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GAS TURBINE ENGINE PRODUCTION IMPLEMENTATION STUDY

VOLUME I: EXECUTIVE SUMMARY

D. E. Lapedes, et al

JULY 1973
FINAL REPORT

Prepared for:

DEPARTMENT OF TRANSPORTATION

OFFICE OF THE SECRETARY
Office of Systems Development and Technology
Washington, DC. 20590

U.S. DEPARTMENT OF TRANSPORTATION

TRANSPORTATION SYSTEMS CENTER
55 BROADWAY
CAMBRIDGE, MASSACHUSETTS 02142

11 October 1973

Mr. J. Weaver, AMR
Transportation Systems Center
Room 1252 M-Building
55 Broadway
Cambridge, Massachusetts 02142

Dear Mr. Weaver:

In assessing future national transportation needs, it is essential to consider alternative automotive power plants. Of the many alternative engines, the gas turbine is the one nonconventional type about which we know the most at this time. The Department of Transportation, in conjunction with the Environmental Protection Agency, has selected this engine type as the basis for a study of mass production implementation factors and potential schedules so as to provide a wider public understanding of the implementation process.

We commissioned the Aerospace Corporation of El Segundo, California, to conduct the study which has now been completed. The results are documented in the two-volume report entitled "Gas Turbine Engine Production Implementation Study." Knowing of your interest in this subject, we have enclosed a copy of the report.

Sincerely,

George Kovatch

George Kovatch
DOT Project Officer

GK/ms

Enclosure

DOT F 1320.1 (1-67)

IITED STATES GOVERNMENT

Memorandum

DEPARTMENT OF TRANSPORTATION
OFFICE OF THE SECRETARY

DATE: September 20, 1973

In reply refer to: TST-44

UECT: Gas Turbine Engine Mass Production Study

OM : Assistant Secretary for
Systems Development and Technology

: The Secretary

I am pleased to transmit a two-volume report, "Gas Turbine Engine Production Implementation Study," which documents the results of a research effort to assess the major factors that affect the capability of the automobile industry to implement mass production of automotive gas turbines. The subject of alternative automotive engines is of considerable interest to this Department, the Environmental Protection Agency, and the Council on Environmental Quality.

The study indicates that on a normal business risk basis, mass production of approximately 300,000 gas turbine engines for cars annually may be possible in ten years, assuming that difficult technical and production problems can be overcome in a timely way. At a greater risk to the customer and the industry, the schedule might be accelerated by two years. The three main production problems relate to investment casting of super alloys for turbine wheels, and production of regenerators and fuel controls.

The Council on Environmental Quality had asked the Department to consider the mass production aspects of alternative automobile engines and former Secretary Volpe accepted the responsibility. The Department has undertaken two principal studies on mass production of alternative engines. The first, dealing primarily with social and economic impacts of conversion to nonconventional automotive power plants, was completed last spring. The second, concerning mass production implementation, is the subject of this report. The Department believes that this study provides valuable information on the significant factors involved in implementation of mass production of gas turbine engines for cars and on production schedules. It is a step towards a better understanding of this important phase of transportation systems development and should prove of value to the Department and to all those interested in the subject.

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16. Abstract

This report presents a summarization and assessment of available information pertaining to the potential for implementing mass production of gas turbine engine-powered automobiles. The main topic covered is the schedule requirement for that implementation. Emphasis has been directed toward identifying those critical or limiting factors affecting timely introduction of gas turbine engine concepts on a mass production basis. A description of basic automotive product development phases, engine manufacturing processes, and gas turbine engine current technology status are included to clarify and augment the discussions, and to permit the necessary understanding of the developed implementation schedules.

Based on data acquired during the period February 28 to April 30, 1973, a period of 8 to 10 years is a best estimate of the elapsed time until 300,000 gas turbine engines are mass produced annually. This estimate is based on a postulated overall product development schedule of slightly more than 11 years. Prior to major commitment of capital resources necessary for adherence to this schedule, automobile manufacturers must resolve three major issues: 1) improvements in engine fuel economy and exhaust emissions, 2) development of new mass production fabrication processes directed at reducing engine unit cost, and 3) statistical evidence of engine durability in fleet test cars.

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PREFACE

This report, prepared by The Aerospace Corporation for the U.S. Department of Transportation (DOT) and the U.S. Environmental Protection Agency (EPA), presents an assessment of available information pertaining to implementing mass production of gas turbine powered automobiles.

The status of the technology and implementation schedule visibility reported herein is that existing at the time of data acquisition visits made to selected firms and agencies during the period February 28 through April 30, 1973. The results of this study are presented in two volumes. Volume I, the Executive Summary, presents a review of important findings and conclusions in the Highlights and Summary sections. Volume II, the Technical Discussion, provides a comprehensive discussion of each study topic and is of interest primarily to the technical specialist. In Volume II a brief discussion of automotive gas turbine engine design approaches and current and advanced technology status is given in Section 2. The reader well-versed in gas turbine engine technology could, without loss of continuity, commence with reading Section 3 which gives an examination of the critical factors involved in automotive gas turbine engine mass production. Section 4 discusses the status of industry progress in automotive gas turbine technology and production development, the potential for converting this experience to the development and production of automotive systems, and the currently postulated product development schedule for a gas turbine powered automobile. For a broad overview of the subject of mass production of gas turbine engines the reader is directed to Section 5 which briefly delineates the potential impact of gas turbine mass production on the automotive industry and on the general public. A brief summary of the current views predominant in each of the automotive and gas turbine firms visited during the course of the study is given in Section 6. Section 7 presents an assessment of gas turbine mass production viability, in terms of current potential and possible government roles for enhancing production viability. Appendix A contains a listing of companies and agencies contacted in the data acquisition phase of the study. Appendix B contains the

Bibliography. Appendix C presents a brief description of the EPA Advanced Automotive Power Systems Brayton Cycle Program.

Appreciation is acknowledged for the guidance and continued assistance provided by Dr. George Kovatch of the Department of Transportation Systems Center, Mechanical Engineering Division, who served as DOT Project Officer for this study and Mr. F. P. Hutchins of the Environmental Protection Agency, Division of Emission Control Technology, who served as EPA Contract Project Officer.

The following technical personnel of The Aerospace Corporation were major contributors to the assessment performed under this contract:

L. Forrest
F. G. Ghahremani
O. Hamberg
W. U. Roessler
W. M. Smalley

D E Lapedes

D. E. Lapedes, Manager
Gas Turbine Implementation Study
The Aerospace Corporation

Approved by:

Merrill G. Hinton

Merrill G. Hinton, Director
Office of Mobile Source Pollution
The Aerospace Corporation

Toru Iura, Associate Group Director
Environmental Programs Group Directorate
The Aerospace Corporation

Joseph Meltzer, Group Director
Environmental Programs Group Directorate
The Aerospace Corporation

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HIGHLIGHTS

Based on data acquisition visits and technical discussions during the period February 28 to April 30, 1973, and other information in the literature, an assessment was made of domestic manufacturers' product development activities, and future plans that impact on the potential for implementation of mass production of gas turbine engine-powered automobiles. A best estimate of the elapsed-time until 300,000 units are mass produced annually is about 8 to 10 years. This estimate is based on a postulated overall product development schedule of slightly more than 11 years. Adequate durations for development and test periods are included in this schedule so as to diminish the manufacturer's risk in proceeding with successive phases of the program. A continuation of program activities and the decisions for commitment of capital funds are contingent upon the automobile manufacturer's assessment of three primary issues: (1) new fabrication processes and reduced mass production manufacturing costs, (2) continued gas turbine technological developments, and (3) experimental verification of durability in typical driving cycles.

With regard to the first issue, three main elements of the gas turbine engine present requirements for new mass production fabrication processes. These engine elements are the regenerator, the fuel control system, and the turbine section. Current manufacturing cost estimates are high for meeting automotive mass production standards in the U.S. with this engine. Attempts at cost reductions have not progressed far enough at this time to offer any optimistic projections. Some efforts at developing new processes with potentially lower costs are in progress.

Concern with the second issue is concentrated on improvements in exhaust emissions and fuel economy: Progress to date in this area has been good and continued funding of development programs by the Federal government along with independent company-funded efforts offers a reasonable chance of meeting initial engine performance goals in the next 2 to 3 years.

The third issue, durability in operating service, remains to be proven in laboratory tests and, more importantly, in actual road tests. Without evidence of durability in service, customer confidence in gas turbine powered automobiles cannot be expected. The manufacturer's financial risk associated with a high potential for recall or increased warranty problems, can be a deterrent to introduction of mass produced gas turbine engines.

If technological goals are achieved, then proof of engine durability and competitive manufacturing costs is required within the next 2-1/2 to 3 years in order to adhere to the postulated 11-year schedule. All three issues must be resolved before automobile manufacturers will have the incentive to commit capital funds for factories and foundries needed for production of gas turbine engines.

In support of the forementioned issues, the following results from the study are highlighted:

A. <u>Mass Production Schedules</u>

1. A best estimate mass production implementation schedule assessment indicates that a total program duration of slightly over 11 years is required to result in gas turbine-powered automobile production at an initial rate of approximately 300,000-plus units per year. This is considered to be a schedule with adequate development and test periods so as to diminish the manufacturer's risk.

2. This implementation schedule incorporates a 4-year period for Concept Development; two years for Research Prototype Development; 44 months for Engine Pilot Plant Installation, Proveout, and Start-up; 3-1/2 years for the Vehicle Production Program Phase (including fleet testing); and a 4-year period for Engine Mass Production Plant Installation and Production Buildup (with a concurrent car line production development program). These various phases are overlapping in conformance with established automobile production development schedule requirements.

3 This 11-year implementation schedule is a reflection not only of the current automotive gas turbine limited technology status with respect to installed performance, overall system configuration selection, and component manufacturing processes, but also of the relative lead time schedule requirements of the automotive industry for the various phases of the automotive product development cycle.

4. An additional timing factor must be considered in estimating implementation schedules, and that is the need to provide a variety of engine sizes to support a given manufacturer's mix of car models. Information on schedule extension needed to provide a variety of engines is recognized but was not addressed at this time.

5. Chrysler indicates that the 11-year period could possibly be compressed to 8 years by telescoping the various schedule tasks. However, this would increase the total costs and the manufacturer's financial risk relative to recall and warranty problems. In particular, the cost of tooling would probably increase because any new tooling developments which become available after the start of the schedule could be incorporated only by replacing the tooling already designed and built.

6 Chrysler is currently underway in the Concept Development Phase of the implementation schedule under a 3-1/2 year, $6.5 million contract awarded by EPA in December 1972. This effort, referred to as the Baseline Gas Turbine Development Program, covers the improvement and demonstration of an automotive gas turbine powerplant using the existing sixth-generation Chrysler engine as the baseline configuration for further development.

7. Ford is currently conducting a 9-month Vehicle Application Study prior to making a decision on proceeding further into the Concept Development phase.

8. General Motors is conducting a passenger car development program. Their efforts have progressed to the early phases of pre-prototype engineering design and manufacturing technique evaluation. However, no final engine type selection has been made.

9. A reduction in the time allocated to the development schedule normally can only be brought about by the need of the automobile manufacturer to meet competition and a willingness to assume greater risks. If the government wishes to accelerate the development schedule, and not rely on normal market competition to control engine development, it would have to provide additional funding support. The current EPA-AAPS program is concentrated on engine and vehicle performance problems. To expedite development effort, the Federal government could consider support of low-cost manufacturing processes and their verification in a simulated production line or pilot plant operation.

10. The role of the Federal government in development of the gas turbine engine for production is viewed with mixed reactions by all manufacturers concerned. Government programs with the objective of enhancing

technological development are viewed quite favorably. In fact, the current EPA-AAPS programs appear to have stimulated automotive industry interest in gas turbine engine development. However, programs that involve manufacturing processes are viewed differently. Government funding directed at solutions to engine production problems would save the manufacturer from expending his own funds and stimulate his interest, but a requirement to reveal unique production processes is viewed as detrimental to a company's competitive posture if the techniques have evolved from proprietary company-funded work.

B. Mass Production Process Developments

1. Mass production (100,000 plus unit per year) of gas turbine engines of any type has never been approached. Engine production rates for aircraft applications are relatively low. For example, United Aircraft of Canada, Limited, a manufacturer of relatively small turbine engines, produces about 300 units per month. In contrast, rates as high as 35,000 engines per month per assembly line are not uncommon in the automotive industry.

2. Heavy duty gas turbine engine programs at Ford and General Motors for industrial, truck, and bus applications are based on eventual production rates considerably below passenger car requirements. These programs do not require the mass production technology of the passenger car in order to be competitive with diesel engines, nor do they require technology and production process-development efforts to meet stringent emission control levels and costs that are competitive with conventional passenger cars.

3. The gas turbine engine is not as adaptable to mass production processes as the piston engine. The gas turbine has two-thirds the number of parts as the piston engine; however, the piston engine has many duplicate parts so that the number of steps in manufacturing the piston engine is less overall than the gas turbine engine. Furthermore, the machining characteristics of exotic materials required in fabrication of the gas turbine engine is a very important consideration.

4. Process factors critical to the mass production process for gas turbines are associated primarily with fabrication of components prior to delivery to the engine production plant. These components include ceramic regenerator cores, fuel control units, and investment castings (or alternate processes such as the United Aircraft proprietary Gatorizing process).

5. The mass production technique for ceramic regenerator cores remains to be fully developed and finalized. The first such cores had problems with cracking, leakage, and heat transfer effectivity.

Corning Glass Works has developed a glass-ceramic matrix, called Cercor, which can be used to manufacture the core. Ford has used this material and claims to have resolved most of the previous technical problems.

6. The design of automotive gas turbine control systems is in a state of flux. Until a specific design philosophy or system is selected, the mass production-related problems are not fully determinable. Once a system is selected and developed, no unusual mass production problems are foreseen. However, efforts must be directed at reducing the present high cost of the fuel control unit.

7. The present processes used in the United States to produce precision investment castings for compressor and turbine components are complex and expensive. While cost-effective for low-production-rate aircraft and diesel engine parts, the casting process is considered to be one of the most critical cost factors for automotive gas turbines. Current investment casting production rates range from 3 to 5 parts per hour. The time cycle from mold-making through casting is approximately 70 hours; the primary controlling factor on production rate is the drying time required for the ceramic molds. In contrast, the current production rate for V-8 piston engine block sand castings is about 155 parts per hour per line.

8. The U.S.S.R. has developed an investment casting process which reduces the production cycle time to approximately 24 hours. The operations have been automated to a point where castings are produced at the rate of 120 parts per hour per line. However, since the metals poured were apparently not Inconel or other high-temperature alloys, it is not known whether the process will permit use of these materials. Also, data on cost per unit produced are not available.

9. The extensive design and test efforts of the automobile manufacturers to reduce manufacturing costs and ensure a reliable product will have to carry over into the supplier industries. Aircraft and industrial gas turbine component designs must be reexamined for low-cost tooling, casting, and machining potential at production levels of 100,000 to 1,000,000 engines per year. There is also the need for suppliers of major components, such as regenerator/recuperators and electronic fuel control systems, to evaluate low-cost manufacturing techniques for high production levels that historically have not been associated with these components.

10. Indications are that there is insufficient capacity in the machine tool industry and in the sheet metal forming industry to match the needs for a gas turbine engine program designed for 10 to 12 million engines per year unless the transition takes place over a period of several years. Even if only 300,000 engines per year were initially manufactured by each firm, it would still be a problem for these industries to meet a sudden demand.

11. The gas turbine engine requires considerably more ductile iron castings than the piston engine. Ductile iron castings are not as available as gray iron, are more difficult to produce, and have a lower foundry yield. The production of large quantities of ductile iron would probably require changes in current gray iron foundry operations. This relates to finer control of material purity and furnace temperatures.

12. The potential problem of supply of cobalt, niobium, and molybdenum needed for high temperature alloys in the turbine section of the engine, will remain until foreign sources agree to expand their mine production capacity. To bring about this expansion, industry and/or government negotiations will have to be initiated to provide some assurance that the required capital investment will prove beneficial to the mine owners; e.g., that the gas turbine engine can be expected to be produced in large quantities for a number of years with a continued need for these raw materials. All other raw materials should be adequate in supply, and the rolling capacity of the steel industry appears capable of meeting the expanded needs for stainless steel sheet.

13. The total capital investment for industry production of 1 million gas turbine engines per year has been estimated by one source at approximately \$400 million (\$140 million for machine tools and \$260 million for facilities, transfer equipment, etc.).

14. Another source has estimated that the capital investment funding required to accomplish a complete conversion to total gas turbine automobile production will be \$5 to \$6 billion. The size of this investment and its possible impact on corporate profit structure may pose a problem to the automobile industry.

15. The high capital requirement, and other economic impacts, including the dislocation of existing labor markets and skills, militate against an accelerated production changeover to gas turbine automobiles. Foundry workers, machinists, assembly line workers, and workers in after-sales repairs are affected. Additional capital investments of unknown amounts are required for equipment to produce processed materials and purchased parts received at the engine manufacturing plant. Not to be overlooked are the investments in after-sales engine repair and maintenance facilities.

C. Gas Turbine Technology Development

1. Most vehicular gas turbines under present development are of the regenerated free turbine type wherein a high-pressure turbine drives the compressor and a low-pressure turbine provides useful shaft power output (similar to the Chrysler sixth generation gas turbine). This split-shaft configuration provides flexibility of operation, especially with a variable power turbine nozzle to provide high torque at low turbine speed and to brake the engine. A conventional three-speed automatic transmission, as used with the spark-ignition engine, is satisfactory for this gas turbine configuration.

2. A single-shaft gas turbine, which is smaller in size and lighter in weight than the free turbine arrangement, has torque-speed characteristics which are not compatible with conventional automotive transmissions. This engine type requires a wide-range multiple-step or continuously variable gear-ratio transmission, such as the Infinitely Variable (IV) transmission. This type of transmission is new and its feasibility has to be proven in extensive tests.

3. The two gas-turbine-engine goals of good fuel economy and low NO_x emissions tend to be conflicting objectives. Good fuel economy requires either regenerative heating or high compressor pressure ratio, both of which result in high combustor inlet temperatures and high NO_x emissions. A variety of unique combustor design approaches are currently being investigated to minimize NO_x formation.

4. The fuel consumption of a highly regenerated engine with a compressor pressure ratio in the range of 4:1 to 6:1 can be improved by about 20 percent by increasing the turbine inlet temperature from 1800°F to 2500°F. Ceramic combustors and turbine nozzles and rotors offer potential capability in this temperature regime. Ford and Westinghouse are investigating the applicability of ceramics under a $10.3 million contract with ARPA. Considerably more development work is required to demonstrate ceramics feasibility in gas turbine components.

5. Water injection (at the compressor inlet or into the combustor) during the maximum power requirement of the gas turbine engine results in an increase in turbine power, thus offering the potential for reducing the engine size for a given application.

D. Durability in Service

1. Principal driveability considerations for the gas turbine-powered car concern standing-start response (lag from idle to required power level), transient acceleration, and braking behavior. In general, the gas turbine car does not have the standing-start response of a conventionally powered vehicle. However, Ford reported that a 1966 Thunderbird with

a model 706 gas turbine engine had acceleration performance that was slightly better than with the standard 428 CID spark-ignition engine. A variable power turbine nozzle may be used to assist in vehicle braking.

2. The noise level of a gas turbine engine is higher than that for the internal combustion engine due to high inlet velocity flow and interference effects. Exhaust noise silencers may be required for the gas turbine automobile. However, the present Chrysler sixth-generation gas turbine engine package is reported not to require exhaust mufflers. The vibration level of the gas turbine engine, on the other hand, is lower than that for the reciprocating engine due to the balanced rotary motion.

3. Although the gas turbine engine itself is compact, the air intake and exhaust ducts tend to be large (five times the air flow of a comparable internal combustion engine), and these have to be packaged properly to meet reasonable envelope requirements and to provide sufficient ground clearance. Such requirements can be incorporated into a new vehicle design, but would be both difficult and expensive to incorporate into existing vehicle designs.

4. Maintenance and durability characteristics of the gas turbine-powered car are generally judged to be superior to the conventionally powered car, based on limited analyses made to date. However, there is a potentially serious service problem for regenerated gas turbines involved with the high frequency of maintenance that has been encountered with the regenerator seal. This seal problem would have to be solved before the regenerated gas turbine would be placed in mass production.

The implementation schedule assessment noted previously is a reflection of the inherent requirement in mass production processes (on the scale of approximately 10 million cars produced per year) to completely define and refine the manufactured product so that the financial risk is at a minimum. Technological breakthroughs in the manufacturing process can greatly reduce the manufacturing development phase of the implementation schedule, but this would not necessarily shorten other phases of the schedule (e.g., prototype vehicle testing). The fact that there are problems associated with expanding the capacity of regenerator and electronic control system manufacturers, and with automating precision investment casting facilities has been noted. Details regarding estimates of capital costs and the time required to accomplish expansion should be discussed further with suppliers to obtain more detailed estimates.

SUMMARY

1. INTRODUCTION

This report presents a summarization and assessment of available information pertaining to the potential for implementing mass production of gas turbine engine-powered automobiles. The gas turbine engine is viewed as a primary candidate for a new automobile power plant because of its prior extensive technological development and the current projections for its ability to meet the 1975/1976 Federal exhaust emission control requirements without the necessity of relying on catalyst emission control systems and incurring their associated cost penalties.

The status of the technology and implementation schedule visibility reported herein is that existing at the time of data acquisition visits made from February 28 through April 30, 1973. During these visits, discussions relevant to gas turbine automobile mass production were held with selected domestic automobile manufacturers, gas turbine engine manufacturers, component suppliers, NASA-Lewis Research Center personnel, and representatives from the Division of Advanced Automotive Power Systems (AAPS) of EPA. To supplement this information in certain areas, data were used from the open literature, from EPA/AAPS Program reports, and from the Production Lead Time study recently completed by The Aerospace Corporation for EPA.

The main topic covered in this report is the schedule requirement for mass production implementation of gas turbine-powered automobiles. Emphasis has been directed toward identifying those critical or limiting factors affecting timely introduction of gas turbine engine concepts on a mass production basis. In addition, associated lead time requirements for tooling commitments, system durability and certification testing, and prototype test programs were considered. A description of basic automotive product development phases and a summary of gas turbine engine current technology status are included to clarify and augment the discussions and to permit the necessary understanding of the developed implementation schedules.

2. GAS TURBINE ENGINE AND POWERTRAIN TECHNOLOGY

The following sections very briefly delineate the current and advanced technology status of automotive gas turbine engines and powertrain in order to provide a perspective from which to view the potential technical areas associated with automotive gas turbine implementation on a mass production basis.

2.1 GAS TURBINE CONFIGURATIONS

Most existing vehicular gas turbine engines use the so-called free turbine arrangement where two turbines are used in series with a high-pressure, first-stage turbine driving the compressor and a low-pressure, second-stage turbine delivering useful power output. This split-shaft scheme allows for flexibility of operation, especially in conjunction with a variable power turbine nozzle which may be used to provide engine braking in addition to its value in providing high torque at low turbine speed. This is the baseline configuration under development by Chrysler in the EPA-sponsored AAPS program.

The single-shaft arrangement, in which the turbine supplies both the compressor power and the net power output, has been used extensively in electric power generation applications where the gas turbine operates at a fixed design point. The torque-speed characteristic of the single-shaft engine is very steep and the torque is virtually not available below about 50% peak speed; for this reason, the configuration requires a wide-range, multiple-step or continuously variable gear ratio transmission.

A simple gas turbine cycle consists of a compressor which increases the air pressure, a combustor in which fuel is added and burned with the air, and a turbine powered by the hot combustion products. The turbine drives the compressor and also produces useful work. The thermal energy in the turbine exhaust from a simple cycle gas turbine is wasted. In a regenerative cycle, the energy in the turbine exhaust is utilized to raise the temperature of the compressor discharge flow, which, for a given engine design power level, reduces the energy input requirement for the combustor. The heat transfer is accomplished by means of a regenerator or recuperator.

2.2 CURRENT COMPONENT DESIGNS

2.2.1 Compressors

The compressor design may be either axial or centrifugal. In an automotive gas turbine, where the maximum air flow rate is of the order of 1-2 lb/sec, the blade height of an axial compressor is very small and maintaining good efficiency is a problem. Hence, in this application the centrifugal compressor is preferred because, in addition to elimination of the blade height problem, (1) the centrifugal impeller (wheel) is rugged and easier to manufacture, (2) maintenance problems are fewer, (3) the axial length is shorter (which improves engine packaging and bearing support loads), and (4) the inertia is lower (which improves engine response).

2.2.2 Turbines

Either axial or radial turbines are feasible for use in automobile gas turbines. Radial turbines are more rugged than the axial type and their performance is less sensitive to variations in tip clearance. They can also be operated at higher speed. In single-shaft arrangements a radial turbine is preferred. However, in split-shaft designs in which the two turbines are in series, axial turbines are preferred because of packaging considerations in the routing of gas flow ducts.

A critical dimensional tolerance impacting performance as well as mass production quality control requirements is the tip clearance for the axial turbine wheel and the shroud clearance for the radial in-flow turbine. The reduction in efficiency due to increased clearance in a radial in-flow turbine is less severe than in an axial turbine. This means that in mass production the quality control of the axial turbine has to be more rigid than for the radial in-flow turbine.

The state-of-the-art of turbine design indicates the possibility of operation at 1900°F inlet temperature for superalloy investment castings without blade cooling. For higher temperatures blade cooling or advanced ceramic materials would be required.

2.2.3 Combustors

The present goals in automotive gas turbine combustor design are to meet or exceed the 1976 emission requirements while maintaining good fuel economy. The two goals of good fuel economy and low NO_x emissions tend to be conflicting objectives. Superior fuel economy requires regenerative heating or high compressor pressure ratio, resulting in higher combustor inlet temperature and high NO_x emissions. To minimize the formation of NO_x, the following design principles are currently being evaluated by industry in both in-house and EPA sponsored programs.

1. Lean primary zone operation
2. Pre-vaporization of the fuel before combustion
3. Fuel-air ratio control by means of variable geometry ports in the primary zone

2.2.4 Regenerators and Recuperators

Regenerators are rotating heat exchangers which operate by alternately exposing the core sections to the "cold" and "hot" compressor and turbine exhaust flows. A seal arrangement separates the "cold" and "hot" sides of the heat exchangers. Both metallic and ceramic cores have been used. In the past, leakage from the high-pressure side to the low-pressure side has been a major problem with regenerators. However, this problem appears to be amenable to solution.

Recuperators are fixed boundary stationary heat exchangers. Compared to the regenerators the recuperators are bulky but require no seal or rotating drive. Materials used in the manufacture of recuperators include mild steel, stainless steel, Inconel, and Hastelloy.

2.2.5 Bearings

For automobile gas turbines, both journal and rolling element bearings are being considered. Journal bearings are used in the Chrysler automobile gas turbine. No special synthetic lubricants are required.

2.2.6 Controls

The turbine inlet temperature and the engine shaft speed have to be controlled to prevent engine failure. In addition to these limit controls, other control functions are required to ensure proper operation of the engine at all times.

At low flow rates compressor surge effects (unstable flow conditions) can produce a significant reduction in compressor efficiency. Variable inlet guide vanes alleviate these problems to some degree. By adjusting inlet guide vane positions, the pressure ratio of the compressor can be reduced without affecting the rotational speed of the engine. The turbine inlet temperature can then be maintained at or near the design point value and this results in marked improvement in specific fuel consumption at part load.

In the dual-shaft arrangement, the variable turbine nozzle changes the nozzle area and velocity direction and as a result changes the power split between the power turbine and the first stage turbine, allowing flexibility in overall pressure ratio of the engine and operation at optimum turbine inlet temperature. Similar to the compressor inlet guide vanes, incorporation of the variable turbine nozzles improves the part-load fuel economy. Another advantage of the variable nozzle is the fact that it can generate braking power by a reversal in nozzle position.

System control involves the overall regulation of component interactions during engine response to driver commands so that all critical operating variables are maintained within safe limits. The major elements of the control system could include the following items:

1. Fuel Control
2. Turbine Inlet Guide Vane Actuators
3. Compressor Inlet Guide Vane Actuators
4. Automotive Starting and Limit Protection Control
5. Transmission Control
6. Hydraulic Clutch Control
7. Power Boost Control Sensors

Control operation could be hydromechanical or electronic. The major difference between the two systems is in sensors, metering sections, and controlled elements. In general, hydromechanical control systems use a rotating shaft as the speed sensing element and a flywheel as the controller to position a metering valve. Electronic control systems have an electromagnetic speed sensing element, electronic controller elements, and electromechanical or electrohydraulic metering sections.

2.3 ADVANCED CONCEPTS

2.3.1 Combustors

Since conventional gas turbine combustors are inherently highly NO_x emitters, it appears that new combustor designs would have to be developed if the gas turbine automobile is to meet the 1976 NO_x emission control requirement. In view of current industry efforts in the area of high-temperature ceramic gas turbines the need for low NO_x combustion concepts becomes even more apparent. New combustor designs are now in the development stages. Although considerable progress has been made to date by industry, much more remains to be done, particularly in the area of durability and off-design operation.

2.3.2 Ceramic Components

The fuel consumption of gas turbine engines decreases as turbine inlet temperature is increased. The specific fuel consumption of a highly regenerated engine operating at a compressor pressure ratio of from 4:1 to 6:1 can be improved by about 20 percent solely by increasing the turbine inlet temperature from 1800°F to 2500°F. In order to operate at these higher temperatures, gas turbine manufacturers have been interested for some time in ceramic turbine nozzles and rotors. In June 1971 Ford/Westinghouse was awarded a $10.3 million ARPA contract to demonstrate that ceramics can be successfully used in high temperature gas turbine components including turbine inlet nose cones, nozzle vanes, turbine wheels, and combustor liners.

2.3.3 Water Injection

Injection of water into the combustor increases the mass flow and alters the thermodynamic properties of the medium, thereby resulting in an increase in turbine power. Water injection is to be operative only for higher power output requirements of the engine. Considering a typical vehicle driving cycle, the engine operates only for a short time under this condition. Therefore, the change in efficiency due to water injection during the period of higher power operation does not have a significant effect on overall fuel consumption. The more positive result, however, is that the engine size can be reduced because of the power boost and the part load operating efficiency will be improved.

2.3.4 Gas Bearings

The successful operation of the oil-lubricated bearings is dependent on the temperature and purity of oil. With high turbine inlet temperatures, there is a chance of heat soak back and a subsequent coking of oil after engine shutdown. The use of gas bearings would eliminate this problem because they are not limited by temperature (they can operate with air temperatures well above 700°F) and, therefore, have a wide range of operating speeds. Also, gas bearings will accommodate misalignment and reduce parasitic power losses.

2.4 TRANSMISSION DESIGN APPROACH

The gas turbine engine generally operates at speeds over 30,000 rpm while the maximum engine output speed required for an automobile is about 5,000 rpm. Hence, the turbine shaft speed has to be geared down to a level practical for automobile driving. This is accomplished by a fixed-ratio reduction gear box installed ahead of the transmission. A transmission has to be selected so that the vehicle torque requirements are satisfied. In general, the free turbine engine torque curve is similar to the piston engine torque curve in that a relatively high level of torque is maintained over the speed range. Therefore, a conventional three-speed automatic transmission as used for the spark-ignition engine will be satisfactory for the free turbine engine.

The single-shaft engine, because of its narrow operating speed range for effective torque, requires a wide range, multiple-step or continuously variable gear ratio transmission, such as the Infinitely Variable (IV) transmission. The infinitely variable transmission is new, and the feasibility of these transmission designs has to be proven in extensive tests before a single-shaft engine can be selected for an automobile powerplant.

2.5 ENGINE/VEHICLE PERFORMANCE

The size and weight of an engine is of prime importance to an automobile manufacturer. In general, both the specific weight and specific volume of a gas turbine engine are lower than for an equivalent spark-ignition engine. Presently, a number of gas turbine engine designs are capable of being installed in a full-size, six-passenger car, with acceptable driving and handling characteristics. However, to match low-speed acceleration capabilities of the current powerplant, engine response time would have to be improved slightly. High speed acceleration is very good and 0-60 mph time is as good as that of the spark ignition engine.

The current fuel economy performance of the gas turbine engine powered-car is below that of 1970 to 1972 cars powered by internal combustion reciprocating engines of similar size and weight. But it is estimated that gas turbine engine-powered cars with superalloy turbine wheels can meet or better the projected fuel economy of 1976 piston engine-powered cars fitted with all required emission control equipment. Whether this can be accomplished with a concurrent ability to meet 1976 Federal emission standards remains to be verified by actual test.

Some additional improvements in both fuel economy and exhaust emission levels of gas turbine-powered cars appear to be attainable by improved component efficiencies, reduction in engine internal heat and leakage losses, and more sophisticated engine control systems. In addition, a significant improvement in fuel economy of about 20 percent is expected solely by the application of ceramic materials to turbine wheels which would permit higher engine operating temperatures.

By application of all possible techniques, one automobile manufacturer has projected an overall possible improvement in fuel economy of about 50 percent.

Current gas turbine engines, while demonstrating remarkably low levels of HC and CO emissions, still show high, unacceptable levels of NO_x. However, recent steady-state tests of combustors combined with analytical studies have shown that redesigned combustors with fuel prevaporization and variable geometry might be capable of meeting the 1976 Federal requirements for NO_x emissions; this represents the greatest technical advancement to date. Tests on a vehicle powered by a gas turbine engine with a modified combustor are required to verify projections of exhaust emission performance and to verify that this performance is achieved with acceptable fuel economy.

2.6 DRIVEABILITY AND SAFETY

Driveability may be defined as the responsiveness of the vehicle to driver commands. Principal driveability considerations pertaining to the gas turbine-powered car concern standing-start response (lag from idle to required power level), transient acceleration, and braking behavior. In general, the gas turbine car does not have the standing-start response of a conventionally powered vehicle, circa 1970. In terms of standing-start acceleration performance it is estimated that the single-shaft system has up to a 1-second delay in starting vehicle motion and the free turbine has up to a 0.4 second delay; the spark ignition engine without emission controls has a delay of less than 0.1 second.

The gas turbine engine contains high-speed rotating components that require special consideration with regard to automobile safety requirements. The engine/vehicle system must be conservatively designed so that even if operation continues beyond the design life of the engine, the occupants of the vehicle will be protected in the event of catastrophic failure. No fundamental difficulties in meeting these objectives for the passenger car turbine are anticipated.

2.7 ENGINE NOISE AND VIBRATIONS

The noise level of a gas turbine engine tends to be higher and composed of different frequencies than that for the spark ignition engine due to high-velocity flow of air at the compressor inlet, high idle speeds, and interference efects of variable inlet guide vanes. The gas turbine engine also lacks the damping characteristics provided by the concentrated mass of the internal combustion engine block. In general, the regenerative gas turbine engine may be expected to have a lower noise level than the simple cycle gas turbine engine, because the heat exchanger in the regenerative case absorbs part of the energy in the exhaust. The vibration level of the gas turbine engine, on the other hand, is lower than that for the reciprocating engine due to its symmetrical rotary design.

2.8 PACKAGING AND INSTALLATION

Generally, the specific volume (ft^3/hp) for gas turbine engines tends to be lower than for spark-ignition reciprocating engines. Therefore, there should be no problem in fitting the engine package into a conventionally sized engine compartment unless combustor or regenerator volumes were to increase substantially. Although the engine itself is compact, the air intake and exhaust ducts are large (the gas turbine has about five times the air flow of an equivalent horsepower internal combustion engine), and have to be packaged properly to meet reasonable envelope requirements and to provide sufficient ground clearance. Ford indicated that packaging the turbine exhaust system was a problem. Installation of the gas turbine engine exhaust system in conventional vehicles would require tear up of the car floor pans. Were the engine less sensitive to exhaust back pressure, smaller ducts could be used.

Chrysler feels that the incorporation of these changes into an existing design might be rather difficult and expensive. For these reasons, Chrysler is thinking in terms of a special automobile for the gas turbine engine that would be introduced at the time of a normally scheduled major model change, which occurs approximately every 3 to 5 years.

2.9 MAINTENANCE AND DURABILITY

Modern piston engines operated in normal passenger car service have been expected to accumulate 75,000 miles to as much as 100,000 miles without requiring a major overhaul. The impact of exhaust emission controls on this type of durability (and the expected reliability) is still under evaluation. The gas turbine engine, with its fewer parts, may, assuming reasonable care and servicing, operate even longer before major overhaul is needed. The potential durability of the engine may be gauged from the fact that the AiResearch Industrial Division, manufacturer of turbo-superchargers, recommends their overhaul on a schedule that coincides with the overhaul of the diesel engine itself at about 300,000 miles.

The contractors involved in an EPA-sponsored engine configuration optimization study effort addressed the problem of gas turbine car maintenance and concluded that scheduled maintenance and service requirements (chassis lubrication, air, and oil filter changes, etc.) would be much the same as for the conventional automobile. Engine-related repairs are different in nature, but are projected to occur at about the same frequency among the aggregate of service or repair items for both engine types.

A potentially serious service problem in regenerated gas turbines concerns the high frequency of maintenance that has been encountered with the regenerator seal. The seal problem has to be solved before this engine type can be placed into mass production.

3. POTENTIAL FOR MASS PRODUCTION MANUFACTURING

3.1 CRITICAL FACTORS ASSESSMENT

3.1.1 Raw Materials

As of 1969, data on the availability of chromium and nickel showed that there could be a problem in regard to quantities needed for production of gas turbine engines. However, on further examination the impact over time should be largely diminished. Inquiries made of stainless steel producers have now revealed that a significant increase in the availability of chromium and nickel has occurred since 1969. A further expansion in production is expected to meet the requirements of the 1976 piston engine unless some drastic change in present emission control concepts occur. Cobalt, niobium, and molybdenum are the only materials that may be critical in their availability.

3.1.2 Processed Materials

Considerably more ductile iron castings are required for the gas turbine engine than for the emission controlled piston engine. Ductile iron castings are not as available as gray iron and are somewhat more difficult to produce. More expensive materials and closer control of processes are necessary,and the foundry yield and production rate is lower than for gray iron. Changes in current gray iron foundries are related to finer control of material purity and furnace temperatures.

The piston engine uses no investment castings but the gas turbine would require an appreciable number using both Inconel and aluminum alloys. Therefore the development of a new investment casting industry supporting the passenger automotive field would be required.

Forgings would tend to range from low-alloy or carbon steels to high-alloy steels. The forgeability of metals is variable; higher alloy metals are less easily forged than low-alloy metals. The cost of forgings would, therefore, increase for gas turbine engines.

Requirements for sheet, plate, wire, tube, bars, and extrusions by weight would remain about the same for gas turbine engine production. The list, however, would also include Hastelloy and stainless steel for the gas turbine engine. It appears that the steel-producing industry has the ability to expand and manufacture these materials in the increased (approximately 12 percent) amount required. The placement of large orders would require that the steel producers also modify some of their normal production operations. The modifications relate mostly to ensuring the purity of the metal by preventing the inclusion of surface scale.

3.1.3 Mass Production Processes

For high-volume manufacture of the gas turbine engine, new handling, loading, unloading, machining, and transfer equipment will be required. Basic materials are generally of higher alloy content and are more difficult to machine than for the piston engine. In some cases, these materials must be heat treated or annealed after machining operations to retain their proper metallurgical characteristics. The gas turbine engine is estimated to have fewer parts than the piston engine (approximately one-half); however, each part is relatively unique whereas the piston engine requires a large number of duplicate parts (e.g., in a V-8 engine there are eight pistons, eight intake valves, eight wrist pins, etc.). While the smallest tolerance for the gas turbine engine is about the same as for the piston engine, the number of such close tolerances is less. For example, the number of machining operations requiring tolerances less than 0.001 inch is estimated at 377 for gas turbines versus 514 for piston engines. Assembly of the gas turbine is visualized as less complex than assembly of the piston engine due to fewer parts involved in the assembly process.

Critical production factors are concerned primarily with fabrication of components prior to delivery to the engine plant; these elements of the engine include regenerator cores, fuel control units, and turbine wheels and nozzles. Investment castings or alternative processes (such as the proprietary Gatorizing process proposed for United Aircraft) are required for mass production to be practical for turbine wheels and nozzles. The mass production technique for ceramic regenerator cores must still be developed. The first such cores were built about 1950 by Chrysler. Uniformity of fabrication was not reliable and problems arose in cracking, leakage, and heat transfer effectivity; Chrysler, therefore, decided to use metal cores. Since that time, Corning Glass Works has developed Cercor, a glass-ceramic matrix, which can be used to manufacture the ceramic core. Ford has used this material and claims to have resolved most technical problems.

The design of automotive gas turbine control systems is in a state of flux. Until a design philosophy is established or until a specific system is selected, the mass production problems related to such a system are not fully determinable. Once a system is selected and developed, no unusual mass production problems are foreseen. However, efforts must be directed at reducing the present high cost of the fuel control unit.

The present processes used in the U. S. to produce precision investment castings are complex and expensive. While this process has been found to be cost-effective for aircraft-type engine parts and diesel engine turbosupercharger turbines, it is considered to be one of the most critical cost factors in developing gas turbine engines for passenger automobiles. A typical current production rate for such a process ranges from 3 to 5 parts per hour. Increased production rates can be obtained by enlarging facilities and equipment and by automating many parts of the process. For example, the dipping of the wax pattern into the ceramic slurries is presently being performed manually. This portion of the process can be automated. Additionally, certain high-production parts can be produced in multiple units by placing the wax patterns on a "tree", dipping the multiple wax patterns simultaneously, and forming a multiple ceramic mold. The time cycle from mold making through casting is approximately 70 hours. (The major factor controlling overall process time is the period required for drying the ceramic casting molds.) These figures can be contrasted with the process for sand castings of V-8 piston engine blocks that takes a total time of about 3 hours in the foundry with a production rate of about 155 parts per hour per line.

The USSR has developed the investment casting process to produce parts for automobiles, tractors, airplanes, sewing machines, bicycles, and motorcycles. Through use of new technology plus automation, the mold making-casting production cycle has been reduced from about 70 to 24 hours. Aside from automating the operation, the USSR has developed new refractory materials which have a short drying time. It can be stated that the USSR has demonstrated the feasibility of producing investment castings at a high rate (estimated at 120 casting molds per hour per line) although the materials poured were not high temperature alloys and the degree of precision in the casting is not known.

Diecasting of compressor and turbine parts is not considered practical at this time. No permanent mold has been fully developed to accept the high-temperature pour of superalloys. While aluminium is the material considered for compressor impellers, no manufacturer has successfully die-cast compressor impellers that can operate at the stress levels encountered in gas turbine engines.

3.1.4 Equipment, Tooling, and Facility Requirements

Foundries would have to be modified and new equipment would have to be installed to produce ductile iron as opposed to gray iron castings.

The investment casting industry would be required to make major modifications to automate the process and to change the technology in order to introduce time saving processes (such as the USSR approach). This would require automatic injection equipment, linear and rotary transfer equipment, automatic dipping, drying, firing, pouring, and cooling equipment plus automated equipment to break molds. Additionally, equipment would be required to separate the extraneous material from the casting clusters and to clean and inspect the castings. While no insurmountable technical problems are foreseen, the amount of new equipment required would place an appreciable load on the machine tool industry.

Manufacture of engine controls would require the establishment of new plants similar to the present carburetor manufacturing plants including automatic equipment to produce and assemble parts.

Regenerator manufacturers would require facilities and equipment similar to the comtemplated catalytic converters to produce ceramic cores and other items.

New equipment and tooling to manufacture the engines would be required to set up a mass production facility. While all of the equipment is relatively standard, the quantities required, when combined with automatic transfer equipment, would place a heavy load on the machine tool industry. This industry load is compounded by the need for machine tools required for automated investment casting facilities, fuel control manufacture, and regenerator production.

It is probable that new facilities would be required to house this equipment, since the production of piston engines and gas turbines is likely to overlap in time. As piston engines are phased out, some of the old facilities could be converted to gas turbine manufacturing operations.

3.1.5 Capital Investment

The total capital investment for gas turbine engine manufacturing plants alone has been estimated by International Research and Technology (IR&T) in a recently completed study for DOT as approximtely $400 million to produce one million automobile engines annually after a gradual production build-up. This compares with approximately $320 million if new facilities to produce the same number of piston engines were required.

Since the facilities for piston engines are already in existence, the only new capital investments for piston engines are those involved with emission controls. The cost of this change is estimated at about $50 million for an annual production of one million cars.

The $400 million for the gas turbine engine manufacturing plants is made up of approximately $140 million for machine tools and $260 million for facilities, transfer equipment, laboratories, assembly equipment, test equipment and other miscellaneous equipment.

It should be emphasized that the $400 million is solely the capital investment for engine manufacturing facilities and that additional capital investments are required for equipment to produce processed materials and purchased parts.

An estimate of required capital investment was also offered by Chrysler. They stated that a total investment of $5 to $6 billion would be required to tool up for an annual production rate of the order of 10 million gas turbine powered automobiles. This cost includes tbe plants and the tooling required by both the manufacturers and the tooling industry. If a gas turbine/spark ignition engine mix would be required for a particular model line then it is expected that this investment would be larger.

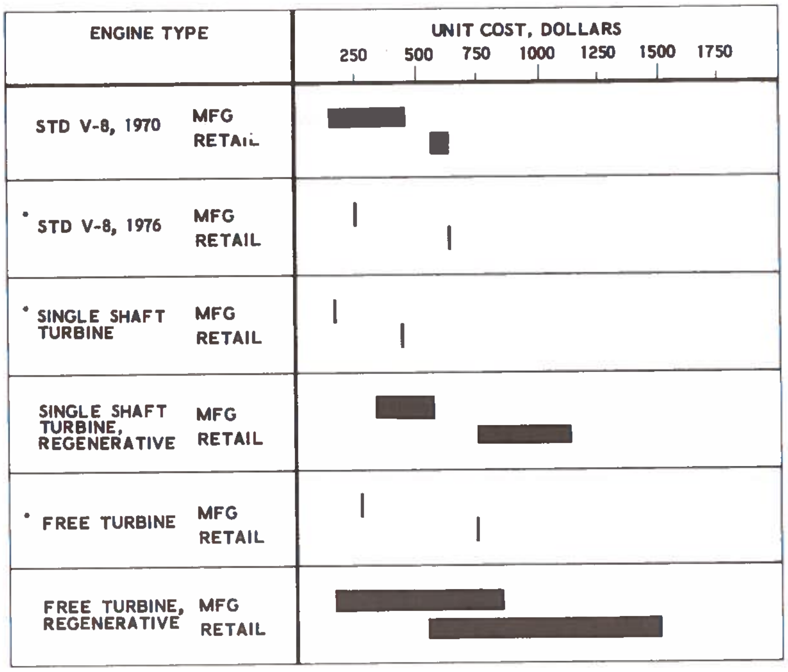
3.2 SUMMARY OF ESTIMATED COSTS

3.2.1 Basic Engine Costs

Estimates of manufacturing and retail costs for each of four gas turbine engines were made (under contract to EPA) by several non-automobile companies.

A summary of results are shown in Figure 1. A considerable spread in cost estimates is evident except of course where the estimate was made by a single contractor.

The automobile manufacturers didn't provide cost estimates for mass-produced gas turbines due to many uncertainties in the cost of components such as precision castings and regenerators. However, Chrysler did



*Estimates by one contractor.

Figure 1. Engine Manufacturing and Retail Cost Estimates

mention that it feels a manufacturing cost of $250 is a reasonable goal at this time. This figure was arrived at by assuming material cost is about 2.5 times that of the current internal combustion engine.

In contrast to the gas turbine engine, costs for a 1970 V-8 piston engine and projected costs for a 1976 V-8 engine are also shown. (It should be pointed out that the 1970 piston engine costs include controls and engine-mounted accessories.) The retail cost estimates for the 1970 V-8 engine have a narrow range while the manufacturing cost estimates show a large spread. The latter are known in detail only by the automobile manufacturers and they consider these figures to be proprietary information. The same effect is evident in the presentation of engine/transmission and total vehicle cost estimates in the next two sections.

3.2.2 Transmission Costs

The estimated costs for engine/transmission combinations for which data are available is shown in Figure 2. These were reported by two of the EPA contractors. As was the case with basic engine cost estimates, a considerable spread is evident in these estimates.

3.2.3 Total Vehicle Costs

Total vehicle cost estimates are shown in Figure 3. Here, the combined effect of any uncertainties in estimates of mass production costs for gas turbine engines, the variations in overhead estimates, and the markup used to arrive at a consumer cost are evident. For example, the direct manufacturing cost spread for the single-shaft regenerated engine is $550, while the spread in the retail cost to the consumer is only $130. Similarly, for the regenerated free turbine, the manufacturing cost spread is seen to be $800, while the consumer cost spread is $600. The magnitude of the spread would appear to substantiate Chrysler's feeling that current uncertainties regarding mass production costs of precision castings and regenerators make it difficult for a manufacturer to arrive at an accurate estimate of engine costs.

3.2.4 Operating Costs

Lifetime operating costs were estimated by the EPA contractors for each engine type based upon the composite driving cycle (Federal Driving Cycle plus steady-state cruise at speeds ranging from 20 mph to 70 mph) for 105,000 miles. The engine-related costs of the turbine-powered vehicles are no higher than the standard 1970 V-8, although an extensive spread exists in the cost estimates. Fuel costs represent a major portion of the engine-related costs and, because of the wide variation in estimated fuel consumption, are a major contributor to the spread in the data.

Vehicle-related costs vary by up to approximately $500. These variances are due primarily to differences in the transmission and residual vehicle costs with only minor differences attributed to vehicle-related repair and maintenance costs.

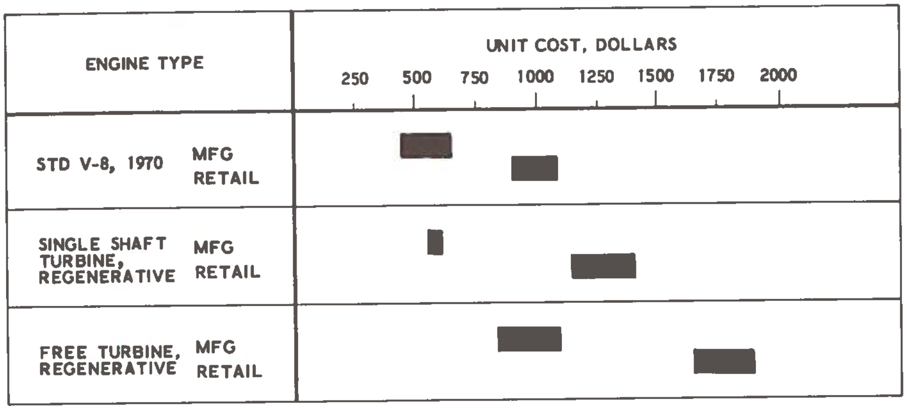
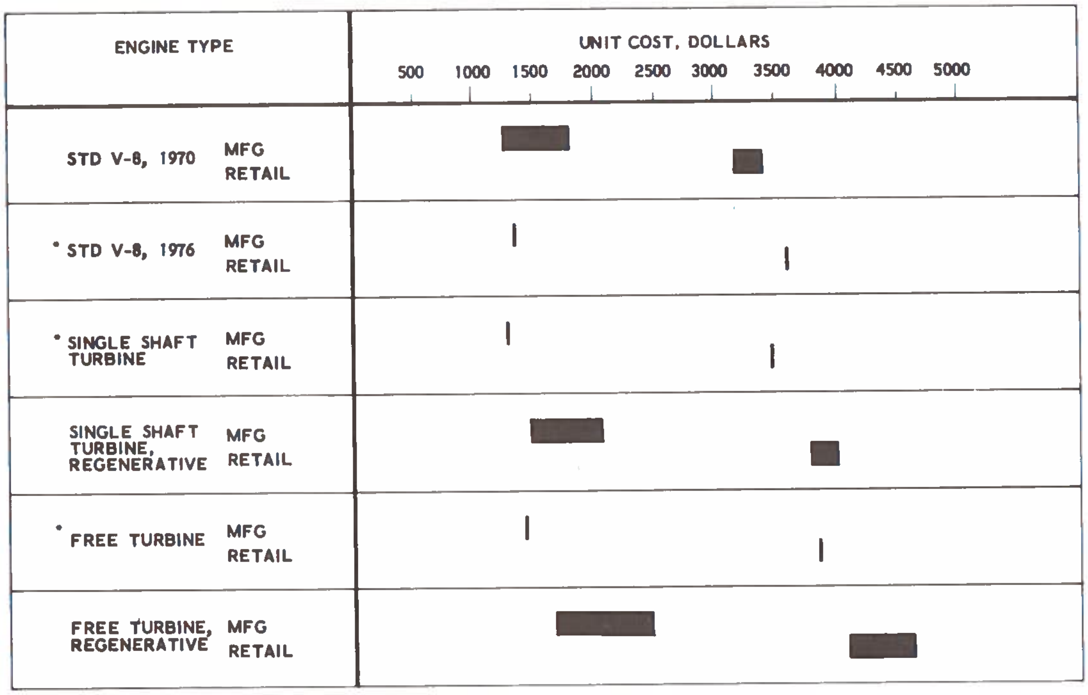


Figure 2. Engine Plus Transmission Manufacturing and Retail Cost Estimates



*Estimates by one contractor.

Figure 3. Total Vehicle Manufacturing and Retail Cost Estimates

The total lifetime operating costs of almost $12,000 are quite similar for each engine, except for the single-shaft regenerated engine where a variation of over $1,200 is indicated. This is essentially the result of differences in engine-related costs.

3.2.5 Possible Techniques for Cost Reduction

Cost sensitivity to production volume indicates that purchased and fabricated parts as well as engine production costs are reduced appreciably as volume increases. In some cases a tradeoff between reduction in material costs and increased fabrications costs exists. In other cases the reverse stiuation exists, i.e., reduced fabrication costs might involve higher material costs. Some means of reducing costs by changing designs and materials are being investigated and some of these are supported by government programs.

Whereas present concepts use metal castings for compressors, studies and experimental development work are being conducted by the NASA Lewis Research Center to produce axial compressor impellers from metal stampings using 17-4 PH sheet metal. This material is a martensitic precipitation-hardened stainless steel made by Armco Steel Corporation.

A proprietary process being developed by AiResearch simplifies investment casting by replacing the expendable wax pattern with a reusable rubber pattern which can be removed from the refractory mold. Other ideas being investigated by some automobile manufacturers are the potential use of plastics for compressor impellers. It is probable that these plastics would have to be reinforced with filler materials.

A proprietary process under investigation by United Aircraft is precision forging (Gatorizing). By use of this process, centrifugal compressor impellers would be forged from sheet metal under high temperature and pressure conditions.

NASA has performed development work on low-cost sheet metal combustor housings with punched holes for film cooling. At this time the durability of this design is not considered sufficient for automotive gas turbine use.

Other work is being performed by NASA to develop a low-cost, air-atomizing fuel nozzle. Problems in meeting NO_x emission control requirements for this type of fuel-air mixing still exist.

NASA's work on producing stamped compressors is also being considered for turbine rotors. The problem is to find a suitable high-temperature material that can lend itself to stamping techniques for accurate and smooth aerodynamic passage at the blade roots.

United Aircraft's Gatorizing process is also under consideration for the production of turbine rotors. For the production of turbine wheels, the use of high-alloy metal powder is being considered. There is still a question whether turbine wheels that are Gatorized can be finished completely by this process or whether some machining may be required.

The area of fuel controls is probably one of the most critical cost reduction items. For aircraft engines, the cost of a fuel control system is estimated at 25 to 30 percent of the total engine cost. A large number of precison parts requiring careful inspection contributes to the high cost. NASA is working on the development of a simple hydromechanical fuel control for aircraft engines that reduces the number of parts required by a factor of ten. Automated techniques for fabrication and inspection should aid in reducing costs.

Development of ceramic components could offer both cost reduction and performance improvement. Because of high strength and good thermal shock and oxidation resistance, silicon nitride and silicon carbide are primarily being considered for turbine applications. In addition, ceramics are very attractive from a cost point of view. Currently low-purity silicon costs 15 to 18 cents per pound, compared to \$6 to \$9 per pound for superalloys. High-purity silicon is currently sold at premium prices. However, Ford feels that the high-purity grade could be mass-produced for about the same price as the low-purity grade.

4. PRODUCT DEVELOPMENT PROGRAMS AND SCHEDULES

In the absence of any special incentives or forcing functions, such as the potential for increased sales, Federal subsidies, or governmental policies on taxation or regulation, the gas turbine automobile, if produced, is likely to be introduced to the automotive product development cycle and to the American market on a gradual basis. The timing schedule will be characterized by cautious, step-wise progress, in line with good business practice and reflecting standard automotive industry procedure for the introduction of new functional systems on conventional car line production programs (but augmented by an additional degree of conservatism because of the extensive changes associated with the gas turbine car).

This section summarizes the status of industry with regard to the potential for implementing mass production of the gas turbine car in a near-term time frame. To provide a vantage point for better understanding the issues involved in scheduling the development and production of gas turbine vehicles, the steps and activities that comprise the product development cycle for conventional automobiles will first be reviewed briefly.

4.1 AUTOMOTIVE PRODUCT DEVELOPMENT CYCLE

The process of developing an automotive product from concept to mass production can be viewed as proceeding in discrete phases. These phases, though highly interrelated and in some instances overlapping in time, may be isolated and characterized in terms of specific activities and operations.

The term "lead time" is a generic phrase that can be (and is) applied to any one of a number of different processes in the automotive development cycle. Two specific terms involving lead time are useful in viewing the automotive development cycle. One of these is Product Development Lead Time and the other is Production Lead Time. Product Development Lead Time is the total time required for the development of the automotive product starting from the initial formulation of the design concept and ending with Vehicle Job. No. 1--the first of the production run of automobiles of a model year to come off the assembly line. That part of Product Development Lead Time encompassing activities concerned with the development of mass manufacturing techniques and facilities is designated Production Lead Time. Specifically, Production Lead Time is defined as the time reserved by the automobile manufacturer to (1) detail the product configuration for mass manufacture; (2) analyze the manufacturing processes; (3) design or plan the equipment and facilities needed to perform these processes, (4) construct, install, and check out the production equipment; and (5) escalate the manufacturing process to full-volume output.

A representative product development cycle may be considered to consist of eight different phases. These phases, along with their timing and typical duration, are shown in Figure 4. The data shown are broadly representative of the practice in the automotive industry; however, the specific details in any one manufacturer's schedule may differ considerably.

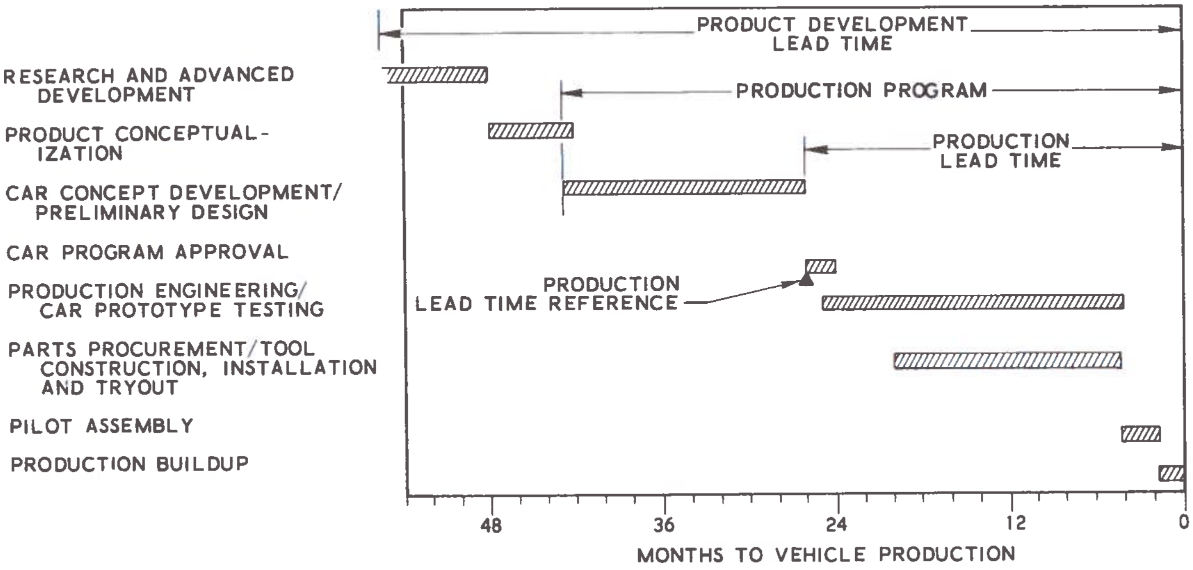


Figure 4. Automotive Product Development Phases

Except for Research and Advanced Development, the overall product development cycle spans approximately 48 months. The milestone marker shown in the chart identifies the point selected as the Production Lead Time reference, which represents the start of significant activity on the development of mass-production processes and facilities. The indicated lead time to Vehicle Job No. 1 is 26 months as compared with a range of 24 to 28 months indicated by historical data from the individual manufacturers.

4.2 GAS TURBINE MASS-PRODUCTION IMPLEMENTATION SCHEDULES

Five manufacturers have provided sufficiently detailed gas turbine product development schedule information (past history and current projections) to enable formulation of reasonable mass-production implementation schedules. In Figure 5, each of the manufacturer's product development schedule estimates has been translated into a common format, permitting individual estimates to be compared.

Several noncommon characteristics may be observed among the timing plans shown. One of these is that individual programs differ in scope: Chrysler and Solar schedules are addressed to engine development, United Aircraft and AiResearch schedules encompass both engine and transmission development, and the Ford schedule reflects the timing effects of both an engine and car development program. Differences in production volume objectives may be also observed. These objectives range from 2000 to 300,000 units per year among the five manufacturers represented. These and other schedule comparison factors are summarized in Table 1 for the five manufacturers who provided data.

It should be noted that an additional timing factor must be considered in estimating implementation schedules, and that is the need to provide a variety of engine sizes to support a given manufacturer's mix of car models. The succeeding discussion refers to only one engine size; information on schedule extension needed to provide a variety of engines is recognized but cannot be addressed at this time.

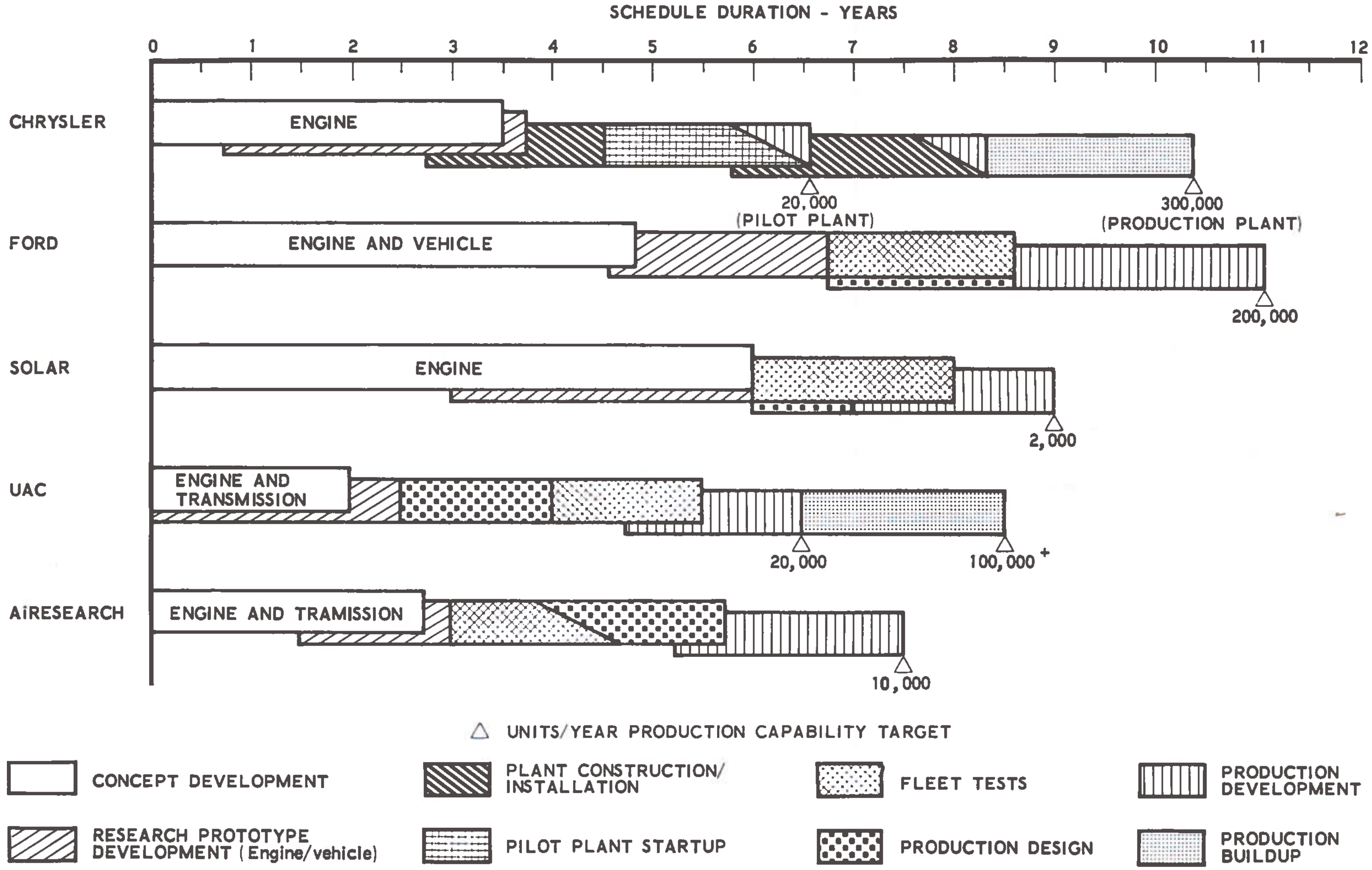


Figure 5. Comparison of Manufacturer's Product Development Schedules

Table 1. Schedule Summary

Manufacturer	Proposed Development Program	Production Target Units/Year	Schedule Duration, Years
Chrysler	Engine	300,000	10^+
Ford	Engine + Vehicle	200,000	11^+
Solar	Engine	2,000	9
United Aircraft	Engine + Trans.	100,000	8^+
AiResearch	Engine + Trans.	10,000	7^+

In formulating a best-estimate mass production implementation schedule, it was decided that the broad differences in philosophy and objectives among the various proposed programs argued against a straightforward consensus of the manufacturers' schedule estimates. Instead, the following approach was used: (1) a composite engine/transmission/vehicle product development program targeted to a production volume of 300,000-plus units per year was selected as the objective for evaluation, (2) appropriate schedule elements in each manufacturer's program were compared and evaluated in the light of past automotive industry experience, and (3) a best-judgment selection of the duration required for each element of the proposed program was made. The resulting schedule is shown in Figure 6. A total program duration of slightly over 11 years is indicated. This timing is considered to provide adequate durations for development and test periods so as to diminish the manufacturer's financial risk in proceeding with successive phases of the product development program. A review of industry progress along this schedule leads to the estimate that annual mass production of 300,000 gas turbine powered automobiles could be possible in about 8 to 10 years from now. This range in time reflects the expectation that progress in approaching mass production capability will vary from company to company. Furthermore, it is estimated that it would take up to another 10 years before the gas turbine powered automobile would constitute the total annual vehicle production (assuming the industry elected to convert entirely to this engine type). A discussion of the rationale supporting the selection of the various mass production implementation program components is provided in the following paragraphs.

It was assumed that a manufacturer would be starting in a position characterized by a background of experience in gas turbine engine development and manufacture for truck, industrial, or other nonpassenger car applications but would lack actual prototype hardware for an automotive design. On this basis a duration somewhat longer than 4 years was assigned to the schedule phase identified in Figure 6 as Concept Development.

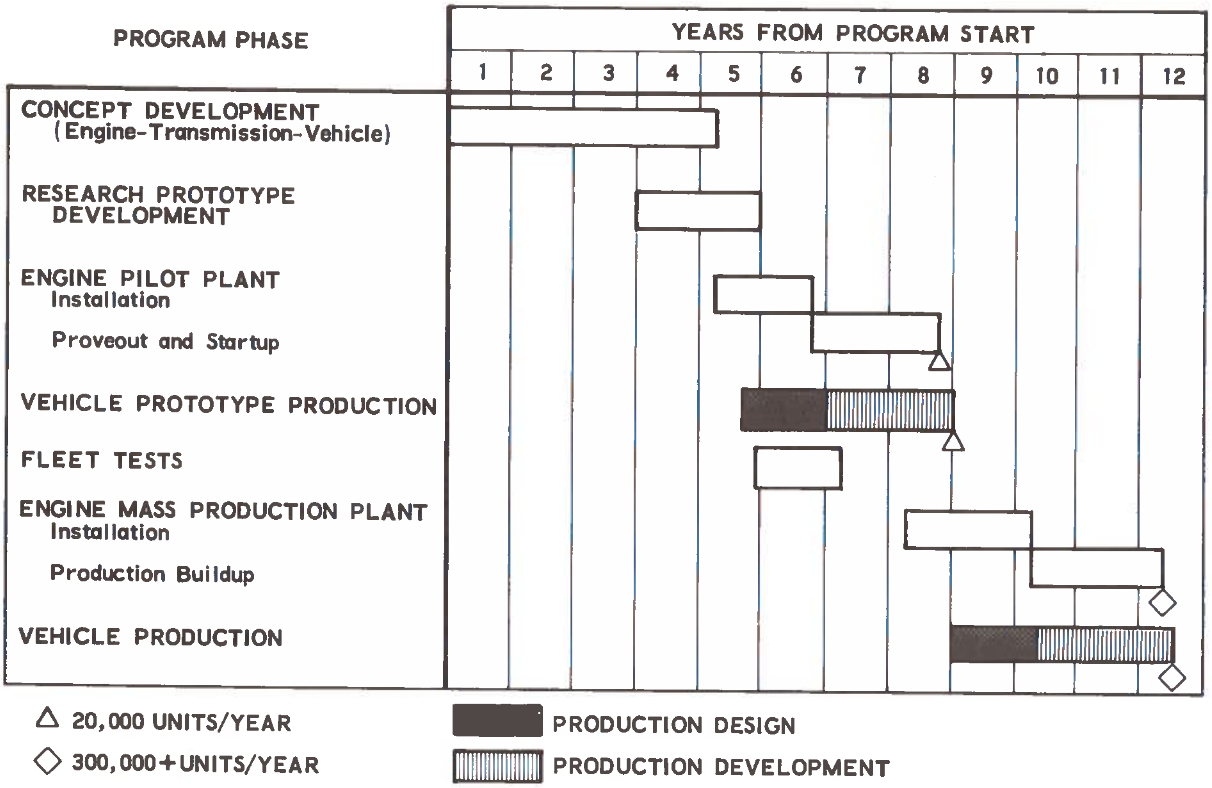


Figure 6. Best Estimate of Gas Turbine Automobile Mass Production Implementation Schedule

In this phase of the program, vehicle application studies would be made and experimental prototypes of the engine, transmission, other powertrain components, and vehicle would be designed, fabricated, assembled, and tested for performance, emissions, fuel economy, and durability on a component, subsystem, and vehicle level. Hardware modifications would be made as required to test the feasibility of different approaches toward meeting engine and vehicle performance and operating specifications. At the end of this phase, the concept feasibility will have been established and demonstrated.

At a point about 3 years into the concept development phase, and based on the progress and results achieved at this point, the engine/transmission/vehicle system would be redesigned and upgraded to reflect the status and improvements identified up to that time. Several of these research prototype vehicles would be built and road-tested for endurance and durability. This effort would proceed in parallel with the continuing concept development program, incorporating additional improvements as they evolve.

In concurrence with Chrysler's opinion it was assumed that the unknowns concerning the mass-manufacture of gas turbine engines, particularly the production techniques for casting turbine wheels and fabricating regenerators, would reasonably call for an investment in a low-volume-production pilot facility to identify appropriate manufacturing methods before committing funds to a large mass-production plant. (The precedent for a conservative approach of this kind is well established in the industry; a recent example is the Engelhard/Ford plan for developing production facilities for 1975 catalytic converter emission control systems.) This phase of the schedule is assigned a duration of 20 months for site selection, facility design, construction activities, and equipment installation. Another 24 months is provided to prove out the manufacturing equipment and accelerate the assembly process to a full-volume-production output of about 20, 000 units per year (as suggested by Chrysler). It is noted that Ford took 3 years in developing its Toledo industrial gas turbine facility, now producing at a rate of about 1000 units per year.

The pilot plant program for engine production would be coordinated with a limited-production car line development plan designed to penetrate the consumer market gradually to test customer reaction and to observe the gas-turbine vehicle performance under customer driving conditions. Accordingly, shortly after the engine pilot plant program was under way, near the fifth year of the program schedule, activities would commence on vehicle prototype production. The first 16 months of this effort, the Production Design Phase, would be devoted primarily to the definition of final production configurations for the various car subsystems.

Early in the production design phase, mechanical prototype vehicles (that is, vehicles representative of the final functional configuration of the gas turbine car) would be built for use in the fleet test program (shown in the timing schedule to begin shortly after the start of the Vehicle Prototype Production Program Phase). The fleet tests would be designed to test the interactions and durability of working components under hot weather, cold weather, altitude, sustained high speed, and other road driving conditions. Twenty or more vehicles would be tested for a period of about 15 months.

The second part of the Vehicle Prototype Production Program, the production development phase, would have a duration of about 26 months and would be devoted to developing the assembly line production processes. It is noted that the overall production schedule of 42 months shown in Figure 6 represents normal timing for the conventional internal-combustion-engine car line production programs.

Toward the close of the engine pilot plant phase, and as successive trial production runs show evidence that the pilot plant fabrication and assembly processes for the gas turbine engine are meeting planned objectives, resources may be committed to a mass-production engine facility, and initial activity to develop a plant with a 300,000-plus unit per year capacity would then begin.

As with the engine pilot plant phase, a vehicle car line production development program would be coordinated with the engine Mass

Production Plant development. The Vehicle Production Phase is shown in Figure 6 to be of a normal 42-month duration which, in this case, could represent the parallel development of production facilities for several car lines.

With regard to schedule compression, Chrysler feels the 11-year schedule could be shortened to 8 years by telescoping the various schedule tasks at an increase in total cost and in manufacturer's financial risk. This financial risk is characterized by potential problems with recall, warranty service, lack of adequate sales volume, etc., all of which are exacerbated by a shortened schedule that does not permit extensive verification of fabrication processes or consumer acceptance.

Chrysler is currently in the Concept Development Phase of its production implementation schedule. In December 1972, Chrysler was awarded a $6.5 million, 3-1/2 year, EPA contract for improvement and demonstration of an automotive gas turbine engine using the existing sixth-generation engine as the baseline configuration for further development. This effort, referred to as the Baseline Gas Turbine Development Program, covers (1) the manufacture of seven Chrysler sixth-generation automotive gas turbines, and installation of three of these engines into three 1973 intermediate-size research vehicles; (2) engine component and vehicle evaluation and development; (3) incorporation of improved components in the engines and vehicles; and (4) final engine and vehicle performance and durability testing using 1973 and 1975 vehicles.

Ford is currently conducting a 9-month vehicle application study. At the end of that time period, Ford will be in a better position to make a decision on proceeding further into the Concept Development Phase.

General Motors is also conducting a passenger car turbine development program. The effort has progressed to the early phases of pre-prototype engineering design and manufacturing technique evaluation; no final engine selection has been made. Both two-shaft and single-shaft regenerative engine types are being evaluated, and both axial and radial-flow components are under consideration.

4.3 HEAVY DUTY, GAS TURBINE ENGINE PROGRAMS

Ford and General Motors have current nonpassenger car gas turbine programs. Ford has a production facility at Toledo, Ohio, with an annual production capacity of about 1000 gas turbines. These are designed for competition with diesel engines for boat drives, electric power generation, oil-field power units, and trucking. Two hundred such engines were manufactured in 1972, and four hundred are projected for 1974. These engines are all hand assembled. Development work on an advanced version will continue through 1973.

At General Motors, the GT 404, a 325-hp regenerated split-shaft engine, is currently in the pilot phase of manufacturing, with full production scheduled in the near future. It has been operating in a number of heavy duty test vehicles including Turbo-Cruiser III, a GMC coach, and a Greyhound coach. This engine is the first of a family of industrial power units planned for development. General Motors expects that by 1980, regenerated gas turbine engines will comprise about 25 percent of Detroit Diesel Allison's production.

It should be noted that the current and projected gas turbine production programs at General Motors and Ford are not mass-production programs in the sense of passenger-car mass-production. More costly production techniques can be used for industrial-type gas turbines, since they are competing with the higher cost diesel engine; and the contemplated production rates are much lower than passenger-car production rates. Therefore, these programs cannot be counted on to address the critical mass-production process, car line production, and integration problems which form the basis of the 11-year implementation schedules developed herein.

Furthermore, the operating requirements for heavy duty engines differ from those associated with passenger cars. Heavy duty engines are expected to operate closer to peak-power output, frequently at near constant speed over long periods. In contrast, the passenger car engine generally operates at part-load for the majority of the time, and its power output is continuously varying such as required in urban traffic. It is difficult to achieve good fuel economy for the gas turbine engine at part-load operation. Also, in the past, the heavy duty gas turbine engine has not had severe emission standards imposed on it such as those that now confront the passenger car.

5. IMPACT OF ENGINE MASS PRODUCTION ON THE AUTOMOTIVE INDUSTRY AND THE GENERAL PUBLIC

The conversion of automotive production to gas-turbine-powered vehicles can be expected to have significant impacts on the industry, its suppliers, and on the general public. The industry impacts are largely economic and relate primarily to the costs of converting present production facilities and other capital equipment to gas turbine manufacture. As noted previously, total capital investment of $400 million was estimated by IR&T for an annual production capacity of 1 million engines. Chrysler estimated it would require $5 to $6 billion to establish an annual production capacity of 10 million gas turbine powered automobiles.

In the short term, these funding levels could represent a significant problem for the industry. Conventional engine production equipment write-offs would add to the industry's short-term financing problem. These and other economic impacts, including the dislocation of existing labor markets and skills, argue against an accelerated production changeover to gas turbine automobiles. Foundry workers, machinists, assembly line workers, and workers in after-sales repairs would be particularly affected.

The impacts of the conversion to gas turbine automobiles on the general public relate to beneficial changes in air quality without the necessity of relying on catalyst emission control systems and their associated cost penalties. Operation and service effects are not considered to be significantly different from those relating to conventional automobiles.

Whereas initial ownership for the gas turbine vehicle may represent a higher investment for the consumer, a consensus of estimates by gas turbine manufacturers, combined with predictions made by the automobile industry, indicates that repair and maintenance costs for the gas turbine will not be significantly greater than those for the conventional engine, However, a new spectrum of repair problems intrinsic to gas-turbine-engine design and operation will become manifest.

6. POSSIBLE GOVERNMENT ROLES FOR ENHANCING PRODUCTION VIABILITY

The role of government in developing the gas turbine engine for production is viewed with mixed reactions by industry. Government programs with the objective of enhancing technological development are viewed quite favorably. However, programs that are concerned with manufacturing processes are looked at skeptically. On the one hand, government funding directed at solutions to engine production saves the manufacturer from expending his own funds and is considered an asset. On the other hand, the requirement to reveal unique production processes is viewed as detrimental to a company's competitive posture, if the techniques have evolved from proprietary company-funded work.

The more likely role of government funding is to promote work on improved engine component efficiencies and novel production processes that will not impair a company's competitive position. As an example, an area of investigation that could most benefit from this approach is the development of processes to reduce the time required to produce superalloy castings. Manufacturers will note, however, that original techniques that are ready for funded development rarely have come to fruition without having been built on a company's previous technology base. Therefore, contract work efforts will have to be carefully stated to avoid compromising a particular firm's proprietary position.

It should also be recognized that the expenditure of large sums of money offers no guarantee that technological or manufacturing problems can be completely resolved. Scientific discoveries cannot be willed, and engineering applications of new information cannot be accelerated arbitrarily. Well-planned, carefully coordinated programs are as essential to progress in product development as substantial funding.

While some limited studies are currently in progress to seek solutions to the problem of manufacturing cost, the future prospects are poor for even limited production until the automobile manufacturers have adequate evidence of cost-cutting procedures. Of equal consideration is the verification of consistent, reliable manufacturing processes. The cost implications of a production line breakdown or of a major product-recall problem traceable to manufacturing quality control cannot be overemphasized. Low cost reliable production techniques must be forthcoming in the next 2-1/2 to 3 years or the postulated 11 year development schedule for gas turbine powered automobiles will have to be extended in duration.