THE ROLE FOR FEDERAL R&D ON ALTERNATIVE AUTOMOTIVE POWER SYSTEMS

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EXECUTIVE SUMMARY

Within the past few years, reductions in air pollutant emissions and fuel consumption of the U.S. passenger car fleet have become important public policy goals. The automobile manufacturers have responded to government regulation or changing market pressures in these areas by modifying the internal combustion engine (ICE), the powerplant which has dominated the passenger car application for almost sixty years. There are, however, alternatives to the ICE which may offer substantial improvements in emissions and fuel economy, but to many people the industry appears reluctant to deal seriously with them, and a Federally sponsored research and development (R & D) program has been called for. This report examines the question: Is it appropriate for the Federal Government to support R & D on alternative automotive powerplants?

This issue is highly controversial. Some argue that emissions regulations and the high level of importance given to fuel economy by car buyers give the manufacturers strong and clear incentives for improvements in these areas. Others argue that without substantial Federal R & D support, potentially attractive alternative engine technologies will not receive the attention they deserve.

In addressing this question, we relied on our experience and knowledge in the area, the available literature (technical publications, Congressional hearings, trade journals, etc.) and on interviews with personnel in the industry, government, and academic organizations involved. We have focussed on questions of public policy since the relevant technology has been adequately addressed elsewhere. The study was divided into four areas:

a definition of the central issue and a set of underlying issues; a review of the technology; an examination of the relevant societal goals and the possible role of R & D in meeting them; and a review of the government and industry experience with alternative powerplants. As a result of this analysis, we have reached the following conclusions:

1) The question is controversial in part because attitudes to several underlying issues--the future of the ICE, the relative weighting of different engine attributes, the risks the automobile manufacturers can reasonably be expected to assume, the nature of the process by which an alternative engine might be substituted for the ICE--influence expectations of appropriate R & D activities in industry and government.

2) Because of uncertainties in the future technological characteristics of alternative engines, the development potential of the ICE, and the marketplace requirements and government regulations which will have to be met, one cannot now forcast whether the optimum passenger car powerplant of the last decades of this century will be the ICE, an alternative, or whether it will even be a single engine for all passenger cars.

3) This uncertainty regarding the future attractiveness of the more promising alternatives can only be resolved through future research and development efforts. Since the passenger powerplant has such a large influence on national air pollution and energy problems, it is important that economically justifiable efforts towards attaining the optimum be pursued.

4) However, only certain objectives and certain levels of effort are appropriate for Federally supported R & D in this area. The most important objectives are providing information to support regulation and policy development, and advancing the state-of-the-art. The former is clearly

the responsibility of the Federal Government, and a sounder framework for such R & D needs to be developed. Depending on industry activities, Federal R & D can play an important role in the latter objective in the earlier stages of the hardware development process where manufacturing and consumer acceptance considerations are not overriding.

5) The incentives to the automobile manufacturers are not sufficient to cause them to perform all the alternative powerplant R & D which can be justified on the basis of potential social benefits from reduction in emissions. The primary reason for this is that the emission standards in the Clean Air Act are in reality coupled to the available technology--the ICE. In the area of fuel economy the incentives and national goals are less clear, but there may be a divergence here as well.

6) Industry programs on a number of alternative powerplants are substantial, but they leave significant gaps. They reflect a reasonable allocation of internal funds to this area, given the current potential of alternative engines and the uncertainty in future regulations which now exists. However, there are projects which industry is not now supporting which appear to be economically justifiable from a public policy standpoint.

7) The principal government program in this area has been the Advanced Automotive Power Systems Program. The program has not contributed significantly to advancing the state-of-the-art, but this was never a major program goal. It has been of significant value in providing a focus for alternative powerplant activities and exchange of technical information, and it has contributed to long-range policy planning. Industry R & D activities could not have served these important functions.

8) There is therefore convincing justification for Federal support

for R & D on alternative automotive powerplants. Some alternative engine technologies are not receiving adequate attention within the automobile industry for sound reasons which are unlikely to change; a government program can support projects which are justifiable from a public standpoint but not a private one. Such a program can make substantial contributions to national air pollution abatement and fuel conservation goals by advancing the state-of-the art of selected engine technologies and by producing the technical data necessary for developing regulations and other policies. A rough estimate of number of projects and project costs suggests that a two to five-fold increase above current alternative powerplant funding--to between $15 and $35 million annually--would be required. The overall goals of such a program would be to reduce the risks inherent in developing and introducing those alternative engines which may have long-term economic and public benefits and which are not now receiving adequate attention, by reducing the current technological and regulatory uncertainty to the point where normal market decision-making mechanisms would be in better alignment with social objectives.

PREFACE

The National Science Foundation's Office of Energy R & D Policy is funding a one-year program in the Energy Laboratory at MIT to provide guidance for evaluating proposed Federal programs of research and development in the area of alternative automotive power systems. This study, which started in June, 1974, is divided into two phases. This report describes the work completed in phase I. Past and current industry and government programs on alternative automotive power systems have been examined, the critical issues laid out, and the potential role for Federal R & D as a policy tool for meeting national goals has been analyzed. The objective of this report is not a technological evaluation of alternative automotive engines; rather we describe the context within which the development of the more attractive of these engines is occurring and seek to define appropriate objectives for Federal R & D, if any, within this context. The scope of our study has been limited to proposed efforts on alternative powerplants; we have not dealt with the areas of alternative fuels, advanced concepts for the internal combustion engine, safety, or any other area, although the methodology we have developed may be appropriate in these other areas as well. In phase II of the study, we will examine in detail a number of powerplant issues to which we could not give adequate attention here.

The data sources used in the preparation of this report have included the available literature -- from government, industry and academic sources -- and extensive interviews with industry and government officials involved in the planning and execution of R & D on alternative power systems. In the following pages, public documents will be referenced where appropriate; interview data will not be referenced, however. Interviews are subject to a number of difficulties which, with the time and resources available for this study, we were sometimes unable to resolve. Chief among these is the fact that the automobile manufacturers and government agencies involved in this very controversial area are under pressure to say and do the "right" things. Other complications we encountered in information gathering and analysis include the difficulty in determining the underlying basis of agency or corporate policies, the proprietary nature of many industry data, and the difficulty in making generalizations about the "Big Three" automobile manufacturers when there are significant differences among them. We were not always able to test these data to the extent we would have liked; some of our findings cannot be stated in an unqualified manner. On the whole, however, we are confident of our judgments and conclusions.

We are indebted to a number of people who have contributed significantly to this study. Dr. Leonard Topper, Office of Energy R & D Policy, National Science Foundation, initiated the program and has been actively involved as contract monitor. Professor David G. Wilson and Mr. Richard S. Morse, M.I.T., contributed useful comments at various stages. The authors interviewed a large number of individuals in industry, government and academia. The time and ideas generously contributed by all these individuals are much appreciated.

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1. THE CRITICAL ISSUES

1.1 The Role of the Federal Government in Alternative Automotive Powerplant R & D.

The automobile and its role in modern American society have been the subject of much attention and many publications. In particular, within the past decade the air pollutant emissions, and, later, the fuel consumption of the American passenger car fleet have had impacts on our society which have made the technological characteristics of the powerplants in these vehicles the subject of extensive controversy. Federal regulation of emissions levels has been instituted, and the automobile manufacturers have responded by modifying the internal combustion engine (ICE), which has been the dominant passenger car powerplant for almost sixty years. There are, however, alternatives to the ICE which may offer substantial improvements in emissions and fuel economy, but to many people the industry appears reluctant to deal seriously with them, and a Federally-sponsored research and development (R & D) program has been called for. This, then, is the central question we have examined: Is it appropriate for the Federal Government to support R & D on alternative automotive powerplants?

With the possibility of substantial reductions in the air pollutant emissions and fuel consumption of the passenger car fleet, why should a moderately funded (tens of millions of dollars annually) Federal R & D program in this area be controversial at all? In fact these proposals, and the modest R & D program the Government has presently underway, have been very controversial indeed. The principal logic for opposing a Federal role has been the following: the air pollutant emissions regulations and the high level of importance given to fuel economy by automobile buyers have given the manufacturers clear incentives for improvements in these areas; the "Big Three" manufacturers (GM, Ford and Chrysler) have vast financial resources (total 1973 sales were over $70 billion) and technical talent available for development of automotive power systems; and the traditionally intense sales competition among the Big Three (and the imports) will drive them toward a least cost, optimal system; thus, it is argued, there is no need for a Federal R & D program.

In an attempt to address this issue, we have conducted an examination of the available technologies, the relevant societal goals and the possible policies for meeting them, and government and industry experience in dealing with automotive powerplants. In order to deal effectively with the central issue, we have made two key assumptions. First, we have assumed that the basic structure of the Clean Air Act will remain intact, i.e., there will continue to be legally mandated emission standards. Second, we have assumed that the passenger car will remain the principal form of personal transportation for the next several decades. We do not consider these assumptions particularly limiting.

While gathering the data for this study we encountered a wide variety of strongly held opinions on the central issue. These opinions are based in part on deeply felt political beliefs on the proper relationship between government and industry. We also found a number of other, more technical, issues which underlie opinions on the central issue. There are widely divergent opinions on these underlying issues within the industry, government and academic circles involved with alternative automotive powerplants.

These issues are important because, to a significant degree, attitudes on them determine expectations of what the automobile industry "should" be doing in its alternative engine development programs. Expectations of what industry should be doing in turn influence judgments of the appropriate R & D role for the Federal Government. In the remainder of this Section, therefore, we lay out these underlying issues in detail and describe the various attitudes on them.

1.2 The Future of the ICE

In the last seventy years hundreds of millions of spark-ignition engines have been produced and operated. Massive production facilities now exist, many of which are relatively new. Mass production methods and the required machine tools have been developed to a high level of sophistication. An enormous amount of experience relating to the design and manufacture of the ICE has been accumulated within the automobile industry. An extensive service industry -- with facilities, trained mechanics, tools and equipment -- has been built up. It is paralleled by a spare parts industry and distribution system. Millions of automobile owners have gained confidence in the ICE, and have developed high and continually increasing expectations of engine performance and reliability. The industry has built up an impressive record of steady improvements in engine design and performance. However, many factors now make the future of the ICE less secure than it has appeared at any time since it came to dominate the market sixty years ago. The general reasons for this change are well known: the magnitude of the automobile air pollution problem, particularly in the larger urban areas, and the concern over petroleum availability and cost. The major uncertainties concerning the future performance of the ICE are presented in terms of emission control, fuel economy, complexity and cost, in Section 2.

In the face of these uncertainties, there now exists a wide spectrum of opinions on the continued viability of the ICE. At one extreme, there is a school of thought which contends that the ICE is certainly doomed, probably within the next decade. Members of this school feel that, even if the ICE's inherently high emissions can be brought to acceptable levels (i.e. the original 1976 standards), it will be done with complicated and expensive add-on devices which carry with them unacceptable cost and fuel economy penalties. They assert that the ICE has had over seventy years of development for the passenger car application, that its potential has been pretty well realized, and that one or more of the available alternative systems should displace it as soon as possible. Thinking along these lines tends to be found in some government, academic and environmental circles and in companies with a stake in alternative powerplants, and is usually associated with advocacy of substantial government R & D programs on alternative powerplants.

At the other extreme, there is a school of thought that holds that the ICE has adapted itself to changing constraints in the past and will continue to do so in the future. Advocates of this school point out that each proposed alternative to the ICE has at least one major defect. This line of thinking is found primarily within the automobile industry, although it also exists in government.

Advocates of these divergent schools of thought are not hard to find, and there are a large number of individuals and groups whose opinions cover the spectrum in between. These attitudes to the long-term future of the ICE, and their attendant expectations, obviously influence judgments as to the "adequacy" or "seriousness" of industry and government efforts in the alternative power systems area. It is our judgment that in the face of the high degree of technological uncertainty concerning each alternative engine, it is not possible at this time to prove that one or more of these alternative power systems would be broadly superior to the ICE. We will address this issue further in Section 2.

1.3 Relative Attribute Weightings

Many engine attributes or characteristics must be compared in making a systematic evaluation of alternative powerplants. Although emissions and fuel economy are often singled out as the characteristics of greatest public concern, other aspects of powerplant design are usually more important to the vehicle manufacturer and individual purchaser. People do not buy minimum emissions maximum fuel economy vehicles. In any assessment of alternative engines in comparison with the ICE, a large number of powerplant characteristics must be evaluated and then compared. Table 1.1 lists those attributes which are normally considered by the manufacturer in such a powerplant evaluation. Some of these attributes are readily quantifiable, many are not.

While such a list is essential in any systematic powerplant evaluation, the relative weighting given each attribute significantly affects the final ranking obtained. This is because most of the alternative engines have some characteristics which are superior to the ICE, and some which are inferior. Different groups, depending on their point of view, give substantially different weightings to these attributes, and these weightings change with time (e.g. there has been a rapid rise in the importance of

Table 1.1

KEY ATTRIBUTES OF AUTOMOTIVE POWERPLANTS[1]

Emissions[a]	Response to abuse and neglect[c]
Noise[a]	Design horsepower versatility[d]
Fuel economy[b,c]	Control ease[d]
Safety[c]	Producibility[d]
Cost[c]	Size[d]
Starting ease[c]	Weight[d]
Driveability[c]	Ability to be integrated in vehicle[d]
Performance[c]	

The attributes are marked to distinguish their major significance as follows:

[a] Government regulations now in effect or expected and must be met.

[b] Potential area for future regulation or government intervention to increase relative importance of this attribute.

[c] Consumer generally identifies these as important engine attributes influencing his choice of vehicle.

[d] Contributes to the ability of the manufacturer to sell engines that satisfy the consumer (usually by way of reducing cost).

[1] From [1], modified.

fuel economy). Within the constraints of regulation, the manufacturer weights these attributes in terms of their effect on sales and profits. Presumably the manufacturer's weighting correlates with that of vehicle purchasers, though individual buyers rarely articulate their needs in as organized a fashion. On the other hand, many within government agencies or public interest groups emphasize one or a few attributes above all others. The broader needs of the individual vehicle buyer, sometimes even his very existence, are often ignored.

It is clear, however, that market forces will dictate the relative weighting of these attributes. Once the manufacturer, in his evaluation of alternatives, has determined that an engine has the potential for meeting anticipated government regulations, he will weight the different attributes in accordance with his experience and expectation of customer demands. To expect any other basis for weighting in a consumer product industry is unrealistic. In this report we will stress the fact that ours is a market system, and that, although the automobile industry is hardly a model of perfect competition, it is dominated by forces of supply and demand within the constraints imposed by the government.

1.4 The Substitution Process

The process by which a substantial change in engine technology might occur within the automobile industry is also an issue, primarily because the nature of this process is not well understood and expectations of the rate of change are sometimes unrealistic. Almost all technological innovations in "mature" industries like the automobile industry follow a similar pattern. New products are first developed to the point where they can be introduced in mass production on a small scale. If performance expectations are fulfilled in actual use, and the demand exists for the new or improved product, then the innovation gradually starts to penetrate the market. In this second stage, the substitution of one product for another occurs in a series of steps of increasing commitment of resources. In this way the risk to the innovator is carefully controlled; commitments of resources follow as uncertainty concerning product performance decreases and increasing demand for the new product is evident. Once the performance in actual use of a new product or technology as been successfully demonstrated (almost always on a scale small compared with the total market) substitution of the new technology in production, for the old, can begin on a large scale. This substitution normally occurs relatively slowly, and the replacement of one technology by another in the automobile industry has typically taken 10 to 25 years.

The public interest in change in automotive engine technology concerns the impact of that change on the average characteristics of the total U.S. automobile population (or some large subpopulation). A third stage in this substitution process is therefore important. Not only must the new technology penetrate the market, it must then be produced in very large volume for several years, during which old vehicles are retired and replaced by the new ones, before any significant impact occurs. This third stage is controlled by the average life expectancy of new automobiles and adds an additional five years or so, after very large volume production is achieved, for a significant impact to occur. Thus the total time before substitution of a new engine might affect aggregate emissions or fuel consumption is very long indeed.

The length of the first stage in this process -- the bringing of a new engine technology into limited mass production -- depends on the current state of development of the engine technology and the degree to which it represents a substantial change from the ICE. For the simpler stratified charge engines this process might take two to three years. For the gas turbine it would take much longer -- say four to eight years.

The longest stage in this substitution process has historically been the second, i.e., market penetration. To quote a prior study of such processes in large and complex industries:

> "The speed with which a substitution takes place is not a simple measure of the pace of technical advance, or of manufacturing, marketing, distribution, or any other individual substitution elements. It is, rather, a measure of the unbalance in these factors between the competitive elements of the substitution. When a substitution begins, the new product, process, or service struggles hard to improve and demonstrate its advantages over the dominant product, process or service. As the new substitution element becomes recognized by commanding a few percent of the total market, the threatened element redoubles its own efforts to maintain or improve its position. Thus, the pace of technical innovation effort -- indeed, the competitive pace of all aspects of the substitution -- may increase markedly during the course of the substitution struggle.
>
> "The rate at which a given substitution proceeds seems to be determined by the complex interplay of economic forces responding to the inherent superiority of a new method." [2]

Thus, this second stage in the substitution process has historically been controlled by market forces. Recently, air pollution regulations have forced this step into a single year, but the new components introduced to meet regulations have been modest in comparison with a new engine technology.[1]

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[1]While the oxidizing catalytic converter has been forced into about 80 percent production in a single year, this new technology has a limited impact on other aspects of vehicle design. Furthermore, since the vehicle is not affected by loss in activity of the catalyst, a much higher failure rate than is normal in an automotive component can be tolerated. Introduction of a new engine is not a comparable process.

The length of this entire process under normal circumstances is often not appreciated, nor are the three distinct stages which must occur before a new engine technology could significantly affect the automobile air pollution problem or total U.S. gasoline consumption. With as substantial a change as conversion to an alternative engine, the entire substitution process from the engine prototype stage through to significant impact on the characteristics of the automobile population (say 25 percent of the cars on the road with the new engine technology) is likely to be very long indeed -- at best some 10 to 20 years depending on the degree of change from the ICE. Clearly Federal (or industrial) R & D can only play a role in the first stage of this three-stage process -- the development to small-scale mass production.

To many this description of the way a new engine would be likely to penetrate the market is not controversial. To others, whose technological expectations have been conditioned by the Manhattan and Apollo projects it appears unacceptably "passive." The dominant role of Federal R & D in achieving the technical goals in these projects has lead many to believe similar Federal efforts could result in a "clean and efficient" automobile engine. But in these projects there was no production conversion phase, nor was there a need to replace an existing technology in a stock of in-use products. Thus, in our judgment, the differences between the Apollo type of project, where Federal R & D was used to support procurement of advanced technology for programs with well defined objectives managed and operated by the Federal government, and the problem we are addressing, are so great that such expectations cannot reasonably be fulfilled.

1.5 Acceptable Levels of Risk

A crucial issue which will come up repeatedly in the remainder of this report is the question of the level of risk an automobile manufacturer should be willing to assume in any attempt to capture the gains of developing and introducing an alternative powerplant which is potentially more attractive than the ICE. The Big Three have been criticized as exercising "undue conservatism" in their approach to alternative powerplants, especially for not introducing a stratified charge or diesel engine to meet the original 1975 emission standards. [4] However, the investment in development, tooling, inventory, marketing, etc. required to bring a new powerplant into initial mass production could be up to several hundred million dollars; even firms the size of the Big Three cannot readily absorb losses of this size. We have divided the risks faced by the industry in development or introduction of an alternative powerplant into three separate aspects: the risk stemming from technological uncertainty, the risk stemming from uncertainty in future requirements, and the risk stemming from the incompatibility of the regulatory structure of the Clean Air Act with the normal substitution process.

The risk stemming from technological uncertainty is simply the usual risk associated with an R & D program; in this case it is the possibility that the program will be unsuccessful in developing a powerplant with the attribute levels that the company has set as its goals. We will deal with the difficulty in establishing goals next, but even with fixed goals the alternative powerplants offer a substantial challenge to the R & D planner.

The alternatives are all at different stages of technology development. The data bases available on each alternative vary significantly in extent and thus reliability. It is the long-term potential of each of the alternatives that is important, not the current status. Estimates of this long-term potential are necessarily based on judgments of the extent to which current development problems can be overcome at acceptable cost.

Furthermore, the ICE technology of today is not static; it can be expected to continue to improve in response to changing requirements. Improvements in emission control, fuel economy, driveability, maintainability and relative costs of the ICE are being eagerly sought and will probably be obtained. Indeed the challenge presented by the continued development of alternative engines is likely to intensify the efforts made to improve the existing ICE technology. Thus "a challenger must be not merely as good -- it must in all probability be quite a bit better to justify that cost and trauma of replacement " [3, p. 1] and it may in fact be the correct technological choice to emphasize continued ICE development.

It is not at all surprising that in the face of this high degree of technological uncertainty, a wide range of opinions exists as to the attractiveness of the different alternative engines in comparison to the ICE. It is not possible to prove that one or more of the alternatives is "superior" at this time. This is reflected in the diversity of present industry and government programs seen in Section 4, and means that there is substantial probability that an investment in an alternative powerplant R & D program will never result in any return.

The second area of risk stems from difficulty in forecasting future requirements. For those attributes which are not government-mandated, this problem is the usual one faced by the industry in forecasting consumer demands. White develops at some length the thesis that the difficulty of forecasting these demands even over the three-to-four year lead time required for the annual model change is a significant determinant in industry behavior. [5] With respect to air pollutant emission standards, along with the expected noise standards and potential fuel economy standards, the industry planner must forecast the results of a complicated political, bureaucratic, and technological interaction. Furthermore, he must do it over the time-frame necessary to develop and produce an alternative powerplant: a decade, at least, for the radical alternatives. And, of course, he must forecast consumer demands and other conditions over this time frame as well.

This aspect of risk has been hotly disputed. To an automobile manufacturer, this uncertainty makes further development of the familiar ICE much more attractive than a substantial investment in the development of an alternative engine of approximately equal performance, with which the manufacturer feels unsure. This uncertainty acts as an even greater deterrent as the investment increases for engine introduction into mass production. In practice, no automobile manufacturer would commit the resources required for the production of an alternative engine until it was clear that the engine would be able to meet regulatory requirements, whatever they may be, for a sufficient period to justify its investment. With the ICE, no comparable risk exists. Given the present regulatory structure for emissions control (all cars must meet the standards in any model year) and the enormous economic importance of the automobile industry, as long as there is a dominant entrenched ICE technology the standards will have to be adjusted to a level the dominant technology can achieve.

In contrast, those groups with a special interest in or responsibility for one powerplant attribute see little development effort being expended on alternatives with high promise in that particular area, because it is unclear that regulations or future requirements in other areas can be satisfied. The diesel engine is a current example where uncertainties in future requirements for NO_x, particulate and odor emissions inhibit any significant development efforts to take advantage of its attractive fuel economy characteristics.[1]

Finally, the third aspect of risk is the increased risk in the substitution process due to the incompatibility between the length of time required to build up production of an alternative powerplant and

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[1]It is generally assumed that if the diesel engine were mass produced domestically, then emission standards would be issued by EPA in order to ensure that the particulate emissions from these engines would not become a public health hazard. However, no such standard has yet been proposed, and, given the pressures of more urgent business, might not be until domestic diesel mass production was imminent or had begun. Depending on the stringency of the standard, and the timing, the manufacturer might be faced with major design changes, or even a shutdown of assembly lines, shortly after initial production. The uncertainty over future NO_x emission standards creates a similar situation for the diesel. Introduction of an engine for which the NO_x control technology is similar to that of the ICE, such as the Wankel, does not add to the risk level in this respect because the new engine will rise or fall with the ICE. With the diesel, however, for which NO_x control technology is relatively independent of that of the ICE, introduction with uncertainty in the standard adds a new element of risk.

the required single-year changes in emission levels under the Clean Air Act. This incompatibility strongly inhibits the introduction of an alternative powerplant with emissions characteristics (or fuel economy, if regulated) superior to those of the ICE. Consider a manufacturer who begins mass production and marketing of a new engine which meets, say, the NO_x standard for 1978 of 0.4 g/mile, while the ICE does not. Accepting normal levels of risk, the manufacturer would expand production gradually when and if the new engine proves itself a more attractive product than the ICE. However, in this situation government pressures to increase the rate of penetration of the new engine would be enormous. Responding to these pressures, which to some degree would be inevitable, could result in, among other things, a substantial disparity between production and demand for the ICE and the alternative, perhaps causing substantial financial losses.

The principal controversy over risk level can be easily summarized: the question is what level of risk the manufacturers should be willing to accept in their investments on alternative powerplant R & D production. Congress, EPA and environmental groups have felt that the benefits of clean air and reduced fuel consumption require a greater degree of risk-taking than the manufacturers have been willing to exercise. But the negative impact of failure falls primarily on the company, while the primary beneficiaries of success would be the urban public at large. This issue is one which will not be readily resolved. It surfaces at several points in this report, for it underlies industry decisions and public expectations regarding alternative powerplant development.

2. AUTOMOTIVE ENGINE TECHNOLOGIES

A consideration of the role of Federal R & D in the automotive powerplant must necessarily include, as a first order of business, a review of the relevant technologies. In this section we will briefly discuss the technical characteristics of ICE and the alternatives to provide the background for subsequent discussions of government and industry programs. The major advantages and disadvantages, and critical development problems for each of these engines will be described. We have not carried out a detailed technical evaluation of these engines, however, since comprehensive and up-to-date evaluations of this type can be found elsewhere. [1,6]

The alternative powerplants are competing to take the place of an entrenched technology. The conventional reciprocating spark-ignition engine, commonly called the internal combustion engine or ICE, has been the dominant automobile engine since the early 1900's. During this period, several hundred million of these engines have been manufactured in the United States alone. Massive facilities now exist for producing the ICE, and there is extensive experience with and understanding of the engine design and manufacturing processes, its operation in actual use, and maintenance and service requirements. Over the past decade, however, powerplant design criteria have been changing in response to Federal emission standards. Modifications have been made and components have been added to the ICE, increasing its cost and complexity; these changes have degraded engine performance, fuel economy and driveability. More recently, indeed within the last year, fuel shortages and higher gasoline prices have upgraded the relative importance of vehicle fuel economy in comparison with other design characteristics. In the longer term, fuel economy regulation and changing fuel composition may lead to even greater changes in desired engine characteristics.

It is unclear at this time whether the ICE can be adapted to meet long-term national environmental quality and energy consumption goals. Even if it can satisfactorily meet these demands, it still may not be the optimum automobile powerplant when all the necessary attributes are considered. Many alternative types of automobile engines have been under investigation for some time, though at different levels of effort. One of these alternatives may offer the individual car owner the desired transportation services, within environmental and energy constraints, at a lower overall cost.

All alternative engines must compete against this "baseline" of the conventional reciprocating spark-ignition engine (the ICE) which dominates the market. Moreover, they must compete against the ICE not as it is today, but as it continues to be developed in attempts to meet changing market requirements and regulations.

Some of the alternatives are quite close conceptually to the ICE; some are already in mass production though they constitute only a small fraction of the market. Thus there is a range of options, both in extent of change from the ICE and in stage of technology development. For the purpose of this study, we classify all engines other than the ICE as "alternatives." Those alternative engines already in mass production we term "available alternatives;" those alternative engines not now in mass production we term "radical alternatives." Table 2.1 lists the engines which are discussed in this study in these three categories.

These engines are at various stages of development. In Section 3 (Table 3.2) we define a sequence of stages which occur in the development of a new technology, namely: applied research, exploratory development, advanced development, engineering development and product improvement. Table 2.2 gives the present stage of the most advanced development program for passenger car usage, for each of the engines described in this section. A detailed description of government and industry programs and where they are being carried out is given in Section 4 and Appendix B.

2.1 The Baseline ICE

The conventional automobile engine is a carbureted reciprocating spark-ignition engine operating on a four-stroke cycle. It is often called the Otto cycle engine, or the internal combustion engine (ICE), though these titles are not sufficiently definitive to separate this engine from some of the other alternatives. The engine, as now produced (model year 1975), is equipped with emission controls -- engine, carburetor, and intake modifications, an exhaust gas recycle system and an oxidizing catalytic converter. The fuel economy, engine performance and driveability of the engine have been steadily decreasing since emission controls were first introduced in 1968. The introduction of the catalytic converter in 1975 model year has apparently reversed this trend. The engine now, however, requires unleaded gasoline and the compression ratio has been reduced so engines will operate on 91 research octane number fuel.

Table 2.1

ENGINE CLASSIFICATION

Baseline

* Conventional reciprocating spark-ignition engine (usually termed the internal combustion engine or ICE)

Available Alternatives

* Wankel spark-ignition engine
* Carbureted prechamber stratified charge spark-ignition engine
* Heavy-weight diesel engine

Radical Alternatives

* Fuel-injected open-chamber stratified charge engine
* Light-weight diesel engine
* Gas turbine engine
* Rankine cycle engine
* Stirling cycle engine
* Battery-powered electric system
* Heat engine hybrid system

Table 2.2

AUTOMOTIVE POWERPLANT DEVELOPMENT STATUS

Powerplant	Status[1]
Baseline	
ICE	Product improvement
Available Alternatives	
Wankel spark-ignition	Product improvement
Prechamber stratified charge	Product improvement
Heavy-weight diesel	Product improvement
Radical Alternatives	
Open-chamber stratified charge	Engineering development
Light-weight diesel	Exploratory development
Gas turbine	Advanced development
Rankine cycle	Advanced developed
Stirling cycle	Exploratory development
Battery-powered electric	Applied research
Heat engine hybrid	Applied research

[1] The status listed refers to the status in the most advanced development program for automotive use.

Many factors now combine to make the future of the ICE less secure than it has appeared at any time since it came to dominate the market sixty years ago. The major uncertainties are:

* whether the ICE can achieve sufficient control of hydrocarbons (HC) and carbon monoxide (CO) emissions to meet the original 1975 (now 1977) standards;
* whether the ICE can meet whatever long term oxides of nitrogen (NO_x) emission standard is eventually chosen;
* whether the catalyst technology which has been developed for HC and CO, and may be developed for NO_x, will be sufficiently durable and maintainable in actualy use;
* how significant special problems associated with this catalyst technology -- e.g. sulphate and particulate emissions -- prove to be;
* whether engine fuel economy losses, which have resulted from emission controls and the change to unleaded gasoline, will continue as emissions are further reduced;
* whether the steady deterioration in vehicle driveability which has occurred as vehicle emissions have been reduced can be halted;
* whether sufficient improvements in vehicle fuel economy can be obtained without also obtaining significant improvements in engine fuel economy.

Two points are especially important to our subsequent discussion. First, the ICE is the dominant automobile engine technology, and it is firmly entrenched in that position. Secondly, substantial development effort is being devoted to the ICE to reduce further its emissions levels, and to improved its fuel economy, performance, and driveability. Potential improvements in the following areas are being sought:

* Mixture preparation: improved carburetion, early fuel evaporation manifolds, fuel injection with exhaust composition feedback controls, quick acting chokes, etc.
* Ignition systems: high energy and long duration spark electronic systems.
* Exhaust gas recycle: improved matching of EGR rate with engine operating conditions for NO_x control with lower fuel economy penalties.
* Catalytic converters: improved oxidation catalysts for HC and CO, reduction catalysts for NO_x, three way catalysts for HC, CO and NO_x, improved secondary air flow control.
* Engine design: low emissions combustion chamber geometries.

On the time scale comparable to that required for developing alternative engines--5 to 10 years--reasonable progress in at least some of these areas can be expected. While the ICE is currently having difficulties in responding to rapidly changing requirements, it still has considerable development potential remaining.

2.2 Alternatives Now in Mass Production

(a) Wankel spark-ignition engine

An alternative spark-ignition engine technology--the Wankel rotary combustion engine--is primarily being developed for its potential manufacturing cost reduction. The engine design employs a three-lobed rotor moving in an eccentric path within a stationary housing. The smaller engine size than the ICE, lighter weight, smaller number of engine parts, and possible redesign of the vehicle to take advantage of these different engine characteristics could all contribute to this cost reduction. Current production versions of this engine show adequate durability but poor fuel economy and high hydrocarbon emissions compared with the ICE. Engine developments now underway indicate that the fuel economy penalty relative to the ICE can be significantly reduced. Because its operating characteristics are so similar to the ICE, the emission control technology developed for the ICE can be easily incorporated. In terms of better meeting public policy goals, this alternative has no advantages relative to the ICE.

(b) Carbureted Prechamber Stratified Charge Engine

This engine concept is not new, but has recently been developed by Honda into an engine with low HC and CO emissions, moderate NO_x emissions, and equivalent fuel economy to the ICE. The concept uses a small prechamber around the spark plug and a dual carburetor and dual intake system to prepare a stratified mixture. A fuel-rich mixture is admitted to the prechamber via a small intake valve. The burning jet issuing from the prechamber after spark plug discharge ensures good ignition of the lean mixture in the main chamber. The Honda version of the engine uses additional emission controls -- spark retard and an exhaust manifold reactor. The potential advantages of this engine are:

* Control of HC and CO to the original 1975 levels without a catalyst.
* Lower cost of the engine, compared with the ICE and its emission controls, at the same emission levels.

The disadvantages appear to be:

* Limited potential for NO_x control much below about 2 g/mile in a

standard size car, and 1 g/mile in a subcompact car, without significant fuel economy penalties.

* Limited potential for improved engine fuel economy relative to the ICE at the same emission levels.

(c) Heavy-Weight Diesel Engine

Diesel engines differ from the gasoline ICE in their method of combusting the fuel. Fuel is injected into the air in the combustion chamber at the end of the compression stroke and ignites spontaneously. Since the fuel can be fully burned with excess air, HC and CO emissions are low. Since throttling is not required, and the compression ratio is much higher than in the ICE, engine fuel economy is as good as or better than any other potential automotive engine.

Automobiles with diesel engines are currently marketed in limited quantities in Europe by Daimler-Benz, Peugeot and Opel. Theee vehicles have met the original 1975 HC and CO standards with NO_x emissions of about 1.5 g/mile; they exhibit excellent fuel economy compared with ICE vehicles of equivalent weight with, however, substantially inferior performance characteristics. These current production diesel engines, which are of the prechamber type, have significantly higher cost and weight than an equivalent ICE and have problems with odor, smoke and noise emissions.

The present automotive diesel engine--which we term heavy-weight--is thus not a suitable powerplant for general automotive use, though it may find greater usage in special applications such as taxis, light-duty trucks and vans. It is not generally recognized that the current heavy-weight diesel engine requires extensive further development before it can be considered as a potentially attractive alternative powerplant in the American market.

2.3 Radical Alternatives

(a) Fuel-Injected Open-Chamber Stratified Charge Engine

This stratified charge engine concept combines some features of the diesel with some of the conventional spark-ignition engine. Fuel (usually gasoline) is injected into the combustion chamber during the compression stroke and the fuel-air mixture is ignited by a spark plug discharge. A number of different concepts of this type are being developed with additional emission controls (EGR, retarded timing, throttling at light load, an oxidation catalyst); emission levels below the original 1976 standards have been obtained with experimental vehicles. Because the fuel octane rating is less important in this type of engine, higher compression ratios can be used. For this and other reasons improved fuel economy relative to the conventional ICE has been demonstrated. The system is still in the developmental stage. Whether currently demonstrated operating characteristics, and any potential improvements, can be realized in mass production engines of this type is not yet clear. Potential advantages of this concept are:

* Improved fuel economy compared with the ICE at the same emission levels.
* Better control of NO_x than is achieveable with the ICE without a durable reduction catalyst.
* Possible tolerance to a range of fuel characteristics.

Potential disadvantages with this concept are:

* High cost of the fuel injection system plus almost full range of ICE emission controls.

* May not be able to meet 0.4 g/mile NO_x standard in actual use.
* Possible problems with particulate and aldehyde emissions.

(b) Light-Weight Diesel

A complete redesign of the current heavy-weight automotive diesel specifically for passenger car use offers the possibility of substantially reduced engine weight and cost. At the same time, new developments in diesel engine technology show some potential for reducing emission levels below those of current diesel engines. Such changes would substantially improve the relative position of the diesel engine compared with the ICE. This improved diesel engine concept is generally referred to as a light-weight diesel. The major advantages the light-weight diesel might offer are:

* Improved fuel economy in comparison with the ICE.
* Reduced maintenance requirements.
* Good control of HC and CO emissions without add-on emission controls, and moderate control of NO_x.

The major problem areas would be similar to those currently evident with the heavy-weight diesel, but less severe, namely:

* Ability to meet 0.4 g/mile NO_x standard is still questionable.
* Potential problems with odor, smoke and particulate emissions.
* Higher cost due to heavier engine and fuel injection system.
* Engine noise.

(c) Gas Turbine

The gas turbine operates by drawing air from the atmosphere through a compressor into a burner where heating by combustion with the fuel occurs, and then expanding the hot high pressure gases in a turbine. In automotive applications a regenerator is generally used to transfer energy from the exhaust gases to the air leaving the compressor. All these processes occur continuously, in contrast to the intermittent operation of spark-ignition and diesel engines.

There is a considerable development history of the automotive gas turbine. Current major areas of uncertainty relate to the need for ceramic components to significantly improve fuel economy, especially at part load, and to reduce manufacturing costs. The development of suitable ceramic components is one of the major technological barriers. The potential performance characteristics of the engine depend significantly on whether success in developing such ceramic components is assumed. The major potential advantages of the gas turbine are:

* Control of HC and CO emissions below the original 1975 standards, with less certain but probable control of NO_x emissions below the original 1976 standard.
* Ability to burn a wide range of petroleum fuels.
* Reduced maintenance costs.

The major problem areas are:

* Part-load fuel economy -- a major problem with metallic components, a lesser problem with ceramic components.
* High manufacturing costs -- a major problem with metallic components, a lesser problem if techniques for fabricating suitable ceramic components are developed.

(d) Rankine Cycle Engine

The Rankine cycle engine is an external combustion engine. Fuel is burnt with atmospheric pressure air in a burner-boiler to evaporate and heat the working fluid -- water or an organic fluid -- to high pressure and temperature. The fluid is expanded in either a reciprocating or turbine expander to supply work to the shaft, then condensed and recirculated to the boiler. The Rankine cycle engine's clear advantage over the ICE is its ability to meet the HC, CO and NO_x standards originally set for 1976, by suitable burner design. Stability of emissions control is, therefore, excellent. It has, however, the following potential disadvantages:

* Higher cost due to larger size and weight, more components, and greater complexity.
* Poorer fuel economy compared with the ICE (though the Rankine cycle has excellent fuel versatility).
* Complexity of controls which results from need to maximize fuel economy and to obtain good vehicle driveability.
* Problems of engine integration into smaller sized vehicles.

(e) Stirling Cycle Engine

The Stirling Engine derives its power output by using heating and cooling to vary the pressure of a fluid within a closed volume; the pressure variations are transmitted via the piston to the shaft. The engine is a closed system using hydrogen or helium as the working fluid. The engine contains, as a minimum, one power piston and one displacer piston per cylinder, one regenerator, one heater (a burner), and one cooler. The ideal Stirling cycle efficiency is that of the Carnot cycle--the maximum attainable between the highest and lowest cycle temperatures. The Stirling engine only approximates the ideal cycle, so actual efficiencies are lower. Relatively limited testing of Stirling engines for automobile applications has occurred to date. Thus considerable engineering development would be required before the engine can be evaluated as a viable automotive powerplant. The long-term potential attractions of the Stirling engine appear to be:

* Fuel economy at least equal to and perhaps better than any other contender, plus excellent fuel versatility.
* Ability to meet original 1976 standards for HC, CO and NO_x.

The major problem areas currently apparent include:

* Design problems--notably in compact heat exchanger area, and engine seals to contain adequately the working fluid.
* Higher cost due to greater complexity and increased weight compared with the ICE.
* Response to normal abuse and neglect may be inadequate; thus engine maintenance may be costly.

(f) Battery-Powered Electric Systems

Electrically driven battery-powered vehicles provide freedom from emissions and from high energy conversion losses at the vehicle location; however, these problems are merely transferred to the location of the electricity generating plant. Thus, the overall desirability of electrically driven vehicles to the general public depends on policy choices that go far beyond the scope of this report.

The limiting factors relating to technical and economic feasibility of electric vehicles are the weight of the system and the operating characteristics of the power source -- the battery. Electric drive systems with excellent operating characteristics have been demonstrated. The development of optimal electric drive systems is not considered to be a significant technical problem, though the weight of the electric motor and controls is likely to be in the 200 to 400 lb. range. There is extensive experience with one battery system -- the lead-acid battery. While this battery is rugged, efficient, reliable and can respond quickly to changes in load, its energy storage density is too low for it to be viable in normal automobile use. Presently available special-purpose vehicles powered by lead-acid batteries can provide ranges of up to 50 miles with modest acceleration, at a high cost. Other currently available rechargeable batteries such as zinc-silver oxide and cadmium-nickel oxide, while superior in some respects, are inherently unsuitable for vehicular applications because of cost and materials availability limitations.

A number of advanced batteries are now under active development. The most promising of the advanced battery systems are sodium-sulfur and lithium-sulfur batteries, which operate at temperatures in the range 300-400^{o}C. These batteries are expected to have adequate energy and power densities to permit the design of electric vehicles with normal automobile performance and range capabilities. Single prototype vehicles are in process of preparation. Should these or other batteries prove attractive -- and an estimated eight year development program would be required, at a minimum -- then the electric vehicle would become a possible alternative to the conventional vehicle. The cost, however, would likely be significantly higher than an ICE-powered vehicle. But the characteristics of electric vehicles are sufficiently different, and the energy supply implications are so substantial, that evaluation of electric vehicles goes beyond the straightforward comparison of different engine attributes. Public policy goals for the long term are an equally important factor.

(g) Heat Engine Hybrid System

A number of hybrid engines which combine a heat engine (often a small ICE) with an energy storage device (e.g. a battery, or flywheel) have been examined, sometimes with modest hardware development. In principle, this combination allows the heat engine to operate at constant speed and optimum conditions at all times. It has been claimed that this system offers flexibility, efficiency and low emissions. These potential advantages must be larger than the weight, cost and inefficiencies of the energy storage unit and the associated transmission and controls for the concept to be attractive. The hybrid systems built to date have been heat engine, battery and electric drive systems. These have been complex and heavy, with disappointingly high emissions and fuel consumption. There is little interest in hybrid systems at this time, apparently because of a general consensus that such systems are not attractive candidates.

2.4 Conclusions Concerning the Technology

At this point it is appropriate to draw some conclusions which will have a strong bearing on the remainder of our analysis. First, it is clear that there are a number of potentially attractive alternatives to the ICE. For example, the Rankine and Stirling cycle systems stand out with low emission levels resulting from the use of external combustion; the diesel, Stirling and open-chamber stratified charge systems offer potentially substantial fuel economy improvements with their high thermal efficiencies, and the Wankel offers compactness and light weight.

However, each of the alternative engines appears now to be significantly inferior to the ICE in at least one important attribute. For example, the Wankel has high fuel consumption and hydrocarbon emissions, the diesel emits odor and particulates, and the Stirling cycle engine is expensive to manufacture. Most of the deficiencies are in areas ultimately related to consumer acceptance. No one powerplant can now be confidently projected as broadly superior to the ICE.

Furthermore, the ICE itself is the subject of extensive development programs to improve its fuel economy and lower its emission levels while preserving its other attractive features. Advances in mixture preparation, ignition, exhaust gas recycling systems, catalytic converters, and basic engine design can be expected.

We have therefore concluded that whether the optimum powerplant for the last two decades of this century will be the ICE, an alternative, or whether it will even be a single system for all passenger cars, cannot now be confidently forecasted. What is clear, however, is that the potential for major gains in ambient air quality and aggregate fuel consumption makes continued development programs in this area worthwhile. Thus we are led back to the central issue: Is it appropriate for the Federal Government to support part of this effort?

3. THE ROLE OF R & D IN OVERALL FEDERAL POLICY

Federally sponsored research and development on automotive power systems is only one of several government activities related to the automobile industry, and thus an evaluation of R & D programs must take account of other policy measures that are being carried out at the same time. A broad perspective is particularly important in the case of automotive research because at times Federal R & D efforts have been viewed less as worthy activities on their own merit than as aids in the implementation of other policies and programs.

In the search for criteria for evaluating R & D expenditures, we begin with a brief review of the context in which the automotive industry has been operating in recent years, with particular attention to the escalation of public goals for the performance of the industry and the Federal regulatory programs designed to achieve these goals. These regulatory activities in the areas of safety, air pollutant emissions, noise, and (potentially) energy consumption are an important influence in the recent life of the industry and in the evolution of its technology. In this context, we formulate a set of four goals that R & D programs may be designed to attain, and identify the different types of R & D that are relevant for this particular industry. Based on this sifting of goals and program types, some preliminary conclusions are reached about appropriate federal involvement in this area.

3.1 Changing Goals for the Automobile

Considering the importance of the passenger motor vehicle in the daily life of the country, the automotive industry has operated with very little government interference over most of its history. Few products have gained such universal acceptance or have played such a critical role in developing the life-style of the nation; yet the major governmental activity in this sector over the years has been road building. Only recently have the design and operating characteristics of the vehicles themselves been perceived as requiring governmental intervention. Regulation began in the early 1960's as a result of concern about passenger safety. At that time the risk of death or injury per mile traveled was falling from year to year, but the total amount of travel was rising faster, and the net result was a rising toll of human and property loss. Roadway engineers had long been concerned with safety, of course, and state inspection programs had regulated safety features such as brakes and lights. For some years the G.S.A. had taken account of safety in their vehicle purchasing. But until the 1960's there had not been government regulation of the vehicle itself.

The history of legislation to control air pollutant emissions is similar to that of safety. So long as the vehicle population was small, automotive emissions did not create a perceptible problem. But as the automobile fleet grew following World War II, and population (and thus traffic) concentrated in cities, automobile air pollution became a public issue. California state legislation controlling vehicle design was first passed in 1963; Federal enforcement powers were first established by the Clean Air Act Amendments of 1965. Emission standards were introduced nationwide in 1968 model year vehicles and have become steadily stricter. The greatest change in the severity of exhaust emission controls came with the 1970 Amendments to the Clean Air Act. The new goal was clear: to ensure at the earliest possible date that no person's health should be impaired by air pollution. Calculations available at the time indicated that approximately 90 per cent reductions in automotive emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) would be needed to achieve this result. The original deadlines set by the 1970 Amendments for meeting these targets were model year 1975 for HC and CO, and 1976 for NO_x.

With the implementation of the 1970 Clean Air Act Amendments, the Noise Control Act of 1972 and the vehicle regulations expected to result from it, and the strengthening of safety legislation, the automotive industry has passed into a new status as an industry heavily regulated in the interest of public health and safety. Naturally, there have been costs to be paid, including disruption of the industry, increased vehicle cost, lowered vehicle performance and driveability, and decreased fuel economy.

Recent events in the world petroleum market have further changed this picture, and now yet another important social goal is being imposed on the automobile -- energy conservation. To some extent, vehicle efficiency will increase in response to higher gasoline prices, but there also are active proposals for federal controls on automotive energy consumption.

3.2 The Influence of Other Federal Programs

A host of policy instruments are being used to achieve these new goals for the passenger motor vehicle. Some are not directly concerned with automotive technology (e.g., safety in road design, urban traffic controls for air pollution abatement) and can be ignored here. The measures applied directly to the motor vehicle and its technology fall into six categories:

(1) performance standards

(2) "good faith" requirements

(3) financial incentives

(4) labeling

(5) "jawboning"

(6) Federal expenditure on R & D

To date, performance standards are by far the most important of these instruments. As noted earlier, the clean air legislation was framed in terms of the percentage reduction of emissions to be attained by particular deadlines; the choice of techniques was left to the manufacturers. The same is true of most safety regulations: vehicles must withstand a crash at a specified speed, cars must not start without safety belts fastened, etc. Most legislative proposals for regulating fuel consumption also are stated in terms of performance standards. In some cases the proposed standards would apply to the individual vehicle -- e.g., a car must achieve a certain fuel economy to be acceptable. Other proposals set performance standards for the overall output of a particular manufacturer so that a goal of reduced energy consumption may be met by a combination of revisions in vehicle design and shifts in the mix of vehicle types and sizes.[1]

The requirement of a "good faith" effort to develop technology with particular performance characteristics is another form of intervention used in

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[1] An alternative form of government intervention would be the setting of design standards, which specify the characteristics of the particular devices to be used to meet some goal. For example, a requirement that passengers be passively restrained in a crash is a performance standard; the mandating of seat and shoulder belts is a design standard. Design standards are not currently an important aspect of Federal intervention in new automotive propulsion systems. Though design standards are occasionally proposed in response to a perceived lack of progress in the development of new engine technologies, the general consensus is that in so complex an area such an approach would be unwise.

the Clean Air Amendments of 1970. Under the Act, provision was made for postponing the emissions deadlines in the event the required technology was not available. One of the conditions that had to be met before such a postponement could be granted was a "good faith" effort by the manufacturers to explore all options for meeting the standards on time. This provision appears to have provided a significant incentive to research on alternative engine technologies during the early years under the 1970 Amendments. As time passes, deadlines are slipped and technology development proceeds, and the importance of this measure no doubt diminishes. In a new circumstance, however, it could once again play a significant incentive role.

Other incentive programs also were incorporated in the Clean Air Act. In particular, the Act included a Low-Emission Vehicle Procurement Program which offered financial rewards to the manufacturers of alternative technologies meeting certain provisions of the law. The government would buy unconventional vehicles for testing and evaluation with R & D funds; if the vehicles were successfully developed it would pay higher than market prices under the program for those cars, thus rewarding the developers (see Appendix A). Apparently the rewards were not commensurate with the magnitude of the task and the risks involved, for this program has never been the focus of significant activity. At present, the automotive industry receives pretty much the same treatment as other manufacturing industries in this regard.

Another type of government activity attempts to influence the vehicle manufacturer by providing information for consumers to use in their passenger car purchase decisions. A program of vehicle fuel economy labeling has recently been introduced by EPA and the Federal Energy Administration (FEA). By presenting standardized information on fuel economy of each vehicle model, the comparison of equivalent models produced by the different manufacturers is made more explicit , and the relative weight given this attribute by the purchaser can be increased. The extensive use in advertising of data generated in the labeling program is some indication of its impact. Harder to evaluate is the technique of "jawboning"--i.e., exhortation of industry by public officials to strive for some goal. Though great political heat may be created in the short-term, it is only in very special circumstances where this approach seems likely to have a substantial long-term influence on technical directions in the industry.

The last category of intervention listed above (though not necessarily the least important) is Federal expenditure on R & D. Federal support of automotive R&D actually predates much of the regulatory activity of the early 1970's. Nonetheless, it has become intimately involved in the regulatory process, and for the foreseeable future the regulatory context (and in particular the imposition of performance standards) is likely to have a dominant influence on most Federal programs in this area.

An example of the pervading influence of the regulatory activity is the effect on technological change of uncertainty about emissions standards. The 1970 Amendments to the Clean Air Act were adopted by an overwhelming majority in Congress, and the emissions constraints written into the law were based on the best data and analysis available at the time. Unfortunately, the evidence to justify any particular level of emissions reduction was weak: health studies were sparse, instrumentation was primitive, and the analysis of the dynamics of air pollution in urban areas was only partially understood. By the same token, the deadlines for achievement of the standards were set without precise knowledge of which technological solutions were feasible or how long the process to their implementation would take. Essentially the law set goals and short deadlines not only for implementation of new technology but for the process of technology development itself.

As it has turned out, the manufacturers have not been able to meet the HC and CO standards set for 1975 or the NO_x standard set for 1976. In 1973 the manufacturers were granted the one-year extensions in the deadlines provided under the law; for each pollutant, interim standards were set which were more stringent than the former standards but considerably more lenient than the full 1975-76 restrictions. By 1974, it seemed clear that the original 1975 standard for HC and CO could not be met even by the 1976 date to which they had been postponed, and Congress passed further amendments to the Act. The deadline for HC and CO was postponed to 1977 and for NO_x to 1978, and the EPA Administrator was given the discretion to grant yet another one-year extension for the HC and CO if needed. Throughout this period, however, the ultimate standards (3.4 g/mile of CO, 0.41 g/mile of HC and 0.4 g/mile of NO_x) have remained unchanged though all have been questioned. In the case of the NO_x standard the EPA itself has called for a change in the standard because of errors in the measurement technique used to determine ambient levels of the pollutant. To date, however, no change has been approved by the Congress.

These dynamic aspects of the Clean Air Act and its implementation provide the automobile manufacturers with a complicated set of incentives and disincentives for alternative powerplant R & D. On the one hand, the uncertainty about standards and deadlines tends to put certain potentially attractive alternatives into a form of technical limbo (as discussed in

Section 1). With the adjustments in standards (particularly for NO_x) that may ultimately come, the relative attractiveness of different options may shift significantly. The manufacturers, however, have little incentive to gamble on this possibility; they can therefore be expected to concentrate their R & D expenditures on those alternatives with the best possibility of meeting the most stringent standards and deadlines now in effect.

On the other hand, the administrative and legislative changing of the standards in response to the unavailability of the technology provides a certain amount of security to the manufacturers in case the ICE cannot meet the goals and these alternatives are not yet available. These changes point up to a difficulty in the Clean Air Act, i.e. that the threat of shutting the industry's production lines if the standards are not met is simply not credible. We need not provide here any details of the impact such a move would have on the national economy; it is a politically unacceptable enforcement mechanism. While it is clear that any overt stifling of pollution control technology by the manufacturers could bring a strong political reaction, it is also clear that the standards and deadlines will always have to be responsive to the technology that is available in sufficient quantity to meet demand. Therefore the Act has not succeeded in internalizing the costs of pollution to the extent intended, and the overall incentives to the manufacturer for development of low-pollution powerplants are actually much less than one might infer from the fixed schedule of standards in the Act.

Thus, these circumstances of changing public goals and evolving government regulation set the context in which Federally financed R & D would have to be conducted. Federal expenditure in this area might be an important policy instrument, but evaluation of programs must take many factors into account.

There are diverse reasons for undertaking these Federal expenditures, and the proper allocation of spending would depend on what Federal authorities hope to achieve. Moreover, "research and development" is not a single, easily-identified type of effort. It encompasses a wide range of activities, some of which may be appropriate for federal support and some not, depending on program objectives and the level of financial commitment.

3.3 Objectives of a Federal R & D Program

Even given specific emissions or fuel economy goals for the automobile, there are several program objectives that might be set for the R & D component of the mix of Federal policies designed to achieve these results. There are four categories of objectives that lie behind most federal R & D programs. In many circumstances, one or another of these objectives dominates program design and administration, although many programs seek multiple objectives and there are inevitable spillover effects, with contributions to objectives that are not explicity stated.

(i) Advance the State-of-the-Art. One possible objective of an R & D program is to advance the state of scientific knowledge and the practical arts of engineering application, and thus to increase the number of technical options available for future consideration. This is the traditional goal of R & D, and is the objective most commonly associated with Federal expenditures in this area. It is, in fact, the objective of much of the R & D supported by Federal funds (e.g., through the National Science Foundation or the National Institute of Health), and it often is the stated goal even when other considerations are important in program justification. Even where advancement of the state-of-the-art and knowledge is not a primary stated goal, most expenditures on R & D yield some by-products or "spin-offs" of increased understanding and widened technical opportunities.

There may be justification for programs with this objective even in relation to an industry and a technology as mature as those involved with the automobile engine. There are circumstances where the self-interests of manufacturing corporations do not correspond to the long-run public interest. Potentially interesting technological developments may remain unstudied because the time horizons are too long or the risks too great for them to be of interest to a private company, or because the corporation cannot hope to realize a return on the R & D investment even though generalized public benefits may be expected.[1] As discussed in Section 3.2, the costs of air pollution have not been internalized as completely as the fixed standards and deadlines in the Clean Air Act imply, resulting in a divergence of industrial and social interests on this account. The overall financial positions of the manufacturers also are an important determinant of the level of R & D on alternative systems. It is reasonable to expect that corporations will be less willing to take on R & D efforts when business is bad (and the opportunity cost of the resources may be high) than when business is good and internal funds are more plentiful.

As suggested above, it is possible for Federal regulations to have the effect of retarding industry R & D in particular lines of inquiry, leaving

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[1] The logic of the arguments that are found to justify Federal intervention through R & D is the subject of some controversy. One useful discussion of the issues from a microeconomics viewpoint is provided by the report "Energy R & D Proposals," prepared for the Ford Energy Policy Project. [7]

gaps that Federal programs may need to fill. For example, the short-term emissions deadlines imposed in the 1970 Clean Air Amendments had the effect within industry R & D programs of placing an extremely high priority on technical developments that would pay off within the original 1975-76 deadlines. Attention to other, longer range, options necessarily diminished in relation to what it might have been with some other set of emissions constraints. In such a circumstance, there may well be strong justification for Federal expenditures to fill gaps in ongoing programs and to explore particular technologies with the intention of making them more available to the private sector, thereby augmenting the pool of technical options.

(ii) Support Governmental Procurement Programs. Very often government R & D is undertaken not primarily to increase society's pool of knowledge but as a step in the procurement process. The bulk of military and space R & D is usefully viewed in this way. The Department of Defense often has a demand for a particular piece of equipment or a system to perform a certain function, yet the technology does not exist, or does not exist in usable form. A necessary first step in procurement is to finance the work required to solve engineering and technical problems, or even to establish the scientific basis for the function to be performed. In the automotive field, an example of this type of program is provided by the work on stratified change engines support by the U.S. Army Tank Automotive Command (see Appendix A).

Naturally, the spin-offs from this procurement-oriented research can be significant. Often these by-products are offered in justification for government expenditures, even when this spin-off potential does not determine the scale, composition, or longevity of the programs in question.

(iii) Develop Data for Regulatory Decision, Policy Formation, and Public Information. A separate and distinct justification for Federal R & D is the provision of background information for government regulatory efforts. In taking actions that directly influence private industries, key scientific and technical facts may be of critical importance; without them costly mistakes are possible. Sometimes the needed knowledge does not exist at all and the government must develop it. In the case of automotive air pollution, for example, Federal agencies had to conduct research on the health effects of pollutants, and on the appropriate driving cycles and instrumentation for emissions testing. These data were needed as a basis for setting regulatory constraints. By the same token, regulatory agencies may need to develop knowledge about the feasibility of achievement of various forms of regulation, or about the ramifications of expected industry responses to particular constraints.[1]

In other situations, the technical knowledge may exist but may not be available to government authorities due to the proprietary interests of the industries involved. In such a case, an important objective of Federally-sponsored research can be to develop this knowledge and make it available in the public domain. In the process, cadres of people experienced in the technology are developed, thus providing a body of expertise that can provide answers to public officials.

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[1]One situation where such research was sadly lacking was the case of the sulfate-catalyst problem. Having adopted regulations that very nearly forced manufacturers to adopt catalyst-controlled vehicles, the Federal government might well have initiated a research program to investigate the full range of possible consequences of such a choice.

More commonly, research results are available from industry sources, but their credibility is challenged because the companies that generated them are interested parties to regulatory action or some public controversy. Without an independent R & D effort, responsible government officials may have no sources of data other than the regulated industry itself, and two types of mistakes are possible in such a circumstance. Either the industry results may be correct but be rejected because there is no way to establish their credibility; as a result, the benefit of the knowledge is lost. Or the industry results may be wrong or biased and be accepted as a basis for government decision. The existence of a federal program can serve as a focal point for meetings and exchange of data by government scientists, large manufacturers, small manufacturers, components suppliers, and inventors. In the process of the government's own work, and these communications, a basis can be established for accepting or rejecting the work of the various industries involved.

Aside from the needs of policy analysis and regulatory decision, the government may have reason to set up research programs to provide information to the public at large. Often consumer protection is the overall objective, although in many situations it is not easy to distinguish between a goal of developing new knowledge and advancing the state-of-the-art (category i), and this objective of verifying and making public the information and experience that may already exist in private corporations.

(iv) Provide "Leverage" on Private Sector Activity. The first three objectives stated above relate to straightforward concerns of government in its role as purchaser, regulator, and provider of public goods such as scientific and technical knowledge. This fourth objective, however, is political in nature. It is a subtle and often unstated purpose of Federal R & D efforts. One instance where this objective becomes relevant is in regulatory situations, where only the regulated industry itself has the data to determine if particular constraints are reasonable, or if certain advanced technological solutions are feasible. Whether based on expert internal judgment or a general resistance to change, corporations may decide not to expend funds to explore certain technical options, and, as earlier discussion suggests, there is little that government authorities can do directly to insure that new or radically different technical options are seriously considered and fully evaluated.

Federal programs can have an indirect influence, however, in that government R & D may trigger a "defensive" R & D effort from industry.[1] No company wants to get caught without the technical knowledge to defend itself against regulatory proposals based on Federal research results or news releases portraying some dramatic success. This is true particularly where the industry has argued certain targets could not be achieved. And so a possible goal of Federal R & D is as an adjunct to the regulatory process -- to goad or threaten industry to undertake parallel R & D efforts of its own, or to upgrade the priority attached to particular programs.

In other circumstances the objective may be even more overtly political. For example, instead of trying to encourage R & D expenditures by industry, a government program may be intended to simply produce results that will embarrass the industry in the public eye and thereby force it to adopt changes faster than it otherwise would, or weaken its ability to fight

[1] As noted earlier, the "good faith" clause probably had a similar indirect influence on industry efforts.

against government regulation in general.

As one might suspect, if the political objective is the dominant one in the design and administration of R & D programs, then there are inherent dangers as well as advantages associated with Federal involvement. The temptation can be very great to misuse preliminary research results in an attempt to arouse media attention and public support for an agency's position. What is more, the very design of R & D programs in a particular technical area may be affected if the political objective of "levering" the industry is paramount -- with programs biased in favor of activities that are likely to be understood and reacted to by key segments of the public.

As discussed in Section 4 and Appendix A, at one time or another each of these four sets of goals has been used as a guide to Federal R & D in the areas of automotive propulsion technology.

3.4 Types of Research and Development

One source of confusion in discussing R & D is the wide range of activities covered by this single label. It is useful, therefore, to distinguish several sub-categories of activity that are important to the automotive industry. Four types of programs may be identified, as shown in Table 3.1.

Basic Research. The first category includes bench-scale laboratory work on scientific concepts and the associated theoretical research and mathematical modeling activities. In the automotive area, for example, this might include studies of the dynamics of flame propagation or the fundamental chemistry of catalysis. As shown in column 3 of the table, it is the type of work that takes place only at the most advanced scientific and engineering research laboratories.

Table 3.1

CATEGORIES OF RESEARCH AND DEVELOPMENT

Type	Nature of Activity	Where Performed
Basic Research	Studies of fundamental concepts; advancement of scientific knowledge.	Universities, private and non-profit research laboratories, government laboratories, and in a few auto industry research laboratories.
Technology Development	See Table 3.2.	See Table 3.2.
Assessments and Impact Studies	Studies of impact of policies or technical developments on the environment, the economy, or on particular industries or labor groups. No direct involvement with hardware, equipment, vehicles, etc.	Universities, think tanks, consulting firms, government agency staff, and some special groups within auto industry.
Performance and Emissions Testing	Take existing vehicles, production models, or experimental prototypes, and test their performance and emission characteristics.	Government laboratories, private testing laboratories under contract to government, auto manufacturers, oil companies.

Technology Development. Table 3.2 identifies five sub-categories of R & D that are relevant to technology development in a large-scale manufacturing industry. They are ordered in such a way as to indicate the sequential process by which knowledge and techniques evolve from preliminary concepts to large-scale commercial production. Naturally, no technical development (such as a new engine design) actually moves in a purely sequential fashion, completing one level before proceeding to the next. But the table does show that these are distinct types of activity, and that latter stages cannot be carried out effectively (or will not be justified on economic grounds) without success in the earlier stages.

At one end of the scale is Applied Research, which takes place in a wide range of organizations. At the other end is Product Improvement, which encompasses the detailed day-to-day work of monitoring the performance of a mass-produced item, conducting R & D on minor corrections and improvements, and preparing them for introduction into the manufacturing process. This kind of work is carried out only by the production divisions of the manufacturing organizations themselves.

As a technical development proceeds down this chain, the amounts of money needed to conduct R & D increase dramatically. For example, Exploratory Development of a new engine concept might be done with a small laboratory and staff -- with a cost range per year between several hundred thousand and a million or so dollars, depending on how radical the concept. To carry out Advanced Development work, costs immediately jump into the several million dollars per year; for Engineering Development the costs jump again an order of magnitude. It has been estimated that to complete

Table 3.2

LEVELS OF ACTIVITY IN TECHNOLOGY DEVELOPMENT

Type	Nature of Activity	Where Performed
Applied Research	Exploration of scientific feasibility and problem solving directly or indirectly related to automotive technology -- including, for example, basic engine design and performance, emissions control, fuel economy improvements, alternative engine systems and alternative fuels.	Government laboratories, chemical and oil company laboratories, universities, R & D firms, vendors, and in auto industry research laboratories.
Exploratory Development	Proving technical feasibility of scientific concepts by building and testing a few engines, either on a dynamometer or in a vehicle.	Primarily in R & D divisions of auto manufacturers, also by oil companies, vendors, R & D firms, and to a limited extent by universities and government laboratories.
Advanced Development	Proving engineering feasibility by building several engines and testing in several vehicles; and then making engineering changes in engine design, subsystems, or components to improve operating and emissions characteristics.	Primarily within the auto industry, as a necessary step in transfer of technology from R & D divisions to engineering divisions.
Engineering Development	Proving manufacturability and economic feasibility, "soft tooling" and extensive testing of prototype vehicles with special attention to improving performance characteristics within cost constraints, making modifications that reduce production costs, and evaluating problems of marketability.	Within the engineering divisions of the auto manufacturers, with staff assistance from R & D and production divisions.
Product Improvement	Refinements made in the product which may add to marketing appeal (e.g. improved fuel economy) and/or and in reducing production cost.	Within the production divisions of the auto manufacturers, with staff assistance from the engineering divisions.

the Advanced Development stage for a new engine concept would cost about $10 million; to complete the next stage -- Engineering Development -- would cost an additional $50 million. As a new engine concept moves through these different phases, the activity tends to move to different parts of the manufacturing organization -- from research laboratories to engineering staff to production divisions. The closer the R & D comes to dealing with problems of manufacturing and marketability, the more heavily is the work concentrated within the automotive industry, because, of course, that is where the required expertise and experience is to be found.

Although a simple chart like Table 3.2 is a crude simplification, the table does suggest several questions which should be asked of a program in alternative engine technology: First, where in the chain of research and development activity should the government program attempt to have its impact? And what level of resources does it take to make a contribution at that level? The sums of money required for advanced development or Engineering development are large, as noted earlier, and what is achievable is therefore ultimately dependent on the overall size of the Federal R & D program. Another consideration in evaluating the amounts of resources required is the existing level of industry expenditure in the area of concern. If the goal is to move beyond industry efforts in a particular area, or to stimulate them, then clearly the resource commitments must be commensurate with existing (or former) industry programs. (On the other hand, even a small program might add greatly to publicly available knowledge, or help establish the credibility of industry results.)

Finally, there was the question of <u>who</u> can carry out the work. For applied research and exploratory engine development, there are a variety of competent research institutions; with additional funds the capacity in these areas could be increased. But when the work comes closer to the manufacturing process, then tradeoffs with other aspects of overall system design, the integration of the engine into a vehicle, extensive field testing, suitability of the design for mass production and marketing questions become important, and the expertise is more and more the province of the automobile industry. This means that the latter stages of R & D can only be done in a cost-effective way by the major automobile manufacturers themselves, or by other industries with similar close contact with this or a similar marketplace. This fact presents an inescapable dilemma to Federal authorities in a circumstance where the R & D activity is closely associated with regulatory activity, as it is in the automotive case.

<u>Assessments and Impact Studies</u>. As part of the process of technology development, there always are some accompanying studies of the impact of a particular technical change on the automobile design as a whole or on the manufacturing corporation and its organization and financial structure. Beyond these partial analyses of technical changes, however, there is a broader range of activity that constitutes a distinct category of R & D. This includes studies of the economic implications, environmental effects, energy consumption, and other social costs and impacts that might attend a particular change in the automotive sector and its technology. This category of R & D involves the tools of applied economics, econometrics, and systems analysis as well as engineering; it may include inputs from other branches of the social and behavioral sciences. Studies of this type often make use

of cross-sectional and time series analyses of empirical information and case studies of particular events or decisions; depending on the circumstance the focus can range from studies of resource availability and the future supply of fuels to the labor market impact of a particular design change. Environmental impact studies are an important activity of this kind. As noted in Table 3.1, much of this R & D is conducted by research institutions, think tanks, consulting firms, and universities. However, in recent years the major automobile companies have built up their own in-house analytical capabilities in this area.

Performance and Emissions Testing. In considering government participation in research and development, there is still another category of activity that needs to be identified. This involves the taking of devices or systems resulting from private sector efforts and simply evaluating them from the standpoint of their public desirability. For example, the Environmental Protection Agency tests the emissions characteristics of large numbers of vehicles as part of the certification process under the Clean Air Act. As a spin-off of this activity, the EPA Laboratories will test and evaluate proposed designs on technical ideas that are brought forth by small firms or individual inventors. (Naturally, the large manufacturers have their own facilities for doing this kind of evaluation.) Furthermore, recently EPA has begun to evaluate and publish the fuel economy characteristics of the vehicles it sees in connection with the certification process.

This form of R & D has its counterpart within the automotive industry. Certain of the major manufacturers have a long-standing tradition of receiving technical ideas from smaller outside component suppliers and inventors, and testing and evaluating them for possible adoption. The benefits from success in this process are very large since the automotive market is so big, and there has been a continuing incentive for outsiders to submit their developments for evaluation. Many of the technical advances in the industry have been introduced in this manner rather than being generated within the major manufacturing organizations themselves.

On occasion governmental agencies have adapted this process for their own use in a regulatory situation. In 1963 the State of California passed a law requiring that exhaust control devices be installed on vehicles sold in the state as soon as two devices were approved by the State Motor Vehicle Control Board. The state then set up testing standards and certification procedures and performed evaluations of devices submitted by firms trying to get access to this large market.

In order to carry out performance and emissions evaluations of this kind, research must be carried out to identify the key parameters to be measured and tested (e.g. fuel economy, acceleration, noise, handling, HC, NO_x, and CO emissions, etc.). Efficient and accurate test procedures and instrumentation must then be developed. A determination must also be made of the levels of performance and emissions which are to be deemed desirable or permissible (of course, with passage of the Clean Air Act the Government has already determined the admissible levels for emissions). Testing and evaluation procedures are rarely settled once and for all because consumer preferences, government regulations, and vehicle technology are constantly changing; thus research and development on the procedures themselves are continuing activities. Both the automobile industry, and the Federal and some state governments support this kind of R & D, obviously with different levels of effort and relative program emphases.

3.5 Appropriate Directions for Federal R & D Efforts

Based on this description of the context in which Federal programs must operate, it is possible to draw some preliminary conclusions about the role that R & D activities might play in the alternative automotive power-plant area. Table 3.3 summarizes the taxonomy of objectives and R & D activities developed in this section. Across the top of the table are listed the four principal objectives of programs in this area; down the left side are listed the different types of R & D that are relevant to the automobile industry. The table indicates which of the different objectives are compatible with the various types of R & D activities. It is not our purpose to comment on the precise nature or magnitude of appropriate Federal R & D in each category. Obviously, specific proposed programs would have to be further justified on their detailed objectives and merits, and in competition with other uses of Federal funds.

The table is subdivided according to the tentative conclusions we have reached, where the number in each box refers to a particular conclusion as discussed below. First, there are several conclusions which follow from the discussion above, and which are not particularly controversial.

(1) Expanding the frontiers of knowledge is a sound objective of government programs and basic research has always been a justifiable activity in this regard. However, basic research

Table 3.3

APPROPRIATE DIRECTIONS FOR FEDERAL R & D EFFORTS

Types of Research	OBJECTIVES			
	Advance State-of-Art	Support Procurement	Data for Policy Regulation and Public Info.	"Leverage" on Private Efforts
Basic Research	(1) Appropriate	(2) All these types of research are appropriate to support procurement	Not usually relevant	Not relevant
Technology Development Applied Research Exploratory Development Advanced Development	(10) May be appriate when problems or options are not being explored.		(3)(9) Appropriate when information not available or credibility questioned	(8) Limited impact on industry R & D programs
Engineering Development	(6) High cost, questionable		(7) Unlikely to be appropriate	
Product Improvement	(6) Not appropriate		(7) Not approprate	
Assessments and Impact Studies	(5) Not usually relevant		(3) Appropriate	
Performance and Emission Testing	(4) Supports technology development		(3) Appropriate	

is not the real issue in this case, for most research at the "basic" level is sufficiently unfocused and removed from "available technology" as to be of only partial relevance to specific applications such as the automotive propulsion systems arrayed in Table 2.1.

(2) No one doubts that the Federal Government should be conducting programs with the objective of meeting procurement needs. All the various types of R & D activity may be involved in this process. However, this has little relevance to Federal R & D in alternative automotive powerplants since procurement needs are minimal. The issue is new engine technology for private passenger cars.

(3) Given the regulatory responsibility of the Federal Government, and the continuing requirement for data to support policy decisions, there is need for Federal investment in R & D on topics specifically related to these functions. In meeting these responsibilities, all categories of R & D may be called for, although Basic Research is likely to be relevant only under very special conditions, and there are stages of Technology Development which are unlikely to be justified as a public expenditure (see paragraph (6) and (7) below). Activities in the areas of Assessments and Impact Studies and Emissions and Performance Testing are of clear relevance to this objective.

Moreover, in this important area of government regulation it can be argued that this R & D needs to be put on a regular, continuing basis and conducted in such a way as to provide better information support than it has to date. When new technologies are being introduced, often under pressure of government regulation, then some agency needs to take responsibility for being sure that the important implications of the shift are known.

(4) Apart from the regulatory responsibility of the Federal Government, and the needs for information for policy development, there is justification for programs of Performance and Emissions Testing on grounds that they support the technology development objective.

(5) Federal involvement in Assessments and Impact Studies is not usually relevant to advancing the state-of-the-art of any new engine technology.

The major policy questions in the automotive powerplant R & D area center on Federal involvement in the process of Technology Development. The R & D associated with this process encompasses a set of activities which might be taken up in an attempt to meet any or all of the objectives outlined above. (For purposes of this discussion we ignore the procurement function and focus on the other three basic reasons for conducting work of this kind.) Several points emerge from our exploration of the issue.

(6) At the level of Engineering Development, the cost of a serious effort rises substantially. Moreover, the nature of the work is such that it can probably only be carried out effectively by the automobile manufacturers and closely related industries. A major part of this development stage would be the integration of the new engine into a vehicle, and extensive testing of the engine-vehicle combination in simulated consumer use. Thus it can only be carried out by the firms which manufacture and market the product. While some stages of Engineering Development might be appropriate for Federal R & D under special circumstances the next stage, Product Improvement, is most unlikely to be appropriate. This stage is dominated by system integration and extensive testing considerations and thus can only be carried out by the manufacturer and marketer.

(7) For similar reasons, the normal goals of the Engineering Development and Product Improvement phases and the objectives of data generation for regulation and policy formation are not consistent. Thus, Federal R & D in these phases would be unlikely to provide data that is relevant to these objectives.

The question thus centers on appropriate Federal activity in the areas of Applied Research, Exploratory Development, and Advanced Development. How should Federal programs be set up to advance the state of knowledge, prepare data for regulatory and policy decision, or apply leverage to the industry in these areas?

(8) Any substantial research activity in a new technical area will spur interest and (perhaps) a parallel effort on the part of industries that have a stake in the area in question. This is a natural aspect of the competitive process and a normal component of industry-industry relations. However, government R & D programs which explicitly or implicitly seek to apply leverage to private sector efforts, while they may generate political pressures, are not likely to have a great influence on the level and direction of industry programs on alternative automotive power systems. As data presented in Section 4 will suggest, the size of past and existing industry programs is too large in relation to Federal efforts, and their coverage too broad, for these firms to be greatly influenced in their own resource allocations by the structure of government programs. When such influence is exerted, it is likely to be because of the inherent value of the research results rather than the threat of a breakthrough which would compromise the industry's position.

(9) The Federal Government often has need to conduct its own R & D in order to prepare data to support regulatory action or other aspects of policy formation. Where industry results may be proprietary or subject to problems of credibility, this need may lead to expenditures on technology development. This need may be particularly strong in situations where the Government is considering changes in the external circumstances in which the industry operates and where public officials need to know the industry's capacity for adaption. For example, work on alternative fuels or on technologies that may be of interest only under certain changes in regulatory restrictions may be called for in this regard.

(10) The greatest controversy in this area of government expenditures on automotive engine R & D surrounds the appropriateness of government attempts to advance the state-of-the-art or open new options in circumstances where no regulatory or procurement functions are directly involved. The crucial question here is the extent of the divergence between industrial and social interests. The fact that the standards and deadlines under the Clean Air Act have had to be adjusted to the levels achieved by the ICE, and will almost certainly continue to be adjusted in the future, implies that the incentives to industry to develop a low-pollution alternative powerplant are not as large as the potential benefits to society. There may, therefore, be a serious divergence of interests. On the energy side, the national benefits are not nearly as clear, but there is no reason to assume that the forces of the marketplace are commensurate with them. Therefore, as the preceding analysis has shown, there may be solid grounds for Federal R & D even in the context of an industry that is committing significant resources to work of this type.

This last conclusion is discussed in greater detail in Section 4, after a review of government and industry programs in the automotive powerplant area.

4. PRESENT ALTERNATIVE POWERPLANT PROGRAMS AND POLICIES IN INDUSTRY AND GOVERNMENT

In the previous sections of this report we have laid out the critical issues concerning Federal support of R & D on alternative automotive powerplants, reviewed the relevant technology, and discussed the potential place for R & D among other government policies regarding the automobile. In this section we will concentrate on what government and industry have done and are doing in this area, to see whether the hypotheses we have developed can be confirmed by the available data. A very brief history of the development of government and industry programs will be followed by a discussion of Federal Agency policies and programs and then industry attitudes toward Federal programs. An overview and comparison of present programs will then be given, followed by a brief look at what we can learn from past and present industry treatment of alternative powerplants and an exploration of a possible Federal role.

4.1 Evolution of Present Programs[1]

The history of the passenger car powerplant can be roughly divided into four periods: (i) from the beginning of the industry in the 19th century through the end of World War I, (ii) between the World Wars, (iii) after World War II through the mid-1960's, and (iv) the present period, beginning in the mid-1960's.

[1]This section draws heavily on [3] and Appendix A.

The first phase was one of intense technological competition between engineers and entrepreneurs who committed themselves to either the steam engine, the battery-powered electric motor, or the ICE. In the year 1900, more than three-fourths of the vehicles produced in the United States were powered by electric or steam systems. All three systems were being actively developed technologically, but sociological, economic and political factors and the differences between the personalities involved were also important in determining their future positions. By about 1920, it was clear that the ICE had triumphed. Although it is impossible to provide a set of definitive technological or other reasons why the ICE won, the most important seem to be: Henry Ford's choice of the ICE for application of his mass production techniques, the decision by General Motors to compete with Ford in the production and marketing arenas rather than on engine technology, the development by Standard Oil of crude oil cracking processes for making the highly refined gasoline required by the ICE, and the general lack of interest among the more successful steam advocates in reaching the mass market with a low-priced vehicle.

The period from about 1920 to 1941 was one of the gradual evolution of the ICE, with very little interest in alternative powerplants for passenger car usage. The crucial advance of the period was GM's development of tetraethyl lead as an antiknock additive, making easier the continuous upgrading of the octane rating of gasoline, and thus a continuous increase in engine compression ratio, which improved the important intensive figures-of-merit of the engine (specific fuel consumption, power-to-weight ratio, etc.). The engines also grew in horsepower, number of cylinders displacement, etc.

During World War II, American passenger car production was halted. As major war-time producers of aircraft and other military equipment, however, the automobile manufacturers gained experience with areas of defense technology which they continued to use in defense contracts after the war. Between World War II and the mid-1960's, some attempts were made to apply some of this and other new technology to automotive powerplants. Most notably, Ford, GM and Chrysler all built prototype automotive gas turbine engines, as did a number of other firms in the United States and Europe. Chrysler went the furthest and received considerable attention for its 50-car test program during the period 1963-1966, but none of the Big Three entered even limited mass production with this engine. Spurred by rapid technological advances in electrical equipment, Ford, GM and numerous smaller companies also built prototype electric vehicles, and Ford, GM and others outside the automobile industry started research on advanced batteries. GM worked on a Stirling cycle automotive powerplant with N.V. Philips of Holland, starting in 1958. With the possible exception of Chrysler's turbine effort, however, these programs appear to have been undertaken on a relatively leisurely basis. The Big Three continued the evolutionary development of the ICE much as before the war, starting with the introduction of the overhead-valve V-8 in 1949.

In contrast to the previous periods, since the mid-1960's the development of the automobile powerplant has been characterized by extensive political interest and government intervention, first because of the air pollution problem and more recently due to the energy issue. Regulations controlling air pollutant emissions became the dominant consideration in the evolution of the ICE, but the emissions issue also stimulated a considerable increase in alternative powerplant programs in industry and caused the initiation of a program in the Federal Government.

The goal of greatly reduced emissions relative to the mid-1960's ICE represented a whole new factor which had to be considered in choosing the optimum powerplant. [8] The possibility of achieving the reductions by using an alternative powerplant generated a great deal of interest within the technical community generally, among entrepreneurs and firms outside the automobile industry looking to market new technologies, and in Congress. Lesser levels of enthusiasm were generated in the Executive Branch of the Federal Government and the Big Three. In 1967 and 1968 hearings held by the U.S. Senate gave all these parties a chance to air their views and a considerable amount of favorable opinion, especially regarding electric and steam systems, was expressed. A 1967 study for the Federal Government by a prestigious expert panel, the "Morse Report," commented favorably on the gas turbine and Rankine cycle engines. At the same time automotive air pollution was becoming a political issue on a national scale. By 1969 Senator Edmund Muskie, considered a leading Democratic Presidential contender, had become popularly identified with the issue, and the Big Three, accused by the Justice Department of conspiring to suppress air pollution control technology, came to be popularly regarded as defenders of the ICE. The State of California, having led the Federal Government in the establishment of emissions standards, assumed the lead again by beginning a program to develop and demonstrate steam-powered motor vehicles.

Industry's response to these pressures was, in part, to substantially expand its alternative powerplant R & D programs, accompanied by a public relations effort quite unusual for technological developments so far from production. The Administration's response, announced in a major Presidential Message on the Environment [9], included the establishment of the Advanced Automotive Power Systems (AAPS) Program. Thus the present programs in both industry and government grew out of a protracted affair in which technology and politics interacted in the national arena.

These programs have continued to be buffeted by technological and political developments. The most important was the sudden rise of energy conservation as a major national goal, adding new strength to the political spotlight on the automobile and once again changing the relative importance of the technological attributes of its powerplant. Other agencies besides EPA (in particular NSF and DOT) developed automotive technology programs, and EPA received a special funding supplement to extend its efforts outside of the alternative powerplants area. Agency roles in the area were not well defined and the proposal for a new agency, ERDA, to absorb the AAPS Program and possibly the others, introduced another element of confusion into the picture. That a sufficiently convincing justification for the existence of the AAPS Program remains to be developed was recently demonstrated when the House Appropriations Committee cut its Fiscal Year 1975 budget by more than half; the Committee believed that the Federal Government should not be developing automotive powerplants. The energy issue, like the air pollution issue before it, has caused the industry to initiate a massive engineering effort to improve the ICE in the short-term, and has changed the relative evaluation of the ICE and the alternative powerplants.

Appendix A is a detailed review of the history of the Federal programs in the alternative automotive powerplants area. It addresses industry programs insofar as they were an important part of the environment for the development of the government programs. The reader is referred to Appendix A, therefore, for further discussion of the period from the mid-1960's to the present.

4.2 Federal Agency Policies and Programs

In this section the present and some of the proposed programs of the Federal Agencies in the automotive energy area will be briefly described, along with the policies which underly them. Programs concerning the ICE will be discussed here to lend some perspective to the discussion of the alternative powerplant programs. An overview and some analysis of the Federal programs, and comparison with industry programs in terms of funding levels and program structure, are provided in section 4.4. A detailed historical and technological summary of the alternative powerplant programs is contained in Appendix B.

(a) Environmental Protection Agency

The Federal Government's principal R & D effort in the civilian automotive powerplant area is EPA's AAPS Program. Appendix A describes the evolution of the policies and program structure of the AAPS Program through the present. It remains centered on the demonstration at the advanced development level of two alternative powerplants, the gas turbine and Rankine cycle systems, in automobiles in 1976. The other recent AAPS Division effort on alternative powerplants has been a study of the use of electric vehicles in several major cities (partially completed). Recently funded or proposed have been studies of an automotive Stirling system, a light-weight diesel, and the development of a ceramic piston and liner. Since December, 1972, the AAPS Division has been funding work on alternative fuels for automotive use, including availability and applicability studies, experiments with methanol and hydrogen injection, and development of on-board hydrogen storage techniques. Starting in 1974 the AAPS Division has been funding potential technological advances for conventional powerplants. So far these have been confined to the design and development of a continuously variable transmission and Rankine cycle systems to use diesel engine waste heat. The AAPS Division has also funded a large number of studies in support of its alternative powerplant efforts, and is presently supporting a comprehensive review of the technological status of all the alternatives by the Aerospace Corporation.

At the present time the publicly stated purpose of the AAPS program is to provide a "credible source of public information" on automotive technologies with reduced environmental impact (an objective discussed in Section 3 of this report). Where this requires a development effort to apply available technology and demonstrate it in a vehicle, this will be undertaken. [10] This self-generated mandate is interpreted quite broadly by the AAPS management, but considerably less broadly by EPA's Washington headquarters, OMB and the Congress, who have held funding levels in close check and turned back a number of proposed AAPS efforts.

The AAPS program has in fact served as a "credible" source of publicly available information on alternative powerplant technology. There is little doubt that the technical community now has a great deal of data available to it from the AAPS Program which is useful in analyses of government policy, research program decisions, etc. The data has made a limited reduction in the uncertainties concerning the technological potential for some powerplant technologies. For example, the studies of hybrid vehicles showed them not to be as promising as originally thought, and development of a gas turbine combustor with NO_x emissions of 0.4 g/mile proved that it could be done. Furthermore, the semi-annual contractors' coordination meetings held under the program's auspices have served as a central public forum for information exchange in this area, and the mere existence of the AAPS staff as a source of expertise within the government has been useful.

However, the two vehicle demonstrations, now scheduled for 1976, will have to be carefully interpreted in order to avoid premature judgments on the technological potential of the gas turbine and Rankine cycle systems for passenger car application. The emphasis in these programs has been to get an operable vehicle on the road on a tight schedule and within a relatively small budget, pressing the technology only with these strict limits. With both systems, but especially the gas turbine, there are foreseeable potential technological developments which may remedy some of the deficiencies which will be seen in the demonstration vehicles.

EPA's Emissions Control Technology Division is now engaged in evaluations of a number of potential fuel economy improvements to current systems, including various improvements to the diesel, system improvements (e.g. variable displacement) to the ICE, and advanced fuel-metering concepts for light-duty vehicle use.

(b) Department of Defense

The DOD, through the Army's Tank-Automotive Command (TACOM) conducts an extensive program for the development of ground vehicles which satisfy unique military requirements. In Fiscal Year 1973 the Mobility Systems Laboratory, which performs R & D within TACOM, had a budget of over $36 million, and a professional staff of 422 engineers and scientists. The TACOM R & D program is justified on a military requirements basis, and thus competes for funding with other DOD R & D programs. It is in direct support of government procurement programs, as discussed in Section 3. The principal effort with potential civilian application is the stratified charge engine program. It will continue and complete the engineering development of an engine for a jeep-type military vehicle. The program is aimed at fulfilling a military requirement for vehicles which make the best possible use of the fuels available, in terms of quantity and quality, in a wartime environment. Because the vehicles are designed for highway use, the emission standards promulgated under the Clean Air Act are legally applicable. This program was partially supported by the EPA AAPS Division during Fiscal Years 1971 and 1972.

The other DOD program with relatively direct automotive civilian application is funded by the Advanced Research Projects Agency (ARPA). This is an effort to develop and demonstrate ceramic components gas turbine engines. The principal contractors are Ford, which is developing ceramic components for an automotive gas turbine, and Westinghouse, which is working on electric power generation applications. Ford and Westinghouse are working closely together in what is intended to be a 5-year multi-million dollar effort; it began in June, 1971. ARPA has chosen to support this high-risk/high-gain effort to establish the usefulness of ceramics in gas turbines, which are used in military applications, including engines for aircraft and ships, auxiliary power units, etc. They expect that this addition to the technological base will contribute to the development of other high temperature applications of ceramics as well.

(c) National Science Foundation

The NSF has begun a program to provide the underlying research base for improvements in operating efficiency and reduction of the air pollution emissions of automotive powerplants. Research subjects will ultimately include heat engine combustion processes, alternate fuel properties and materials problems. In August, 1974, the first seven grants under this project were announced. The efforts funded include studies of lean automotive combustion, prechamber stratified charge engines, emulsified water-hydrocarbon mixtures, and mixtures of alcohol and hydrocarbons.

The NSF is now sponsoring a major ($0.7 million in Fiscal Year 1973, $0.9 million in Fiscal Year 1974, and continuing) advanced battery development by supporting Ford's sodium-sulfur battery program. Other NSF projects related to the automotive energy issue are a study of the national gasoline demand, an evaluation of methods for reducing the aerodynamic drag of trucks, and a technology assessment of alternative powerplants.

(d) Department of Transportation

DOT has embarked on a major Automotive Energy Efficiency Program. Funding control for the program rests with the Office of the Secretary but it is managed by the Transportation Systems Center. It will evaluate the technology and production means to improve the effectiveness of energy utilization to decrease the dependence on petroleum resources of the nation's transportation vehicles and systems. It was begun in Fiscal Year 1973 and is concentrated on technology which will be available for production in 1980. It was funded at $0.3 and $2.1 million in Fiscal Years 1973 and 1974, respectively, and $6.4 million was proposed for Fiscal Year 1975. It is designed to develop the essential technical information necessary for public discussion and to support DOT's responsibility for development and implementation of Federal policy regarding the energy consumption of the transportation sector (as discussed in Section 3). Present DOT policy is that DOT will not support hardware development, and that its automotive programs are designed solely to provide information. Included in this program are: evaluations of stratified charge and diesel engines, fuel injection systems, improved carburetion and ignition systems, improvements to conventional transmissions, and other components that appear to have promise for improving fuel economy of production vehicles; evaluation of devices to reduce aerodynamic drag of large trucks; evaluations of energy storage devices, such as batteries and flywheels, and non-petroleum-based fuels that appear to be useful in transportation vehicles and systems (see discussion of AEC battery programs); establishment of a data base and the development of the simulation models necessary for assessment of the effects of the present and projected automobile, truck and bus fleet; evaluation of production capability within the automotive industry; and the development of a conceptual framework for analytical evaluation of the effects of the evolving vehicle fleet.

In the alternative powerplants area, the Office of the Secretary in DOT supported two very useful and widely circulated studies, one by International Research and Technology on the impact of introducing an alternative powerplant, and one by the Aerospace Corp. on possible production schedules for an automotive gas turbine.

Other parts of DOT are also supporting R & D efforts on automotive energy consumption. The Transportation University Research Program is supporting studies of hydrogen as an automotive fuel, methanol as a gasoline extender, closed loop engine control, automotive energy management techiques, and an advanced concept for an external combustion engine. The Federal Highway Administration is funding studies of the energy conservation potential of carpooling, reduced backhaul by trucks, and improved traffic control. The Urban Mass Transportation Administration has a program which will develop, test and install a flywheel energy storage system in a trolley bus vehicle to evaluate its capability to reduce energy consumption through regnerative braking and extension of trolley bus service to areas without overhead power wires now being served by diesel buses.

(e) Federal Energy Administration

FEA's Office of Energy Conservation has proposed a program it calls "Automotive Energy Conservation Potential and Policy Analysis," which would study in detail the present and future characteristics of the motor vehicle population, the full social costs of its manufacture and operation, and to use this information to define and evaluate appropriate government policies in the automotive area. Initial funding in Fiscal Year 1975 of $1.5 million was proposed.

The Office of Energy Conservation has also proposed a major program for the development of automotive Stirling systems and heat stores to supply energy to them. It was initiated within FEA out of concern that a technology, which the Office of Energy Conservation staff saw as highly attractive but long-range and high-risk, was being neglected by the other agencies.

(f) Atomic Energy Commission

Since 1965 the AEC has supported a battery development program at the Argonne National Laboratory. AEC's program has been an exploratory program, presently aimed at a lithium-sulfur battery for electric utility load-leveling; studies of automotive uses have at times been supported by other agencies. AEC is now supporting most of the automotive application work is an important spin-off from its primary mission-oriented work that might not otherwise be continued.

(g) United States Postal Service

The USPS does not engage in research and development except as it relates directly to unique USPS responsibilities (e.g. mail handling); so it does not support R & D on automotive systems. It does, however, continuously monitor developments in the automotive area and attempt to utilize the best available technology in the performance of its mission. In this context the USPS initiated in 1972 a program to evaluate the potential for state-of-the-art electric vehicles using lead-acid batteries to fulfill various USPS vehicle missions. Results were already sufficiently favorable by April, 1974, for awarding of a procurement contract for 352 vehicles.

4.3 Present Industry Attitudes Toward Federal Programs

Any consideration of Federal automotive R & D must consider industry attitudes toward such programs. Furthermore these attitudes reveal important aspects of how the major corporations view their roles in the technology development process.

Industry's attitudes toward Federal programs are revealed by their past behavior as reviewed in this report, and in the public and private statements of its representatives. The differences between the Big Three in this area are substantial.

In recent testimony before Congress, a GM representative stated:

> "We have watched closely the advanced automotive power systems activity carried out under the auspices of the Environmental Protection Agency. It is our impression that this program, on balance, has been useful.
>
> "While excessive amounts of money have been spent in areas where answers to questions were already known or on matters which were not crucial to evaluation of powerplant potential, in many instances, government-sponsored R & D has confirmed or supplemented corresponding R & D in the industry. We naturally are anxious to pick up any new ideas which might be developed, but we found little new as yet. Many of the conclusions now being arrived at in the government program look very much like our own reached several years ago.
>
> "The program has, of course, been useful to educate a large number of people in the government and technical community about

> some of the intricacies of automotive powerplants, vehicles and manufacturing problems. Because of this development, our relations with those outside the industry have been eased. While this has been useful to us, it is doubtful that such a spin-off benefit to private industry was either contemplated or can constitute justification for the rather substantial public funds expended." [11]

GM apparently also has a policy of not accepting Federal Government funding for automotive R & D. They have not bid, and have no current intentions of bidding, on AAPS or other comparable government contracts. Their policy is that if they judge any technology to be of potential value to their business, then they will explore it on their own funds; potential loss of proprietary interest has been a major consideration. Their commitment to research is substantial; the GM Research Laboratory annual budget is on the order of \$50 million and they are in the process of a 50 percent expansion. The total extent of their R & D program (including the work of the Engineering Staff) is obviously much larger. With this technology base, they are quite confident that little worthwhile automotive technology goes unexploited. They have followed the AAPS Program quite closely, however; for example over thirty GM technical personnel were in attendance at the May, 1974, AAPS Contractors Coordination Meeting.

Ford is less critical of the direct usefulness of government automotive R & D programs and emphasizes that automotive expertise should be involved in the programs. [12] In a somewhat more moderate version of GM's policy, they are quite willing to bid on government contracts when they feel that their patent rights are adequately protected, as with their ARPA work on ceramic turbine components. [12] They are negotiating with EPA on several AAPS contracts, although patent problems have been difficult to overcome.

They have proposed several efforts to the AAPS management in areas such as NO_x reduction in a light-duty diesel, which although important, fell below other problems in their evaluation of expected pay-off. Thus they see government funding as a way for them to extend their options into areas where they do not feel they can justify corporate expenditures. Ford has also stated that:

> "the AAPS Program, even though they have very limited funds . . . has had an effect in stimulating activity in the auto industry and outside the auto industry . . . we are certainly not opposed to the incentive that comes from Federal money and Federal support for such research." [12]

Similarly, in the past (before the Clean Air Amendments of 1970 were passed) Ford testified that they would participate in Federal Clean Car Incentive Program. [13]

Chrysler welcomes government support of alternative powerplant developments, at least through the advanced development stage. This has been the basic thrust of their testimony [14], and is clearly indicated by the fact that the AAPS Program is supporting a major part of their gas turbine program. However, it appears that much of the EPA funding is going to the building of engines for EPA use, while Chrysler's funds are concentrated on developments in key problem areas. Through this division of labor they are protecting their proprietary interests.

The views of the smaller firms on the fringe of the industry tend to be very favorable to government programs. These firms include automobile component manufacturers, innovative firms trying to develop and market new ideas, and aerospace-style technical organizations selling development programs for a profit margin on sales. Like other groups with a financial interest in new automotive technology, they tend to consider the Big Three as overly conservative in their innovation and feel that the government has a useful role in supporting innovations which would not otherwise be supported. Those firms which are interested in someday selling a product are, however, very concerned with the patent protection policies of the Federal Government in R & D in this area.

4.4 Overview and Comparison of Industry and Government Alternative Powerplant Programs

In this section the overall funding levels and program structure of the alternative powerplant R & D programs in government and industry will be reviewed and compared. It must be emphasized once again that these programs have evolved out of a complicated history of political pressures and technological developments. Sections 4.1 and 4.2 summarized the general features of the government programs, and examined the political and bureaucratic aspects, and along with Appendix A showed how the objectives for the programs were chosen. Section 3 discussed in general terms how these objectives influence the type of R & D and, for hardware programs, the level of development at which government programs can be effective. For the AAPS Program, the government's major civilian hardware program, the choice of technologies was made primarily in reaction to the content of the industry programs which has, in turn, evolved out of continuing experience and development, in each technology, within the automobile industry and elsewhere. This experience with each individual technology is addressed in Appendix B, which also provides descriptions of the present industry and government programs.

Table 4.1 gives overall funding figures for the relevant industry and government R & D programs. Several features of these data are worth explicitly

Table 4.1

AUTOMOTIVE POWERPLANT R & D EXPENDITURES
($ million)

Calendar Year	67	68	69	70	71	72	73	74	75	76
Alternative Powerplants										
GM	1.6	4.7	8.5	11.3	18.9	20.8	23.7	22.4	22.5	22.3
Ford	4.8	4.9	6.6	8.0	13.0	20.3	26.5	NR	NR	NR
Chrysler	NR	NR	NR	.1	.3	.8	3.9	6.0	NR	NR
Industry Total	6+	10+	15+	19.4	32.2	41.9	54.1	53+	NR	NR
AAPS Program			.3	2.2	4.3	9.1	9.8	12.3	7.0	
For Comparison										
Industry ICE Emissions Control	35+	40+	60+	89.4	154.0	210.4	282.0	299.6	300+	300+
Total Gov. Civilian Automotive Powerplant							19.9	22.8	25.7	

Table 4.1 (continued)

Notes to Table 4.1:

1. Industry expenditure data is from each company's "Application for Suspension of the 1976 Motor Vehicle Emission Standards," May, 1973, reprinted in "Research on Ground Propulsion Systems," Hearings before the Subcommittee on Space Science and Applications of the Committee on Science and Astronautics, U.S. House of Representatives, Feb., 1974 (No. 26).

2. Industry figures for 1967-72 are actual expenditures, 1973-76 were projected as of May, 1973. Some skepticism has been expressed concerning the magnitude of the Ford and GM figures. The auto industry profit crunch of 1974 may have seriously affected 1974 planned expenditures.

3. Industry figures are "direct expenditures," which include "salaries, wages, premiums and related benefits, applicable to the personnel working directly on the project...(and)...the material costs, outside services and other miscellaneous direct costs connected with the project," at least as defined by GM (attachment to letter from F.W. Bowditch to J.B. Heywood, Aug. 7, 1974.)

4. Industry work included relates to alternative powerplants as defined in this report, except only emission-related expenditures on the Wankel are included.

5. NR means Not Reported.

6. Industry figures are reported by Calendar Year, Government figures by Fiscal Year. Government figures are listed one-half year behind Calendar Year heading.

7. AAPS figures were obtained from EPA except for Fiscal Year 1975 where we have shown expected result of the appropriations legislation still in Congress. Total U.S. Government civilian automotive powerplant expenditures were obtained from various sources.

8. It should be noted that a fraction of AAPS expenditures are not related to alternative powerplants, and there have been some U.S. Government expenditures on alternative powerplants by programs other than AAPS.

noting. First, industry expenditures in the alternative powerplants area have risen continuously since 1967. This dramatic increase is clearly directly related to emission standards, the "good faith" requirement, and the very high levels of political pressure associated with the Clean Air Act. Second, they have remained only a fraction of the expenditures on emissions control R & D for the ICE. This reflects both industry's continuing commitment to domestic production of the ICE (a response to the time frame for the emission standards in the 1970 Clean Air Amendments), and relatively higher cost of engineering development and product improvement as compared with less advanced stages of R & D. Third, the AAPS program, which remains the Federal Government's principal civilian alternative powerplant program, has always been much smaller than industry efforts. However, the bulk of industry expenditures has been on the stratified charge engine, which has been at the most advanced stage of development. Industry expenditures on radical alternatives are probably about 50% of total alternative powerplant work, e.g. about $25 million in 1973. Thus the $6-8 million which the AAPS Program has been spending annually on radical alternatives has been about 30% of the industry budget.

Finally, military programs aside, the AAPS program constituted the principal expenditure of Federal funds in the automotive emissions and energy areas from its initial funding in Fiscal Year 1969 through 1974. In Fiscal Year 1975 the cut in AAPS funding and the rise in other agencies reflects a greater emphasis on shorter term problems, consisting primarily of technology evaluation and policy development programs, reflecting both the crisis atmosphere surrounding the energy issue and Congressional disapproval of Government powerplant development efforts.

Table 4.2 summarizes, approximately, the program status of each automotive powerplant within the automobile industry and the government. The regularities and contrasts reflect the similarities and differences of opinions concerning the relative merits of the powerplants and the differing roles the relevant organizations see themselves playing. Comparing organizations' efforts, the AAPS Program's work on only two systems indicates its strategy of concentrating its limited resources. Among the Big Three, Chrysler's overall level of effort stands out as much lower than Ford's or GM's, as also seen in Table 4.1.

Between technologies, the ICE is, of course, the single engine now in domestic production for automobile use. It is receiving far more attention in industry than in government, for obvious reasons that have been previously discussed. The situation is similar in the available alternatives. Each of these available alternatives is, by our definition, in mass production somewhere in the world and could, therefore, be mass produced domestically within a few years. This closeness to mass production has caused a hesitancy within the government to work on these systems, even though some have potentially favorable characteristics in the fuel economy and emissions areas. GM's Wankel program stands out in clear contrast to the lack of interest at Chrysler and Ford, both of whom have evaluated it in detail. Mass production of GM's Wankel, once scheduled to begin in the 1974 model year, was recently postponed indefinitely due to the problems with emissions and fuel economy.

Among the alternatives other than the Wankel, the prechamber stratified charge engine is the closest to domestic mass production. The Big Three feel that such an engine, like Honda's CVCC, could be put into mass production

Table 4.2

AUTOMOTIVE POWERPLANT PROGRAM STATUS

		Baseline	Available Alternatives			Radical Alternatives						
		ICE	Wankel	Pre.-Ch. Strat. Charge	Heavy Weight Diesel	Op.-Ch. Strat. Charge	Light Weight Diesel	Gas Turbine	Rankine Cycle	Stirling Cycle	Electric	Hybrid
GOVERNMENT	AAPS	2	0	0	0	0	0	3	3	0	1*+	2 (FCCIP)
	Other	1 (EPA,DOT)	0	0	1 (EPA,DOT)	4 (TACOM)	1 (EPA)	3 (ARPA)	2 (CALIF.)	0	3+ (several) 4* (USPS)	0
INDUSTRY	GM	5	3	3	2	2	2	3	0	0	2*+	0
	Ford	5	0	3	2	3	2	3	0	2-3	2*+	0
	Chrysler	5	0	2	2	2	2	3	0	0	1*+	0
	Other	5 (many)	5 (Toyo Kogyc)	5 (Honda)	5 (several)	2 (VW)	1 (several)	3 (VW)	2 (Saab)	2-3 (Phillips & U.S.)	2*+ (many)	2 (P-E)

Scale: 0 = no program
1 = studies
2 = small program
3 = major program
4 = scheduled production
5 = in production

Footnotes: * lead-acid cells, special duty vehicles

\+ advanced batteries

(at about 500,000 engines per year on one engine line), about four years after the decision to go ahead. It cannot now meet the 0.4 g/mile NO_x standard in a mass production version, but considerable effort is underway, especially at Ford and GM, to accomplish this. Ford has committed itself, with some qualifications, to mass production of the engine if the NO_x standard were set at 2 g/mile (See Appendix B).

The heavy-weight automotive diesel is already in mass production in Europe and Japan. It is generally conceded that a new design of a light-weight diesel would have to be developed for large-scale domestic automobile use. The heavy-weight diesel engine, like the prechamber stratified charge engine, could be put into mass production within a few years. There is a high level of interest in the automotive diesel within government circles due to the good fuel economy and low HC and CO emissions shown by presently produced diesels relative to the ICE. Industry feels, however, that the fuel economy advantage is not nearly as great as this simple comparison indicates, that the diesel will be expensive, will have great difficulty in attaining the original 1976 NO_x standard, and that the diesel's odor and particulates emissions levels represent a regulatory problem of unknown but potentially serious magnitude. Thus their level of interest in the diesel is considerably lower than in the stratified charge. (This is one example of the difference between government and industry views of the relative levels of importance of various powerplant attributes.)

Among the radical alternatives, the gas turbine engine stands out with a consistently high level of interest in both government and industry. The automotive gas turbine has been under development by each of the Big Three intermittently since World War II. In the mid-1960's Chrysler came very close to commencing limited mass production of a passenger car version, and Ford and GM will probably be marketing heavy-duty automotive gas turbines (for buses, trucks, and ships) before the end of the decade. EPA, ARPA, and each of the Big Three are working hard to overcome the principal problems now facing the engine: part load fuel economy, cost, and meeting the original 1976 NO_x standard in a mass-producible engine.

The other alternatives are receiving uneven attention. EPA's Rankine cycle program stands out; Ford and GM have worked on Rankine cycle systems within the last six years, and feel that their R & D funds are better spent elsewhere. EPA's Rankine cycle program exists because of this lack of attention in industry despite the system's potentially very low emissions levels. Ford's Stirling program stands out as unique at this time. GM had an active Stirling engine program for 12 years ending in 1970. There are now several proposals within Government to support Stirling engine R & D due to its potentially favorable emissions and fuel economy characteristics, but cost and controls remain problems. Ford, GM, and the Federal Government are supporting advanced battery work, and there is a high level of optimism within the technical community that within a decade or two an electrically powered vehicle will be available utilizing some of this technology. In the meantime, however, the only production of electric vehicles for street usage is for the United States Postal Service, whose relatively undemanding routes can be satisfied by an electric vehicle with lead-acid batteries.

4.5 Evaluation of Industry Programs

The automotive industry has been widely criticized for "undue conservatism" both in the extent of its alternative powerplant R & D programs and its decision not to enter into mass production with a diesel or stratified charge engine. For example, in April, 1973, in his decision to postpone for one year the original 1975 emissions standards, the Administrator of EPA stated:

> "All the applicants have evidenced a slowness to pursue alternate technologies that I have found both disturbing and frustrating. It seems fairly clear now, that if these companies had begun early in 1971 to develop a capability to produce other kinds of engines, and particularly the stratified charge type engine developed by Honda, large numbers of 1975 automobiles could probably achieve the statutory standards. I recognize, however, that in making this criticism of the manufacturers' development programs I am aided by hindsight. For I cannot be certain that the low emission potential of alternate engine systems such as the stratified charge engine, and the adaptability of alternate engines to a wide range of automobiles, could have been foreseen two years ago. Indeed, as I have stated above, we know relatively little about the stratified charge engine at this time.
>
> "The manufacturers generally may have demonstrated undue conservatism and lack of foresight in not pursuing alternate systems more vigorously. However, I cannot conclude that their present state of progress in these areas is a result of bad faith on their part." [4]

Similarly, in an October, 1973, report the staff of the Senate Air and Water Pollution Subcommittee stated:

> "The staff was not able to determine from the available information why, if the auto manufacturers other than General Motors believe that the catalyst is unacceptable, and involves the great risks suggested, those manufacturers do not take a few risks and begin producing one of these available alternative systems. Such systems can be produced and the evidence indicates they could have been introduced within the four years which the Clean Air Act allowed from enactment to the date when new cars must meet the 1975 standards.

"The argument has been raised that the problems in meeting the NO_x standards make the risk of adopting an alternative engine too great. But if so, then the same risk that the manufacturers allege has barred commitment to clean engines should also have barred G.M.'s commitment to the rotary in 1972 or Ford's commitment to a new V-6 engine in 1971. If there is no such NO_x risk for these engines, why is there a risk for the stratified charge or the diesel?" [15, p. 99]

These criticisms essentially reflect the controversy, discussed in Section 1.5, over the appropriate level of risk the automobile industry should be willing to absorb in order to achieve the potential gains available from alternative powerplants. We certainly feel no obligation to defend the industry's behavior in this or any other area; on the contrary there may be indeed much to criticize in the industry's handling of the air pollution and energy issues. However, it does appear that this particular criticism reflects expectations for the behavior of the automobile industry unlike those usually made of American industry. We have not performed any detailed analyses of the industry's R & D or production decisions, and, indeed, such an evaluation would be very difficult given the industry's reticence to discuss the details of its programs. These are investment decisions, however, and, following the usual pattern are evaluated on a return-on-investment basis, i.e. analysis or judgment of internal costs and benefits. When viewed in this light, the industry's approach appears to us, on the whole, a reasonable one. It is also one which is unlikely to change unless the internal costs and benefits are changed.

As discussed in the previous section, the industry is conducting substantial R & D programs on alternative powerplants. These efforts are concentrated on systems which will probably be able to meet the legislated emission standards, be attractive to automobile consumers, and not introduce any significant new elements of risk into the industry's dealings with the regulatory process. The diesel is one example, which we have cited previously in this report, of a potentially attractive powerplant not presently exciting much industry interest. Facing an imminent NO_x standard which it is generally felt cannot be met by a diesel engine without a technical breakthrough, and unknown but potentially stringent particulate and odor standards, the industry has quite reasonably chosen to concentrate its R & D efforts on other systems.

With regard to the production decision, the industry's programs show a similar pattern. GM has come very close to marketing a Wankel engine domestically (and may still do so), GM's Opel subsidiary is marketing a diesel in Europe, Chrysler came very close to establishment of a limited gas turbine assembly line in 1966, and Ford has made a qualified commitment to mass produce a stratified charge engine, all of which indicate that, under the right conditions, the Big Three are willing to produce alternative powerplants.

Each of these R & D or production investment decisions was a complex one. In each case the expected return from the investment was strongly affected by questions involving air pollutant emissions as well as the many other factors the industry must consider. The industry's approach has been conservative but, it seems to us, no more conservative than might be expected given the environment its consumers and the Government have made for it. From the existence of substantial R & D programs and several instances of close approach to production, it does appear that the manufacturers will pursue an alternative powerplant technology once they have decided that it is in their economic self-interest to do so.

4.6 Appropriate Federal Programs

In Section 3.5 we concluded that Federal R & D programs on alternative automotive powerplants in the technology development area might be appropriate in certain circumstances. With regard to the objective of supporting regulation and policy development, it would be appropriate where the ability of the industry to modify its product and the full impact of any government-induced modifications needed to be better understood. With regard to advancing the state-of-the-art, there might be solid grounds due to the divergence of societal and industrial interests.[1] Our examination of industry programs has shown that the technological and regulatory uncertainties associated with the air pollution regulations are one important determinant of the level of interest in industry in a given technology. If there is a system which is potentially attractive from an air pollution and/or fuel economy standpoint, then the appropriate roles for government R & D converge toward clarifying the costs and benefits, i.e. reducing the risks, to industry in investing in that technology. Essentially, then, the Government programs would adjust the regulations and change the status of the technology so that the normal market decision-making mechanism would give results more closely aligned to society's interests. This might or might not mean that the industry would proceed with further development.

In Section 4.5 we reviewed industry programs and concluded that the industry's approach was a reasonable one, on the whole, and unlikely to change unless external conditions were changed. The question then remains

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[1]The other types and objectives of Federal R & D are not reviewed here.

as to whether there are projects which seem appropriate for public funding; either "gaps" in industry programs or areas where a parallel or additional effort would significantly add to reduction of technological uncertainty or provide important public information. We have made no quantitative cost-benefit studies, nor has our analysis been sufficiently detailed to allow us to make a comprehensive or well documented list. However, we do feel that we can offer several examples to make the point.

The development of a light-weight diesel will once again serve as an example. A well-run government program on a light-weight automotive diesel would serve, at a minimum, to define the lower bounds of NO_x, particulate and odor emissions (although odor presents continuing measurement problems), and the tradeoffs between these and other attributes, including fuel economy. If the program were able to attain NO_x emission levels meeting the presently promulgated standards in an otherwise competitive engine, it can be assumed that industry interest in the technology would pick up dramatically. The principal remaining problems would be the particulate and odor emissions, but by then the government would have enough information to understand what was technologically possible, and would therefore be in a position to compare this data with air quality impact studies and determine the necessity for and effects of emission standards for these pollutants. One way or the other, regulatory action could be taken to resolve the uncertainty involved with these standards. If, as now appears more likely, the program did not attain the required NO_x level, then at least this fact would have been confirmed by a credible source and a decision could be made as to whether it was worth raising the standard in order to encourage interest in the diesel. The crucial point is that a government program could help reduce both the technological and regulatory uncertainty regarding the diesel. With the information gained, the benefits to the industry would more nearly coincide with those to society as a whole, and industry's own self-interest would be directed toward a socially desirable goal.

Other areas of justifiable government support might be the "barrier" problems associated with some systems. The Stirling cycle engine offers potentially substantial benefits in the emissions and fuel economy areas; it is unlikely to ever be mass produced, however, unless a suitably inexpensive design for the heater head is developed. An effort to supplement the Ford-Philips-United Stirling program should be considered. The use of ceramic components in the automotive gas turbine appears to be a similarly attractive area. We could, of course, list numerous projects with expected benefits not adequate to justify their costs, however, our analysis has not addressed the project evaluation procedures or selection criteria except in the most general terms.

We have previously mentioned the secrecy with which the industry tends to shield its technological developments, especially concerning the details of its programs. This makes it difficult to assess the status of the programs, but it also denies the use of much of this information in the public process of policy and regulation development. Furthermore, because the industry has such a stake in this area of policy, and has in any case lost much of its credibility with regard to technical information, industry data on alternative powerplants would be of limited usefulness. Thus the use of information on alternative powerplants for policy development is a benefit which can best be obtained from government programs of this type.

Each of these programs carries a price tag of $2-7 million per year; we would expect them to result in prototype engines or improved components in 3-5 years and probably to continue on with further development for a number of years beyond that. We list these three programs as examples, and are confident that a more careful, exhaustive, and detailed examination will develop others and provide a more detailed justification in terms of social costs and benefits. Four to eight such programs might cost from $15 to $35 million per year. This would represent a two-to-fivefold increase over the present AAPS Program, and a sixty to one hundred and fifty per cent addition to present industry programs on radical alternatives.

5. CONCLUSIONS

In this section the discussions of the previous four sections are focused on the central issue of this report: Is it appropriate for the Federal Government to support research and development on alternative automotive powerplants? The most controversial aspect of such Federal support is in the area of hardware development.

Behind this central issue are a number of broader areas of controversy relating to alternative engines -- the future of the ICE, the relative weighting of different engine attributes, the different types and degree of risk the automobile manufacturers can be expected to assume. It is argued that attitudes towards these factors significantly influence expectations of appropriate levels of R & D activity in industry and government. Particularly important to the central issue is the process by which an alternative powerplant would be introduced into the present passenger car distribution and maintenance system; the experience with the Manhattan and Apollo projects has led to unwarranted expectations for rapid changes in the impacts of the passenger car fleet. Because of the long times needed to replace the inventory of manufacturing equipment and then of the in-use vehicles, successful alternative powerplant R & D, whether in industry or government, would not substantially affect the average characteristics of the passenger car fleet until at least a decade after its completion.

In Section 2 the alternatives to the ICE are discussed and compared with each other, and with the ICE. The comparison shows that there are a number of candidates whose emissions and fuel consumption characteristics are potentially superior to those of the present ICE, but that each alternative has at least one important attribute in which it is inferior. There is no powerplant which currently stands out as broadly superior to the present ICE, and the uncertainties regarding the future attractiveness of the more promising alternatives will not be resolved until substantial further development efforts take place. The ICE, moreover, has considerable remaining potential for development. We therefore conclude that one cannot now forecast whether the optimum passenger car powerplant of the medium-term future will be the ICE, an alternative, or whether it will even be a single engine for all passenger cars. However, because the passenger car powerplant has such a significant influence on the national air pollution and energy problems, it is important that economically justifiable efforts in attaining the optimum not go unattended.

The review in Section 3 of national goals with regard to air pollutant emissions and energy consumption of the automobile, and the possible policy instruments for achieving these goals, suggests that only certain objectives of Federal R & D are appropriate. Federal R & D in support of government procurement has long been accepted, but is not the issue here, since the market for automobiles is almost entirely a private one. We also argue that although Federal R & D had been used in the past to "lever" the industry, it is unlikely to be effective in the future in that role either politically or technologically. With regard to the central issue, we conclude that for the purpose of supporting regulation and policy development, and for advancing the state-of-the-art, Federal R & D might have an important role to play depending on the extent of activities within the industry. To be effective, Federal R & D would be confined to the earlier stages of hardware development, where the cost would not be prohibitive, and where manufacturing and consumer acceptance considerations would not be overriding.

We point out that, in spite of the apparently fixed standards and deadlines in the Clean Air Act, the emission standards are in reality coupled to the available technology. The standards have been and in the near future will continue to be adjusted to levels which the dominant ICE technology can meet. Thus, in our judgment, the incentives to the manufacturers are probably not sufficient to cause them to perform all the alternative powerplant R & D which can be justified on the basis of the potential net social benefits from reduction in emissions. On the energy side, the national policies and goals are less clear, but it similarly appears that the advantages of a reduced dependence on foreign petroleum supplies result in a similar incentive for R & D, beyond that provided by the marketplace. Furthermore, the benefits to public policy development are even more unlikely to be fully accounted for in industry R & D budget decisions. With these hypotheses in mind, it was necessary to examine the present industry programs to see whether there are projects which have not been undertaken but appear to be justifiable when the larger social benefits are included, and to look at the government programs to see what benefits have been obtained.

The principal government program in the civilian alternative automotive powerplants area has been the AAPS Program. We find that the goals and structure of the program have never been widely accepted, nor very well justified, and that they have been unstable and generally of a short-term nature. The AAPS Program has not contributed significantly to advancing the state-of-the-art, but this has never really been implemented as a major program goal. The program has, however, been of significant value in providing a public focal point for alternative powerplant activities. It has fostered the exchange of information among activities outside of the Big Three, and even some inside, and served as a relatively impartial source of expertise to government, academia and innovators. The technical information provided from the program has contributed significantly to long-range policy planning, a program role that would not and could not have been undertaken by industry.

We find substantial alternative powerplant programs in industry, especially at Ford and GM. These efforts cover a number of the important alternative engines, but leave significant gaps. However, the details of the technology tend to be closely guarded and thus it is difficult to assess their progress. The information generated is not really available for development of public policy and, given industry interest in that policy, would be questioned as to credibility in any case.

The industry programs have been developed primarily in response to the air pollution emission standards and the "good faith" requirements of the Clean Air Act, but the standards and the uncertainty in their future levels have also made some otherwise potentially attractive projects too risky for industry funding. In our judgement the industry programs reflect a reasonable approach to the allocation of internal funds to this area, given the potentials of the different engine technologies and the current environment for alternative powerplant development that the Government and the public have created. However, we conclude that there are projects which, because some of the risks applicable to industry projects are not relevant for the Federal Government, and because there are social benefits not counted by the industry, appear to be economically justifiable from a public policy standpoint.

A review of industry experience in dealing with alternative powerplants is presented. Although we would have preferred to perform an analysis with considerably more depth, it now appears to us that the manufacturers will develop alternative powerplants and offer them in the marketplace when the risk in doing so is at a sufficiently low level to justify such programs economically. This risk depends on the uncertainty as to whether sufficiently attractive technological characteristics can be attained for a given powerplant and on the uncertainty in what levels of certain attributes will be required by Federal regulations. The minimum risk is clearly associated with continued emphasis on the further development of the ICE, and the industry can certainly be counted on, in the present environment, to press that technology as far as it will reasonably go.

We therefore conclude that there is a convincing justification for Federal support for R & D on alternative automotive powerplants. Our reasoning can be summarized as follows. Some of the alternative powerplants have the potential for significant long-term contributions to national air pollution abatement and fuel conservation goals. However, given the current uncertainty in these alternative engine technologies and the context within which the automobile manufacturers must operate, there is a divergence of industry and public interests. Some of these alternatives are not receiving adequate attention within the automobile industry for sound reasons which are unlikely to change. There are, therefore, substantial contributions that a well thought out and carefully executed government-funded program can make towards meeting these national goals by advancing the state-of-the-art in selected engine technologies, and in producing the technical data necessary for developing long-term regulatory and other policies. The goal of such a program would be to reduce the risks inherent in developing and introducing those alternative engines which may have long term economic and public benefits and which are not now receiving adequate attention, by reducing the current technological and regulatory uncertainties to the point where normal market decision-making mechanisms would be in better alignment with societal objectives.

We have only addressed in general terms the many important structural aspects such a Federal program would entail. For example, we have not attempted to compile a comprehensive list of important technical projects. Nor have we developed a firm recommendation for overall program magnitude, although a rough estimate of number of projects and project costs suggests that a two to fivefold increase above current alternative powerplant funding -- to between $15 and $35 million annually -- would be required. Our analysis has concentrated on the central issue: Is it appropriate for the Federal Government to support research and development on alternative automotive powerplants? We conclude -- yes it is.

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Appendix A

REVIEW OF LEGISLATIVE AND ADMINISTRATIVE HISTORY OF FEDERAL ALTERNATIVE AUTOMOTIVE POWER SYSTEMS PROGRAMS

In order to understand the present Federal programs in the alternative automotive power systems area, it is necessary to understand the complex set of forces which resulted in the initiation of these programs and their evolution over time to the present. The development of these programs has been a halting, waivering affair, with important actors at many levels of government, and in industry and academia. Strongly held positions have been hotly contested, and, in general, these programs have probably received as much attention per dollar expended as any other Federal programs in recent years.

This short history will focus on the Advanced Automotive Power Systems (AAPS) Program. The AAPS Program was begun in the National Air Pollution Control Administration (NAPCA) of the Department of Health, Education, and Welfare in early 1970, was moved with NAPCA to the Environmental Protection Agency (EPA) in December, 1970, and, in February, 1975, most of it will be transferred from EPA to the new Energy Research and Development Administration (ERDA). It was the first Federal R & D effort directly concerned with civilian motor vehicle powerplants, and today remains the central development program in this area. Military programs, whose beginnings well predate the civilian programs, will be discussed only where direction interaction between these two types of programs has occurred. Actually the first Federal R & D programs directly concerned with civilian passenger car technology were in the safety area; they were authorized by the National Traffic and Motor Vehicle Safety Act of 1966, and began shortly after its signature into law on September 9, 1966. The most notable of these have been the Experimental Safety Vehicle (ESV) Program, now completed, and its follow-on, the Research Safety Vehicle (RSV) Program. Powerplant technology has not been an important factor in these programs, however, so they will not be discussed here.

Pre-1970 Events

The recent active concern with civilian automotive propulsion technology within the Federal Government had its beginnings in the air pollution issue. After a decade of contention between the County of Los Angeles, the State of California, the Federal Government, and the automobile manufacturers, Congress in 1963 amended the Clean Air Act to provide for (among other things) research on motor vehicle pollutant emissions, and in 1965 amended the Act again to provide for national air pollutant emission standards. As expertise on the issue began to be developed and the magnitude of the required reductions in emissions levels began to be preceived, the idea of looking into the possible advantages of alternatives to the ICE[1] gained respectability, at least outside Detroit. The political climate regarding the automobile industry at that time had taken a strong anti-industry turn in 1965 with such events as the disclosure of the investigation of Ralph Nader by General Motors and charges by the Los Angeles County Board of Supervisors that the industry was suppressing pollution control technology. This atmosphere supported investigations into relatively radical solutions to the motor vehicle air pollution problem.

[1]"ICE" here refers to the carbureted, spark-ignited, reciprocating internal combustion engine used worldwide for passenger car propulsion. "Alternative" will refer to any other potential passenger car propulsion system.

Interest in the Congress began to "gather steam" in 1966; four bills were introduced, two each in the Senate and the House, which would have specifically authorized studies or R & D efforts to examine alternatives to the ICE. In February, 1967, the Subcommittee on Air and Water Pollution of the Senate Public Works Committee (headed by Senator Edmund S. Muskie) held a set of hearings on "Problems and Progress Associated with Control of Automobile Exhaust Emissions," which included tours of GM and Ford's research and development facilities. [1] Gas turbine engines, advanced batteries, and electric vehicles were proudly demonstrated and discussed as potential solutions to the air pollution problem, but only in the distant future.

In the spring of 1967 and one year later in 1968, in response to more proposed legislation, joint hearings were held by the Muskie Committee and the Commerce Committee specifically dealing with the need for Federal R & D on alternative powerplants. [2,3] The various interests which testified at these hearings reflected diverse attitudes, many of which are very much present today. Mr. Harry F. Barr, Vice President, Engineering, at GM, could have been speaking for all the Big Three (i.e. GM, Ford and Chrysler) when he stated "While we believe our industry can attain further substantial air quality improvements with our internal combustion engines at much less cost than any other proposals to date, we will continue to pursue vigorously the development of all potential sources of power having improved efficiency and lower pollutant levels." [2, p. 255] This and other Big Three testimony indicated their view that the ICE looked like the best engine for the future, but that in any case they were on top of all the alternative technologies and that thus no government program was needed.

A number of scientists and managers from universities, small companies, and other organizations not connected with the Big Three, however, had very different opinions. Dr. Robert U. Ayres, with Resources for the Future, stated, in answer to a question from Senator Muskie, that "So far as I can judge, it (the ICE) has been developed about as far as it can be. It looks as though it is inherently an inappropriate engine for the purposes that it is being used for. And from the standpoint of the user, the public, it is my belief that an external combustion engine would satisfy our needs better." [3, p. 13] Dr. S. William Gouse, then of Carnegie-Mellon University, asserted that, at the low emission levels forecast as future requirements, the steam engine would be "simpler and less costly" than the ICE, and that the principal problems holding up its development were the question "Will someone invest to develop the reliability necessary?" [3, p. 87] and the fact that "Resistance (to) change is enormous and that the capital requirements... would be very large." [3, p. 81] Mr. J. A. McIlnay, Vice President of the Electric Storage Battery Co., (now ESB, Inc.) testified, in regard to an electrically powered vehicle which his company could develop: "the public is not only ready for it,...the public is asking for it," and that "here is a role for the Government...to make some funds available for development." [2, p.56] Thus by mid-1967, a significant school of thought was developing which held that the available alternative engine technology was not being exploited by the Big Three, and that, in light of the potential public benefit of cleaner air, government-funded R & D was appropriate.

The key officers of the Executive Branch did not yet share this belief. Stuart Udall, Secretary of the Interior, stated in the 1967 hearings: "I think the Administration view at this point is that industry ought to bear the main burden, and that we are not convinced that Federal input into the research effort on electrically powered automobiles would be advantageous at this time." [2, p. 311] They suggested that the committees not take any action before the completion of a study then underway. In January, 1967, a Panel on Electrically Powered vehicles, chaired by Mr. Richard S. Morse of MIT, had been formed under the U.S. Department of Commerce Technical Advisory Board. The "Morse Report," [4] published by the Panel in August, 1967, became a widely-quoted document addressing almost every aspect of the automotive air pollution issue. Its recommendation no. 14 stated:

> "The Federal Government should initiate a five-year program, in total amount of approximately 60 million dollars, to support innovative developments useful in the establishment of future emission standards in the following areas:
>
> a) Energy sources for vehicles;
> b) Vehicular propulsion systems;
> c) Emission controls;
> d) Special-purpose urban cars; and
> e) General-purpose cars," [4, p. 45]

i.e., it proposed a modest development effort, whose principal purpose was to support the regulatory program. It further recommended that "Federal, State, and local governments should incorporate low emission performance criteria as factors in the purchase of vehicles for their requirements," [4, p. 46] i.e. that government purchasing power be used to subsidize low emission systems development by providing a well defined market.

Also in mid-1967, the National Air Pollution Control Administration, through the Public Health Service laboratory in Cincinnatti, let two contracts for studies of the technological and economic characteristics of the various alternatives to the ICE and their potential for competing with it in the 1980 time frame or sooner. A study by the Battelle Memorial

Institute, covering all the alternatives to the ICE except electric drive, noted the low emissions of external combustion systems for Rankine or Stirling cycle applications, relative to the uncontrolled ICE, and recommended the development of an advanced technology Rankine cycle engine and research programs on the problems associated with the Stirling and gas turbine engines. [5] The other study, by Arthur D. Little, Inc., was more equivocal concerning the electric vehicle's place in the future, stating that its disadvantage in life-cycle costs "would have to be regarded as a social cost for the elimination of air pollution," but that a coordinated Federal program could probably bring battery technology to the point of giving an electric vehicle performance equivalent to an ICE-powered vehicle. [6] While the formal final reports of these two studies were not published until October, 1969, the reports were submitted to NAPCA in March, 1968.

These hearings and studies had no concrete impact as, through mid-1969, no significant legislative or administrative actions were taken by the Federal Government concerning the alternative powerplant issue. It was during this period, however, that the "environmental movement" became a political force worth courting. Vanishing Air [7], written by a team from Ralph Nader's Center for Study of Responsive Law, attacked both Congress and the Administration, as well as the automobile industry, for laxity on the air pollution issue. Such attention intensified the competition between President Nixon and Senator Muskie for leadership on this issue. The Nader report developed at some length the thesis that the automobile industry was committed to resisting technological change.[1] The potential air pollution benefits of the steam engine were extolled, and the industry was chastised for not taking it

[1] For example, the titles of Chapters 2 and 3 of Vanishing Air are "The Automobile Industry: Twenty Years in Low Gear," and "The Automobile Industry: Nothing New Under the Hood," respectively.

seriously. The 1969 consent decree between the automobile manufacturers and the Department of Justice, ending a technology-sharing agreement between the manufacturers which the Government had claimed was part of a conspiracy to suppress air pollution control technology, also contributed to the public feeling that the industry was not serious in its development efforts.

In industry, activities on alternative systems expanded during this period. GM, in particular, built a number of demonstration vehicles and accompanied their debuts with a major public relations effort. On May 7, 1969, GM held a symposium called the "Progress of Power Show" at the GM Technical Center with these vehicles on display for both the trade and national media. The following August, a number of these vehicles, along with those of other firms, were demonstrated before the President's Environmental Quality Council,[1] which had been meeting with President Nixon at San Clemente.

Of particular significance in this technological public relations campaign was GM's handling of a Rankine cycle-powered car built by the GM Research Laboratories. The vehicle was a 1969 Pontiac Grand Prix, in which GM's "SE-101" steam powerplant was mounted. The NO_x and HC emission levels of this vehicle were reported as being well above the 1980 HEW goals (which later became the original 1976 standards), and in fact inferior to those of "recent developments with experimental manifold reactors in spark ignition engines," and its fuel economy a factor of 2 1/2 to 3 times worse than that of an equivalent ICE-powered vehicle. [8] Several other significant problems were prominently reported. GM's efforts were severely criticized in the Nader report as an effort to discredit Rankine cycle technology. An anonymous GM researcher was quoted in the report as saying

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1 This was a designated group of Cabinet officers; it was renamed the Cabinet Committee on the Environment after the National Environmental Policy Act of 1969 created the present Council on Environmental Quality.

"There was no attempt (by senior management) to control our research. They didn't have to. We were given less than one year to come up with something. With that kind of time limit, we had to take the most conservative engineering approaches." [7, p. 26-7] According to the Nader report: "The results inevitably underscored the disadvantages of the steam engine." This incident left the impression with many people of more moderate persuasion than the Nader group that the automobile industry, and GM in particular, was purposely not giving alternative systems a fair chance to compete with the ICE, and the affair is still cited today as a motivating factor for the AAPS Program.

One result of these well publicized charges of industry suppression of technology was that the ICE itself became something of a lasting symbol for industry reticence in dealing with the air pollution issue. At a later Congressional hearing, an EPA official defending the moderate funding level of the AAPS program was forced to state: "There is nothing immoral about the internal combustion engine. It really doesn't matter from the public's point of view whether the combustion takes place in the expander or outside. What the country needs is fuel-efficient (and, of course, low-emissions) vehicles."[9, p. 96]

In mid-1969, the Executive Branch was beginning to respond, piecemeal, to some of these pressures. NAPCA let two small contracts for detailed studies of passenger car Rankine cycle systems, and the Urban Mass Transportation Administration made a grant to the California State Assembly for a joint demonstration project on Rankine cycle-powered buses. In August, Dr. Lee DuBridge, the President's Science Advisor, discussed a possible Federal alternative powerplant R & D program at a press conference on motor vehicle emissions.

Finally, in December, 1969, the Office of Science and Technology, of the Executive Office of the President, formed an Ad Hoc Panel on Unconventional Vehicle Propulsion, chaired by Dr. David V. Ragone, then of Carnegie-Mellon University, and consisting in all of seven scientists and engineers (four from universities, John J. Brogan of NAPCA and Dr. Richard L. Strombotne of DOT, one from a non-Big Three company). Dr. S. William Gouse, by then of OST, was the panel's secretary. The panel visited the Big Three and several smaller companies, weighed the technological status and potential attractiveness of the principal alternative systems against the development efforts underway in industry and concluded that a Federal R & D program was "urgent". [10] The panel's preliminary conclusions were a crucial input to the decision to embark on a major program.

Meanwhile, a "Federal Low-Emission Vehicle Procurement Act" was (again) introduced in the Senate; the Act would provide for the Federal Government to pay premium prices for low-emission vehicles. In January, 1970, Federal officials testified before some irritated members of the Public Works and Commerce Committees that they could not endorse the proposal because the President was planning a major message on the environment and they were not sure what he would say. [11]

Establishment of the AAPS Program

In his message to Congress on the Environment on February 10, 1970, President Nixon announced the establishment of the AAPS program:

> "I am inaugurating a program to marshal both government and private research with the goal of producing an unconventionally powered virtually pollution-free automobile within five years. I have ordered the start of an extensive Federal research and development program in unconventional vehicles, to be conducted under the general direction of the Council on Environmental Quality." [12]

He also issued an order for what became the Federal Clean Car Incentive Program (FCCIP), where the Government would buy unconventional vehicles for testing and evaluation, and endorsed the Federal Low-Emission Vehicle Procurement Act then before Congress.

The principal justification for the establishment of the AAPS program was for "insurance". This is more-or-less explicitly stated in both the OST report and the President's message. At that time there was a proposed set of emission standards for the 1975 model year (which corresponded roughly to the model year 1973 standards later actually implemented) and a less official set of "HEW Research Goals" for the 1980 model year (which corresponded roughly to the "original 1976 standards" under the 1970 amendments to the Clean Air Act, at this writing applicable to model year 1978). The OST panel report stated:

> "In spite of intensive industry efforts, there is a probability that the gasoline engine (i.e. the ICE) will not be clean enough to meet long-term air quality requirements (i.e. the 1980 HEW Research Goals). This probability is sufficiently high to warrant serious attention to alternative powerplants.
>
> "The present level and quality of efforts (i.e. the industry efforts) is not consistent with the importance of the automotive air pollution problem and the uncertainty surrounding future emission levels from gasoline piston engines. It is urgent that Federal action be taken now, because the development of automotive powerplants to the production stage is a long process." [10, p. 1]

In other words, the panel felt that it was necessary for the Government to take out "insurance" against the possibility that, because of their commitment to modifying the ICE, the industry might not have an engine ready for production in 1980 to meet the research goals. In the President's words:

> "I hope this will not happen. I hope the automobile industry's presently determined effort to make the internal combustion engine sufficiently pollution-free succeeds. But if it does not, then unless motor vehicles with an alternative, low-pollution power source are available, vehicle-caused pollution will once again begin an inexorable increase." [12]

Aside from the stated "insurance" motivation, there were several other contributing factors to the establishment of the AAPS program. A very important one was the desire by the Nixon Administration to take a new initiative in its competition on the automotive emissions issue with Presidential-hopeful Muskie (this thesis is more fully developed by Jacoby and Steinbruner [13]). A second factor was the supreme confidence in American technology, developed by the space program (Neil Armstrong had walked on the moon only seven months before the President's message) and the associated, widely felt, desire for utilization of some of the aerospace engineers, recently laid off with much publicity from the space program, on a "socially relevant" problem.

An important aspect of the AAPS Program, as initially conceived, was to be the direct involvement of the automobile industry. The OST report stated "The Panel also believes that strong efforts should be made to involve the automotive companies in these programs right from the start." [10, p. 8] It was recognized that this was a necessary prerequisite for an early introduction of the alternative powerplants into production. This industry involvement was to be accomplished in two ways. First, the Government would buy industry-developed vehicles through the FCCIP and Low-Emission Vehicle Procurement Program as mentioned in the President's Environmental Message. Second, it was expected that the Big Three would be successful bidders on many of the AAPS development contracts.

In the spring of 1970, the CEQ assigned NAPCA the responsibility for management of the AAPS Program. In order to assist CEQ in its overview function, the Advisory Committee on Advanced Automotive Power Systems (ACAAPS) was formed. The ACAAPS consisted of experts from the academic community and representatives of the Big Three. It was initially chaired by Prof. Ernest S. Starkman, then of the University of California at Berkeley. The Big Three were included in an initial attempt to coordinate AAPS efforts with ongoing industry projects. ACAAPS meetings were also intended to serve as a mechanism for coordinating the AAPS Program with the efforts in other agencies (principally, at that time, the Army).

Immediately after the delivery of the President's message and the subsequent designation of NAPCA to run the program, a detailed AAPS program plan was developed. It was based on NAPCA's interpretation of the President's directive and the recommendations of the OST Panel. The basic technical goal of the program became the demonstration of a minimum of two different unconventional powerplants in standard size automobiles by February, 1975, making possible the production and public sale by industry of such vehicles by 1980. [14] To meet this goal, the program plan developed by AAPS management (in Ann Arbor) incorporated the following elements [15]:

1. Initial evaluation of seventeen candidate systems: gas turbine, organic-based Rankine with reciprocating and turbine expanders, water-based Rankine, hybrid systems with either electrical or flywheel energy storage and one of six heat engines (gas turbine, one of three Rankine, ICE and diesel), and all-electric. The evaluation would be based primarily on contracted design studies.
2. Selection, by mid-1972, of three candidates for development into "first-generation" hardware. Three engines of each successful candidate would then be produced; two of each would be used for dynamometer testing and one saved for a spare.

3. Two systems would then be selected, by July, 1973, for development into second generation hardware. A minimum of five vehicles would be powered by each engine, and four months of road testing would be completed by the target date of February, 1975.

The all-electric vehicle schedule did not quite follow the above outline; rather, it was intended to fund basic research on several advanced battery concepts which, if proven feasible, could be used in a vehicle in place of one of the systems selected above. It should be noted that, in accordance with the definitions used by the OST panel, neither the stratified charge or diesel engines were considered unconventional enough to fall within the scope of the program. The Stirling engine, rated last of the five alternatives discussed by the OST Panel (after the gas turbine, hybrid, Rankine and electric, in that order) was not directly addressed by AAPS; rather, it was intended to monitor the development program of the N.V. Philips Company of Holland, which was already well underway. As can be seen, a key concept was that at all times during the program at least two different types of powerplants would be investigated in parallel, thus providing an element of redundancy to increase chances of success.

Implementation of this program plan was well underway by late 1970. $2 million had been allocated to AAPS from Fiscal Year 1970 NAPCA funds, and levels of $6, $11, and $18 million were programmed by NAPCA for Fiscal Years 1971, 1972, and 1973, respectively. The plan was approved by the ACAAPS and the NAPCA Washington headquarters, which, from an early date, gave considerable leeway to the AAPS management in Ann Arbor. Contracts for the design of several different hybrid systems were let, advanced battery development was being supported (at Argonne National Laboratory), and work on external combustion components and the organic-based reciprocating Rankine cycle system was well underway. On December 2, 1970, the Environmental Protection Agency (EPA) was created, and the AAPS program was transferred with the bulk of NAPCA regulatory operations into EPA's Office of Air Programs (most of NAPCA's R & D effort was transferred in the EPA Office of Research and Monitoring).

The AAPS management was also assigned responsibility for the FCCIP and the technical aspects of the implementation of the Federal Low-Emission Vehicle Procurement Act, which had passed the Senate and was expected to become law. The two programs were designed to be complimentary. The FCCIP was designed to provide an interim market for experimental vehicles: if a developer could successfully pass through successive stages, the Government would buy up to 500 vehicles for field testing. If still satisfactory, the General Services Administration would then, under the Act, buy the vehicle for normal Government use, at a premium price if necessary. Of course, low-emission vehicles not developed under the FCCIP would also be eligible for GSA procurement under the Act. In October, 1970, a Request for Proposals under the FCCIP was released by NAPCA, and a total three-year budget of $20 million was approved within the Administration for the FCCIP. Preliminary indications were that about 30 proposals would be received, including several from U.S. and foreign automobile manufacturers.

Two other important policies in the initial AAPS management plan should be mentioned, both of which have been followed to date. First, it was never intended that NAPCA would develop any significant in-house hardware development capability. The AAPS Program was intended to be, and has remained, strictly a contracted affair (although some testing of engines is performed by EPA at Ann Arbor). Second, since early in the program there have been regular public briefings by AAPS management and contractors, held about twice a year. The purpose of these "Contractor Coordination Meetings" has been to bring the contractors for each system together regularly to facilitate technical coordination, and to make the information developed in the program available to all interested parties, including other Federal agencies, the automotive industry, the academic community, etc. The proceedings of the meetings have been published and widely circulated.

Impact of the 1970 Clean Air Act Amendments

On December 31, 1970, President Nixon signed into law the Clean Air Amendments of 1970. This legislation required rapid acceleration of virtually all aspects of the Federal air pollution control program and extended its regulatory coverage into several new areas. The crucial provision concerning motor vehicles was that ninety percent reductions in new vehicle emissions (resulting in emission levels corresponding more or less to the 1980 HEW Research Goals) were written into law for the 1975/6 model year (the CO and hydrocarbon standards were effective in model year 1975, the NO_x in 1976; the Administrator of EPA was authorized to grant,if necessary,a one year extension for each standard). The Amendments thus demolished the "insurance" justification for the existence of the AAPS Program: it was recognized by all concerned that none of the "radical" alternatives being considered by the program could possibly be brought into mass production in time to meet the legislated standards.

In response to the Amendments, officials in the Executive Office of the President proposed a budget cut in the program, starting in Fiscal Year 1972. EPA resisted and a set of meetings and memoranda followed, involving senior

EPA management, and OST, OMB and White House personnel. The issue was resolved in July, 1971, by drastic changes in the justification, program plan and overall funding level for the AAPS Program. The crucial aspects of the settlement were [14]:

1. The "insurance" justification for AAPS was dropped. AAPS became an integral, but subservient part of EPA's automotive regulatory program. At that time tempers in the automobile industry were still very hot over passage of the 1970 Amendments. Disaster to the national economy was threatened by industry spokesmen, who said that the standards could probably not be met. To support EPA in this contest, "the AAPS Program became a lever with which to put maximum pressure on industry to meet the 1976 emission standards with conventional engines, by seeking to provide a demonstrated technology for alternative power systems that can." [14]
2. In order to implement the new "lever" role, AAPS funding was concentrated on the two of their alternatives which appeared, at that time, to have the best chance for meeting the standards in a realistic vehicle by the February, 1975, goal. These were the Rankine cycle and gas turbine systems. Furthermore the stratified charge system was brought into the program because of its potentially low emissions and because it was the subject of an ongoing development effort by the Army, to which EPA could contribute at a relatively small cost and test in hardware at an early date. Funding of hybrid and all-electric systems, whose potential value appeared (at that time) high but long range, was stopped, in order to maximize the probability for early success with the three chosen systems.

3. Approved Fiscal Year 1972 funding remained at the $11 million planned by EPA, but Fiscal Year 1973 funding approval was held to $11 million rather than EPA's planned $18 million.

These revisions to the AAPS Program were presented to the ACAAPS, and both academic and industry members objected to each of the three changes. Shortly thereafter, however, the new program scored what EPA officials consider a major success in its "lever" role when, on September 24, 1971, President Nixon announced to an audience in Detroit that a jeep powered by an Army-developed stratified charge engine, tested under the support provided by the AAPS Program, became the first motor vehicle to meet the 1976 emission standards.

The "lever" role continued to be the official justification for AAPS for the next two years or so. For Fiscal Years 1972 and 1973 total AAPS funding was settled at $9.7 million and $9.8 million, respectively, of which $9.1 million and $8.7 million were devoted to the gas turbine and Rankine systems, and $0.4 million and $0.2 million to the stratified charge. The AAPS management proposed broadening the program into work on the all-electric and light-weight diesel systems, with increased overall funding levels, but was turned down by its Washington headquarters. Basic questions concerning the program's role continued to be asked, but as long as the program remained at a stable, relatively low, funding level it did not provoke any serious controversy over its continued existence.

There were, however, two changes made in the program. In response to the slowly rising national concern on the energy issue, the AAPS management announced in December, 1972, that fuel economy was being given "coequal" status with emissions reductions as an objective of the program's development efforts. Somewhat later, but in support of this, initial steps were taken to change the demonstration vehicles for the gas turbine and Rankine systems from the standard to compact weight class.

The second change was made at about the same time when Washington approval was sought and received to support studies in two new areas. One study was to determine the potential applicability and environmental impact of the use of electric vehicles in the Los Angeles area. The objective of this effort was to see whether, in the urban area with the worst automotive air pollution problem, electric vehicles could realistically be a significant part of an air pollution control plan. If so, then presumably Federal support for further battery development would be justified. The other "new mission" study, conducted by two contractors, was on potential alternatives to gasoline as automotive fuels. These two contracts were considered to be in support of long-range AAPS Program planning.

The "lever" role for the AAPS Program was never widely appreciated outside of EPA management and those very familiar with EPA's internal policies. From the very existence of the hardward development programs many people drew the conclusion that EPA intended to be and was in fact engaged in actually advancing the state-of-the-art and in attempting to induce the industry to do likewise. Dissatisfaction within the EPA with the "lever" role led to encouragement of this conclusion. For example, in a September, 1972, technical paper, AAPS personnel stated:

> "Although the overt goal of the AAPS Program is to demonstrate the hardware of alternate power systems, the covert goal is to stimulate the industry to absorb the technology developed in the program and then to further develop the candidate systems into production engines." [16][1]

The Clean Air Amendments had another, unintended, impact on the AAPS program. The Amendments wrote the previously proposed Federal Low-Emission Vehicle Procurement Act into law as Section 212 of the Clean Air Act.

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[1] This "covert" goal of stimulating industry R & D is a part of "technological lever" as compared with the "political lever" role discussed above.

However, the tight new emission standards absorbed resources that the automobile manufacturers would have used for entering the FCCIP. The remaining potential entrants, small companies not involved in vehicle production, were, for the most part, never able to raise sufficient capital to develop vehicles adequate to enter the program.[1] Through Fiscal Year 1973 EPA had been able to spend only $25,000, on one vehicle, out of the initially budgeted $20 million for the program. The Section 212 program proved to be a similar failure. To date only two applications have been made under the program; both were for electric vehicles whose performance was unacceptable to the Federal Agencies involved. Thus, between the manufacturers' unhappiness with the AAPS Program's new lever role and their concentration on meeting the new emission standards, the Clean Air Amendments had an inhibitory effect on the joint industry-government effort originally envisioned.

On the positive side, the Clean Air Amendments were at least partially responsible for two efforts by Federal Agencies with special vehicle needs to venture into low-emission alternative powerplant programs. The Army's program was mentioned above. Since the early 1960's the Army's Tank-Automotive Command had been supporting the development of stratified charge engines to provide its jeeps with an efficient powerplant with a multi-fuel capability. A legal determination that the emission standards of the Clean Air Act applied to jeeps forced the Army to work toward meeting the tight new goals. With some EPA funding assistance they in fact met the original 1976 standards with their engines. The other effort was a program for the testing and procurement of electric vehicles by the U.S. Postal

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1 See testimony in [17] of V. Wouk of Petro-Electric Motors, one of the small firms which tried to enter the program.

Service. This program was initiated in response to a Government-wide effort to demonstrate leadership in pollution control, which included motor vehicle emissions.

1973 AAPS Role Change

By early 1973 it appeared that the "lever" role for the AAPS Program was no longer valid. EPA's Washington management felt that EPA had achieved a sufficiently strong position in its ongoing struggle with the automobile industry over the legislated emissions standards. Furthermore, since the Honda CVCC engine, the Mazda Wankel and the Mercedes diesel, all alternatives to the ICE, had met the original 1975 standards, several had come close to the original 1976 NO_x standard, and that the 1976 NO_x standard would probably be raised anyway, it appeared that further demonstrations along these lines would not significantly support EPA's regulatory role.

In response, the AAPS management in Ann Arbor developed a case for the continuation of the AAPS Program as a provider of "correct and factual information from a credible source regarding the availability of technologies which can be applied to reduce the negative impact of the automobile on the U.S. consumption of natural and energy resources and on the environment." The information would, of course, also be used by Federal Government policy makers in the development of national policies related to the automobile. The gasoline shortage which began in the summer of 1973 and reached "crisis" dimensions during the Arab oil embargo had generated a host of proposals within the Congress and the Executive Branch for reducing the fuel consumption of the national automobile fleet, significantly raising the level of interest in automotive technology and thus, in the opinion of the EPA management, the requirements for technical information developed outside of the industry. Thus EPA's Washington headquarters accepted the new "public information" role for the AAPS Program, and it remains the principal publicly stated justification for AAPS today. [9]

By this time the AAPS Program appeared to be the subject of wide interest as the technical community involved in automotive technology programs grew. From the first AAPS contractor coordination meeting to the most recent attendance has grown from 20 to 500.

Impact of the Energy Crisis

The latest event which has been an important force shaping Federal R & D programs in the automotive area has been, of course, the "energy crisis." The existence of an energy "situation" began to receive the active attention of high level Federal policy makers sometime during 1971. The issue received an increasing amount of publicity through the following year. The first important impact on the automobile fleet was the development of spot shortages of gasoline in the summer of 1973. In October, 1973, the Arab oil embargo was initiated, raising the energy crisis to the top of the Nation's concerns. Partly due to its position as a major consumer of petroleum products, and partly due to the decision by the Federal Government to emphasize the production of fuels for home and industrial use rather than gasoline, the motor vehicle was particularly affected by the embargo. The long lines at some service stations, the public appeals by Government officials for eliminating unnecessary driving, and the lowering of the interstate highway speed limit, all received considerable attention in the media and had personal impact on the American public. Improving the fuel economy of the national motor vehicle fleet became a national priority, and government-sponsored R & D seemed to many people to be an obvious implementing measure.

Through Fiscal Year 1973, the impact of the energy crisis on Federal funding of automotive R & D was not a significant addition to the ongoing efforts aimed at emissions. Beginning in Fiscal Year 1974, however, automotive energy R & D drew funding within the budgets of several agencies which had not been previously involved in a significant way, in particular DOT and NSF. With the announcement by President Nixon of a 5-year, $10 billion energy R & D program, and the development under Dr. Dixy Lee Ray of the initial integrated plan for the R & D program [18], OMB made available to the agencies specially earmarked energy R & D budget supplements for Fiscal Years 1974 and 1975. The automotive propulsion area remained a controversial one, receiving special attention within the Executive Office of the President. The "Ray Report" recommended $53 million for advanced auto propulsion R & D in Fiscal Year 1975; OMB approved only $33 million. Even so the increase (from $23 million in Fiscal Year 1974) encouraged further development of automotive energy R & D projects by the Federal agencies. The expertise available in EPA's AAPS Division attracted new funds from this pool for work in automotive technology other than the ongoing Rankine cycle and gas turbine efforts, lending a <u>de facto</u> approval to an aggressive expansion into the automotive energy area. One EPA official described these efforts as "bureaucratic soonerism." In some specific areas, however, EPA's Washington management has halted proposed AAPS programs which they did not see as part of the EPA mission.

Also causing confusion was the President's proposal for the establishment of an Energy Research and Development Administration (ERDA). Initially it was planned to move the AAPS Division into ERDA. For a while there was considerable uncertainty as to whether Congress would agree to this transfer, but, on October 11, 1974, the Energy Reorganization Act of 1974 became law. ERDA will come into existence 120 days later and will incorporate the hardware development activities of the AAPS Division; the analysis and assessment function will remain with EPA. The move, strongly supported by most of the responsible Administration officials and especially the AAPS management, has important implications for the AAPS mission. As part of an agency devoted to R & D, it is widely presumed that the AAPS management will be given a freer hand to engage in R & D for the explicit purpose of advancing the state-of-the-art, rather than being constrained under an "insurance," "lever," or "public information" role. The uncertainty of the place of AAPS and other Federal automotive R & D efforts within ERDA, while the legislation was under consideration, motivated the expansion of various agency programs as a mechanism for protecting R & D "territory."

As preparation for the move to ERDA, the AAPS management has considerably broadened their conception of the future role of the program. They have tried to analyze future issues of public policy which will require government automotive R & D efforts, and have concluded that the questions of depletion of scarce materials and dependence on foreign resources (besides petroleum), both in terms of the possibility of supply disruption and impact on balance of payments, will be important. [19] In an even broader context, the model of the government-industry relationship in aircraft development, where the bulk of the major technological advances have been funded by the Federal Government, has been proposed as analogous to the relationship between the automobile industry and a future AAPS Program. [20]

The continuing questioning and the weak political base of the AAPS program was amply demonstrated as late as June, 1974, when the House Appropriations Committee cut the Administration's proposed $17 million Fiscal Year 1975 budget back to $7 million, and questioned their R & D role. Their report stated:

> "The Committee recommends that instead of EPA developing new systems, the $7.2 million...be used to test new systems as they are developed by private industry. These funds should be used by the Agency to bring together information on all new developments, both foreign and domestic, for the purpose of making available to the public information on new developments and to support the American automobile industry in the production of the best possible vehicles for the American consumer." [21, p. 64]

The proposed funding increase had brought the program to the Committee's attention, and their belief that powerplant R & D was a job for industry led them to the cut. The restriction to testing and information gathering was modified by remarks on the House floor, but the $7 million budget level was sustained in conference, effectively eliminating any efforts other than the continuing Rankine cycle and gas turbine projects. Thus the future of the AAPS Program remains as cloudy today as it has been since a Federal alternative automotive powerplant R & D program was first proposed about eight years ago.

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Appendix B

GOVERNMENT AND INDUSTRY PROGRAMS ON ALTERNATIVE AUTOMOTIVE POWER SYSTEMS

In this appendix the history and present status of each of the major potential alternatives to the ICE for automotive use will be discussed.

An overview of the history, including the political aspects, is given in Section 4 of the report. Also contained there are discussions of overall funding levels of alternative powerplant R & D programs, and a summary and comparative analysis of the magnitude of each powerplant program within the Big Three (Ford, GM, and Chrysler), EPA, and other industry and government organizations. The purpose of this appendix is to supplement the report with more detailed data in two areas: industry's historical treatment of each alternative to the ICE, which has led to the present industry and government programs; and present industry and government programs and plans, both R & D and production, for alternative powerplants. The emphasis will be programmatic rather than technological; Section 2 of this report contains technical descriptions, and detailed technological analyses and comparisons are available elsewhere. [1,2,3]

As discussed in Section 1, this report is concerned primarily with powerplants for passenger car propulsion. In that context, the following definitions have been used here (as elsewhere in the report): "ICE" -- the carbureted, reciprocating, spark-ignition, internal combustion engine used worldwide for passenger car propulsion; "alternatives" -- those powerplants other than ICE which have been seriously discussed for passenger car application; "radical alternatives" -- those alternatives not now in mass production. The term "available alternatives" will occasionally be used to refer to those alternatives now in mass production.

A central factor dominating this discussion is that these powerplants are, in fact, alternatives, i.e., there exists a single engine technology which now completely dominates the passenger car application. While there are substantial R & D (and even production) programs for some alternatives, their total magnitude is considerably smaller than the level of effort now being applied to studying and improving the ICE. This is true in both industry and government and has been so since the ICE's rise to dominance before World War I. This is a crucial aspect of the environment within which alternative powerplant R & D exists: the attributes of the alternatives are measured relative to those of the ICE, and the attributes of the ICE have been and are continually improving. This Appendix will not discuss the past or present work on the ICE, but, where relevant, the evolution of the alternatives will be discussed in light of the continued evolution of the ICE.

Finally, it is worth repeating a note of caution. As discussed in the Preface, this appendix is based on information provided largely by the organizations whose work is being discussed. The area of alternative automotive powerplant R & D remains a controversial one, and there are incentives for distortion of information. Use of independent sources, and cross-checking of data have been attempted wherever possible, but the opportunities have been limited. Thus, especially in the areas of unwritten organizational policies, judgements, and motivations, this Appendix may contain some inaccurate statements.

Diesel Engine

The potential applicability of the diesel engine to the American passenger car market has been the subject of considerable controversy. As is well known, the diesel engine is widely used in many heavy-duty applications, automotive and otherwise. Since 1936 it has also been in mass production for light-duty motor vehicles; over a million have been manufactured in Europe and Japan [1], and the Mercedes-Benz, and more recently the Peugeot, have been marketed in the United States. One of the European manufacturers, Opel, is a GM subsidiary. GM and Ford have considerable manufacturing experience with diesel technology, ranking first and second, respectively, in worldwide diesel engine production. [4]

The diesel engines presently in mass production for light-duty automotive applications do not provide vehicle performance comparable to that typically expected in American passenger cars. They can meet the original 1975 emission standards without add-on devices and do have superior fuel economy, but also smoke, particulate, odor, noise, and low-temperature starting problems and relatively high weight and initial cost. Because of these problems, they have not sold well in the United States: diesel-powered vehicles have typically constituted about 14% of Mercedes' U.S. sales in recent years. [5] Even in Europe, where fuel economy has always been more of a significant factor in sales, diesels have constituted less than 20% of combined Peugeot and Mercedes sales [1], and less than 3% of overall sales. [6] Based on these considerations, the Big Three have never offered a domestically produced diesel-powered passenger car. [7]

It is possible that with a substantial redesign from presently used concepts a diesel with a significantly improved power-to-weight ratio could be designed and manufactured as a suitable competitor to the ICE in the American passenger car market. Such a "light-weight" diesel could cost less than the "heavy-weight" diesels now in use in both the passenger car and truck markets, at a sacrifice of some durability, which is now very high relative to that of the ICE. EPA has funded a study with Ricardo and Company Engineers of England to examine a wide range of design alternatives to the presently used configuration, but it is generally felt that a redesign of the substantial magnitude required puts the light-weight diesel in the "radical" alternative category.

The odor and particulate emissions of the diesel constitute a formidable disadvantage. As used here, "particulate" emissions refers to the solid content of the exhaust, while "smoke" refers to the characteristic of exhaust visibility. While the exhaust of a diesel may be invisible, it may still have a particulate content considerably higher than that of a comparable ICE. Particulate emissions of electric powerplants and other stationary sources are heavily regulated. Smoke from heavy-duty vehicles is regulated by a visibility standard, which can be met by light-duty diesels as well.

It is widely assumed that, if the diesel were to be installed in a significant fraction of new American vehicles, then EPA would set motor vehicle emission standards for its odor and particulate emissions. The industry, operating on this assumption, does not know what to expect in the level of the standards relative to present emissions. A commitment to mass produce in the face of this uncertainty is obviously very risky. EPA is conducting an "impact" study of the effects of widespread use of diesel-powered passenger cars, but is clearly not close to setting any standards in anticipation of American mass production. In fact it is possible that, due to the press of shorter-term business, EPA would not set standards before plans for such production are at least announced, whereas such plans might never be made without established standards. This dilemma is clearly an inhibitory factor for the Big Three against significant commitments of resources to diesel technology. Although not an uncertainty in the same sense as the odor and particulate emissions, NO_x emissions are also a problem with the diesel. NO_x reduction techniques proposed for use on the ICE are not applicable to the diesel due to the different combustion process and chemical composition of its exhaust; there is considerable pessimism in the industry concerning the attainment of the original 1976 standard.

In spite of all this, with the recent increased emphasis on fuel economy the Big Three's interest in the diesel has picked up somewhat. There seems to be little doubt that the diesel can be mass-produced, though at higher cost than the ICE. At GM, the Research Laboratories are looking at NO_x reduction techniques, there is an effort on the Engineering Staff to reevaluate the diesels which are presently available, and several of the passenger car divisions are testing diesels in their vehicles. Ford's total diesel effort is funded at less than $1 million per year; they presently rate it a poorer short-term prospect than the stratified charge and a poorer long-term prospect than the Stirling or gas turbine. Chrysler has been doing some single-cylinder experiments aimed at NO_x reduction and testing some commercially available engines in passenger cars. On the whole, though, the Big Three's programs can be described as being in a "holding pattern," primarily due to uncertainties with likely but unknown emission standards and difficulty in attaining a known one.

There is a high level of interest in the diesel within government circles, because of the good fuel economy and inherently low CO and hydrocarbon emissions. Due to the wide familiarily with the technology, however, there has been a resistance within the Government to funding R & D projects other than studies. EPA's impact study was mentioned above; EPA has also commissioned a design optimization for the heavy and light-duty truck applications and the passenger car. DOT has funded several projects which have analyzed the potential impact of widespread diesel usage on the national automotive fuel demand.

Wankel Spark-Ignition Engine

Unlike the other systems discussed here, industry consideration of the Wankel has not been based on air pollution or fuel economy considerations. The Wankel's advantage over the ICE lies in its relatively small size and weight per unit of power, and this has stimulated interest among the automobile manufacturers.

There have been many rotary piston engine concepts explored in the past century. Attention is now centered on a rotary piston configuration based on the Otto cycle (like the ICE), that was invented by Felix Wankel in 1953. The first prototype of this engine was successfully run in NSU Motor Werke in Germany in 1957. NSU owns the basic Wankel patent, having bought it from Felix Wankel, and began marketing the engine in Europe in a passenger car in 1964. [1] By 1967, a number of motor vehicle manufacturers, including Citroen, Toyo Kogyo, Daimler-Benz, Alfa Romeo, and Rolls Royce, had obtained licenses, but no American automobile manufacturer. [8] The Japanese firm Toyo Kogyo began production of Wankel-powered passenger cars in 1967 and exporting them to the United States several years later. GM bought a license for U.S. Wankel engine production in November, 1970, and Ford of Germany bought one in November, 1971, for production in Germany.

Active development for uses other than the passenger car has been pursued in the United States primarily by Curtiss-Wright. Engines with power outputs from 0.6 hp to 780 hp have been built, with potential uses in model airplanes, lawnmowers, snowmobiles, boats, and aircraft, as well as automobiles. [1]

Along with its weight and size advantage relative to the ICE, the Wankel also has somewhat lower NO_x emissions, but its hydrocarbon and CO emissions are higher. Its fuel economy is unfavorable, however, and the recent rise in importance of this attribute has diminished the interest in the Wankel, among all parties. Toyo Kogyo's Wankel-powered vehicle, the Mazda, rose continuously in U.S. monthly sales after its introduction, reaching a peak of 11,000 in March, 1973, and was forecast to go considerably higher. EPA's widely publicized fuel economy data came out and showed the Mazda's fuel economy to be substantially poorer than that of other vehicles in its weight class. [9] With the gasoline shortages in the summer of 1973 and the Arab oil embargo that fall, the Mazda's sales dropped off sharply. In March, 1974, 5,300 were sold. [10] After considerable controversy over the testing procedure, EPA and Toyo Kogyo agreed on a more complete testing program, which reaffirmed the Mazda's relatively high fuel consumption [11], and Mazda sales have not recovered.

GM believed that by using an exhaust catalyst for hydrocarbon and CO emission control, rather than the thermal reactor used on the Mazda, they could reach a fuel economy that, with the engine's size and weight advantages, would make it a successful product. [6] Because its emissions characteristics are basically similar to those of the ICE, there would be no new risk associated with having to meet the pending tighter standards. They therefore planned to introduce the engine in a subcompact during the 1974 model year. Their investment in the Wankel has included $50 million in license rights for the period 1970-75 [12], $50-60 million in production tooling, and a substantial development and engineering effort. Some work on rotary engines remains in the Engineering Staff and GMRL, but Chevrolet Division has principal responsibility, along with Hydramatic Division which was assigned production responsibility.

With the rise of the energy issue, GM postponed introduction of the engine to the 1975 model year to do further work on its fuel consumption. [6] On September 24, 1974, GM announced that mass production was postponed "indefinitely," due to difficulties in attaining a sufficiently high fuel economy while still meeting the 1975 emission standard for hydrocarbons. [13] The 1977 standard for hydrocarbons was also apparently a major concern. [14]

Ford explored the Wankel, but, in early 1974, after an investment of approximately $10 million, the program was terminated due to their pessimistic evaluation of the engine's fuel economy characteristics. [15] Chrysler also evaluated the engine and decided not to pursue it.

Because its primary advantages have been commercial there have been no government programs on the Wankel (other than the EPA testing mentioned above).

Stratified Charge Engine

Of the many modifications to the ICE combustion process which can be termed "stratified charge," only a few have received serious attention in American industry. In the United States, the first important effort was Texaco's invention of a "knockless" engine in the 1940's. In 1965 the U.S. Army Tank-Automotive Command began funding a number of concepts, reached the engine demonstration stage with both the Ford PROCO and Texaco TCCS systems (both open-chamber) and, in 1972, selected the Texaco system over

Ford's for engineering development. [1] Ford's program is continuing in-house without Army support. It was an Army jeep powered by a Ford PROCO engine that, in September, 1971, became the first motor vehicle to meet the original 1976 standards. The prechamber concept has long been used in diesel engines; it is now being actively developed as a stratified charge technique for spark-ignition engines by a number of companies. The Honda Motor Company of Japan has begun mass production of vehicles with their CVCC engine (a prechamber engine). In the spring of 1972, a CVCC in a small car met the original 1975 emission standards without the use of an exhaust catalyst or exhaust gas recirculation. [16] The dramatic developments by Ford (for the Army and EPA), and Honda's developments, received a great deal of publicity and generated considerable interest in the automobile industry in the stratified charge concept. The Honda development, especially, resulted in some feeling that automotive technology was not being as aggressively pursued in the U.S. as it was overseas, and some embarrassment to American industry.

There are two basic classes of stratified charge engine that are today considered alternatives to the ICE. The fuel-injected open-chamber engine, exemplified by the Texaco TCCS and Ford PROCO engines, combines some aspects of the diesel and of the ICE. The use of fuel injection may allow significant improvements in fuel economy, multi-fuel capability, and substantially reduced emissions, but it is a major departure from the ICE, is not close to mass production, and must be considered a radical alternative. The prechamber stratified charge engine uses two separate fuel-air mixtures, at different fuel air ratios, to achieve stratification. The richer stream enters through a small prechamber, off the main chamber, where it is ignited. The jet from the rich mixture ignites the leaner mixture in the main chamber.

The configuration requires a second carburetion system and a redesigned cylinder head with a second set of intake valves, but is much closer to the ICE than the open-chamber system, and is in mass production. While it offers some advantage in emission levels relative to the ICE, it does not have the potential fuel economy or multi-fuel advantages of the open-chamber systems.

Honda, long a motorcycle manufacturer, entered the 4-wheeled vehicle market in 1962 with a line of very light trucks. In 1967 they produced their first passenger car. [17] Their CVCC program began in 1969 when, according to Honda, they completed a review of the available pollution control technology, and decided that an approach aimed at modifying the basic combustion process in the ICE would best satisfy their requirements. By early 1971 the CVCC concept was completed, by the spring of 1972 they had a prototype engine, and between then and May, 1973, they built 150 engines and accumulated 1 million miles of road experience. In late 1972 they committed themselves to mass production, [18] and in December, 1973, the first CVCC-equipped cars rolled off the production line. [17]

As of May, 1973, they planned to build 500,000 CVCC-powered automobiles. in 1975, of which about 250,000 would be committed to the US market. [18] The CVCC R & D program cost about $50 million; they also spent $20 million to convert one engine line to the CVCC, and planned an additional $80 million for a new CVCC line. [18]

Ford appears to have the most aggressive stratified charge engine program of the Big Three. On May 23, 1973, the President of Ford stated to the Subcommittee on Air and Water Pollution of the Senate's Public Works Committee that, if an NO_x standard in the neighborhood of 2.0 g/mile were established on a long-term basis by the end of 1973, and if Ford's development efforts went as expected, then Ford would put some variant of a stratified charge engine into mass production on one engine line at the rate of about 500,000 per year, for the 1977 model year. [4] In June, 1974, a Ford spokesman reaffirmed and updated the statement, stating that production could begin about three model years after the NO_x standard was changed, and that the engine would probably be the CVCC concept. [19] Aside from GM's plans for the Wankel, which has no significant emissions or fuel economy advantage over the ICE, Ford's statement is the closest an American manufacturer has come to committing themselves to mass production of an "alternative" passenger car engine. It is clear that such a commitment could not have been made without a substantial program through engineering development of a specific engine. Although these programs were initiated in the Product Planning and Research Staff, the Engine Division has become heavily involved. Through May, 1973, Ford had invested about $6.5 million of its own funds in the PROCO system and had received $1.3 million from the Army. [4, p. 1037] Ford has also negotiated an agreement with Honda for CVCC technology (they have reportedly paid Honda $5 million to date) [18] and at this time the PROCO and CVCC concepts are competing with the ICE for late 1970's production. They have estimated that it would cost about $70 million to build a new engine line for stratified charge engine production, if only the cylinder head were radically changed from the ICE. [4, p. 1056]

Although they do not have Ford's long history of stratified charge engine development work and do not appear to be as close to possible production, GM does presently have an active program in this area. Their work on the "torch ignition" engine, a prechamber concept somewhat different from the CVCC, is being handled primarily on the Engineering Staff, where 50-75 people are involved in applying the concept to the 140 and 350 CID Chevrolet engines. About 30 prototype engines have been built. Some directly related combustion work is also being done at GMRL. Their much smaller program on open-chamber stratified charge concepts is entirely at GMRL, and is presently confined to single-cylinder studies. GM has had some limited interaction with Honda, but they state that their work is based on literature which was published in the U.S. and the Soviet Union in 1960. [6]

Chrysler's stratified charge development program seems to be at a much lower level of effort than GM's or Ford's. They have worked with Texaco on utilizing the TCCS concept, since the early 1950's, but at the present time they are only working with a single four-cylinder TCCS engine in a Cricket. [20] In the fall of 1973 Chrysler signed an agreement with Honda (like Ford, they have reportedly paid $5 million to date) [17] to study the CVCC engine on two Honda Civics and on two 350 CID Chrysler V-8's. [20]

Among the other industry efforts to bring the stratified charge concept to fruition, it appears that Volkswagen's is probably the most significant; it appears to be a small effort using several single and multi-cylinder engines modified to the prechamber concept. [21]

The Army's stratified charge engine program has been previously mentioned. It began in 1962 with a review at TACOM of all the potential systems which might combine the fuel economy and versatility of the diesel with the light weight and manufacturability of the ICE. The fuel economy and versatility requirements are aimed at reducing the necessary logistical support and minimizing the impact of refined fuel unavailability during war-time. As the program proceeded these aspects developed well, and the engine also appeared to have very low emissions. The NAPCA Cincinnatti laboratory tested an Army engine as early as 1968. With the passage of the Clean Air Amendments of 1970, EPA's AAPS program turned its attention to the stratified charge as a short-term alternative, and contributed a total of $550,000 in Fiscal Years 1971 and 1972 to the TACOM program to further support the low emissions aspects and then to buy several engines. Because the vehicles intended to receive the engine were designed for highway use, they are subject to emission standards, so meeting the relevant emission standards was one of the Army's goals already. In Fiscal Year 1975 TACOM is supporting the building and shock testing of fifteen 90 hp engines; White Motor Co. is building the engines to Texaco designs. Besides the White-Texaco contracts there are a number of supporting efforts examining the details of the combustion process and other aspects of the TCCS concept. As of February, 1974, Fiscal Year 1974 and 1975 funding for stratified charge work was budgeted at $1.8 million and $1.9 million, respectively.

EPA's investment in the Army program paid off handsomely toward EPA's "lever" goal when, in September, 1971, an Army jeep with a Ford PROCO engine developed by TACOM with some EPA support and tested under EPA funding, was announced by President Nixon to a Detroit audience as the first vehicle to meet the original 1976 standards. EPA stopped development funding of the Army stratified charge after fiscal year 1972 as the Army proceeded to engineering development. They have, however, continued testing and evaluation of the PROCO and TCCS engines they bought and also three Honda CVCC engines in Civics. [22]

Gas Turbine Engine

The gas turbine engine has been the object of the largest R & D programs, and come the closest to mass production of any radical alternative since the rise to dominance of the ICE. With the use of the jet engine in aircraft after World War II, each of the Big Three began development programs. Interest fluctuated until the rise of the air pollution issue. EPA and each of the Big Three now have substantial programs.

Chrysler's automotive gas turbine program has been the most publicized. [23] Design studies begun in 1939 were interrupted by World War II and did not pick up again until the early 1950's, under the direction of the Product Planning and Development Staff. An engine was laboratory-tested, and, in late 1953, a gas turbine-powered Plymouth was driven in Detroit. Continued development was supported by vehicle testing in traffic, cross-country trips, consumer reaction tours, etc. Finally a "Fourth Generation" engine was installed in fifty specially designed vehicles and, from October, 1963, to January, 1966, these vehicles were driven by 203 drivers for three months each. Chrysler felt that the gas turbine had a number of inherent advantages that would make it a valuable product: smoothness, easy cold starting with instant heat for passengers and immediate defrosting of windows, longer life and lower maintenance, reduced oil consumption, elimination of the cooling system, etc. [14, p. 2760] By 1963 they felt they had reached the point in their development when extensive consumer evalution was required.

Chrysler received a great deal of favorable publicity for the consumer test program, and the corporate management was quite pleased with it. Most of the sample drivers were "enthusiastic" about their vehicles, but there were some problems in the areas of low-speed fuel consumption, noise, engine braking and acceleration lag. High manufacturing costs remained a problem, but Chrysler seems to have had confidence that, in the long run, it could be made competitive. A fifth generation engine was designed and preliminary plans were made for production of 500 engines for sale in Dodge vehicles. However, for a number of reasons, these plans were never implemented. The technological problems mentioned above were given as the reason in September, 1967. [24, p. 2762] A more recent publication mentions "prevailing economic conditions" and required burner development to meet forecast NO_x emission requirements. [23, p. 39] It has been estimated that to repeat the fifty vehicle test program today would cost one to two hundred million dollars (including engine development).

Chrysler's gas turbine program fell to a much lower level of funding after 1966. A sixth generation engine was developed, with work on reduction of NO_x emmissions receiving increased attention. However, 1970 alternative powerplant expenditures were reported as only $100,000 [12], as engineers were assigned to ICE emissions control tasks. In December, 1972, Chrysler was awarded a $6.5 million, multi-year contract by EPA's AAPS Division to serve as their gas turbine systems contractor. Chrysler is now funding its own parallel work at the level of $1-2 million per year.

EPA's AAPS program had, from its inception in 1970, considered the gas turbine a prime candidate as a low-emissions alternative to the ICE. In mid-1971, along with the Rankine cycle engine, it was chosen for full support and demonstration. In contrast to the Rankine cycle case, however, gas turbine engines incorporating modern technology were available in vehicles. EPA therefore decided to follow a problem-solving approach, concentrating its resources in key areas. Because virtually all the modern automotive gas turbines used the same regenerative split shaft system, EPA also decided to determine whether or not this was the best long-term approach. A battery of contracts were therefore let for cost studies, cycle optimizations and low-emission burner development. An interagency agreement with NASA was concluded to provide technical assistance from the Lewis Research Center. EPA then chose Chrysler as their systems contractor, to provide a baseline engine and integrate into it the developments of the component contractors. Besides the combustor work, important developments continue on substitution of a ceramic regenerator for the metallic one used in the baseline engine (to improve fuel economy), development of a reasonably inexpensive control system (by AiResearch Div. of Garrett Corp. on subcontract from Chrysler), development of variable inlet guidevanes for the compressor, and the development (by Pratt and Whitney Aircraft Co. and AiResearch) of low manufacturing cost turbine wheels (which may or may not be used in the upgraded engine). Demonstration of the upgraded engine in a compact vehicle is scheduled for 1976. EPA is confident that the vehicle will meet its goal of one-half the original 1976 emission standards, and have competitive fuel economy. Through Fiscal Year 1973 EPA had invested $7.3 million in its gas turbine program.

GM's first automotive turbine was announced in January, 1954. Different versions were installed in a passenger car and a bus. By 1958, an improved, regenerative engine, the "GT-305", was announced, and was installed in a passenger car and a truck tractor. Up to this point the work had been performed in the GM Research Laboratories (GMRL)! The GT-305 was modified by GM's Allison Division (now part of Detroit Diesel Allison) and sold to a limited number of customers for various applications for evaluation purposes. Subsequently, responsibility was returned to GMRL, where the GT-309 was developed. [25, 26] Further evolution has resulted in the GT-404. This engine, in the 325 hp range, is a regenerated split-shaft system for heavy-duty application. A Detroit Diesel design is now in pilot production and a number are in the field being evaluated. [6 & 26, p. 4-33] GM has stated that they expect gas turbine engines to be 25% of Detroit Diesel Allison's production by 1980. [26, p. 4-33]

Work on a passenger car gas turbine engine apparently waned while the GT-309 and GT-404 were the center of attention, but passage of the Clean Air Amendments of 1970 caused GM to take another look. [27] In about mid-1971, a Passenger Car Turbine Development Division was formed on the Engineering Staff, and it has been supplemented by a task force of personnel from Detroit Diesel Allison, GMRL, Manufacturing Staff, the car divisions, etc. It has been reported that 300 people from 23 GM divisions were involved as of early 1973. [26, p. 4-33] GM claims to have met the .4 gm/mi NO_x standard with a gas turbine vehicle on a dynamometer, but with a very complex combustor configuration.

Ford's automotive gas turbine program began in 1952, [28] and, like GM's, has culminated in a heavy-duty turbine which is close to production. In 1971 a plant in Toledo, Ohio, was converted to produce annually 1000 of these engines, in the 400-500 hp range, for truck, bus, marine, generator, and other applications, automotive and otherwise. [26] Production was stopped after the first 200, however, due to corrosion problems with the ceramic regenerator. They hope to have the problem soved by late 1975, with a \$2-3 million per year development program now underway.

In 1970, as part of their evaluation of all potential alternatives to the ICE, Ford concluded that with the turbine inlet temperature limited by the use of a metal turbine, the fuel economy of a gas turbine passenger car would not be competitive. They determined through laboratory burner tests that they could probably meet the .4 g/mile NO_x standard. In contrast to GM and Chrysler, they therefore decided that rather than proceed with a prototype vehicle development and demonstration program, they would concentrate on developing ceramic components.

Later that year, in something of a coincidence, their experience and expertise in the development of ceramic compments for gas turbine engines attracted the attention of the Army and ARPA. ARPA was interested in developing and demonstrating the use of ceramics in gas turbine engines. They worked out contracts with Ford, for the passenger car application, and Westinghouse, for electric power generation. ARPA is funding a 5-year program; it began in June, 1971 with the letting of a \$10.3 million contract to Ford with Westinghouse as subcontractor.

The goal of the Ford effort is to demonstrate a gas turbine engine with uncooled ceramic high temperature components at turbine inlet temperatures of 2500^{o}F for 200 hrs. on an appropriate duty cycle. Such an engine should achieve an efficiency improvement of 20-30% and approximately a doubling of power-to-weight ratio (relative to a state-of-the-art 1800^{o}F engine) as well as significantly reduced manufacturing costs. Eventually, of course, a more appropriate passenger car lifetime (3500 hrs.) would have to be demonstrated. Ford is funding a parallel in-house effort at about \$2 million per year.

There has been, and continues to be, considerable work outside of the Big Three in this area. The world's first turbine-powered passenger car was built by Rover in England in 1950. This effort has ultimately resulted in a heavy duty truck engine at British Leyland. In the early 1950's Boeing demonstrated a truck powered by a gas turbine engine of their design. [25] More recently, Caterpillar Tractor and International Harvester have reportedly been developing heavy-duty automotive turbine engines, and Fiat and Volkswagen (in Europe) passenger car turbine engines. [24, p. 2758] The Williams Research Corp., a manufacturer of small gas turbine engines for aerospace applications, has been working on passenger car turbine engines for 18 years, often in conjunction with the major car companies. [29]

Rankine Cycle Engine

Programs for the development of automotive Rankine cycle systems presently exhibit the greatest disparities between the activity levels of the different sectors involved in automotive R & D. At the present time none of the Big Three is investing significantly in Rankine cycle technology. The Federal Government, through the AAPS Program, invested $14.4 million dollars during Fiscal Years 1969-1973, is continuing to fund the program at $2-3 million per year, and will demonstrate its system in a vehicle in 1976. Among the innovators and entrepreneurs, the last decade has seen a flurry of activity, which is actually just a peak in the stream of activity which, every five or ten years for the last century or so, has resulted in a demonstration vehicle.

These disparities result from the fact that the technology to build a

Rankine cycle vehicle whose road performance approximates that of the modern passenger car, but with lower emissions, is readily accessible to any good machine shop (unlike the Stirling or gas turbine systems, for example). However, to achieve competitive "packageability," easy start-ups, freeze protection, and acceptable fuel economy requires a substantial investment in the latest mechanical technology. The Big Three have reached the conclusion that their investments on alternative powerplants are better made in other systems. The Federal Government, partly in response to this Big Three neglect, has disagreed. The innovators and entrepreneurs have, so far it seems, over-estimated the market for the vehicles with low emissions, but with one or more non-competitive features, which they have been able to demonstrate to date. The highly polticial atmosphere surrounding the air pollution issue, the feeling that the Big Three were not giving the technology a "fair shake," faith in the application of the available modern technology, and a certain amount of nostalgic feeling toward the old "steamers" all contributed to this optimism.

GM's recent automotive Rankine cycle program took place during the years 1968-1970. Ricardo and Co. of England were hired to perform a design study; Besler Developments Co. designed, built, and installed a modern version of the old Doble engine in a Chevelle for GM; and GMRL built the SE-101 and mounted it in a Pontiac. [30, 31] The SE-101 program cost on the order of $10 million. As previously discussed, the performance of the two water-based, reciprocating, systems built was disappointing (see Appendix A). Beginning in 1970 GM began providing technical assistance and some hardware to Lear Motors. At the present time GM's only activity in the Rankine field is to "maintain cognizance of developments outside of GM." [30]

Ford's principal effort on the automotive Rankine cycle was in partial support of the work of the Thermo Electron Corp. on an organic-based system in this area. The relationship began in about 1968 and terminated in late 1973, after a total investment by Ford of over $5 million. Thermo Electron has been and remains a principal AAPS contractor, receiving $3.4 million for Fiscal Years 1969 through 1973, and they also had invested about $3.5 million of their own funds through May 1973. Ford has indicated that cooling, packaging, weight, and, most importantly, fuel economy were the limiting problems. [19]

Chrysler has apparently never had a significant Rankine cycle development effort, but they now have a subcontract from Scientific Energy Systems, the AAPS Program's principal Rankine cycle contractor, to assist them in vehicle integration.

The Rankine cycle program that has probably received more attention than any other has been Bill Lear's.[1] Lear founded Lear Motors, Inc., at Reno, Nevada, in 1968, with the intention of developing and marketing an alternative to the ICE. By May, 1973, he had invested about $15 million of his personal funds (by his own account) and had received $500,000 from the DOT (UMTA)-State of California program for a Rankine cycle bus demonstration. [33] During 1973 Lear Motors held a $900,000 contract from the AAPS Program, but they could not meet the performance they had promised, and EPA has made efforts to recover the funds. [34] As of late 1973, Lear's system used water and a turbine expander. Lear's program has apparently fallen to a low level of effort (see hybrids section).

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[1] For example, see [32].

Two other private efforts worth mentioning are those of Jay Carter Enterprises and the Williams Engine Co.[1] The Williams vehicle was a partially open cycle, water-based system with a reciprocating expander. Engines were built in several size ranges, and vehicles were built and demonstrated using the system, during the 1950's and 1960's, and received alot of publicity. In 1966 they offered, through the Steam Automobile Club of America, to sell engines and install them in vehicles, at $10,250 apiece; [35] they received ten orders but were never able to deliver due to unexpected costs. [36]

The Carter car was recently tested by EPA; it was found to be the first vehicle to meet the original 1976 standards without any catalytic converters or other exhaust gas treatment devices, but the fuel economy was termed a "major problem." Its fuel economy was 15 mpg over EPA's Federal Driving Cycle, as compared with 22 mpg for the same vehicle, a Volkswagen Station Wagon, with the standard engine. [37] The Carters subsequently stated: "We are working on our second system, it will be unquestionably superior to the ICE engine [sic] and it will just flat blow the lid off this thing." [38] An AAPS official stated that EPA had provided some technical advice to Carter, that it looked like the engine was a "good piece of work", and that, even though they had made extensive efforts to contact everyone working on automotive Rankine cycle technology, there seemed to be a reservoir of back-yard mechanics working on automotive steam engines.

The only vehicle manufacturer now actively engaged in automotive Rankine cycle development is Saab Scania in Sweden. Theirs seems to be a comprehensive but small program, very far from production. [39]

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[1]No relation to Sam Williams of Williams Research Corp.

The first Federal R & D effort on automotive Rankine cycle systems was supported by the Urban Mass Transportation Administration of the Department of Transportation. Grants were made to the State of California and the City of Dallas for Rankine cycle-powered buses. Four different buses were designed (one was Lear's), built, and tested in local transit service. The program was completed in December, 1972. In general, the results were very disappointing, especially in fuel economy as compared to the conventional diesel systems. [1] The California State Assembly has followed the bus program with the California Clean Car Project. The Aerojet Liquid Rocket Co. and the Steam Power Systems Co. have contracts under the project to design and build Rankine cycle-powered passenger cars. Testing of the vehicles by State Agencies was scheduled to begin in July, 1974, and be completed several months later.

The EPA Rankine cycle program is presently the major effort in this area. The Government's interest was attracted in the late 1960's by the obvious potential for low emissions from the continuous, atmospheric pressure, external combustion used in Rankine cycle systems. The first contract was let in 1969 to Thermo Electron Corp. for a preliminary design study. With the establishment of the AAPS program and its concentration on shorter-term systems, the Rankine cycle joined the gas turbine as the focus of EPA's development efforts. Because there was neither a generally agreed upon choice of key design parameters nor an acceptable "baseline" engine (in contrast to the gas turbine) EPA chose to fund four competing system contractors: Lear with a water-based turbine system, Scientific Energy Systems (SES) with a water-based reciprocating system, Aeroject Liquid Rocket Corp. with an organic-based turbine system, and Thermo-Electron Corp. with an organic-based reciprocating system. In late 1973 the SES system was chosen for development through the vehicle demonstration, with support of Thermo Electron continued at a lower level through engine prototype, as a back-up. The SES engine will be demonstrated in a compact car in 1976. [40] It will incorporate the work of a number of EPA's component contractors. The emissions target of one-half the original 1976 standards will be met, but the fuel economy will be somewhat lower (10-30%) than comparable ICE-powered vehicles. Through Fiscal Year 1973 EPA had invested $14.4 million in its Rankine cycle program.

Stirling Cycle Engine

The Stirling cycle engine offers possibly the best long-term prospects for low emissions and high fuel economy. It uses external combustion like the Rankine cycle, but has a theoretical thermal efficiency as high as the maximum thermodynamically possible. It has a number of very important engineering problems, however, which have limited interest in it for mass production applications. Most important among them are the cost of the heater head which consists of many small tubes of expensive metal alloy, the lack of a simple mechanism for controlling the power output while maintaining thermal efficiency, and difficulties in containing the gaseous working fluid.

The modern development of Stirling cycle power systems has principally been accomplished at the Philips Research Laboratories, Eindhoven, Netherlands, the main part of the research arm of N.V. Philips.[1] Their program began in 1938; it was initially intended to meet a demand for quiet generation of electric power for radios at remote sites, but the invention of the

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[1] N.V. Philips is the eighth largest industrial corporation in the world according to the August, 1974, Fortune rankings. They are known in the U.S. for their Norelco line of electrical appliances.

transistor virtually eliminated the demand. The automotive application is only one of a large number that Philips has explored in its continuing efforts. [41] Estimates of Philips' total investment in Stirling technology range up to $100 million. United Stirling, a Swedish firm, half privately and half government-owned, bought a license from Philips and has also been actively developing an automotive Stirling engine. Two German licensees MAN and MWN have built heavy-duty engines and demonstrated one in a bus. Philips (at their Aachen, Germany, laboratory) has also worked on an electrically charged heat storage system for use with its Stirling engine.

GM was a licensee of Philips from 1958 to 1970, and invested $10-15 million in Stirling technology during that time. [30] The analysis, design, construction and testing of a number of engines was involved, including 25,000 hours of operating experience. [42] The program was terminated by top management when it appeared that several key problem areas could not be overcome within the then-forseeable future. "GM believes the Stirling engine to be unsuitable for passenger car use." [30]

In about 1970, Ford conducted an in-house review of Stirling technology. Philips at this time was actively seeking a licensee in the American automobile industry to replace GM. [41] After considerable technical dialogue and some in-house testing at Ford, Ford management became optimistic with respect to the key problem areas and proceeded to negotiate an agreement with Philips, in 1971, and another with United Stirling, in 1972. [19] At the present time there is a three-way set of coordinated agreements, giving Ford access to all the relevant technology at United Stirling and Philips, and, subject to some minor limitations, an exclusive license for worldwide application of the technology to passenger cars. With Philips, Ford is jointly engineering a 170 hp engine for installation in a Torino late this year. The United Stirling effort will develop a 55 hp engine and will mount it in a Pinto. The program is being managed by the Product Planning and Research Staff at Ford.

In mid-1975 Ford will reach a major decision point on its Stirling program. If "proof of principle" has been demonstrated in the vehicle tests then a second four-year effort aimed at a pre-production version will be undertaken. Here the emphasis would be on optimizing the fuel economy and other performance characteristics, and the manufacturing costs, while meeting the emission standards. Should this effort reach a satisfactory conclusion, the responsibility would be transferred from the Product Planning and Research Staff to the Engine Division, and mass production could begin as early as four years later. It appears at this time that the key technical "barrier problem" is the cost of the heater heads. If it appears that a major advance is needed, then the engine program would probably be stopped and Ford would consider approaching the Government for support of basic work in the area.

The Ford program is presently the only significant automotive Stirling program in the United States. Like the case of the gas turbine, the modern Stirling engine may be considered "high technology," requiring a substantial resource commitment in order just to put a presentable vehicle on the road. Unlike both the gas turbine and Rankine cycle engines, it is clearly a high risk item, involving several problems for which an incremental development approach will probably not be adequate, and, furthermore, there is little experience with the system in the United States. The features have resulted in a situation where, similar to the gas turbine, there are no American "innovators" demonstrating vehicles or even selling technology and only the automobile manufacturers have had significant continuing programs.

Because of the potentially low emissions and high fuel economy a number of Government programs have been recently proposed by EPA and FEA, but none have been implemented. EPA's is aimed at a passenger car engine along the lines of Philips'. FEA has proposed the development, in stages, of a passenger car using a Stirling engine powered by a heat store. Heat would be transferred from the store to the engine by a heat pipe, eliminating the need for an on-board combustion system. The store could be "charged" at the owner's residence either electrically, or from a combustion system or solar heat. The first prototype would be a 10 hp engine in a "minicar." FEA has also proposed the development of heavy-duty engines, in the 400 hp range for trucks and in the 3600 hp range for locomotives. FEA estimated the cost of these programs at about $32 million over five years.

Battery-Powered Electric System

There is a long history of electrically driven vehicles, as there is with steam engines. Since the early days of the automobile industry it has been relatively easy, using lead-acid batteries and off-the-shelf electric motors, to build a vehicle which looks and behaves more-or-less like the commercial passenger cars of the day. And since the early days the fundamental problem has been the same: the total energy that can be stored in a reasonable weight of batteries limits the vehicle's range, and the rate at which batteries can be drawn down without significantly reducing the total available energy limits the vehicle's speed and acceleration. Other batteries besides the lead-acid system are available and can somewhat alleviate either the power or the range limit, at considerable cost, but it remains the battery which is the key technological defect of the electric car.

The air pollution and energy issues focused renewed interest on electric vehicles. However, in neither area would the widespread replacement of ICE-powered passenger cars be the panacea that has sometimes been suggested. It would, however, change the impact of personal transportation in ways that might ease both problems. An electric vehicle does not emit air pollutants, but does cause an increase in load and thus emissions from the powerplant which was the source of electricity for its battery. Thus NO_x, CO and hydrocarbons on the street are traded for NO_x, SO_2, particulates and heat, or radiation and heat, at the powerplant. Similarly, a requirement for gasoline is replaced by a requirement for electricity. There are some complicated trade-offs which must be made. EPA has funded a detailed examination by the General Research Corp. of these tradeoffs for the Los Angeles, St. Louis and Philadelphia areas.

There have been two main trends in the development efforts on the electric vehicle. The first has consisted of the many attempts to develop a vehicle using lead-acid or other off-the-shelf batteries and market it for some specialized use, usually involving short trips in urban areas, e.g. mail or retail delivery, or the "urban car" for short-range commuters or urban housewives. A large number of companies, including all the Big Three, have worked on this approach; among them have been the firms now involved in production of golf carts, fork lifts, coal mine equipment, and the like. In no case has anything like mass production been approached in the U.S.[1] It is, however, generally agreed that electric vehicles using lead-acid or other currently available batteries can never satisfy more than a negligible fraction of the passenger car demand. EPA has suggested the possibility that such vehicles could be brought into use in areas with major air pollution problems through government regulation. [43]

The other major R & D thrust has been on advanced batteries, which would make an electric vehicle competitive in performance and, hopefully, cost. A number of companies involved in manufacturing batteries, for one use or another, are engaged in R & D in this area,including Ford and GM. It is possible, if not even likely, that this reasearch will result in a viable passenger car prototype within a decade or two. It has been estimated that a total of $4-6 million per year of public and private funds are now being invested in battery research in the United States and a slightly smaller amount in Western Europe and Japan. [44]

A third, less important, area which has been considered as part of an electric drive system is the fuel cell. A fuel cell would convert the chemical energy of on-board fuels directly to electricity, much like a continuously replenishing batter. However, while fuel cell technology continues to be developed for space and several other uses, due to a number of formidable problems there are no programs to apply it to motor vehicles.

GM has been involved in electric vehicle development for over a decade. In the early 1960's studies in the Engineering Staff on the

[1] In 1967, however, it was estimated that there were approximately 40,000 electrically powered urban delivery trucks in Great Britain, although this corresponds to a production rate of only several thousand a year.

potential for motor vehicles of electric power technology developed in the space program led to the building of a prototype in a Corvair body in 1964. They refer to it as "Electrovair I"; it used silver-zinc batteries supplied by Yardney Electric Co. A second prototype, with improved controls, was built in 1966. [45] "Electrovair II" was designed to perform like a contemporary passenger car except in range, which was 40-80 mi. on a single charge. [46] "Electrovan," a light delivery van-type vehicle was also built in 1966 using a hydrogen-oxygen fuel cell supplied by Union Carbide. [46] The purpose of these vehicles was to confirm that, in fact, power source performance and cost were the limiting factors in electric vehicle development and to better define the requirments on an electric power source in this application. These objectives being completed [47] responsibility for GM's electric vehicle activities was returned to GMRL.

GM has been active in battery development since 1959. [30] Aside from an interest in electric vehicles, GM also is a major producer and marketer of batteries through its Delco-Remy Division. The battery research program at GMRL now involves about 20 professionals. Until about one year ago, the principal effort was on the lithium-chlorine battery which showed excellent performance but required the storage of chlorine gas at 650°C, causing obvious problems. Attention now centers on the lithium-sulfur cell.

Ford also has a long-standing interest in electric vehicles and advanced batteries. In 1967, Ford and its subsidiary, Ford of Britain, designed and built the "Comuta," a 1200 lb., 6 ft. long vehicle, with a top speed of 40 mph, designed for inner city use. [46, 49] This was followed in 1970 by an electrically powered "Cortina Estate Car," which weighed 3100 lbs. and had a top speed of 60 mph. 100 lb. of nickel-cadmium batteries gave the vehicle a range of 40 mi. at a constant speed of 25 mph, or 18 mi. on the Ford City Economy Route. Above 30 mph its acceleration and passing ability were limited. [49] Since these exercises, Ford's vehicle work has been primarily concerned with computer simulations and design studies optimizing the characteristics of electric vehicles to satisfy various markets. [19, 50]

In the battery area, Ford's Scientific Research Staff has developed the sodium-sulfur cell. Although this system does not match the potential performance of the lithium-chlorine system, its performance could be adequate for passenger car usage, and it does not involve the safety hazard of compressed chlorine. It still needs to be kept at 300^{o}C, however. Small laboratory cells and batteries of cells have been demonstrated, but a substantial effort over the next fifteen years or so is likely to be required before a marketable product will be ready. [19, 51] Ford's program is now under partial NSF sponsorship ($700,000 in Fiscal Year 1973, $900,000 in Fiscal Year 1974, and continuing).

Chrysler has no significant electric vehicle programs, although they have been actively following a number of the other programs with consultations and visits.

Outside of the Big Three, a large number of companies have fielded an electric vehicle of some sort within the last decade or so. Among them, Battronic Truck applied to the Federal Government's Low Emission Vehicle Certification Board for designation as a low-emission vehicle under the Clean Air Act, which would allow the Government to buy their vehicles at a premium price. They were refused once because their vehicles did not meet the performance requirements of the Federal agencies, but have applied again.

The U.S. Postal Service is now conducting the largest American program on vehicles with lead-acid cells. In 1972 the USPS initiated a program to evaluate the potential for state-of-the-art electric vehicles using lead-acid batteries to fulfill various USPS vehicle missions. The typical USPS delivery mission profile, for example, appears quite favorable to electric vehicles as it is a short range, multi-stop, closed cycle with a lot of idle time and only moderate speeds and accelerations. The USPS paid for the design and fabrication of three different quarter-ton capacity electric vehicles, which were built and went into testing in early 1973. Subsequently thirty vehicles of a single, different, design were leased. Testing of these vehicles in various areas of the country, under different weather conditions, and on various types of routes, continues at this writing. However, the results have been sufficiently favorable that the USPS decided to proceed with an initial procurement; in April, 1974, AM General was awarded a contract for delivery of 352 electric vehicles.

In the advanced battery area there are a number of efforts underway aside from those at GM and Ford. TRW, Dow Chemical, General Electric, Gould, Exxon and Atomics International each have programs with four or more professionals at work. The largest program, however, is at the Argonne National Laboratories, under Federal Government support, with a staff of about 25. [52] The AEC has supported the ANL program since 1965. It has been an exploratory program, presently aimed at a lithium-sulfur battery for electric utility load-leveling. At various times the AEC funding has been supplemented by other agencies to examine the application of the ANL Li-S system to automotive uses. ANL received $350,000 and $480,000 from EPA's AAPS Division in Fiscal Years 1970 and 1971, respectively. The NSF then picked up the automotive application program and carried it through November, 1973, when the AEC became the major supporter with some contribution from DOT. Total Fiscal Year 1975 funding of the ANL battery program is $3.3 million, consisting of $2.7 million from the AEC for the basic and utility work, $500,000 from the AEC for development of an Li-S battery for automotive application, and $100,000 from DOT for design and testing of automotive Li-S batteries.

Heat Engine Hybrid System

The potential advantages of hybrid systems have been the subject of much debate over the past decade. In the automotive context, the term hybrid is usually used in reference to a combination of a heat engine with some other sort of drive which runs off an energy storage system.[1] The potential advantage is that the heat engine can be sized at less than the peak vehicle power requirement, and then operated in an on-off mode, either running at a single optimum setting or not running at all. In the simplest configuration, the vehicle would be powered only off the storage system; the heat engine would come on and recharge the storage system whenever its energy content got below a specified level. The advantages

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[1] The Army uses the term "hybrid" in reference to stratified charge engines.

of small size and single-point operation could significantly reduce the fuel consumption, emissions, and cost of the heat engine. These potential advantages must be larger than the weight, cost, and inefficiencies of the other drive, the energy storage unit, and the associated transmission and controls.

GM built two hybrid vehicles in the mid-1960's. Both used batteries and an electric drive; one used an ICE and the other used a Stirling cycle powerplant for the heat engine. GM found them inefficient, heavy, costly and disappointly high in emission levels. [30]

At the outset of the AAPS program, EPA commissioned a number of studies and experiments with hybrids, considering various types of heat engines, and either batteries with an electric drive or a flywheel and a mechanical drive. A total of $1.8 million of Fiscal Year 1970 and 1971 funds were invested. Before the work was completed, EPA had changed its program structure and concentrated its money on less risky systems. However, the results generally indicated that hybrid vehicles were not very promising.

Two private companies have recently invested in hybrid systems. Petro-Electric Motors, Ltd., of New York City designed and built a hybrid using an ICE and batteries. [53] After investing several hundred thousand dollars of their own money (according to one estimate) they submitted their vehicle to EPA for testing under the Federal Clean Car Incentive Program. The results were mixed and are not yet completed, but they received about $25,000 from EPA under the program.

The other company is Lear Motors. Their latest venture is a design for a bus using a Rankine cycle heat engine and a flywheel, for which they are soliciting further support. [54]

There is little other interest or programs on hybrids at this time. A related project, however, is now being supported by DOT's Urban Mass Transportation Administration. They are supporting the development of a "flywheel trolley," which would use electric power from its lines to energize a flywheel, allowing it to travel beyond the routes covered by its electricity supply. $610,000 of Fiscal Year 1974 funds have been allocated to the project.

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