing to pay for the existence of a socially beneficial gas turbine engine is very large.

3.5 The Private Value of the Gas Turbine Engine

A socially valuable gas turbine engine is not necessarily viewed as an economically attractive technology by the individual consumer. Because the consumer, together with the management of the automotive manufacturers, make the individual technology choices in our economic system, it is necessary to examine the economic value of the gas turbine in private terms as well as social terms. The simple economic model developed in Section 3.3 can also be applied to determine the potential total operating benefits associated with the gas turbine from a private standpoint. It is necessary, of course, to first identify the sources of disparity between the social and private cases.

The first and most obvious effect is the removal of the social premium on the fuel price, to reflect the actual market (retail) price seen by the vehicle owner. This does not, however, affect the price differential between the baseline and the gas turbine fuels.

The second difference might arise due to the privately perceived discount rate applied to the initial cost, which is expected to be higher than the social discount rate (see Federal Support (3-1, Sect. 5.4) for a detailed discussion). To investigate the effect of such a possibility, we have used a private real annual discount rate of 15% as compared with the 4% used in the social base case. Unfortunately there is little in the way of empirical support for any particular choice of private discount. Our choice of 15% would represent substantial "short-sightedness" on the part of automobile buyers, i.e. a very uneconomic weighting of first cost relative to operating cost.

The private benefit calculations examine the effect of each of these sources of disparity separately and in combination. The effect on the maximum benefits and on the breakeven specific cost ratio across technologies is shown in Table 3.7. (Note that all other parameters are held constant at the levels in social base case.) The private benefits are also shown (only for the mature metallic free-shaft turbine) in Figure 3.4. The effect of using private prices, for the metallic free-shaft turbine, is to reduce the maximum admissible specific initial cost premium from about 40% above to about 30% above that of the ICE. The effect is more pronounced for the more advanced technologies. In both cases the principal effect is due to the high private discount rate we have posited, rather than our estimated social premium on fuel. However, it seems clear that the gas turbine, an option which trades capital for fuel, suffers when the value of fuel relative to capital is higher for the nation as a whole than for individuals. An engine which is socially valuable may not be privately valuable.

The analysis so far has focused on the evaluation of the gas turbine engine given that it exists and that the vehicle body and fuel production logistics network have been adjusted to minimize the overall system cost. If the engine were in fact put into production and attained widespread use, the system would no doubt adjust. Initially, however, the newly introduced gas turbine would face an environment optimized for an automotive vehicle fleet using entirely ICEs, except for a few diesels. The gas turbine must be attractive during this phase as well as in the long run if it is to ultimately succeed.

A full discussion of the problems specific to the introduction process (i.e., the transition to an alternative powerplant) may be found in Federal Support (3-1, Sect. 5.4). We will only briefly summarize them here, and then proceed to examine the private desirability associated with the gas turbine in the transition.

Table 3.7

SUMMARY OF GAS TURBINE TOTAL PRIVATE OPERATING BENEFITS

CASE	PARAMETER CHANGE FROM SBC	RELATIVE BREAK-EVEN SPECIFIC INITIAL COST (r_{BE})	MAXIMUM PRIVATE BENEFIT (¢/mi) (B @ r_i =1)
I **MMFST Cases**			
MMFST SBC		1.42	0.66
PM1	r = 15%	1.32	0.84
PM2	P_o = 59.3 ¢/gal	1.42	0.66
PM3	both of the above	1.32	0.84
II **ADSST Cases**			
ADSST SBC		1.54	0.75
PA1	r = 15%	1.37	0.86
PA2	P_o = 59.3 ¢/gal	1.51	0.71
PA3	both of the above	1.36	0.82

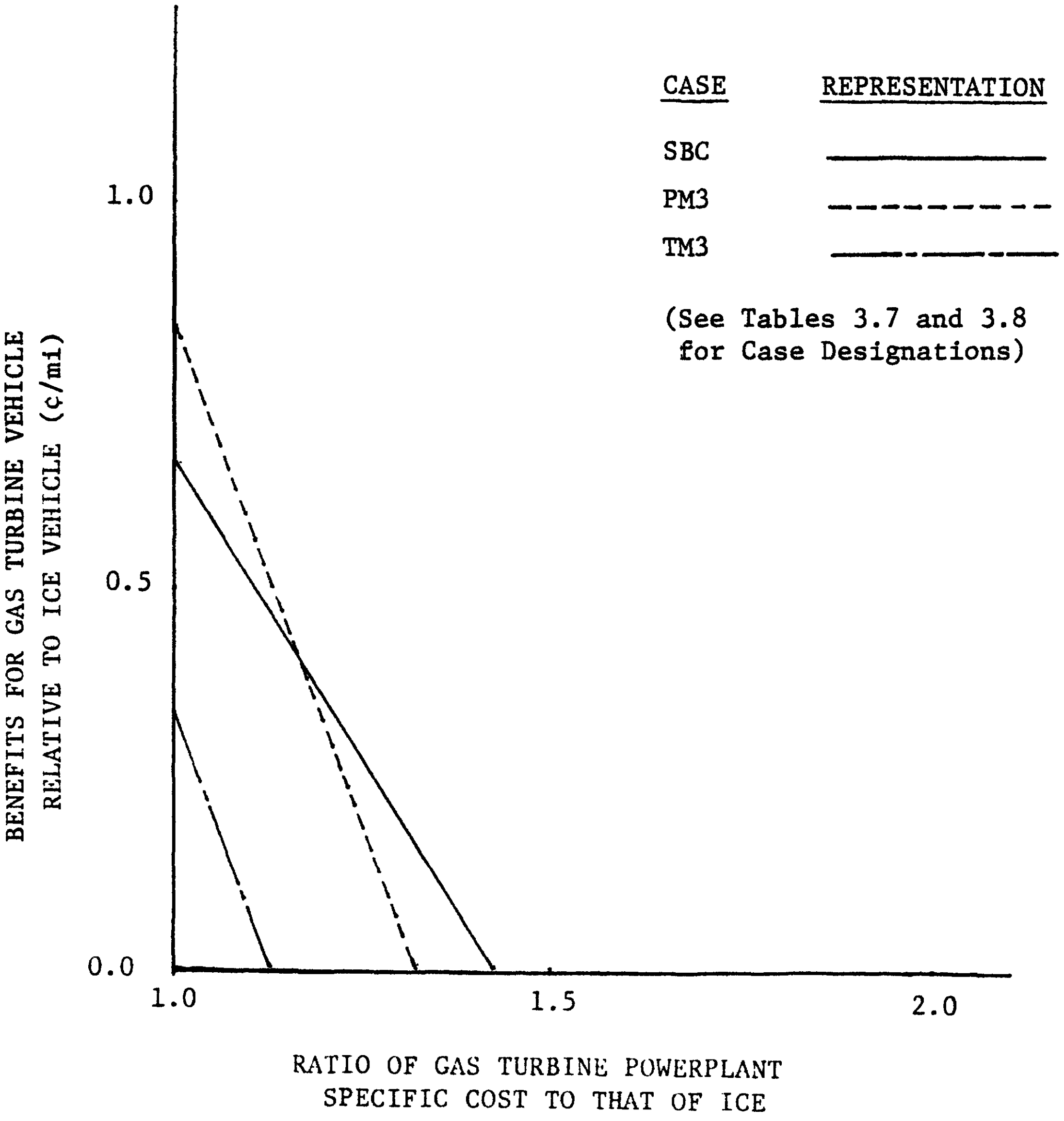

Figure 3.4

PRIVATE AND TRANSITION BENEFITS FOR THE MATURE METALLIC GAS TURBINE AS A FUNCTION OF GAS TURBINE POWERPLANT SPECIFIC INITIAL COST RELATIVE TO BASELINE ICE.

The introduction of a powerplant into the marketplace is the focal point of the long technology development and production process[1]: it determines the long-term commercial success of the alternative powerplant. Underlying the introduction decision is a massive commitment on the part of the industry and very high levels of risk and dollar exposure. Historically, the decision criterion used by the industry for making technological changes has generally been that an innovation at least match every relevant attribute (except cost) of the system it replaced. Cost increases would be tolerated only if commensurate net gains were clearly realizable in other attributes. The crucial determinant of a positive introduction decision will be an initial cost that consumers find attractive; the introduction decision will follow only after the economics of manufacture and operation of the gas turbine have been clearly quantified.

The status of the nonpecuniary attributes of the gas turbine (in its various technological stages) was dealt with in detail in Section 3.2.3. To summarize, the gas turbine appears to be as good as or better (especially with respect to noise and vibration) than the ICE in these attributes. As for the readily quantifiable attributes, initial cost and fuel economy are the key unknowns. In addition, there is uncertainty as to the maintenance requirements and durability of the gas turbine. The former is a problem not so much because of any intrinsic feature of the technology (the gas turbine is far less complex than the ICE) but because these services may not be available to the consumer, especially in the transition.

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[1] See Chapter 2 of Federal Support (3-1) for a detailed description and analysis of the process of technology development and production in the automotive industry, as it would apply to an alternative powerplant and with examples of other innovations from the past.

The crucial feature of an alternative powerplant introduction, namely that it would take place in an environment dominated by the ICE, has important implications for the potential value of the gas turbine in the transition. We will focus on two readily quantifiable effects and examine their impacts on the total operating benefits associated with the alternative powerplant.

First, the gas turbine may be forced to operate on gasoline in the transition because of: (i) the lack of an adequate infrastructure to supply the gas turbine with alternative fuels; (ii) the absence of any incentive in the short term for those components of the infrastructure not in the control of the manufacturer, namely the petroleum refining and distribution industry, to provide a supply of the alternative fuel. Presumably then, the fuel price advantage attributable to a fuel less highly refined than gasoline may not be realized.

Second, one important consequence of the manufacturer's attempt to minimize the fixed cost of the innovation is that the gas turbine would likely be offered in a vehicle body designed for the ICE -- in other words, the gas turbine would be designed for the highest possible degree of integrability. This behavioral postulate has been substantiated most recently by the approach adopted by GM's Oldsmobile Division in introducing diesel-powered automobiles -- essentially retaining the original V-8 ICE powerplant layout to allow integration into vehicles designed for the latter (3-56).[1] For an alternative powerplant like the gas turbine,

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[1] See also Federal Support (3-1. Chap. 2) for other examples.

which has a higher power density (i.e., a lower specific weight) than the ICE, this would lead to suboptimal vehicle configurations: by not utilizing the savings in vehicle weight that can result from the weight propagation effect, the gas turbine would be installed in a heavier vehicle than necessary. In our simple model we can quantify this effect by setting the weight propagation factor (k) to unity, which fixes the nonpropulsive weight of the automobile.

Table 3.8 lists the potential private total operating benefits in the transition for the metallic and advanced systems. The "base case" here is the private static case (PM3 and PA3 of Table 3.7); the effects of zero fuel price differential and null weight propagation have been examined separately and in combination. The metallic case (TM3) is also shown in Figure 3.4. The effects are relatively dramatic -- the maximum benefits are decreased by about one half, and so, roughly, is the allowable specific cost premium over the ICE. The characteristics of the transition process thus have important effects on the value of the gas turbine.

Thus, if our behavioral postulates are correct, the gas turbine vehicle looks much less attractive during the transition process than later when vehicle design and the fuel system have adjusted. In our simple model, a metallic gas turbine engine with a specific initial cost between 13% and 32% higher than that of the ICE would be privately attractive in the long run, but not during the transition unless a

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[1] See <u>Federal Support</u> (3-1, Chap. 2) for other examples.

Table 3.8

GAS TURBINE BENEFITS DURING TRANSITION

CASE	PARAMETER CHANGE	RELATIVE BREAK-EVEN SPECIFIC INITIAL COST (r_{BE})	MAXIMUM PRIVATE BENEFIT (¢/mi) (B @ $r_i = 1$)
I <u>MMFST Cases</u>			
MMFST PM3		1.32	0.84
TM1	$k = 1$	1.27	0.72
TM2	$\Delta p = 0$	1.18	0.46
TM3	both of above	1.13	0.34
II <u>ADSST Cases</u>			
ADSST PA3		1.36	0.82
TA1	$k = 1$	1.28	0.67
TA2	$\Delta p = 0$	1.25	0.57
TA3	both of above	1.17	0.41

made and a low-cost but compatible fuel is widely available. Thus it might not make it through the industry innovation process. Further, as previously discussed, engines with specific initial costs up to 42% higher than the ICE are, in our simple calculations, socially valuable. Thus, between private undervaluation of vehicle attributes and behavioral problems of technological change, there is a substantial range of initial cost wherein a socially valuable gas turbine might never make it to the vehicle showroom.

3.6 Summary and Conclusions

In this chapter we have examined the gas turbine engine as a potential alterantive to the ICE for the passegner car powerplant of the future. Our principal goal has been to shed some light on the issues facing federal policy-makers in this area. Should the federal government be supporting R&D efforts on this technology? If so, what should be the general thrust of those efforts? These are the apparently modest questions we have attempted to address.

The automotive gas turbine, as a system, is not a new or exotic technology. Since the successful development of the aircraft jet engine during World War II the basic concepts have been well known. After the war virtually all major automotive manufacturers, domestic and foreign, recognized the potential for the system in ground transport and conducted development efforts. In the mid-1960s the Chrysler Corporation made probably the most dramatic demonstration of a passenger car innovation since most of the major features of the modern passenger car were fixed in the early 1920s, when they built and distributed fifty gas turbine-powered automobiles to carefully selected individuals for three months each over a total period of twenty-eight months. However, while most consumers were generally satisfied, the fuel economy, acceleration lag, and several other features of the engine were not considered satisfactory. Chrysler did not proceed with mass production of the engine. While tightening emission standards were cited as a principal cause for this decision, it seems clear that Chrysler was, more importantly, not able to produce the engine at a cost which would make it an attractive option to consumers. With the inferior attributes demonstrated, that cost would likely have had to be less than the comparable ICE.

Now, over a decade later, Chrysler is testing in vehicles an engine which has gone through three development generations since those consumer tests. Much of the intervening work has been substantially supported with government development funds. The new "upgraded" system roughly matches the contemporary ICE in fuel economy, and in the other important consumer attributes, and surpasses it in emissions reduction. But again its production costs are too high to make it attractive to consumers. The present engine could probably be put into production in five to eight years; during that period technology changes in the production ICE would allow it to roughly hold its own on efficiency while it met tightened emission standards. Thus, while advances have been made, they have not been sufficient to make the available gas turbine engine technology competitive with the contemporaneous ICE. The experience at Ford, General Motors, and a number of other automotive and heavy duty prime mover manufacturers around the world has been similar to Chrysler's.

Our analysis of the benefits to be gained from gas turbine technology provides some quantitative support to this view of the present status of gas turbine technology. While the superior specific weight and power-speed characteristics of the presently available system mean that buyers would be willing to pay somewhat more for the system than for the competition, and that the "maximum" benefits which could be attained are substantial, only the most optimistic cost estimates bring the system within the economic range. Substantial uncertainty surrounds these calculations, as demonstrated in our analysis, but the qualitative conclusion seems sound. Further, it is true whether one makes the calculation from the point of view of society as a whole or from that of a private individual.

The economic properties of the gas turbine vehicle have been limited by the available materials technology. The efficiency and power output of a heat engine depend strongly on the maximum temperatures of the thermodynamic cycle. In a gas turbine those peak temperatures are experienced by components which must simultaneously resist substantial stresses. Superalloys -- special steels -- must be utilized to attain the cycle temperatures necessary for attaining the efficiency and weight characteristics of the gas turbine which now make it competitive in value with the ICE. At the same time, these superalloys are the key elements of the high cost of the system which make it, overall, economically unattractive. Expensive materials and processing techniques are required by superalloys.

There now exists the potential for a discrete change in materials technology. Ceramic materials have the potential to tolerate higher temperatures, under load, than superalloys. Dramatic efficiency and weight improvements in the gas turbine engine would thus be possible. Our economic calculations indicate that a gas turbine engine making heavy use of ceramics in its hot parts could be a very valuable engine. That is, it would be worth a substantial cost premium over the ICE.

The extent of this extra value is highly uncertain. It depends on the extent to which ceramic components can be manufactured in quantity to meet the different demands of the various parts of the engine. Even for a given degree of ceramics utilization, the attributes of the engine are highly uncertain. Optimized engines making exensive use of ceramics are differently configured from present gas turbines, therefore calculations at the potentially improved cycle parameters do not have the experience behind them that those for metallic technology do. Furthermore, processing technologies may be very important in determining the design of ceramic components, and therefore efficiency and power decreases may have to be accepted relative to what could be attained if the geometries producible with superalloys could be maintained. There are numerous other nontechnical sources of uncertainty in the value of ceramic gas turbie engines; the future price of fuel is probably the most significant. Our calculations leave little doubt, however, that the availability of ceramic components for the automotive gas turbine engine would be worth a substantial sum of money.

However, the cost of gas turbine engines produced with ceramic materials is even more uncertain than the value of the metallic system. The basic materials costs of ceramics may be extremely low -- sand and air may be the principal inputs. However, conventional rules-of-thumb relating product costs to materials costs are not likely to be relevant. There is virtually no experience in processing ceramic materials in such a manner as to mass produce engine components of consistently acceptable quality. Furthermore, as a brittle material, ceramics are generally less forgiving than metallics. Flaws tend to propagate rather than dissipate, so consistency in processing is of critical importance. Thus presently unknown, but possibly very expensive, processing techniques may be required. This is true especially for the turbine rotor required for advanced systems.

But technical uncertainty, be it in product or process technology, is subject to resolution -- through research and development. The potentially very large, but simultaneously very uncertain, benefits available from a ceramic-based automotive gas turbine engine make it an excellent candidate for a major R&D effort. The level of detail in our analysis does not permit us to define clearly the specific engine components which should be the subject of the program. Within the technology classifications used in this report, it is not clear whether such an effort should be focused on the intermediate or the advanced engine. But the focus on a ceramic-based engine, to the relative neglect of further work on the metallic engine, is the key.

This conclusion is robust with respect to the existence, or lack thereof, of a continuously variable transmission. The development of such a CVT results in a major improvement of the baseline system. The CVT is <u>necessary</u> for single-shaft gas turbine systems, but also a useful supplement to free-shaft systems. Without a concurrent CVT program, whether funded publicly, privately, or shared, a gas turbine program must focus on the free-shaft system. But in either case a ceramic-based gas turbine system is very valuable.

A somewhat secondary consideraton is the relative focus on new engine systems, as compared to a focus on specific components using ceramic materials and the basic ceramic-processing technology. Our analysis sheds some light on this issue. The answer depends on whether the system in its interrelationships would be sufficiently different to be worth the complications of the simultaneous design of new ceramic components for it. As discussed above, however, the value of the ceramic-based turbine depends on system attributes, and this value is the standard against which costs must be compared. Thus, while there is little doubt that a ceramics R&D program must focus on process technology, an accompanying engine definition program appears a necessity as well.

But this leaves unaddressed the question of who, in our system of economic organization, can be expected to pay for this R&D. The high value of the potential benefits does not alone justify the expenditure of taxpayer revenues, since the essential arguments should hold well with corporate boardrooms as well. Put succinctly, a ceramic-based gas turbine engine would be a highly profitable product. If there is no disagreement between government and industry concerning the distribution of the technological outcomes of the research, and the prices with which those attributes will be valued, then the case for government subsidies must rest on the ability of the corporate interests involved to capture the potential benefits. These general arguments are presented in Chapter 2 of this report. There we concluded that, in the general case of alternative automotive powerplants, the argument for government support is certainly not one which is convincing in its strength or its general applicability, but that the analysis does provide some clues as to the circumstances where industry support is likely to be inadequate.

The major automotive manufacturers claim that their ceramic gas turbine development programs will progress without government assistance, but that the rate of progress would be greatly accelerated if supplemental government support were available. As discussed in the following chapter, such statements are not verifiable after the fact. The question, then, is whether such assertions are plausible given what we know about the economics of the gas turbine engine. The key considerations are discussed as they apply to alternative automotive powerplants generally in Chapter 2 of this report, and they will not be reviewed here. However, here we will examine briefly how these considerations relate to the case of automotive gas turbine engines.

In the case of the metallic engine, it is extremely difficult to find compelling reasons for government support; it is difficult even as of five years ago when the present government program was initiated. The long history of automotive industry efforts and their resulting expertise, and the long-standing incentives and actual development efforts for heavy duty competitors for the diesel, all point to the conclusion that most worthwhile R&D projects were most likely being privately funded.

The case of ceramic-based engines seems different. Two considerations seem to dominate. First, the development of ceramic materials for use in heat engines would be a major technological advance which would affect many areas beyond the passenger car fleet, or even the transport sector. The heat engine is society's principal means for converting fossil fuels into useful work. The availability of low cost, high performance, ceramics would have important benefits for most forms of transporation, for electric power generation, etc. Further influence would be felt in metallurgical and chemical process industries where loads must be borne at high temperature.

Second, as analyzed in the body of the report and discussed above, the state of ceramics processing technology is relatively primitive, and the technology is a particularly challenging one. Therefore high risk projects extending over long periods will be necessary to make any new techniques commercially available. A ceramic-based gas turbine engine program may properly be put into the category of research or initial development, rather than final development. This again implies that the nature of the results will not be readily predicted, and uses for them which are not now foreseen will probably arise.

Thus we find the traditional economic argument for the support of the development of advanced technology a most compelling one in this case. It is difficult for any single private entity to be at all certain of capturing more than a small fraction of the benefits which could result from a ceramic gas turbine R&D program. The principal benefits might not even occur in the automotive sector. This argument leads one to consider a ceramics technology program which is not so focused on automotive technology as that discussed here. However, it also leads us to view the industry proposals for cost-shared ceramic gas turbine programs as reasonably equitable, in the sense that both the corporate shareholders and public taxpayers would be risking money on reasonable gambles for their own ultimate benefit.

It is very important that such efforts be cost-shared with one or more automobile manufacturers. Their money must be committed as a signal that their management believes in the future commercial viability of the engine. Further, it is these firms which have the expertise, and the incentive, to make the system ultimately marketable. It is also important that companies with greater experience than the automotive industry in dealing with ceramic materials be made an integral part of the program. Present DOE plans seem roughly consistent with these guidelines.

Finally, our analysis indicates that the ultimate success of a gas turbine development program will depend on the process by which the engine is integrated into a system optimized for ICE-powered vehicles. The gas turbine can generate more power per unit weight than the ICE, and can burn a less-refined fuel. A substantial part of the economic attractiveness of the system is lost if a new vehicle body is not designed for the engine, or if a distillate fuel is not widely available. The automotive industry, in combination with the petroleum industry, has generally moved very gradually into engine innovations, and such will likely continue to be the case. R&D programs are weak tools for dealing with such difficulties. However, the development and introduction of a ceramic-based gas turbine engine is sufficiently distant in time that such transitional difficulties need not be a significant concern at the present time.

APPENDIX

Powerplant Attribute Values from the Literature

Table 3.9 lists values available in the literature of powerplant attributes needed as inputs to the total operating cost model developed in Section 3.3.2. The values shown in Table 3.9 are, in the majority of cases, not directly reported as such in the literature. Where necessary, therefore, these values were estimated according to the powerplant attribute definitions made in Section 3.3.2.

The power-speed parameter was estimated from normalized engine-power versus engine-rpm characteristics, or from tabular data (as in the case of Rand (3-36)).

Specific weight of the respective powerplants was estimated, where necessary, by adding the estimated weights of transmission and any emissions control equipment applicable, to the weight of the basic engine.

The efficiency estimates are especially crude, since it is difficult to obtain an average brake efficiency over a specific driving cycle in the open literature. However, our total operating cost model only requires estimates of the relative efficiency of the alternative powerplant with respect to the ICE. In our model, fuel economy is directly proportional to efficiency and inversely proportional to vehicle inertia weight. Therefore, where necessary, we have estimated relative efficiencies from relative fuel economy values given in the literature by adjusting for inertia weights; the implicit assumption is that the other factors contributing to fuel economy, embodied in the constant K_F (see Section 3.3.2), are the same across powerplants. Note that relative efficiencies are given with respect to the present ICE baseline as reference. Recall that in Section 3.2.4 we estaimted that the improvement in baseline efficiency through 1985 may range from -5% to

+ 5%. This has been taken into account in choosing the relative efficiency values used in the total operating cost calculations made in Sections 3.4 and 3.5.

Data on powerplant specific costs are relatively scarce and very uncertain. Costing methodologies used differ from one source to another and there is a wide spread, therefore, in the estimates. Where necessary, the estimated costs of transmission and any emission control equipment applicable are added to basic engine costs. All absolute costs given are in 1977 dollars.

Table 3.9

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

I. Powerplant Speed Parameter

POWERPLANT	SOURCE	VALUE(S)	COMMENT
ICE	1) JPL (3-2, p. 10-25, Figure 10-1)	1.22	For "mature" engine
	2) Rand (3-36, p. 88)	1.32	For roughly contemporary engines
ICE-CVT		1.0	Equipped with CVT
MMFST	1) JPL (3-2, p. 10-25, Figure 10-1)	1.11	For a "mature" metallic FSGT
	2) Chrysler (3-57)	1.14	Sixth generation Chrysler turbine
	3) Amann (3-58)	1.14	For a "typical" free-shaft engine
	4) Williams Research Corporation (3-59)	1.08	For the "WR-26" engine
INFST			No difference from MMFST foreseen
INSST		1.0	CVT requirement
ADSST		1.0	CVT requirement

II. Specific Weight (lb/hp)

POWERPLANT	SOURCE	VALUE(S)	COMMENT
ICE	1) JPL, ATSP (3-60)	5.0 to 5.4	For an "advanced" ICE powerplant in compact size range
		5.5 to 5.8	For an "updated baseline" ICE powerplant
	2) JPL (3-2, p. 5-41, Figure 5-12)	5.6 to 6	For a "mature" ICE powerplant
	3) Rand (3-36, p. 88)	4.6 to 5.5	Contemporary powerplants (transmission and emission systems weight included)

Table 3.9 (continued)

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

II. Specific Weight (lb/hp) (continued)

POWERPLANT	SOURCE	VALUE(S)	COMMENT
ICE-CVT	1) Sunstrand Aviation (3-9, p. 3)	No significant difference from ICE	Estimated for ICE with hydromechanical transmission
	2) Mechanical Technology Incorporated (3-10, p. 34)	No significant difference from ICE	Estimated for ICE with hydromechanical transmission
MMFST	1) Chrysler (3-61)	4.3 to 4.5	Estimated by including transmission weight based on Rand (3-36)
	2) JPL (3-2, p. 5-41, Figure 5-12)	4 to 4.3	Corresponds to roughly compact class powerplant
INFST		No significant difference from MMFST	Potential for weight reduction due to replacement with ceramic stationary hot-parts uncertain, but likely not significant. Assumption of no advantage over MMFST conservative
INSST		About 10% better than INFST	Once again, uncertain, but based on trend of specific power values for single shaft powerplants relative to free-shaft powerplants from JPL (3-2), we have conservatively assumed a 10% improvement over MMFST

Table 3.9 (continued)

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

II. Specific Weight (lb/hp) (continued)

POWERPLANT	SOURCE	VALUE(S)	COMMENT
ADSST	1) Mclean (3-6)	2.2	Crudely estimated by scaling projections for engine weight per unit air mass flow with material density and a characteristic size. Estimated (from Rand (3-36)) weight of transmission included. Refers to nominally 100 hp powerplant
	2) JPL (3-2, p. 5-41, Figure 5-12)	3.1	Applies to a powerplant of about 150 hp

III. Efficiency

POWERPLANT	SOURCE	VALUE(S)	COMMENT
ICE			Present ICE baseline used as reference
ICE-CVT	1) Orshansky Transmission Corporation (3-30)	20% improvement over ICE	Improvement due to replacement of conventional automatic transmission by CVT in test vehicle
MMFST	1) Chrysler Upgraded Engine (3-35)	About the same as or marginally better than present ICE	Represents (yet unachieved) program goal
	2) JPL (3-2, p. 3-17 and p. 5-26)	About the same as JPL's "mature" ICE	Derived from fuel economy figures for compact class vehicles of equivalent performance by correcting for differing inertia weights

Table 3.9 (continued)

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

III. Efficiency (continued)

POWERPLANT	SOURCE	VALUE(S)	COMMENT
MMFST (cont.)	3) Volkswagen (3-54)	Around 10% better than present ICE	Derived from fuel economy figures, for roughly compact class vehicles
INFST	1) Schultz (3-25)	Roughly 10% improvement over metallic turbine	Rough estimate of improvement due to ceramic stationary hot parts
INSST	1) JPL (3-2, p. 5-6)	The single-shaft turbine has an efficiency roughly 10% higher than a comparable free-shaft, i.e., both metallic configurations	
ADSST	1) NASA, Lewis Research Center (3-52)	From 10% to 40% better than ICE-CVT, about 30% to 60% better than ICE	Range due to possible variations in design, for a turbine operating at 2500°F turbine inlet temperature
	2) Mclean (3-6)	About 25% improvement over ICE	For a turbine inlet temperature of 2500°F
	3) Detroit Diesel Allison (3-21)	About 20% to 30% improvement over metallic turbine engine	Applies to engines for commercial vehicles
	4) JPL (3-2, p. 3-17, and p. 5-25)	About 50% improved over JPL's "mature" ICE	Estimated as in the case of MMFST (see above)

Table 3.9 (continued)

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

IV. Powerplant Specific Initial Cost ($/design hp)

ICE	1) JPL (3-2, Chap. 11)	11-13	"Selling price" estimate for mature powerplants of roughly compact size, adjusted for inflation to 1977 dollars
	2) Rand (3-36, p. 34 and p. 88)	8.5-9.5	Based on a "sticker price" of $1.13/lb of engine, in 1973 dollars, adjusted for inflation and bracketing engines of from 100 to 150 hp; transmission and emission control equipment costs at $1.99/hp are added after adjustment for inflation to 1977 dollars
ICE-CVT		About 10% higher than than for ICE	Rough estimate based on cost of hydromechanical transmission that is about 30% higher than standard automatic (3-9, 10)
MMFST	1) Volkswagen (3-54)	2-2.6 times initial cost of ICE of same horsepower	Refers to "production cost" of engines of 100 to 150 hp
	2) JPL (3-2, p. 11-12)	16-19.4	"Selling price" estimate for a powerplant of 107 hp equivalent in performance to a 150 hp ICE

Table 3.9 (continued)

POWERPLANT ATTRIBUTE VALUES DERIVED FROM LITERATURE

IV. Powerplant Specific Initial Cost ($/design hp) (continued)

INFST		-	
INSST		-	
ADSST	1) Volkswagen (3-54)	1.4 to 2 times initial cost of ICE of same horsepower	Brackets "production cost" of engine of 50 to 100 hp

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4. FEDERAL RESEARCH STRATEGY

4.1 Introduction

In this chapter we turn our attention to the strategic choices faced by a federal R&D agency supporting technology development and production (TD&P) of advanced automobile engines. We include in our category of "advanced" engines the gas turbine and Stirling engines, which are not expected to see commercial application prior to the late 1980s.[1] We exclude nearer-term alternatives such as the diesel and stratified charge engines which are now available or could be in the early 1980s. The discussion of the advanced engine programs will concentrate on the last three stages of the TD&P process -- initial development, final development, and introduction. We will pay particular attention to strategic and competitive relations among the key participants. Needless to say, all of the advanced engine programs entail significant technical and economic risks about which there is great uncertainty and some disagreement.

The set of choices to be made by the federal agency in this area may be crudely decomposed into a three-level hierarchy. At the highest level is the question of whether the federal government should be supporting work in this area at all. The middle level is the set of what we term "strategic" choices which determine the general framework and structure of the program. The lowest level is the myriad of details which must be decided for each research project.

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[1] Note that the term "advanced" here is used to refer to any of the technology levels (metallic, intermediate, and "advanced") discussed for the gas turbine in the previous chapter and for the Stirling in (4-1).

In this chapter the prior decision that there will be an active federally supported advanced automotive powerplant R&D program is taken as a given. The analysis presented in Chapter 2 above indicates substantial ambiguity as to whether this should be the case. Nevertheless, such a program now seems to have a reasonably secure place within the larger program of energy R,D&D.

The key policy issues now hinge on the specific features of the program, and these are what we address here. The most important part of the effort will be to define just what the key choices are. The level of analysis engaged in here proves unable to provide many convincing normative distinctions. The relative desirability of the potential advanced powerplants is not addressed here. There is a wide consensus in the technical community that the gas turbine and Stirling engines represent the power systems with the best potential for displacing the internal combustion engine and the closely related variants (the diesel and stratified charge systems). Electric and hybrid systems are dealt with in a separate government program, and are not considered here. Nor is the Rankine cycle engine, the other potential advanced heat engine which might compete with the gas turbine or Stirling for a place in the government program; it is not considered technical or economically competitive.

Thus only the choices concerning the gas turbine and Stirling systems against a broadly defined baseline are considered. Further, for purposes of our analysis, we will assume them to have equally favorable technological and economic prospects. The economic analyses reported in Chapter 3 of this report and Chapter 5 of Federal Support (4-1) indicate highly uncertain but potentially large benefits from either, and do not allow any detectable distinction. The key difference of relevance here is the number of firms which are involved with each.

The core of the analysis is the relationship between the powerplant R&D programs of the firms of the automotive industry and the support for such programs by the federal government. The analysis must, on one hand, respect previous patterns of behavior in the U.S. automobile industry and, on the other hand, acknowledge the novelty (and uncertainty associated with that novelty) of developing and producing an advanced engine, especially with government support.

One of the historical patterns which we will assume for the future is that there will be no significant production of advanced automotive powerplants in the United States except by the three firms which have produced all but a tiny fraction of those engines for the past half-century. These are, of course, the automotive "Big Three" -- General Motors, Ford, and Chrysler. Thus only the Big Three firms and the federal R&D agency (which is the U.S. Department of Energy) are considered. Clearly, other firms may be party to certain advanced engine development programs, although typically in subcontractor roles. Nor is the additional complication created by several federal R&D agencies hiring firms to do development work considered here, especially DOE's use of NASA as an intermediary in contracting for research.

The analysis follows in four sections. In Section 2 we define the goals we assume for the federal R&D agency and the Big Three. Next, the process of Technology Development and Production (TD&P) in the automotive industry is reviewed, with a focus on the pattern of technology change

4.2 Goal Definition for the Federal R&D Agency and the Automotive Manufacturers

Before appropriate government strategies to support industry TD&P can be discussed, the goals of the government and important actors in the U.S. automobile industry must be reviewed. A convenient distinction is made between conceptual goals, which determine general strategic principles, and concrete goals, which determine real activities.

For the R&D agency, the conceptual goal stated earlier (4-1, p. 89) need only be repeated:

> to reduce (for automotive transportation) life-cycle costs with inputs valued in social terms (for social analysis) or in market prices (for private market analysis), while meeting legislatively established environmental standards.

After the passage of the Energy Policy and Conservation Act (EPCA), fleet average fuel economy standards must also be added to the constraints. However, since the EPCA standards apply to the new car sales fleet average, their incorporation into the analysis of individual vehicles is complex and uncertain, as seen in Chapters 2 and 3 above. Allowing for the qualifications expressed in Chapters 2 and 3, it remains reasonable to suppose that the federal government will value decreases in fuel consumption and in emissions more highly than the public or the Big Three.

The agency's concrete goal can be divided into three parts. First, it wants to encourage more technological options for advanced engine designs which have equivalent or improved fuel economy and emissions in comparison to the ICE. Second, it wants to encourage successful commercial adoption of advanced engines which have attractive social attributes in the U.S. automobile market. Third, it wants to accomplish these in a way which is most effective per dollar expended by itself. In particular, it would like to avoid merely substituting its own dollars for expenditures which would have been made by the firm in any case. Indeed, it would like to stimulate increases in private expenditures with its own. Obviously, success in meeting this goal cannot be measured easily, due to ambiguity of firms' intentions as affected by government expenditures.

The Big Three automobile firms -- General Motors, Ford, and Chrysler -- complete the set of important actors. They alone among domestic manufacturers can be expected to place significant numbers of cars on the road possessing advanced engines. Their conceptual goal is to maximize the market value of the firm. They achieve this through making investments which maximize the value discounted to the present of expected future cash flows. Of course, we are concerned here only with the firms' activities within the automobile industry, not elsewhere.

We will omit direct discussion, here and later, of a large number of "dependent" firms within the U.S. automobile industry: parts suppliers, tooling manufacturers, and research firms. We also will not discuss, except in the context of specific engines, American Motors and foreign automobile manufacturers, who hold relatively small shares of the U.S. market. To a simple approximation, the major decisions affecting the powerplants of the U.S. automobile fleet over the next decade can be assumed to be determined by the Big Three firms and the federal R&D agency.

The Big Three firms' goals involve two parts defined along a continuum; the parts differ only in a qualitative way and do not necessarily require different activities. First, the firm wants to develop an advanced engine, which it hopes to successfully introduce and establish in at least a niche within the market. Second, the firm wants to maintain the capability to imitate quickly in production an advanced engine introduced by a competitor.

In the first part of its goal, the Big Three firm attempts to maximize its market value directly through introduction of its own new engine. In the second part, the firm tries to minimize its losses from an unfavorable competitive situation. It is, in fact, insuring itself against the downside risk of another firm achieving the "successful" engine.

There are a number of areas where one might anticipate discrepancies between the goals of the Big Three and those of the R&D agency. First, as discussed above, there may continue to be differences between the agency's measures of social costs and benefits and the Big Three's market prices.

Second, presumably the federal R&D agency is indifferent to the source of the development of the "successful" advanced engine, while each Big Three firm strongly prefers to develop it "in-house," i.e., it wishes to avoid having it developed by one of its competitors. There exist significant potential losses for firms which do not lead in technological innovation. The government favors all increases in relevant technological options and introductions of advanced engines into the market (although it may be concerned about the transfer across firms of the technology). Yet individual firms favor only increases of options the benefits of which they can appropriate, and they are clearly threatened by engines introduced by competitors.

Third, there may be some potential for conflicting goals related to differences in importance placed on industry stability during periods of transition in the automobile fleet from the baseline engine to an advanced engine. Again we presume that the federal R&D agency is generally indifferent to changes in market shares caused by the introduction of an advanced engine. However, it would certainly strive to avoid the bankruptcy of one of the Big Three, so as to preserve at least the level of competition which is present now. Presumably it would also wish to avoid major disruptions of production, or significant increases in foreign market share. While it is very unlikely that there would be a new domestic entrant into the American market,[1] it is not implausible that one of the firms (especially Chrysler) might go bankrupt during a major transition period.

Certainly there appears to be no satisfactory reason for the R&D agency to possess a hidden agenda of changing the structure of the U.S. automobile industry through its support of R&D. The government -- through antitrust actions -- has far more direct means of affecting the industry structure.

However, individual firms are definitely concerned about any changes in their market shares. Unless either the total or the domestic producers' share of the U.S. automobile market expands, increased sales

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[1] According to White (4-2) it appears very unlikely that a new firm can enter the U.S. automobile industry. Even with the possession of a dramatically improved engine and car design, a new entrant would require a minimum production capacity of 800,000 cars per year and a billion-dollar expenditure.

of cars with one type of engine take away from sales of cars with other engines. An advanced engine must substitute in use for the baseline engine, shifting sales between firms and divisions of firms.

The problem of stable transitions during substitution of engines becomes exacerbated when one takes into account the numerous government interventions into automobile market (such as emissions and fuel economy standards, and fuel and vehicle taxes), and the uncertainty about future interventions. As discussed in Chapter 2 above, the staged introduction of emissions and fleet fuel economy standards generally encourages incremental rather than radical changes in individual cars and their engines, and in the composition of the new car fleet as a whole. Changing the car's technology, especially through advanced engine design, is only one of the tools available to the Big Three firms to meet the standards. They may also decrease the size and weight of the vehicles, and (to meet the fleet average fuel economy standards) increase the relative prices of large, fuel-consuming cars. R&D programs on advanced eninges offer a very attractive but uncertain route to meeting these standards. Yet, in selecting their programs, the Big Three firms may be juggling more operational goals -- particularly in meeting changes in annual standards -- than is the federal R&D agency.

As a minor point, the agency is primarily concerned with outcomes in the U.S. while the Big Three are concerned with their worldwide profits. However, since a large percentage of the Big Three's sales occurs in the U.S., this difference may not be operative.

Finally, there is at least some concern that the government spread its R&D funds equitably among the Big Three firms. Some argue that only the relative merits of a firm's bid on a given contract should be considered, while others argue for consideration of the total research shares to each firm. If R&D funding is considered a simple subsidy, then equity among shareholders of the firms might be a plausible concern. It is more likely the case, however, that it is a possible competitive edge achieved with government-supported technology that is of concern, and thus equity is not really an issue but rather the agency's impact on market structure.

4.3 Review of the Process of Technology Development and Production in the Automotive Industry

Issues of government research strategy necessarily depend very heavily on the decision process in the automotive industry. Therefore it is worthwhile to review the conceptual model developed previously (in Chapter 2 of Federal Support) of that process. While the presentation here necessarily overlaps the previous one, the emphasis here is somewhat different. First, a clear distinction between technical and economic considerations is maintained. Second, the present emphasis is on the perspective of individual firms. Third, certain areas where trade-offs appear to be available are made more specific. The focus here is on the three central stages of the process of "Technology Development and Production" (TD&P) -- Initial Development, Final Development, and Introduction, and the decisions to invest in them.

4.3.1 Technical Learning in TD&P

In order to simplify a necessarily complex analysis, it seems worthwhile to separate technical learning and decisions based primarily on technical information from economic interpretation of technical information and decisions based primarily on financial considerations. For a private firm maximizing its market value, in general financial considerations will dominate purely technical criteria in TD&P decisions. Here, however, the perspective is that of a research director at one of the Big Three firms who is responsible for the development of technological capability for an engine but not for its application in the business.

There are four important types of technical questions relevant to the later stages of advanced engine development. First, at what time will the engine be ready to move on to the next stage, and, most importantly, to be introduced? Second, what will be the technical performance of the product at the current stage and later? Third, what will be the cost of the development program and of the engine in actual production? Fourth, what will be the usefulness, in a technological sense, of the development program and the product's attributes?

Learning in the TD&P process is fundamentally achieved through "doing" (4-3, pp. 156-157). Typically, conceptual problems become more clearly defined by attempts to arrive at solutions to very concrete engineering problems. Within a firm, the engineering staff becomes familiar with an engine's particular attributes and develops greater ease in handling problems. One can argue strongly for "economies of experience" derived from past investments in manpower and machinery for a particular engine.[1] Obviously in the case of the ICE, all Big Three firms are extremely familiar with the engine's most subtle properties. Yet, even in the case of the gas turbine, there is a long history of involvement by the engineering staffs of the Big Three firms.

Clearly, complicated dynamics of competing firms' plans and executions of development programs cannot be captured through the artifical designation of individual firm activities into sequential stages at once and for all decisions about whether or not to proceed.

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[1] See (4-4) for an empirical exploration of economies of experience for a very different industry.

Firms always have the option to delay or accelerate decisions, to place a project on a different schedule, and particularly to rethink decisions after examining the outcomes of their own and others' projects. Despite differences in the ability to resolve technical questions at different stages, firms will make go/no go decisions depending on the development program's likelihood of meeting its targets and the probability of other programs meeting their targets. Certainly there is room for disagreement among participants over appropriate targets for different engine programs. However, we are willing to assume -- given the availability of public reports and frequent conferences -- that the Big Three firms are quite well informed about each other's programs despite differences of opinion concerning the future potential of different engines.

During the central three stages of TD&P, there are five important engine attributes about which uncertainty may focus. First, there is the power output of the engine per unit of fixed input (e.g., horsepower per pound of metal). Obviously an engine's principal duty is to move the car; it should do so with the smallest possible engine.

Second, efficiency of the advanced engine is a critical factor. Again the size of the vehicle and the timing of the introduction of the mandatory fleet average fuel economy standards (from EPCA) determine the relevant requirements for engine efficiency.

Third, emissions standards must be met by the vehicles powered by the advanced engines. Currently, the staged introduction of emissions standards is designed to accommodate modest annual changes in the baseline ICE. Any implicit trade-offs between different types of emissions are arranged for the ICE (potentially with some modifications). Certain advanced engines, although much superior to the

ICE in some types of emissions, may face costly penalties in meeting other constraints, such as particulate emissions.

Fourth, the bulk, weight, and packaging of the engine must be considered for fitting the engine into the rest of the car. Weight is of course particularly important because of its impact on fuel economy.

Fifth, the cost of manufacturing the engine becomes critically important prior to a decision to begin production. Costs will depend on a large number of factors, but particularly on the product's design, materials requirements, and tooling needs. The cost of manufacture can be expected to decline significantly with the development of the engine design and experience in producing engines.

During the Initial Development Stage of the TD&P process for an advanced engine, performance is typically not measured with the engine in the vehicle. Ranges but not exact measures for efficiency (and thus vehicle fuel economy) and emissions are obtained. Generally, important information is generated about the final necessary size of the engine, but little about its cost of manufacture. Certainly most of the technical information concerns the potential performance of an engine in production. Specific targets for the engine's final capabilities cannot easily be formulated.

During the Final Development Stage, several generations of prototype engines are tested on dynamometers and in actual cars. Much greater emphasis is placed on realizing the engine's potential performance, maximizing fuel economy, and satisfying emissions standards. Targets for these attributes can be defined quite well, and the engine's potential, with the best possible design, can be determined. Placing engines in vehicles creates a direct source of information on the engine's "fit" to the car. Finally, engineering design work provides much more accurate estimates of manufacturing costs. In fact, the cost of producing the engine at introduction, and in more mature production, may become the critical factor in comparison to the baseline engine.

During the Introduction Stage for an engine, learning on all remaining areas of technical uncertainty takes place -- at a rapid pace and potentially at a very high cost (should the engine fail). In particular, the firm receives far more extensive feedback about the engine's performance on the road and in actual consumer use. Also the firm should learn very quickly about techniques for manufacturing the engine.

The timing of introduction of an advanced engine depends primarily on market as opposed to technical factors. However, in delaying or advancing introduction the Big Three firms face a trade-off between learning in preproduction engineering and learning in production. Despite their large accumulation of experience in manufacturing ICEs, the Big Three firms would still face considerable difficulty in forecasting actual costs of producing new engines at different points in time. We assume that the Big Three use sophisticated techniques in planning and executing production. However, the simple tool of a learning curve can approximate the typical experience of a firm in reducing manufacturing costs. For a doubling of cumulative output, average cumulative costs per unit tend to decline by a fixed percentage.

This tool allows one to estimate crudely the costs of producing engines as the firm progresses from a production prototype engine to the first and subsequent production runs. The expected decline in cost arises from changes in product design, production flow, materials and supplies, tooling and equipment scheduling.

The firm may face another important trade-off in balancing product design improvements against the costs of production changes.[1] In determining its strategy at introduction, the firm may attempt either to maximize the engine's performance or to minimize its cost of production.

4.3.2 Economic Expenditures and Returns in TD&P

In this section the economic, or financial, interpretation of the value of technical learning during the TD&P process for advanced engines is examined. Generally one can view an investment in TD&P as similar to any investment: expenditures are made now for returns expected later. The payoffs of TD&P to the Big Three firm correspond to the goals outlined in Section 4.2 above. The primary payoff corresponds to the goal of developing the "successful" engine. This event occurs when the firm introduces an advanced engine which replaces the baseline engine in part of the U.S. market. From the perspective of the late 1980s, one will be able to identify one engine (or perhaps two, or none) actually introduced from among several of the current candidates. However, one uses too narrow a definition of the economic value of activities in TD&P if one only places a positive value after the fact on actions leading in a linear sequence to a "successful" engine.

The secondary payoff to investments in TD&P corresponds to the goal of quick imitation of a competitor's engine. This rises from insurance, provided by development work, against the loss of competitive position in

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[1] This is demonstrated in the discussion by Abernathy and Wayne (4-5) of the experience of Henry Ford.

the event that a competitor introduces an advanced engine. Clearly there can be no value in projects which never produce a commercial engine. However, these projects, like all development projects, may have once had valuable content in the form of a special sort of asset. This asset is the option to proceed to the next stage of development of an engine, and maintains a positive value until there no longer exists a potential for commercial introduction of the engine (4-6, p. 46). Thus certain projects can provide temporary hedges for a firm against certain outcomes, even if they do not eventually lead to a successful engine.

There are other features of the economic aspects of the TD&P process which make investments in it somewhat unusual. First, an advanced engine has a direct payoff only if its attributes dominate those of the baseline engine in at least part of the U.S. automobile market _and_ if the engine is introduced into that part of the market. We need to look again at the technical attributes of the engines to measure their economic value in market prices. The comparison is between engine and the baseline of the late 1980s (most likely the ICE, diesel, or stratified charge engine) on the technical attributes discussed above. Clearly, if the advanced engine is superior in all attributes to the baseline engine, one can state unambiguously that the former dominates the latter. However, it appears unlikely that an advanced engine would prove superior in all attributes.

Second, the price of the advanced engine (which must be compared to its cost of production) must be derived from the market value of the combined attributes of the engine within the total car. Initially, the advanced engine may substitute for the baseline in only certain automobile sizes or certain models. Again there is great difficulty in determining market prices on regulated emissions. Perhaps even more ambiguous is the price of fuel economy given the fleet average fuel economy standards, in this case, as discussed in Chapter 2, the value of fuel economy to the consumer; presumably the latter is based only on the discounted flow of expenditures on fuel. Through raising the initial price of cars, the firm may be able to shift some of the burden of this "implicit tax" on fuel consumption to purchasers of cars with high fuel consumption. However, in the absence of government taxes and subsidies the firm may have to subsidize internally the production of certain engines, or car sizes, to achieve its desired mix of car sales and to meet the fleet fuel economy standards (4-7, Chapter 3).

Third, investments in TD&P, like other investments in R&D, but unlike typical corporate investments, frequently require for their justification the expectation of short-term monopoly profits in exploiting the competitive advantage of a technical innovation. It is a common view that firms need the reward of abnormally high profits as a motivation for risky investments in R&D. Yet one of the Big Three firms in the automobile industry may not be able to appropriate all the benefits of its innovation -- due either to certain benefits accruing to purchasers as "consumer surplus" or to implicit constraints on the firm preventing it from capturing its full advantage. The firm leading with a prominent fuel-saving innovation might not be able to withhold the licensing of rights or to raise the price of its engines.

Fourth, an increase in the number of advanced engine programs can be expected to increase the likelihood of the introduction of a "successful" advanced engine and provide insurance against several program failures.

Yet the economic benefits of advanced engine programs depend inversely on progress made in the baseline engine. As a secondary effect, an increase in the number of advanced engine programs decreases the likelihood that any one particular engine will achieve technical attributes dramatically superior to those of the next best. Further, the expected economic benefit of a particular engine program may be reduced slightly by the addition of other promising candidates in the field.

Fifth, TD&P programs have an unusual pattern of expenditures, different from many other investments. To a rough approximation, expenditures increase by an order of magnitude in proceeding from one stage to the next. Initial Development may cost $10 million, Final Development $100 million, and Introduction, $1 billion. Not even a Big Three firm can make decisions to expend such large sums of money casually.

The assumption here is that there exists greater uncertainty for a Big Three firm in interpreting the economic value of its in-house and competitors' programs than in estimating their technical status. Clearly the costs of developing and producing advanced engines and the market prices of engine attributes may fluctuate significantly during the next decade. Yet if the firm is lucky it can estimate the expected values of different advanced engines along the key attributes and eliminate investments in certain engines. Still, there are caveats one must recognize in ranking engines along expected economic returns from a direct sequence of stages from Initial Development to Introduction. First, the rankings are usually ambiguous now and are likely to change in the future. Second, the development of several engines, perhaps through Initial and Final Development, may be necessary for development of a more advanced engine. Third, there may be a value to particular firms in certain engine programs as hedges against competitors' developments.

We have presented the technical and economic aspects of the TD&P process from the perspective of a Big Three firm, able independently to implement the total process. The maintained assumption is that the firm has the resources to do what it wants on its own without government financing. However, in the next section the respective roles of the Big Three firms and the federal R&D agency in combined R&D ventures are examined more directly.

4.4 General Analysis of Strategic Choices to Be Made in Advanced Power System R&D Programs

Decisions for all parties in the area depend on evaluations of industrial projects as investments and then arrangements for financing. The firms and the agency first select among engine projects based upon their expected return adjusted for risk. Then the firms and agency make final decisions on programs based on their willingness to finance the programs, either independently or jointly. In other words, one can initially examine advanced engines solely as investments. However, one must consider secondarily the effects of financial contracts between parties, especially between large private firms and the government.

Therefore in this section we take the following approach. First we define and discuss the parameters which describe individual engine R&D projects, as investments. Next we describe the properties of R&D strategies, or combinations of projects, as they are available to each firm, and to the agency, and review generally the circumstances which would affect the reltive desirability of the strategies. The section closes with a review of the areas where difficulties associated with negotiations between the agency and the firms make strategic choices difficult.

4.4.1 Considerations in Project Selection

In this subsection the key considerations in project selection will be laid out. The first four are parameters which differentiate advanced engine projects. It would be desirable to construct the parameters so that they are as distinct and independent of each other as possible.

However, certain of the parameters frequently must be coupled to one another in actual applications. The parameters defined here are intended to be relevant to both the private parties and the R&D agency in setting their respective strategies.

We define the first parameter, like several others, roughly along a continuum -- based on the stage in the TD&P process and level of technical difficulty (and riskiness, therefore) of the advanced engine project. Presumably, at the time of consideration, the most advanced engine designs will only be ready for Initial Development. Less advanced engines will be ready for Final Development, while certain engines could be nearly prepared for Introduction (perhaps prematurely for advanced engines prior to the late 1980s). The stage of development of different engine programs carries importance for the Big Three firms in planning for baseline engines in the fleets in future years. This stage of development has importance for the R&D agency because of the government's traditional role (outside of industries involving direct government procurement) of supporting earlier rather than later stages of development . The R&D agency has a more difficult case to make in supporting a firm introducing an advanced engine if it does not intend to grant substantial long-term support.

The second parameter is the financial riskiness of the engine project. The two types of risk -- technological and economic -- are, as discussed above, somewhat independent. The former is included here in the first parameter and the latter in the second. For example, one engine may require very little technical advance but may carry high economic risks due to uncertainties in the market values of its attributes. Another engine might require a very risky technological breakthrough. Assuming success in that breakthrough though, the engine might be introduced with little economic risk.

A third parameter is the degree to which an engine promises advances in either marketable attributes or in "social" attributes not fully valued in market prices. The Big Three firms are very unlikely to develop an engine with socially valued attributes that are not coupled to attributes valued with suitable market prices. Generally the R&D agency is most concerned with supporting engines with socially valued attributes, particularly low emissions and fuel consumption. However, major problems could occur if the agency zealously supports an engine which could never achieve market acceptance, even if it were socially valuable, unless the agency intends to subsidize the engine in the long term (after its introduction), or expects federal policy to legally change the value of the social attributes.

The fourth parameter, again defined along a continuum, focuses on whether to develop a whole engine system or to concentrate on certain key components. A "components" strategy seems attractive if the success of one or more engine systems is contingent on the successful resolution of the manufacture of a certain component. Sometimes the expense of developing prototype engines can be delayed until a breakthrough in a particular component (such as a ceramic turbine wheel) creates immediate possibilities for several engine types. On the other hand, a "systems" strategy might be advocated if it were possible to learn more quickly about different engine configurations. Certain components once believed to be critical for success might lose their importance with a modification to the overall system.

Beyond the four project parameters, there are three other key considerations involving the firm's or agency's choice of projects in fashioning a satisfactory strategy. The fifth consideration is the number of different engines in the strategy. This requires the most complicated analysis, as a variety of factors encourages behavior in conflicting directions by the Big Three firms and the federal R&D agency. Here as in all R&D cases the investor is faced with a problem of forecasting technolgical outcomes, given different allocations of resources and different paths to the solutions. Further, after a "bet" has been made on a technical outcome, the investor must then bet on the economic benefits associated with the outcome.

The same arguments can be made for a diversification of engine programs that are made for parallel R&D strategies. The pursuit of several engine programs represents a decision to delay selection from among engine candidates until more information is available. The value of this type of action derives from an improved choice of the best approach, and a better hedge against failure of all approaches. (Also, to be discussed below, there is enhanced competition among teams.) The strategy is justified under several conditions. There must be a reasonably well-defined task target attribute, in the case of advanced engines. There should also be a high priority in achieving these attributes. Further, several approaches must be available to fulfill the task. Finally, the preferred approach cannot be currently identified (4-8).

The number of engines supported in a strategy depends positively on the differences in the approaches and the differences in the estimates of the engine attributes from the various approaches, and depends negatively on the costs of the approaches. Again, the costs of engine development increase tremendously in the later stages of TD&P. Therefore, diversification across engines is far more likely to be reasonable if the time at which a selection can be made occurs early in the process rather than late. It would probably be unwise for a firm to conduct several engine projects through the Introduction Stage if the firm could have curtailed the inferior program earlier (4-9, p. 82).

Competitive factors also affect the choice between types of projects. Therefore a sixth consideration, which is relevant primarily to the federal R&D agency and less important to the Big Three firms, must be introduced. This is the decision to support diversified or duplicate efforts at different firms. It depends almost entirely on the agency's assumptions about the nature of competition in R&D among the Big Three firms. Specifically, the issue is whether the most competition arises from several teams working on the same advanced engine or from several teams working on different engines.

The first type of competition might be called "technical." A firm, and specifically its technical staff, may respond most directly to competition for the completion of a task when another team is assigned to the same task. If this type of competition is judged important, it would certainly encourage government support of duplicate efforts on the same engine at different firms.

The second type of competition might be called "business" competition. A firm, and particularly its general management, might respond most to the total R&D strategies of the other firms. It would not necessarily feel obligated to match on a one-to-one basis the projects of its competitors. It might be assumed that the second type of competition, because of its generality, would, if operative, dominate technical competition. In this case, the R&D agency need not be concerned to find multiple teams for each engine.

Finally a seventh consideration is necessary. It is a matter of choice by the Big Three, but a key factor to be considered by the R&D agency. The strategies for all parties will depend on both the economic potential of the engine programs and their sources of financing. In particular, different strategies should emerge based on company <u>responses</u> in the TD&P process to the potential availability of government support.

There appear to be two important aspects, again different but not entirely independent, involved in potential Big Three responses. First, a firm may be to various degrees willing to pursue work it does not consider privately profitable to its central business of building cars. A firm obviously rejects many engine programs with large amounts of risk and inadequate expected returns. Yet a subset of the programs may have adequate social returns so as to be worth undertaking. The question, then, is the degree to which a given firm will apply its resources, even if subsidized by government funds, to projects it would not consider profitable when evaluated without consideration of the subsidy.

Second, a Big Three firm may impute some penalty on development work financed by government funds. That is, a dollar received from the government might be valued at well less than one dollar. Presumably the size of the penalty would depend on the company's ability to appropriate the benefits of the work (whether it had given up plans, patent or licensing rights) and on the difficulties in contracting with the outside party.

We might define four types of responses of the firm which combine the two aspects of the seventh parameter. First, the firm could decline to work on any advanced engine program which it did not consider privately profitable. Further, it could consider the penalty for receiving one dollar of government funding to be at least the dollar itself. In this response, the company selects only the projects that it cares to finance internally, and does not accept federal subsidies even for these. (This response appears to summarize the position until recently of General Motors.)

In the second response, the firm could be willing to perform certain projects which it did not deem privately profitable. Further, it could consider the penalty for receiving one dollar of government funding to be significantly less than the dollar itself. However, the firm would choose to conduct, under its own financing, all projects considered privately profitable. Presumably certain "high risk" projects would be acceptable for government funding and company operation. (This response appears to represent that of the Detroit Diesel Allison Division of GM and the stated positions of Ford and Chrysler.)

In the third response, the firm might be willing to perform with government funding certain projects not privately profitable <u>and</u> certain projects which it <u>does</u> consider profitable. In other words, the firm could subtitute government funds for its own funds in both profitable and unprofitable ventures. The penalty on receiving a government dollar for any engine project in this case is valued at less than one dollar.

Fourth, a firm may be willing to conduct any research suggested by government without concern for its content. In the other three responses we have assumed that the firms would refuse any project with no positive potential benefits for developing advanced automobile engines. However, it is possible that a firm could sell the services of its research laboratories in a manner similar to an R&D firm performing contract research on a "cost-plus" basis. None of the Big Three firms states a willingness to perform this type of function. Assuming their obvious commitment to the automobile business and a limited capacity in the short run to expand their research staffs and facilities, only a single situation in which one of the Big Three firms would show this response can be imagined. In this case, the firm would perform development work on a high-visibility project in order to demonstrate government-industry cooperation and improve its public image.

If a firm has a "Type One" response, there can be no contract between the government and that firm.

In a practical sense, there is substantial difficulty in separating company responses two and three. If the government negotiates successfully a contract with one of the firms, it does not necessarily know whether it is in fact financing a profitable or unprofitable venture. If the firm is truly showing a Type Two response, the government's dollars do not substitute for research dollars which the firm would otherwise spend itself. In fact, the addition of the engine project may make other projects more attractive. As in priming a pump, government dollars might induce increased expenditures by the firm. However, if the firm truly is showing a Type Three response, government dollars may merely be substituting for company dollars. As stated previously, this is inconsistent with the previously hypothesized goals of the federal R&D agency.

Since no firm can be expected to state explicitly that it would conduct its development program in exactly the same manner and over the same time horizon independently of the source of funding, the R&D agency must use careful judgment in estimating the differential impact of its investment on the firm's actions. In fact, the government should be careful in negotiating, particularly with Ford and Chrysler, that these firms are not really showing response Type Three, instead of Two, and substituting government dollars for their own without changing their planned engine programs. Clearly the best protection for the government derives from tough bargaining in arriving at contracts.

4.4.2 Strategies for the Big Three and the Federal R&D Agency in Supporting Automotive R&D

In this section several model strategies for the Big Three firms, and several for the federal R&D agency, are presented. They combine the project parameters previously discussed into distinct "packages." Clearly there exists a very large number of possible strategies combining the parameters into all sorts of configurations. Furthermore, the strategies of each party must depend greatly on those of the others.

In the first company strategy, the firm becomes a "specialist." It concentrates all of its own resources (allocated to advanced engines) in what it considers the most likely candidate for commercial introduction. The firm selects its "best" candidate -- the one with minimum business risk -- after the Initial Development Stage, and goes with it at full speed through the Final Development and Introduction Stages, assuming continuing success. The engine is likely to be in the less technically advanced category of advanced engines corresponding, for example, to the metallic gas turbine engine discussed in Chapter 3 above. In this case, the firm is developing an entire engine system and will itself perform or hire out all essential activities. Assuming that the company has a Type Two response to government funding, it funds this high priority project by itself. That is, it views the project as privately profitable and, given its aversity to government funding, supports it internally. Assuming a Type Three response, the firm obtains, if possible, some funds from the R&D agency. That is, if it is not averse to accepting government funding, it seeks to substitute those funds for its own, without changing its R&D project. Clearly the specialist strategy does not offer the company strong protection against the successful development of other engines by its competitors.

In the second strategy, the Big Three firm maintains a defensive posture, attempting to maximize its "protection" against other firms' competitive advantages from engine programs. The firm spreads its development efforts over several engine types in different stages of TD&P. The firm invests in several engine types to hedge against developments made by competing firms. This strategy depends on the partial duplication of the efforts of other firms and offers significant possibilities for commercial introduction by other companies. Generally the projects duplicated will tend to involve whole engine systems (so that the firm is prepared for a rapid Final Development Stage). with limited technical risk but significant financial risk (if pursued aggressively by the leading firm). Pursuing this strategy, the firm expects to maintain some in-house familiarity with any engine successfully developed by a competitor. Again depending on whether the firm has a Type Two or Type Three response to government funds, it will finance its projects internally or will seek government support.

In the third strategy the Big Three firm places its bet only on very "advanced technology." In this case, the firm must implicitly expect significant positive shifts in the baseline engine. Further, it must be well aware of the very high cost of the Final Development and Introduction Stages for any advanced engine. Therefore, the firm concentrates on Initial Development of technically sophisticated engine components, hoping for a breakthrough that will facilitate development of a much improved engine system. This strategy requires the smallest direct expenditure, at least in the near term, and produces a small probability of a very large economic return in the distant future.

By not investing resources in less advanced solutions, the firm clearly hopes that it can imitate easily or purchase from its competitors the manufacturing technology necessary to match a competitor's less technically advanced engine in the market . It would seem reasonable to expect that this type of strategy would be financed largely by the federal R&D agency, as it entails risky technology with a distant economic return.

The two remaining possible strategies for a Big Three firm require little description. In the fourth strategy, the firm goes all out in supporting a wide variety of advanced engine programs. The firm invests large sums of its dollars (and those of the government, if available) in the hope of selecting as soon as possible the truly "best" engine. In the fifth strategy, the firm does little development work on advanced engines. This strategy requires either a pessimistic forecast of other competitors' efforts or belief in the firm's own ability to imitate quickly a new engine even without an ongoing effort of its own.

In setting its strategy the federal R&D agency must be particuarly responsive to the Big Three strategies, which are not usually explicitly stated or necessarily consistent over time. In its first strategy, the R&D agency acts as a "specialist," like a firm, allocating its total support to the engine most likely to achieve commercial introduction. The government can pick from among all of the engine types and, unlike the Big Three firms, from among each of the automobile manufacturers' projects. Again, with the current high level of uncertainty about the potentials of different engine types, the R&D agency may find itself in agreement or disagreement with the Big Three firms. If the agency chooses to encourage development of an engine type in which one firm is currently "specializing," there may be no use for additional government expenditure to accelerate the program. If the agency picks an engine that no firm is actively developing, it should first reexamine the reasons for its disagreement with the Big Three. Then the agency should determine whether one of the firms has the capability and commitment to perform the development with government funding. In the most likely case, the agency will provide supplemental support to an engine already in development by at least one of the firms. Hopefully it will actually accelerate the company's research, and not merely substitute government for company dollars.

This strategy does not expand the "protection," for the industry and the nation as a whole, of assuring at least one "successful" advanced engine in the marketplace in the late 1980s. It also could create certain problems of equity in supporting exclusively one firm's efforts. Some special provisions might have to be made to aid in the transfer of technical knowledge and manufacturing experience to other firms in the event of a successful introduction. This strategy does, however, promote the development of the strongest commercial option, and encourages the accelerated introduction of an advanced engine into the market.

In the second strategy the federal R&D agency concentrates its investments in an advanced engine with significant "social attributes." The R&D agency selects an engine which has received relatively little private development attention but has very positive social attributes coupled with at least a few favorable market attributes -- excepting, perhaps, initial cost. In this case, the R&D agency would probably have to grant large subsidies to the firm to develop the engine and would hope for some breakthrough in cost. This strategy depends critically on the later incorporation of the social attributes into market prices, perhaps through changes in the emissions and fuel economy standards or implementation of taxes and subsidies.

In the third strategy, the federal R&D agency supports several advanced engine programs to maximize its "protection" against the possibility of no advanced engine appearing on the U.S. market during the 1980s. In no sense does this strategy offer the government and automobile industry additional insurance against the failure of the advanced engine programs. This insurance is provided by the continued improvement of the baseline engine -- currently the ICE and in the near future possibly either the diesel or stratified charge engine. Actually only the electric vehicle programs offer significant additional insurance against the lack of availability or the gross unattractiveness of fossil fuel to power automobiles.

To pursue this strategy of limited protection, the R&D agency might assume that the Big Three firms respond primarily to "technical" competition. One might reasonably expect both that a "successful" engine would be introduced faster and that other firms would quickly imitate the leading firm's production. The R&D agency would have to exercise judgment in offering to the Big Three the minimum support necessary to encourage duplicate efforts. In particular, duplicate efforts could arise if the government funds only one or no teams at all.

In a fourth strategy, closely related to the third, the federal R&D agency again seeks protection against the development of no new advanced engine. In this case, the R&D agency might assume that firms respond mainly to "business" competition. The government would then support programs on diverse engine designs, betting on the pressure of competitors' total R&D programs to induce increased company expenditures. As always, the R&D agency risks substituting its funds for company funds and spreading too thinly its limited resources. The advantages of this strategy lie in the increased encouragement for firms to insure themselves against competitors' innovations and in decreased ability of one firm to appropriate monopoly profits from its innovation.

In the fifth model the R&D agency supports exclusively development of more "advanced technology" applicable to several advanced engines. Here the government bets against fairly heavy odds on a very large but delayed economic payout. It can fund a variety of research institutions, including Big Three research laboratories, R&D firms, tooling and component suppliers, and nonprofit organizations, to develop new applications of materials and manufacturing technology. Clearly this strategy offers the government the widest range of possible participants. Yet there may be significant problems in directing the research efforts toward a consistent goal and in transferring technical knowledge to the Big Three firms, which are finally the only parties capable of performing TD&P on an advanced engine toward implementation.

Again, there are two final strategies for the federal R&D agency -- to fund everything, or to fund nothing. Both of these alternatives obviously appear to be very unlikely choices. The former requires a large and indiscriminate role for the government; the latter ignores the apparently strong political arguments for government action.

4.4.3 Key Areas of Ambiguity in Choosing a Federal Strategy

The ambiguity related to advanced engine R&D arises from two main sources: lack of full information about current (and, obviously, future) projects, and disagreement among parties about available information.

First, at this point in time, there is a high degree of uncertainty about the potential of the competing engine designs that might be introduced successfully in the late 1980s. The analysis in Chapter 3 of this report and Chapter 5 of Federal Support (4-1) documents this in some detail. With such a long time horizon, disagreements within firms and across firms about the best course of action seem very legitimate. The R&D agency should recognize these disagreements and weight the firms' opinions according to their allocation of inhouse funds to different projects. Clearly firms give strong signals in their budgets about their estimates of the potential likelihood of an engine introduction. The agency could disagree reasonably with some or all of the firms on certain technical and economic judgments. However, the agency should check before funding a privately "underfunded" project to see whether it truly has positive "social" potential and is not an unattractive project from the perspective of all parties. In particular, the federal R&D agency should respect the manufacturing and marketing expertise of the Big Three firms, which should certainly exceed that of the government.

Second, there are persistent problems associated with contracts between parties. As stated previously in the discussion of company responses to government funding, one can never determine exactly the differences between company plans with and without government funding. Currently, government support to advanced engine R&D still represents a small fraction of the total Big Three allocation to technology development. However, with the availability of long-term government support, the burden of financing research could shift, at least in part, from the Big Three to the public.

There are also difficulties associated with the limited number of potential parties with which the R&D agency can contract. Frequently the government will be constrained to accept bids from as few as three contractors (or not even all of the Big Three). For development of engine systems components and more basic research, the government may face more candidates. Presumably the Big Three are capable of hiring subcontractors so as to complete their tasks more efficiently. With some negative political side effects the R&D agency could hire foreign automobile manufacturers; however, this would probably create more trouble in monitoring contracts. Foreign firms also have fewer resources and less concern for the peculiar problems of doing business in the American automobile market.

In all contracts between parties, one can potentially confront a "moral hazard" (4-10, pp. 313-319). In examining outcomes after the fact, one cannot always separate chance occurrence from events created by a party's specific decision. In the general case of advanced automobile engine development, no particular problems should arise since the firm and the R&D agency both presumably desire a favorable outcome for the program. However, if a firm carries out parallel development programs, one supported by its own funds and the other supported by the government (requiring some limitations on the firm's patent and licensing rights), success may "automatically" shift only to the company-sponsored work.

Third, the lack of precedent for government support to the TD&P process in the automobile industry creates several potential hazards. In particular, considerations often reputed to be politically important cannot be met clearly by any one the R&D agency's strategies. There are no promises of early commercial payoffs for an advanced engine. Certain engines, such as the metal gas turbine and Ford's Stirling engines, could be demonstrated soon in actual vehicles. Yet neither engine is even nearly ready for commercial introduction. These engines are "research tools," not "commercial" engines. The expected high rate of failure of the advanced engine programs also seems unpalatable for the public. With extensive additional expenditures, the government can force programs to achieve technical success. However, it cannot force commercial acceptance for a risky, new consumer product. Finally, there exists considerable political disagreement concerning the appropriateness of any government interventions in the later stages of product development. In particular, different parties place more or less emphasis on fairness in the allocation of government support and on the smoothness of the automobile industry's transition to a major new engine.

Fourth, inherent in the concept of any "strategy" is a coherent plan that designates actions contingent on a variety of potential outcomes. A true strategy requires consistency in goals and methods for meeting those goals. It also requires flexibility in modifying actions in response to new information and circumstances. Thus, the federal R&D agency must strike a balance between consistency and flexibility in maintaining a strategy over time. Certainly, without a stable strategy the R&D agency merely introduces into the business environment of the U.S. automobile industry one more source of government-induced uncertainty.

4.5 Strategic Choices Available to the Federal R&D Agency

We now begin a three-part exercise to apply the above-developed analysis to the government's decisions now at hand. As always, the test of any analytic framework is whether it provides increased understanding of the available alternatives and indicates likely consequences of actions. In the first two parts here we will discuss the options available to the federal R&D agency to support TD&P on the gas turbine and Stirling engines. Again, we have confined the choice of options to versions of these two engines, omitting nearer term solutions such as the diesel and stratified charge engines and more distant future solutions such as the electric vehicle.

In the third part, we present a brief description of apparent Big Three strategies, before proposing alternative strategies or "packages" of actions, for the federal R&D agency. At this point we primarily are interested in actual contracts between the government and Big Three firms. However, we will not pursue specific aspects of the contract process, but will suggest programs with which the governmment might wish to become involved.

We might provide a quick review of the concrete goals for the government and Big Three before introducing the options through which they might implement their respective strategies. The federal R&D agency wants to increase the available technical options (with reduced emissions and fuel consumption), to avoid substitution of government dollars for private dollars, and to focus its expenditures on advanced engines with large potential payoffs in commercial introduction. A Big Three firm wants to develop an engine through the stage of successful introduction into the U.S. automobile market and to protect its competitive position in the event of competitor introduction of an engine. Also, the critical engine attributes include performance, fuel economy, emissions, size and cost of manufacture.

Options for R&D on the Gas Turbine Engine

For several reasons the gas turbine engine provides an interesting case for government support. First, all of the Big Three firms have long histories of involvement with the engine type in passenger car and other applications. Second, all three firms currently show strong interest in the engine. Third, there are a number of different versions of the engine, varying in their requirements for technical innovation and in their potential for successful commercial introduction. As in the general case, significant uncertainty and disagreement surround each of the options, and all parties do not favor the same options. Fourth, critical engine attributes for the gas turbine are emissions (long-term standards can probably be met), fuel economy (which depends on the version of the engine), and manufacturing cost (which for near-term versions greatly greatly exceeds that of the baseline ICE).

We will introduce the alternative programs available for the gas turbine, distinguishable by the parameters outlines in Section 4.4. The first version consists of an all metal turbine engine -- currently being developed by Chrysler and the Engineering Staff of General Motors. A major problem for project selection begins here. There are two potential configurations for the gas turbine: the single shaft (simpler but requiring a continuously variable transmission (CVT)) and a free-shaft version not requiring the CVT. There is definite disagreement over the better option for an engine receiving commercial introduction. GM has been working on the double-shaft engine at its Engineering Staff and on a single-shaft engine at Detroit Diesel Allison Division. Officers at Chrysler and Ford have stated that they favor the single-shaft configuration for introduction. The metallic free-shaft gas turbine is currently in final development and is a candidate for perhaps premature introduction. As discussed in the previous chapter, the limited technical riskiness of this engine seems to be matched by its limited promise for commercial success.

The second version is the "intermediate" gas turbine engine. Vehicles using this version of the engine show gains in fuel economy of 10% to 25% over the 1977 baseline ICE, through the use of ceramics in the hot flow path -- except in the turbine rotor, the most important component. Again, the choice of a single- or double-shaft configuration for the engine system has not been resolved. From discussions with industry officials, there appears to be a general consensus at Chrysler and Ford, of skepticism concerning the success of commercializing an "intermediate" engine with only this range of improvement in fuel economy over today's vehicles. In fact, both GM and Ford are currently forecasting 20% improvement in the fuel economy of the baseline engine by the early 1980s using the nearer term diesel and stratified charge engines. Thus, to predict the successful commercialization of the "intermediate" gas turbine, one requires an optimistic forecast about the fuel economy (and manufacturing cost) of the "intermediate" gas turbine <u>and</u> a pessimistic forecast about the fuel economy of the baseline engine in the 1980s. This engine is currently ready for final development, with all Big Three potentially interested in programs of government support.

The third option involves the development of an "advanced" gas turbine engine. This engine has ceramic components in all hot flow parts, including the turbine. These parts allow increased operating temperatures and offer up to 50% improved fuel economy over the 1977 ICE-powered vehicles and significant improvement over the baseline engines projected for the 1980s. This engine is currently ready for the Initial Development Stage. It would involve more a "components" than a "systems" program, as defined above. There is the greatest technical uncertainty associated with this program, but also the greatest potential for applications of the new technology to other advanced engines (particularly the Stirling), given a breakthrough. If the materials and manufacturing problems are resolved to satisfaction, then the advanced gas turbine can be introduced with a larger expected economic payoff. Currently Ford has a substantial ceramic component program with some government support. Chrysler has a small program -- involving certain suppliers -- which is funded internally. General Motors has no active program in this critical area.

We will delay discussion of possible courses of action for the federal R&D agency in supporting gas turbine programs until after we have introduced the Stirling options.

Options for the R&D on the Stirling Engine

In this second of three parts we will introduce the options available for development programs on the Stirling engine. In some ways the Stirling engine provides a less interesting case than the gas turbine. The federal R&D agency has far fewer options, since Ford, a relative newcomer to the Stirling, is the only Big Three firm currently interested in directly participating in a program. General Motors dropped completely its Stirling engine program in 1970; Chrysler has never had such a program. Ford has coordinated its efforts with Philips, now the most experienced developer of this engine, and United Stirling, a highly regarded new participant. The technical and programmatic history and the key factors affecting the economic value of the Stirling engine are laid out in <u>Federal Support</u> (4-1, Chap. 5).

There are several complications bearing on the Stirling case that are not relevant to the gas turbine. First, the federal R&D agency cannot necessarily contract directly with Ford for the sale of patent and licensing rights. Many of these belong to Philips.

Second, Ford does not necessarily possess all the experience and expertise currently available on the Stirling. However, because it coordinates its efforts with Philips and United Stirling, the government does <u>not</u> appear to have a likely separate candidate with which to contract. There has been some discussion of forming a new team of United Stirling and U.S. engine manufacturers. Given the pooled technology available to Ford and the apparent lack of interest at Chrysler and GM, there seems to be no obvious vehicle for <u>duplication</u> of the Stirling efforts by several teams or <u>diversification</u> of efforts on several phases of engine development.

Third, the R&D agency faces all of the typical problems involved in contracting with a single party. There are no other parties to force competitive bids for a fair contract. In particular, Ford does not necessarily have to show its full hand in negotiating. A cost-sharing type of arrangement with tough bargaining on the part of the government provides the only signal of Ford's true priority on the Stirling. Also, without other teams in the competition, the federal R&D agency has greater difficulty in accounting -- even after the fact -- for the degree of technical success of the program. We have here the potential for a classic situation of "moral hazard": the R&D agency cannot distinguish between outcomes deriving from chance events and those dependent on particular decisions by Ford (4-10).

Fourth, it is difficult to interpret Ford's statement that it will run the same Stirling program, but over a longer time horizon, if it does not receive government support. Surely, even with the uncertainty of events a decade into the future, planners must have different targets for the attributes of an engine introduced in the late 1980s rather than the middle 1990s. Planners must expect a steadily improving baseline engine and must accommodate advanced engine programs to the best estimate of baseline programs.

Yet there are some close parallels between the Stirling and gas turbine engines. The Stirling engine faces the same critical attributes. Emissions standards can probably be satisfactorily met. Fuel economy should be improved significantly above the current ICE (estimates are between 15% and 30%), with the additional possibility of using lower grade fuels than gasoline. The cost of manufacturing -- particularly the heater head -- is expected to be a major problem in developing the engine for commercial use.

The proposed plans for Stirling engine programs resemble those for the gas turbine. In the first version a "metal" Stirling engine using ceramics only in the pre-heater would be developed. A brief design review would be followed by a components and full system programs.

In the case of the Stirling, program reviews become critical because of the negative signals given by both General Motors and Chrysler as to their estimates of the estimates of the likelihood of commercial success for the engine. Ford and the R&D agency need strong evidence for allocating a large expenditure for final development of the improved engine not supported by other firms.

In the second Stirling option, an "advanced" engine, using extensive ceramic parts -- in the heater head and elsewhere -- would be developed. The Stirling engine, like the gas turbine, would perform considerably better, especially in fuel economy, with the increased operating temperature allowed by ceramics. Currently a program designed to develop ceramic components, as opposed to an entire system, would appear most useful. However, there are several different configuration options for the Stirling which are not as well understood as those of the gas turbine. This uncertainty may be reduced given increased familiarity of engineers with the engine. Still, a metal Stirling -- developed as a full system -- might prove to be a necessary step to an "advanced" Stirling engine. Finally, there would be some technical crossover between the advanced component programs for the Stirling and gas turbine engines.

Models for Combined Strategies

In this third part, we will attempt to combine our discussions of options for the gas turbine and Stirling engines into proposals for strategies for the federal R&D agency. We might provide here a quick review of the available options. First there is the metallic gas turbine, nearly read for possible introduction by Chrysler. Second, there is the "intermediate" gas turbine (in single- and double-shaft versions) ready for final development by all of the Big Three. Third, the advanced gas turbine is available now as a components program.

Fourth, the "metal" Stirling could enter final development by Ford. Fifth, the "advanced" Stirling engine could begin as a components program, again by Ford.

The government must obviously accommodate its strategy to those of the Big Three firms. Therefore we will begin with a quick overview of what appear to be the company strategies at the current time. As always, there are problems in determining company intentions <u>with</u> and <u>without</u> government support. Generally, a company's priorities will be reflected in the relative allocations of its own dollars to different projects. Yet some of the firms may be happy to substitute government dollars for their own even in high priority projects.

Chrysler appears to have the easiest strategy to pin down. All its efforts to date have focused on the gas turbine engine. It has nearly completed development on the metallic gas turbine and seems eager to work on "intermediate" and subsequently advanced gas engines. Chrysler appears willing to bet only on the advanced gas turbine for commercial introduction. Yet its strategy, while definitely that of a "specialist" ready to introduce a successful engine, would apparently not be pursued atall without government funding. Chrysler will not and cannot match <u>on its own</u> the efforts of other firms on different engines.

General Motors has a strategy which is somewhat more difficult to define. Significantly, its large size and divisional structure allow for quasi-independent actions within different parts of the firm. Its funds are currently supporting work, in the Engineering Staff, on a metallic free-shaft engine. Detroit Diesel Allison is interested in developing a single-shaft intermediate engine -- with some government support. Prior to its decision in 1970 to curtail the program, the company had extensive experience with the Stirling. Altogether, its strategy appears to be one of maintaining protection against another firm's introduction of the engine. GM is matching other firms' efforts (relying on its past experience in the case of the Stirling). The diversification of efforts within GM on the gas turbine, although focusing on different approaches, shows evidence of its interest in competing head to head with other teams on technical developments. Only in ceramic components does GM not anticipate matching efforts.

Ford's strategy is most difficult to place in a single category. Players now anticipate a lot of shared development dollars between Ford and the federal R&D agency, obscuring to some degree Ford's priorities. Obviously the firm appears aggressive both on its own account in developing the engine and in acquiring government dollars to support its efforts. Ford distinguishes itself from the other firms in its development of the Stirling engine. In allocating most of its own dollars to this area Ford appears to be pursuing a "specialist" strategy, although with a different bet from the other firms. Yet the company, perhaps as hedges against favorable outcomes for other firms' engines, appears interested in developing (with government dollars) an intermediate gas turbine and advanced ceramic components.

To pursue its concrete goals of increasing technical options, avoiding substitution of government for company dollars, and increasing the likelihood of commercial introduction of an engine with improved social attributes, the government could pursue one of several strategies. We will present four strategies, executed through government funding (at least in part) of one or more of the program options for the gas turbine and Stirling engines. We have not set an arbitrary budget to which each strategy must conform. Rather, we take as an assumption that government spending will be adequate but not wasteful given its intentions. We cannot pretend here to specify exact levels of expenditures, precise timing of projects, or the appropriate share of government support for all options. These are obviously the concerns of contract negotiators.

In the first "specialist" strategy, the government supports development by one firm on a single engine program most likely to achieve successful introduction. The R&D agency conceivably could choose to support the immediate introduction of the metallic gas turbine. Yet the government very likely may find no company willing to place its own money on such a project, even with government funding. The most likely candidate, Chrysler, has stated no commitment to introducing this engine. General Motors, using technology in its Engineering Staff, the other possible candidate, has showed no willingness to receive any government support at all. This project has the political attractiveness of a near-term commercial demonstration but the financial prospects of a failure.

In pursuing a "specialist" strategy, though, the government would more likely have to choose between the intermediate gas turbine and the metal Stirling engine. Again there is disagreement about the ability of the intermediate turbine to offer substantial enough improvement in engine attributes, particularly fuel economy. Still, Chrysler, Detroit Diesel Allison, and Ford might be very interested in an intermediate gas turbine development program. Again, two of the Big Three are currently voting against the Stirling. Yet the government's dollar may go further with the Stirling toward adding a new technical option for the industry.

With either the choice of the intermediate gas turbine or metallic Stirling, the government must be accountable, in supporting a leading firm, to arguments concerning fairness in funding. Also, there may be no means for the agency to accelerate the program of a firm already specializing in a given area. Finally, this strategy offers no additional hedges against the failure of even the "best" approach.

In the second strategy the R&D agency supports each of several duplicate efforts to develop the same engine. The obvious candidate is a final development program for the intermediate gas turbine. A less obvious alternative is a components program for the advanced gas turbine. Unfortunately, the Stirling engine does not afford at present another team to compete with Ford.

If the government does decide to support (not necessarily requiring large government funding shares) two or three efforts on the intermediate turbine, it would presumably be operating under certain assumptions. First, it must perceive "technical" competition, independent teams simultaneously working on similar engine designs, as a crucial force in advanced engine development. Second, it must assume either that the intermediate gas turbine can achieve successful commercial introduction or that the intermediate engine must precede development of the advanced engine. Third, it must believe that duplicate efforts will create a better design. In particular, one could be able to select as obviously superior either the single- or free-shaft configuration for final development and later introduction. Clearly the attractiveness of this strategy weakens when expenditures increase and several firms do not show active interest. We will delay the discussion of duplicate efforts on advanced gas turbine components.

In the third strategy, the government supports diversified efforts on different engines. This strategy depends on the assumption that "business" competition drives the developmental process. Firms examine the total portfolio of projects within the industry in determining their actions. This strategy offers the best hedge against failure of all the advanced engine programs, as many of the outcomes will be independent of one another. Any program not currently funded internally by one of the Big Three would be a good candidate for government funding under this strategy. Again, the agency must avoid hopeless projects rejected for sound reasons by the Big Three, and must resist substituting its own dollars for those of the companies. Under this strategy the metallic Stirling would very likely receive at least partial funding and the intermediate gas turbine would not. An advanced components program either for the gas turbine or Stirling might also be considered. This program would offer diversification "across time," insuring that preliminary work would continue on sophisticated ceramics technology.

Clearly the logical extension of a "diversified" government strategy is funding by the government of all conceivable advanced engine programs. Without any restrictions on government expenditures, the agency could pursue an "all out" strategy -- supporting introduction of the metallic gas turbine, final development of several intermediate gas turbines and the metallic Stirling, and initial development of advanced gas turbines and advanced Stirling engines.

In the fourth and final proposed strategy, the federal R&D agency supports advanced cermic component efforts, on either or both the gas turbine and Stirling engine(s). In this area, there would be little possibility that the government would substitute its dollars for those of the Big Three. None of these firms is in fact pursuing an exclusively advanced strategy. Because this type of development is close to basic research, there is a greater potential for crossover use of the technical results and greater difficulty for the individual firm to appropriate the benefits. The government could fund several Big Three firms (Chrysler, Ford, and the Detroit Diesel Allison Division of GM all appear interested) and several other experienced ceramic firms (such as Westinghouse, General Electric, and Corning Glass). Since this program does not necessarily require the immediate development of a complete engine system, the government could fund several duplicate efforts rather inexpensively.

This approach places the federal R&D agency and the Big Three firms into a "wait and see" position. More complete information could be provided about critical components for decisions on all of the advanced engines. There are other attractive features of this approach. Government support could be spread farily across firms. This strategy definitely appears most complementary to those of the Big Three firms. It does stress the expansions of technical options and promises large economic payoffs if successful. Finally, this approach prevents the government from making large, premature investments in the final development of advanced engines that are unlikely to succeed at introduction.

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