REPORT NO. DOT-TSC-OST-73-26

73-26

GAS TURBINE ENGINE PRODUCTION IMPLEMENTATION STUDY

VOLUME II: TECHNICAL DISCUSSION

D. E. Lapedes, et al

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

JULY 1973
FINAL REPORT

Prepared for:

DEPARTMENT OF TRANSPORTATION

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

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT-TSC-OST-73-26		

4. Title and Subtitle GAS TURBINE ENGINE PRODUCTION IMPLEMENTATION STUDY, VOLUME II: TECHNICAL DISCUSSION	5. Report Date JULY 1973 6. Performing Organization Code
7. Author(s) D. E. Lapedes, L. Forrest, F. G. Ghahremani, O. Hamberg, W. U. Roessler, W. M. Smalley, M. Hinton, T. Iura, J. Meltzer	8. Performing Organization Report No. ATR-73(7323)-1, Vol. II
9. Performing Organization Name and Address URBAN PROGRAMS DIVISION THE AEROSPACE CORPORATION EL SEGUNDO, CALIFORNIA 90045	10. Work Unit No. OS314/R3531 11. Contract or Grant No. EPA 68-01-0417
12. Sponsoring Agency Name and Address DEPARTMENT OF TRANSPORTATION OFFICE OF THE SECRETARY, OFFICE OF SYSTEMS DEVELOPMENT AND TECHNOLOGY WASHINGTON, D.C. 20590	13. Type of Report and Period Covered FINAL REPORT JANUARY 1973 - JULY 1973 14. Sponsoring Agency Code

15. Supplementary Notes

CONTRACT ADMINISTERED BY:
ENVIRONMENTAL PROTECTION AGENCY
DIVISION OF EMISSION CONTROL TECHNOLOGY
ANN ARBOR, MICHIGAN 48105

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.

17. Key Words	18. Distribution Statement
automobile, design and technology, engines, gas turbine, mfg. costs, mfg. processes, mass production, schedules	DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22151.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	260	

Form DOT F 1700.7 (8-69)

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.

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LIST OF ABBREVIATIONS

AAPS	Advanced Automotive Power Systems
AMA	Automobile Manufacturers Association
ARPA	Advanced Research Projects Agency
BSFC	Brake Specific Fuel Consumption
CD-1, CD-2	Conceptual Design
CID	Cubic Inch Displacement
CO	Carbon Monoxide
DOT	Department of Transportation
EDM	Electro-Discharge Method
EFC	Electronic Fuel Control
EPA	Environmental Protection Agency
EVC	External Vaporizing Combustion
FDC	Federal Driving Cycle
GMC	General Motors Corporation
GVM	Grams per Vehicle Mile
HC	Hydrocarbon
IR&T	International Research and Technology Corporation
MPG	Miles per Gallon
NAPCA	National Air Pollution Control Administration
NASA	National Aeronautics & Space Administration
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NSF	National Science Foundation
OEM	Original Equipment Manufacturer
PD-1	Preliminary Design
SFC	Specific Fuel Consumption
USEDC	Uniform Simplified Emission Driving Cycle

SECTION 1

SECTION 1

INTRODUCTION

1.1 BACKGROUND, OBJECTIVES, AND SCOPE

For well over 20 years, the gas turbine engine has been proposed by many as a powerplant to supplant the spark ignition engine in the automobile. Initial interest in the gas turbine for automotive application stemmed primarily from postulated advantages in the areas of reduced maintenance requirements, longer engine life, reduced engine weight and volume, and lower manufacturing costs occasioned by fewer engine parts and simpler assembly operations. Many experimental gas turbine powered automobiles have been built in the interim; however, except for Chrysler's 50-car, gas-turbine consumer evaluation test program in the period 1963-1965, none has been subjected to customer use and/or production in any sizeable quantity. Poor fuel economy, inadequate engine response and braking, insufficient engine power, and excessive noise have generally characterized the gas turbine automobile to date. Because of high estimated manufacturing costs, some companies (e.g., Ford and General Motors) have concentrated more recent developmental efforts on engines for trucks and buses. In this application, higher engine production costs allow the gas turbine engine to more reasonably compete with diesel engines.

The requirements of the Clean Air Act, as amended in 1970, with regard to automobile exhaust emissions has led to an accelerated interest in the gas turbine powered automobile and its potential to meet the requirements of the act without additional add-on emission control devices. The reason for concentrating on the gas turbine engine in this study is this potential for meeting emissions standards and its extensive technological development.

The Environmental Protection Agency (EPA) Division of Advanced Automotive Power Systems (AAPS) has sponsored a comprehensive research and development program aimed at improving gas turbine and gas turbine component performance levels to the point where the gas turbine could compete with the conventionally powered automobile, in terms of vehicle performance and fuel ecomomy, while concurrently meeting the stringent 1976 Federal emissions standards.

Aside from the issues of automobile performance and exhaust emissions levels, there remains the issue of gas turbine production potential and the resulting cost impact on both the consumer and the automotive industry. Because of previous uncertainties concerning automotive gas turbine mass production, the present study was initiated with the following major objectives:

1. To identify and assess those factors affecting timely introduction of gas turbine engine concepts on a mass production basis, to highlight those factors which appear to have a limiting effect with regard to mass production, and to assess their validity and impact on the mass production process.
2. To establish meaningful schedules for domestic mass production implementation of gas turbine powered automobiles, to structure these implementation schedules so as to reflect the feasibility and practicality of acquiring and integrating such advanced engines with the automotive system mass production process.

The study was principally focused on a baseline vehicle representing an "average" passenger car. Vehicle specifications developed in the EPA-AAPS program (e.g., weight, capacity, maximum speed, acceleration, etc.) were used to characterize the baseline vehicle. The free-turbine, low-compression ratio, regenerated gas turbine cycle selected by EPA for detailed development in the AAPS program was selected as the baseline engine, although other engine cycles were also evaluated where they were considered pertinent to a potential impact on the implementation cycle.

Both normal and compressed (expedited) implementation approaches were examined. The range of possible production rates, from initial introduction into a mixed production of both gas turbine and conventionally powered vehicles to approximately 100 percent of the light-duty vehicle market, were considered for their impact on the implementation schedule.

1.2 ACQUISITION OF RELEVANT DATA

Principal data sources consisted of technical discussions held with representatives of the domestic automotive industry, gas turbine industry, critical component suppliers, EPA-AAPS program, and NASA-Lewis Research Center. Data from the literature used to supplement these discussions are noted herein where they are of particular relevance. In this regard, recent economic impact studies sponsored by the Department of Transportation (DOT) and the National Science Foundation (NSF) were relied upon for supporting data. Another supporting data source is the Production Lead Time Study recently completed by The Aerospace Corporation for EPA (Division of Emission Control Technology), which provided a reference implementation schedule representative of current automotive mass production activities for both normal and expedited cases for vehicles incorporating conventional spark-ignition engines.

Appendix A contains a listing of companies and agencies contacted, date of contact, and principal personnel involved. Appendix B provides a listing of some recent publications germane to the subject of gas turbine engines.

1.3 COVERAGE OF REPORT

Results of the study are reported in the following order and context:

Section 2: Gas Turbine Engine and Powertrain Technology
A review of various automotive gas turbine engine design approaches and current and advanced technology status. This section provides a delineation of the hardware requirements and characteristics of the gas turbine engine, which is prerequisite to a discussion of mass production manufacturing techniques and implications.

Section 3: Potential for Mass Production Manufacturing

An examination of the critical factors involved in gas turbine mass production. This section treats raw and processed materials, production processes, capital investment requirements, and gas turbine related unit costs.

Section 4: Product Development Programs and Schedules

An examination of the status of industry progress in gas turbine technology and production development and an assessment of the potential for converting this experience into the development of gas turbine automotive systems. Particular emphasis is placed on the prospects for implementing mass production of the gas turbine car in a near-term time frame.

Section 5: Impact of Engine Mass Production on the Automotive Industry and the General Public

A brief delineation of possible economic and other impacts on the industry, suppliers, labor market, and the general public.

Section 6: Summary of Current Automotive and Gas Turbine Industry Attitudes

A brief summary of the current views predominant in each of the automotive and gas turbine firms visited during the course of the study.

Section 7: Assessment of Mass Production Viability

An overview assessment of the current potential for gas-turbine-car production implementation, including possible government roles for enhancing production viability.

SECTION 2

SECTION 2

GAS TURBINE ENGINE AND POWERTRAIN TECHNOLOGY

2.0 INTRODUCTION

If the gas turbine powered automobile is to replace the internal combustion engine powered automobile, it must meet the following requirements:

Prevailing exhaust emission control requirements, without aftertreatment devices.
Fuel economy comparable to or better than advanced piston engine cars.
Comparable torque and acceleration characteristics.
Packageability and compactness in conventionally sized vehicles.
Lower manufacturing cost.
Lower maintenance and operational costs.
Comparable driveability and durability.
Safe at all operating and environmental conditions.

These requirements dictate the use of unique technological approaches. The advanced gas turbine technology developed in the aircraft industry should be critically evaluated for application to automobiles. New technology must be developed to overcome any performance deficiencies identified. In this regard, it is noted that the aircraft engine is designed to operate most of the time at a fixed power output, while the automobile engine must operate for the most part over a wide range of power outputs.

In the following sections, the status of current and advanced technology will be discussed with respect to the above requirements. These sections will provide an understanding of the hardware requirements for the gas turbine engine, which is a prerequisite to the discussion of mass production manufacturing.

2.1 ENGINE DESIGN APPROACHES

2.1.1 Gas Turbine Configurations

Most existing vehicular gas turbine engines use the so-called free turbine arrangement where two turbines are used in series. In this arrangement, a high pressure first-stage turbine* drives the air compressor and a low-pressure second-stage turbine** delivers useful shaft power output. This split-shaft scheme allows for flexibility of operation, especially in conjunction with a variable power turbine nozzle. For example, the variable turbine nozzle may be used to provide engine braking, in addition to its value in providing high torque at low turbine speed.

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 characteristics 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 a continuously variable gear ratio transmission.

2.1.2 Gas Turbine Cycle Analysis

A simple gas turbine cycle utilizes 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. A temperature-entropy diagram depicting this process is shown in Figure 2-1. The thermal energy in the simple cycle turbine exhaust 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. The regenerator is a rotating disc heat exchanger that alternatively exposes

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*Also referred to as the gasifier or compressor turbine

**Also referred to as the power turbine

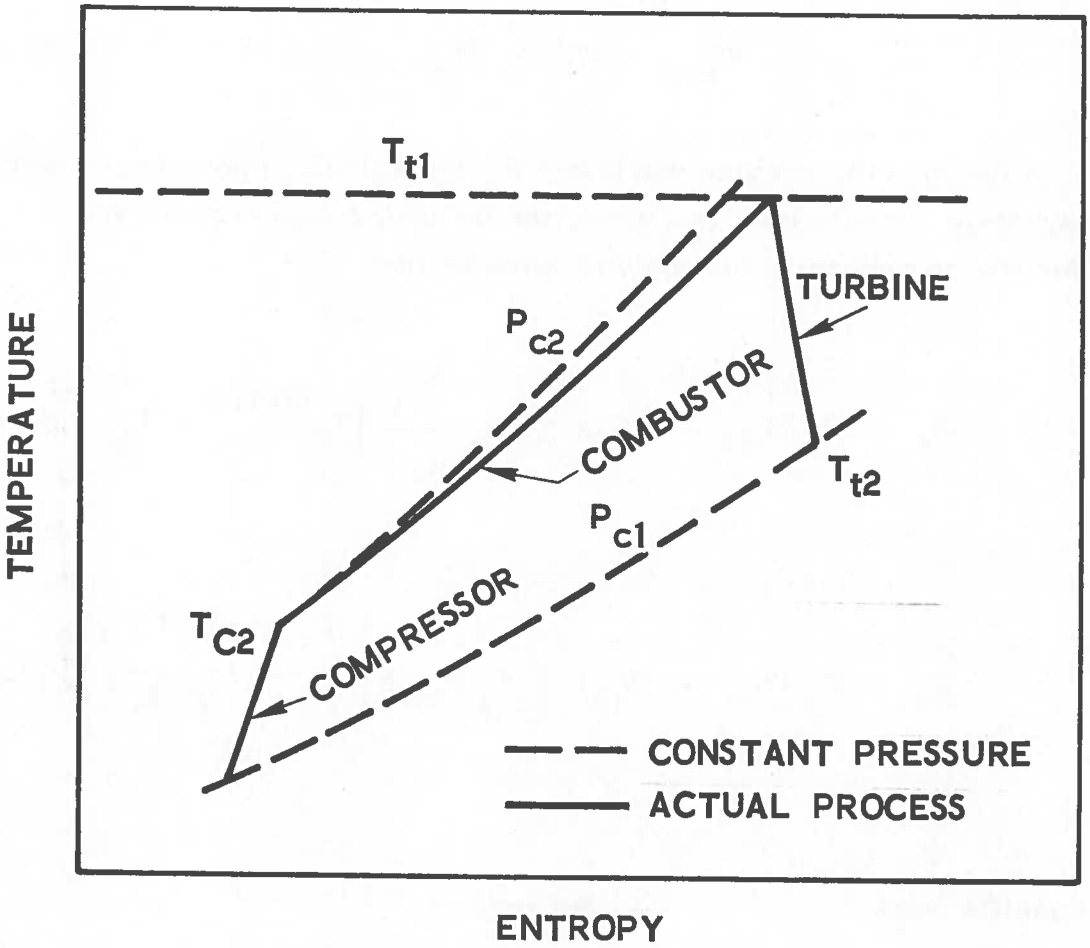


Figure 2-1. Temperature-Entropy Diagram for Simple Cycle Gas Turbine

the heat exchanger core by sections to turbine exhaust gases and compressor outlet air. The recuperator is a fixed (static) heat exchanger with separate passages for turbine exhaust gases and compressor outlet air. A schematic of this equipment is presented in Figure 2-2.

The specific net work output of a gas turbine is given by

$$W_{net} = W_t - W_c \qquad (2\text{-}1)$$

where W_t is the specific turbine work and W_c the specific compressor work. If thermodynamic correlations are used, the following expressions are obtained for the compressor and turbine work terms

$$W_c = C_p (T_{c2} - T_{c1}) = C_p \frac{T_{c_1}}{\eta_c} \left[r_c^{(\gamma-1/\gamma)} - 1 \right] \qquad (2\text{-}2)$$

$$W_t = C_p (T_{t1} - T_{t2}) = C_p T_{t1} \eta_t \left[\frac{r_t^{(\gamma-1/\gamma)} - 1}{r_t^{(\frac{\gamma-1}{\gamma})}} \right] \qquad (2\text{-}3)$$

where

W = specific work

T = temperature

C_p = specific heat

r = pressure ratio

γ = ratio of specific heats

η = efficiency

Subscripts

c = compressor

Cx = cold side of heat exchanger (Fig. 2-2)

Hx = hot side of heat exchanger (Fig. 2-2)

t = turbine

1 = inlet

2 = discharge

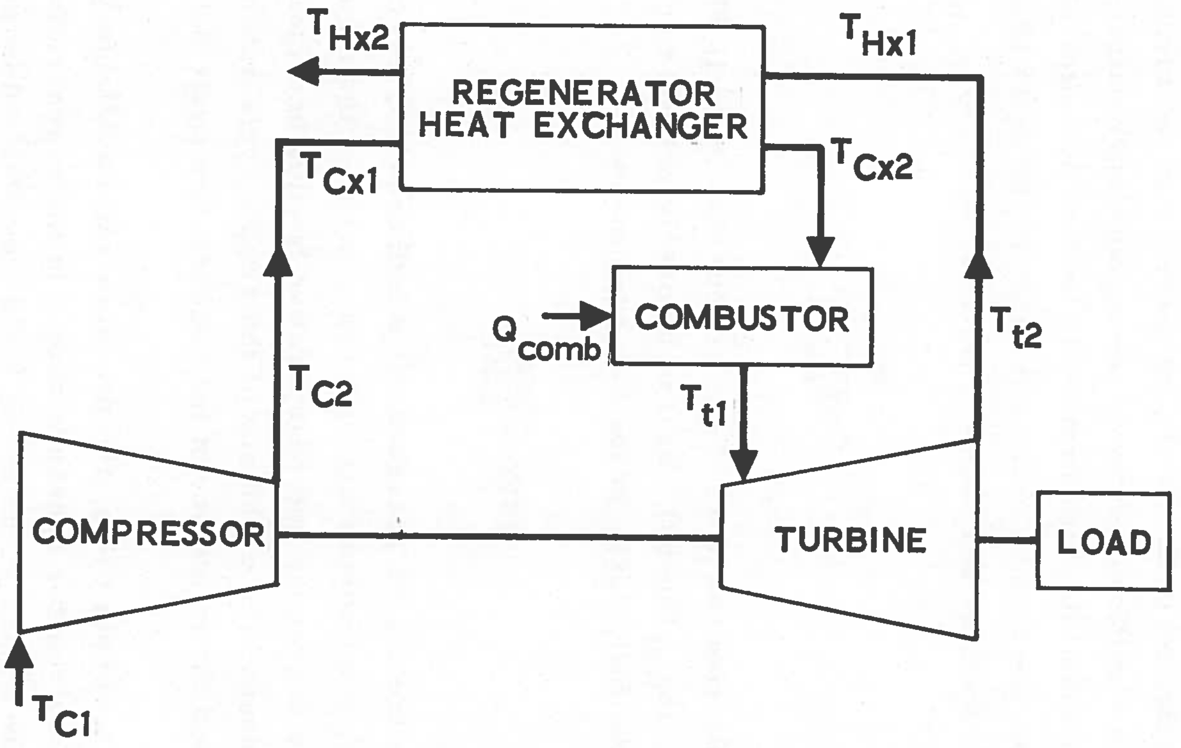


Figure 2-2. Schematic of Equipment for Gas Turbine Regenerative Cycle

To increase the net work output of the gas turbine the compressor work has to be reduced and/or the turbine work has to be increased. As indicated in Eq. (2-3), an increase in the turbine inlet temperature has a significant effect on the turbine work output. However, the operational turbine inlet temperature is limited by material properties.

The gas turbine cycle efficiency is the ratio of net specific work output to the specific heat input to the combustor, Q_{comb}

$$\eta = \frac{W_{net}}{Q_{comb}}$$

Another term indicating the level of gas turbine efficiency is SFC (specific fuel consumption, lb_{fuel}/hp-hr). SFC is inversely related to η and the lower heating value of the fuel, LHV, in the following manner

$$SFC = \frac{2544}{\eta LHV}$$

As the engine pressure ratio is increased, at constant turbine inlet temperature, the temperature difference between the turbine and compressor discharge decreases and regenerative heating becomes less significant. For this reason, the efficiency of the simple cycle optimizes at high pressure ratio, and the efficiency of the regenerative cycle optimizes at low pressure ratio.

In a simple cycle, the pressure ratio available in the turbine is reduced by the combustor pressure drop. In the regenerative cycle, additional pressure losses occur in the "cold" and "hot" flow passages of the heat exchanger which further reduces the turbine pressure ratio and the turbine work output.

The effect of pressure ratio on cycle performance is shown in Figures 2-3 and 2-4 (Ref. 2-1), where the brake specific fuel consumption (BSFC) is plotted as a function of compressor pressure ratio for a range of

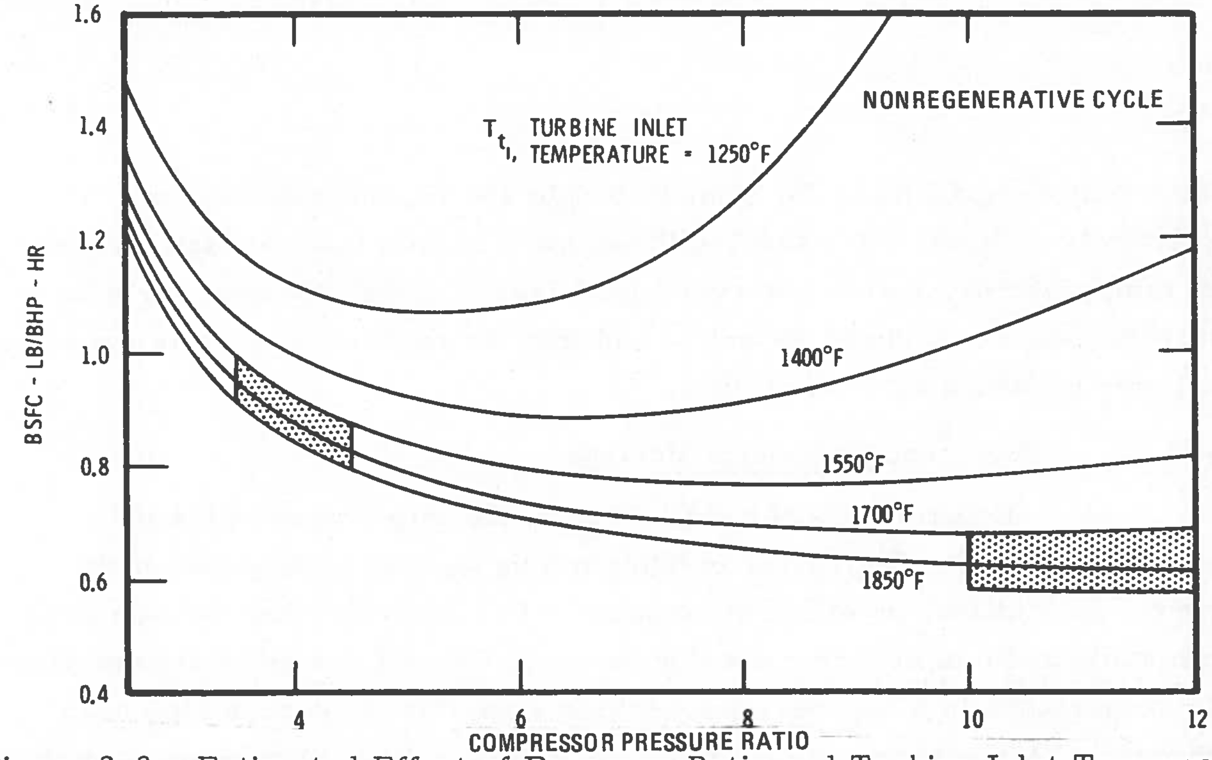


Figure 2-3. Estimated Effect of Pressure Ratio and Turbine Inlet Temperature on Fuel Economy for Nonregenerative Cycle (Ref. 2-1)

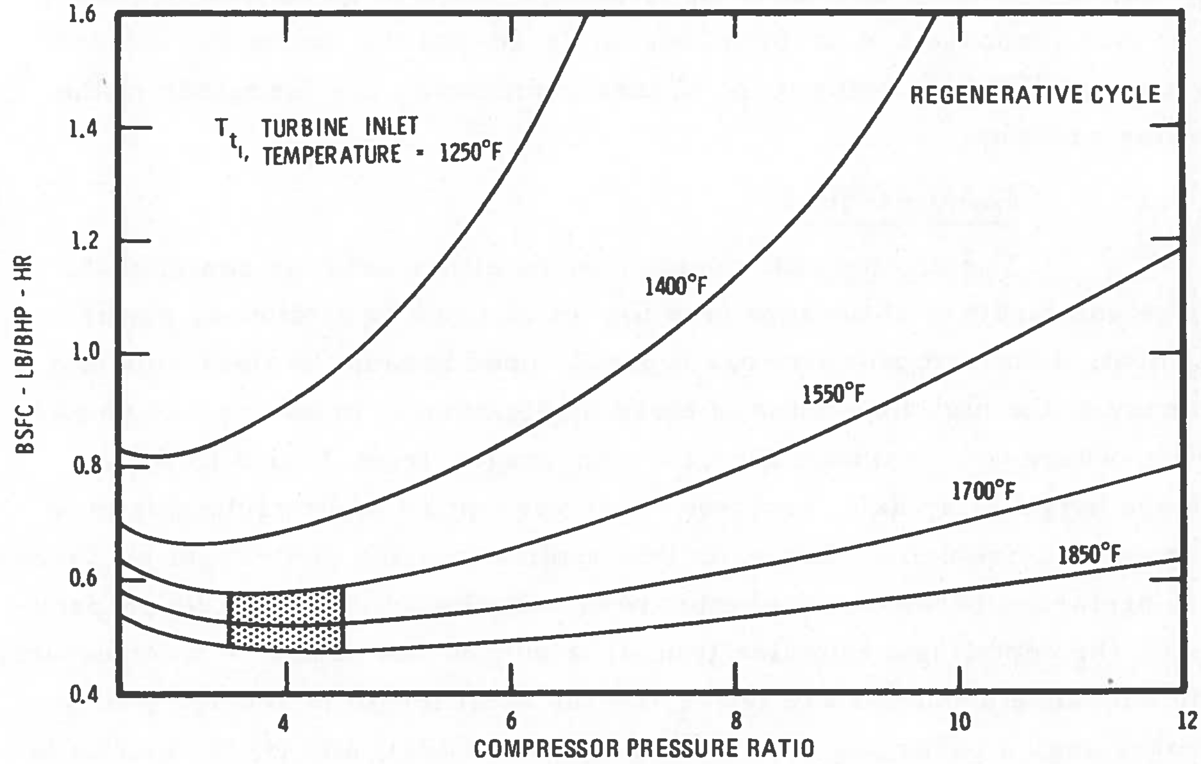


Figure 2-4. Estimated Effect of Pressure Ratio and Turbine Inlet Temperature on Fuel Economy for Regenerative Cycle (Ref. 2-1)

turbine inlet temperatures for typical simple and regenerative cycles, respectively. Figures 2-3 and 2-4 illustrate the point that, at high turbine inlet temperatures, the simple cycle optimizes at a high compressor pressure ratio ranging between 10 and 12 and that the regenerative cycle optimizes at a lower pressure ratio of about 4.

2.1.3 Current Component Designs

Equations (2-2) and (2-3) show the importance of the compressor and turbine efficiencies in determining the net work output of the system. In addition, an efficient combustor is important from the standpoint of emission and fuel economy considerations. Careful design of regenerators and recuperators in a regenerative cycle is important to ensure high heat exchanger effectiveness and low pressure losses. Other components, such as bearings, have a significant impact on maintaining mechanical integrity of the engine. Engine control components also have to be defined to ensure that proper response and performance designed into the engine is realized over the complete operating map. These components are discussed in the following sections.

2.1.3.1 Compressors

The compressor design may be either axial or centrifugal. In large gas turbines of the type used for jet aircraft or stationary power equipment, axial compressors are typically used because of their superior efficiency at the high flow rates of these applications. In an automotive gas turbine, where the maximum air flow rate ranges from 1 to 3 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).

In the centrifugal compressor design, two impeller configurations may be used: radial or backward-bladed impellers. In the radial design the high velocity of the flow entering the vaned diffuser results in high losses, thereby limiting the operating range of the compressor due to surge, an unstable flow condition. In contrast, the backward-bladed impeller exit velocity is low, resulting in a shift of the surge line towards lower flows which increases the operating range of the unit. For the same design pressure ratio, the backward-bladed impeller has a larger diameter and this increases the size of the engine. In automotive gas turbines, the compressor has to operate without surge over wide ranges of flow and rotational speed. Therefore, on the basis of performance considerations only, the backward-bladed impeller design is preferred. Other considerations governing the selection of impeller design include stress levels, associated material requirements, and size. Figure 2-5 (Ref. 2-2) shows performance

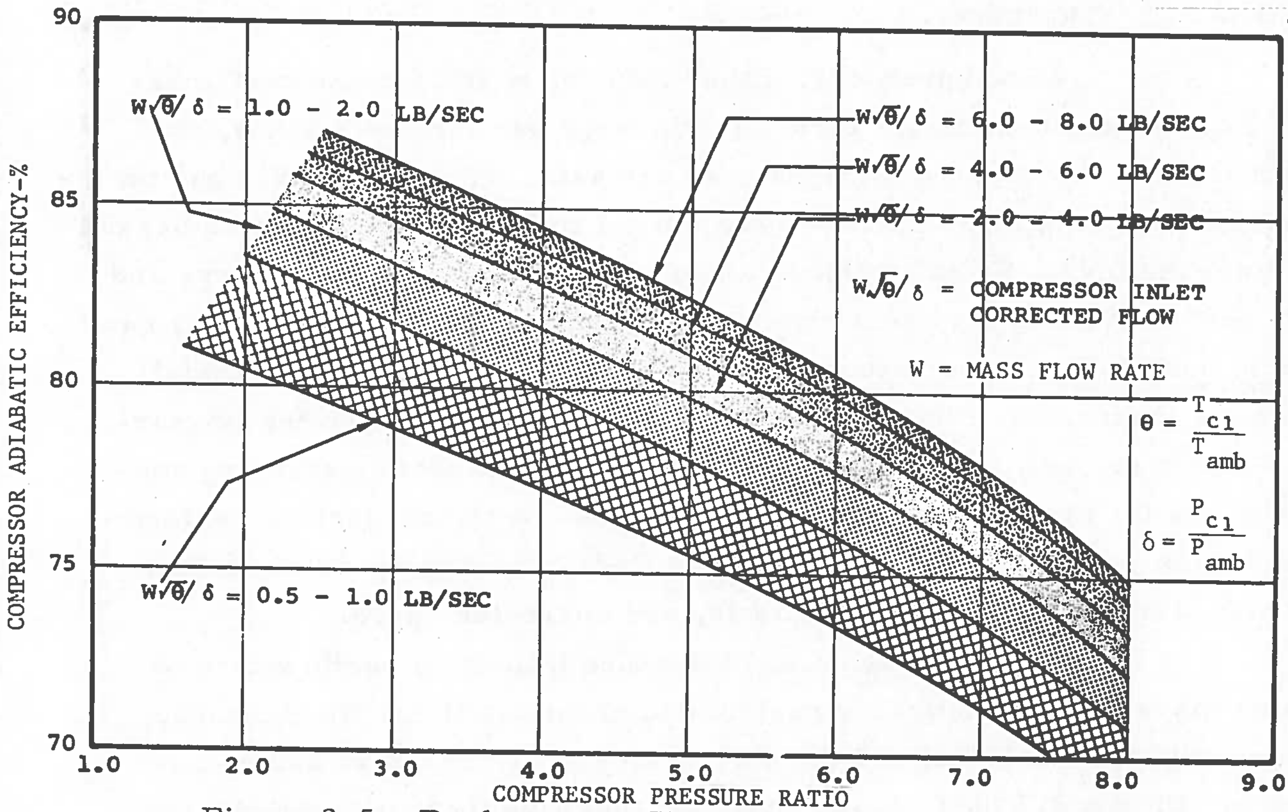


Figure 2-5. Performance Characteristics for Single-Stage Centrifugal Compressor (Ref. 2-2)

characteristics representative of both radial and backward-bladed centrifugal compressors as a function of pressure ratio and compressor flow rates, corrected to standard inlet conditions. These data are based on tests of many AiResearch compressors and are considered to reflect the current state of the art.

Important parameters affecting the performance of centrifugal compressors are the clearance between the impeller and the shroud and the ratio of impeller-to-shroud clearance to blade width at the tip of the impeller. In general, the relationship between efficiency loss and tip clearance is linear. Typically, the clearance losses vary between less than 1 percent for large compressors to about 3 percent for very small units.

With regard to impeller materials, aluminum can be used for pressure ratios up to about 4.5:1. Beyond that point, steel alloys and titanium are required in single-stage designs.

2.1.3.2 Turbines

Like compressors, either axial or radial turbine configurations may be employed in gas turbines. In large gas turbine engines, the flow rates are high and the turbines used are axial. For automobile gas turbines with maximum flow rates of only about 1 to 2 lb/sec, axial or radial turbines are feasible. 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 for the routing of gas flow passages. A typical turbine performance map is presented in Figure 2-6 (Ref. 2-2), showing the relationships between corrected flow, pressure ratio, and corrected speed.

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. Figure 2-7 (Ref. 2-3) shows how sensitive these dimensions are.

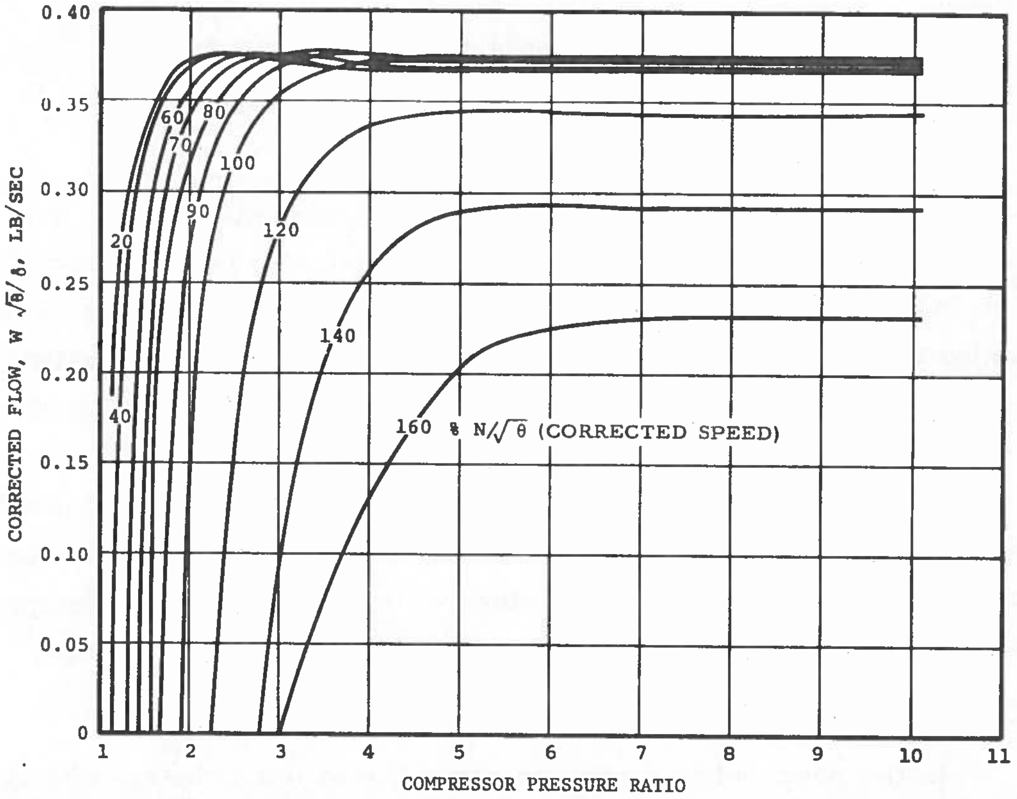


Figure 2-6. Estimated Turbine Performance, Single-Shaft Recuperated Engine (Ref. 2-2)

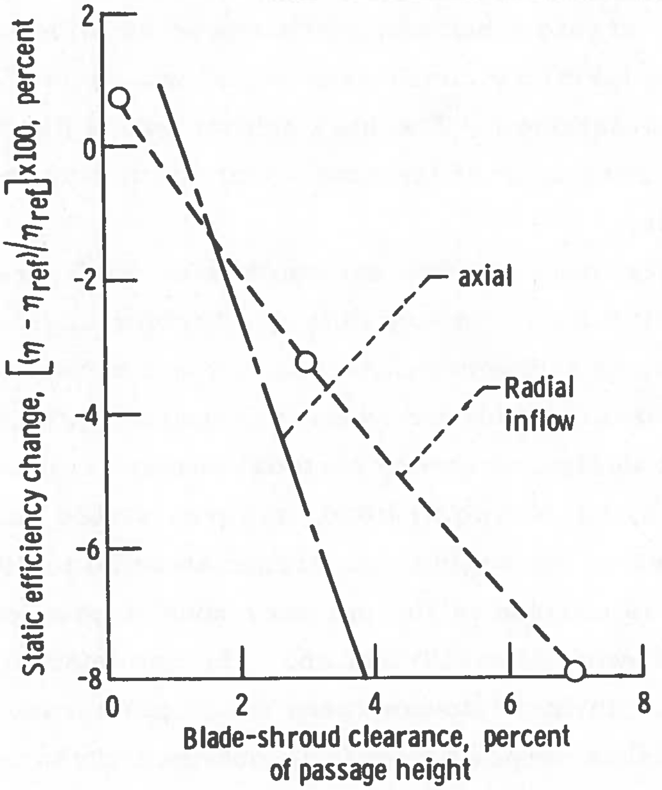


Figure 2-7. Comparison of Effect on Static Efficiency of Clearance Variation. Uniform Percent Clearance at Rotor Entrance and Exit for Radial-Flow Turbine (Ref. 2-3)

Here, the effect of clearance on efficiency for a 5-inch axial turbine is compared with a 6-inch radial turbine. As indicated, 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 nominal design point operation at 1900°F turbine inlet temperature for super alloy investment castings without blade cooling. For higher temperatures, blade cooling or advanced ceramic materials would be required.

2.1.3.3 Combustors

In the past, when emission control was not a design objective, the prime consideration in gas turbine combustor design was simply to produce the highest overall combustion efficiency in a compact configuration. The basic approach is to create a hot combustion zone by injecting fuel in a recirculating flow region (primary combustion zone) where near-stoichiometric air/fuel conditions are maintained. The high primary zone gas temperatures are reduced in the secondary zone of the combustor by mixing the combustion products with dilution air.

An example of a conventional combustor configuration is the device selected by Ford for its 707 heavy duty gas turbine engine. The design, illustrated in Figure 2-8, is a reverse-flow, can-type combustor which utilizes a fuel-atomizing nozzle and an air swirler installed in the dome of the unit (Ref. 2-12). In this design, a strong toroidal vortex is generated along the combustor axis which, according to Ford, assures stable combustion at all operating conditions of the engine. Approximately 20 to 30 percent of the total engine air flow is utilized in the primary zone to provide a primary air/fuel mixture ratio between about 20 and 35. The combustion gases are diluted with secondary air injected downstream of the primary zone in such a manner that a uniform flow velocity profile is obtained at the entrance to

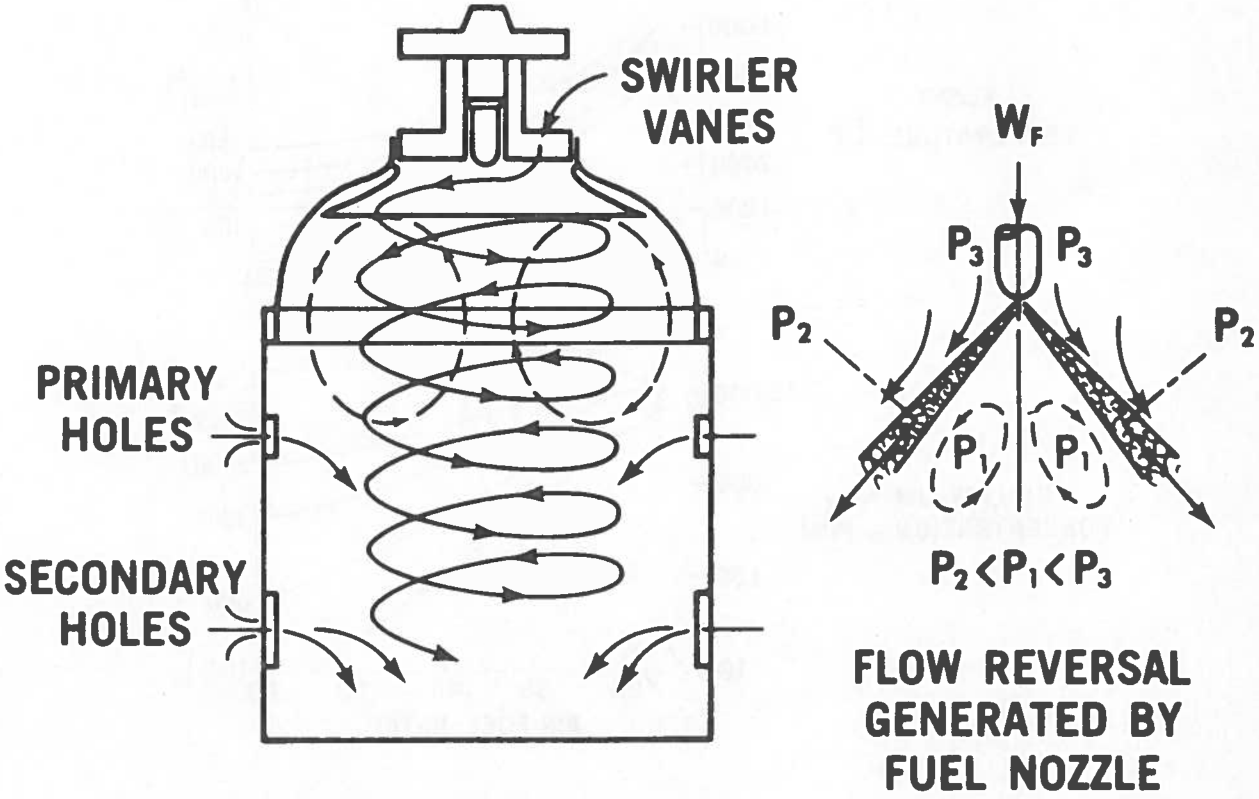


Figure 2-8. Flow Path for Reverse-Flow, Can-Type Combustor (Ref. 2-12)

the gasifier. This design satisfied Ford's initial objectives for stable combustion, high combustion efficiency, low pressure drop, long life, low cost, and low emissions.

The present goals in automotive gas turbine combustor design are to meet or better the 1976 emission standards while maintaining good fuel economy. The two goals of good fuel economy and low NO_x emissions tend to be conflicting. Superior fuel economy requires regenerative heating or high compressor pressure ratio, resulting in high combustor inlet temperatures and high NO_x emissions. Figure 2-9 (Ref. 2-4) illustrates this fact. As the combustor inlet temperature is increased (for the same equivalence ratio) the combustor temperature and the NO_x levels increase. To minimize the formation of NO_x, the following design principles are currently being evaluated by industry (Refs. 2-4, 2-5, 2-6, 2-7):

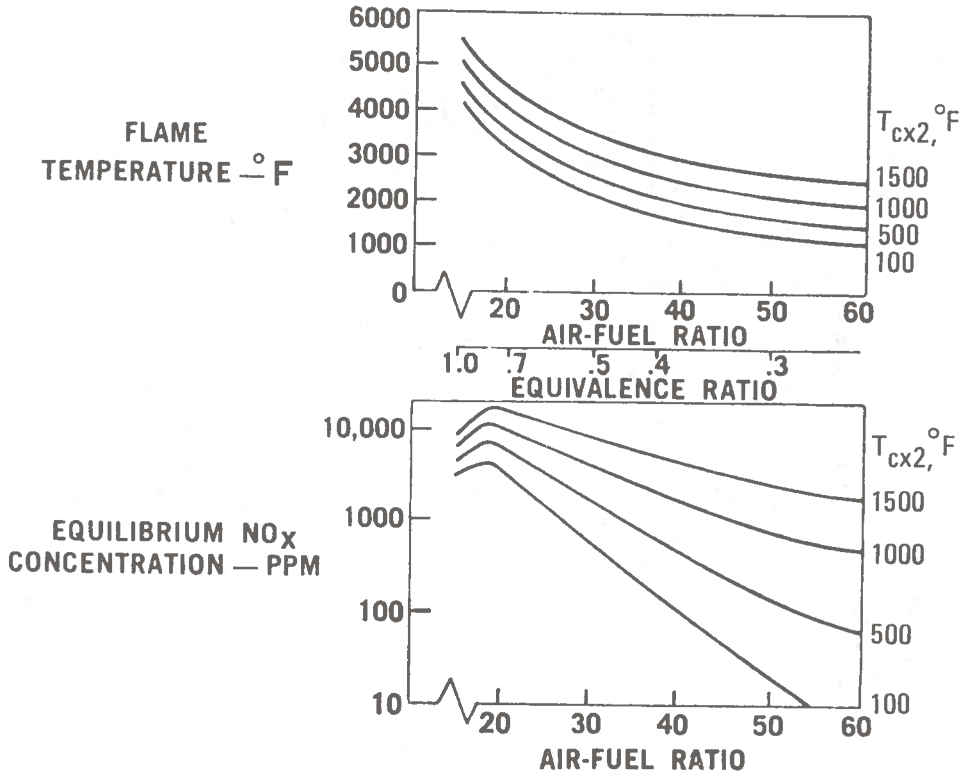


Figure 2-9. Estimated Flame Temperatures and Equilibrium NO_x Concentrations as Functions of Air/Fuel Ratio for Various Combustor Inlet Temperatures (Ref. 2-4)

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

An example of a fixed-geometry combustor configuration is the current Chrysler combustor. This combustor consists of a 90-degree spray, air-atomizing nozzle, and utilizes 31 percent of the total air in the primary zone. The primary zone reaction volume is very small, in order to minimize the residence time of the combustion gases at the high combustion temperatures, and, hence, minimize the formation of NO_x.

Secondary air is injected immediately downstream of the primary zone to quench the NO_x reactions and complete the hydrocarbon (HC) and carbon monoxide (CO) oxidation reactions.

2.1.3.4 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. As illustrated in Figure 2-10 (Ref. 2-2), a barrier seal separates the "cold" and "hot" sides of the heat exchangers. Both metallic and ceramic cores have been used. The effectiveness of these rotating heat exchangers, defined as the ratio of heat transferred into the cold fluid to the amount of heat available in the hot fluid, can be very high. Values of the order of 0.9 have been achieved with regenerators designed for automotive gas turbine applications.

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 solvable.

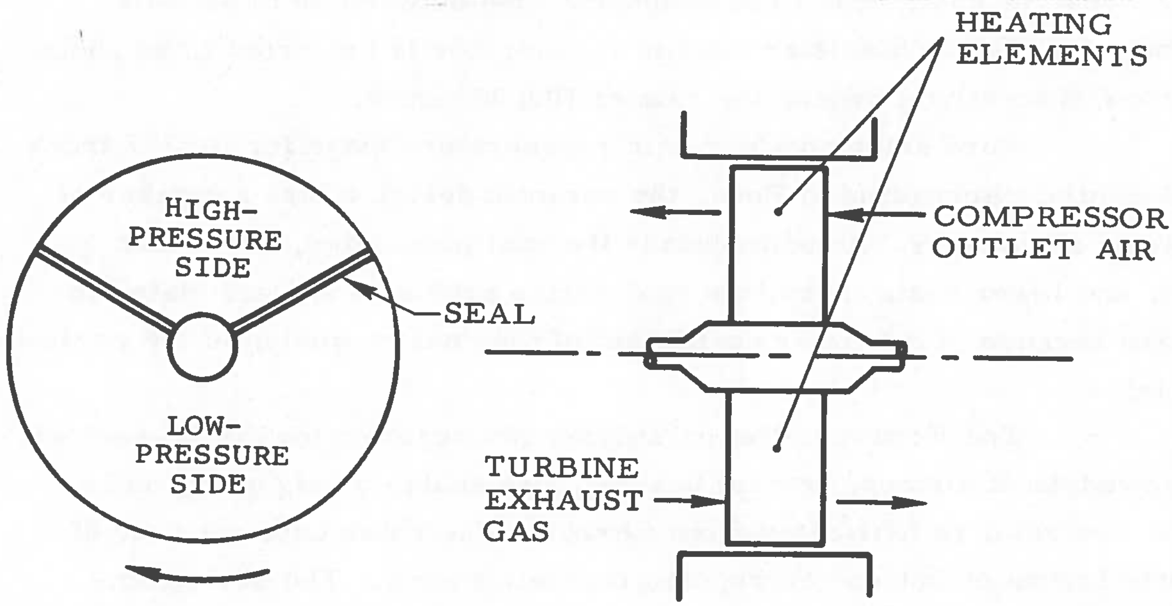


Figure 2-10. Disc-Type Rotary Regenerator (Ref. 2-2)

Recuperators are fixed boundary, stationary heat exchangers. For automotive applications, the effectiveness of these heat exchangers can be as high as 0.85. Compared to regenerators, recuperators are bulky but require no seals or rotating drive. Materials used in the manufacture of recuperators include mild steel, stainless steel, Inconel and Hastelloy (Ref. 2-8). Mild steel has been used for low-temperature applications in stationary gas turbine plants. An excellent recuperator material is 347 stainless steel which has good creep strength and hot erosion resistance at elevated temperatures (Ref. 2-8).

From a packaging, performance, weight, and cost point of view, the regenerators are preferred for automotive gas turbines. Currently, the glass-ceramic regenerator is growing in favor. The two major suppliers of ceramic regenerator cores are Corning Glass Works, which manufactures Cercor (Ref. 2-9) and Owens-Illinois, which makes Cer-Vit (Ref. 2-10). Both manufacturers utilize honeycomb construction, with Cercor having straight triangular passages and Cer-Vit hexagonal passages. The advantages claimed for glass-ceramic regenerators are compactness, low density, and low cost. The Cercor density runs between 30 to 42 lb/ft^3. The cost of a 17-inch diameter Cercor regenerator is projected to be about $40 based on an annual production rate of 100,000 units.

Ford selected a ceramic regenerator design for its 707 truck engine family. According to Ford, the ceramic design offers a number of significant advantages, including better thermal properties, lower unit weight, and lower cost. Also, the seal design problems are alleviated in this case because of the lower coefficient of thermal expansion of the ceramic material.

The Ford installation utilizes two regenerator discs, each of which consists of a rotor, central bearing, two seals, a ring gear, and a cover. The rotor is fabricated from Cercor. The rotor core consists of alternate layers of flat and corrugated ceramic sheets. The seals comprise a rubbing metal shim coated with a material designed to minimize friction and wear. The regenerators are driven from the accessory gear train.

Chrysler, on the other hand, experimented with ceramic regenerators as early as 1950. Because of many design difficulties resulting in unreliable operation, cracking, low effectiveness, and high leakage after about 4000 hours, Chrysler dropped the ceramic approach and decided to utilize all-metal regenerators in its fourth- and sixth-generation automobile gas turbine engines. Chrysler feels that metal regenerators have lower seal friction and are less expensive at current production levels than ceramic configurations. In terms of leakage flow, the two types are considered equal. Even though Chrysler continues to favor metallic regenerators for reasons of performance, reliability and cost, they nevertheless are working on the development of improved ceramic designs.

General Motors selected a disc-type regenerator for its current GT-404 heavy duty vehicle engine. The regenerator was designed so that, initially, metallic elements would be used; eventually, when proven to be satisfactory, ceramics could be used to replace the metallic discs. A twin disc, with each disc 25 inches in diameter and 3 inches thick, is made by winding 430 stainless steel strips. A corrugated and a flat strip are used and, after the disc is formed, copper braze powder is applied and the disc is brazed in a vacuum furnace. The surfaces of the disc are machined by an electro-discharge method (EDM) to provide smoothness for improved sealing of surfaces. The seal material is graphite for operation at temperatures less than 800°F; mixtures of metal oxides are used for higher temperatures. The seal consists of 0.060-inch thick sheet metal with a weather-strip type of sealing leaf attached to the seal structure. Regenerator effectiveness has been tested at 0.85.

2.1.3.5 Bearings

Both rolling element and journal bearings are used in gas turbine engines. The rolling element bearing is preferred in aircraft gas turbines because of superior friction characteristics under variable temperature and load conditions. In stationary gas turbines, journal bearings are used to take advantage of their long service life (Ref. 2-11). For automobile gas turbines, both journal and rolling element bearings are being considered.

In recent years gas bearings have been developed for aircraft auxiliary power drives. This design does not require lubrication and might eventually be used in automotive gas turbines as well. A more detailed discussion on gas bearings follows in Section 2.1.5.5.

Journal bearings are used in the Chrysler automobile gas turbine. No special synthetic lubricants are required. Peak bearing temperature is observed approximately 8 minutes after engine shutdown as a result of heat soakback into the journal. To minimize bearing temperature rise, Chrysler utilizes a heat-diffusing aluminum support around the bearing.

2.1.3.6 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. For example, at part-load, the engine would operate at reduced turbine inlet temperature, resulting in poor fuel economy unless certain control devices, such as variable compressor inlet guide vanes and variable turbine nozzles are used. These devices and the overall control system are discussed in the following sections.

2.1.3.6.1 Compressor Variable Inlet Guide Vanes

The compressor performance is governed by three basic parameters: rotational speed, pressure ratio, and flow rate. At low flow rates, compressor surge effects can produce a significant reduction in compressor efficiency. Incorporation of variable inlet guide vanes alleviates these problems to some degree. By adjusting the position of these guide vanes, 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 improvements in specific fuel consumption at part-load.

2.1.3.6.2 Turbine Variable Nozzle

In the dual-shaft arrangement, the variable 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. This allows flexibility in control of the overall engine pressure ratio 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. This is illustrated in Figure 2-11 which shows the performance of a free turbine engine without the variable turbine nozzle and Figure 2-12 which shows the same engine with the variable nozzle (from Ref. 2-2). Another advantage of the variable nozzle is the fact that it can generate braking power by a reversal in nozzle position.

The braking effect obtainable from the variable nozzle feature is illustrated in Figure 2-13 which shows braking force characteristics as

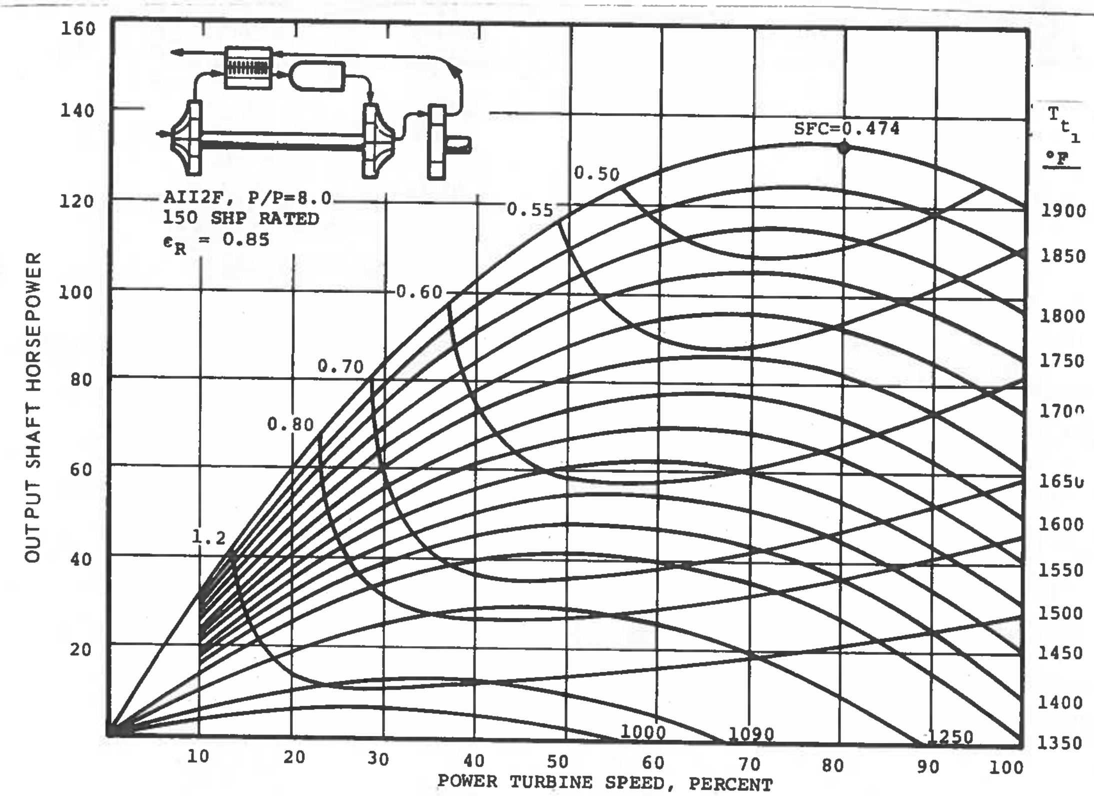


Figure 2-11. Estimated Output Shaft Power for Recuperated Free-Turbine Cycle, 85°F Day (Ref. 2-2)

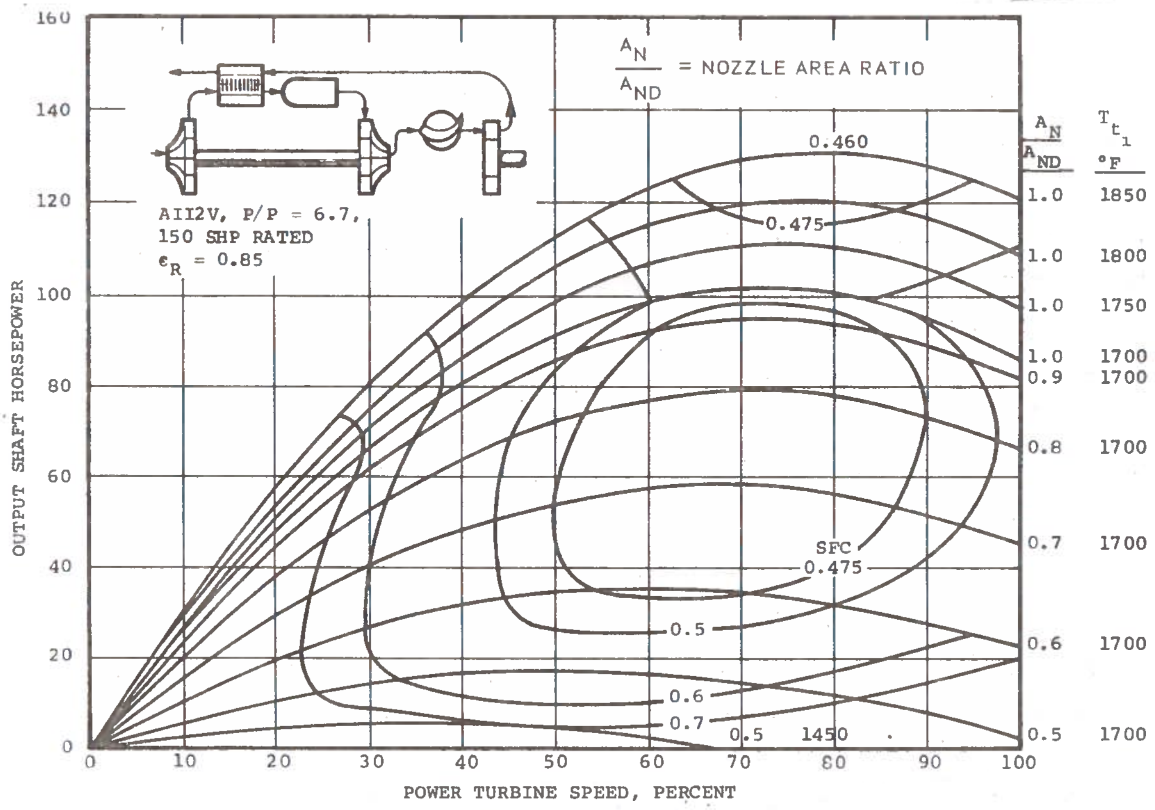


Figure 2-12. Estimated Output Shaft Power for Recuperated Free-Turbine Cycle with Variable Power Turbine Nozzles, 85°F Day (Ref. 2-2)

a function of car speed for two of Chrysler's free turbine, variable nozzle engine designs (Ref. 2-28). The most recent Chrysler design, the sixth-generation engine, was modified from the fourth-generation design to achieve better braking characteristics. Also shown in the figure is the braking force of a V-8 engine-powered vehicle with the transmission in the drive position. As indicated, the braking power of the sixth-generation gas turbine engine is substantially higher than that of the fourth-generation engine and slightly better than the braking power of the standard automobile.

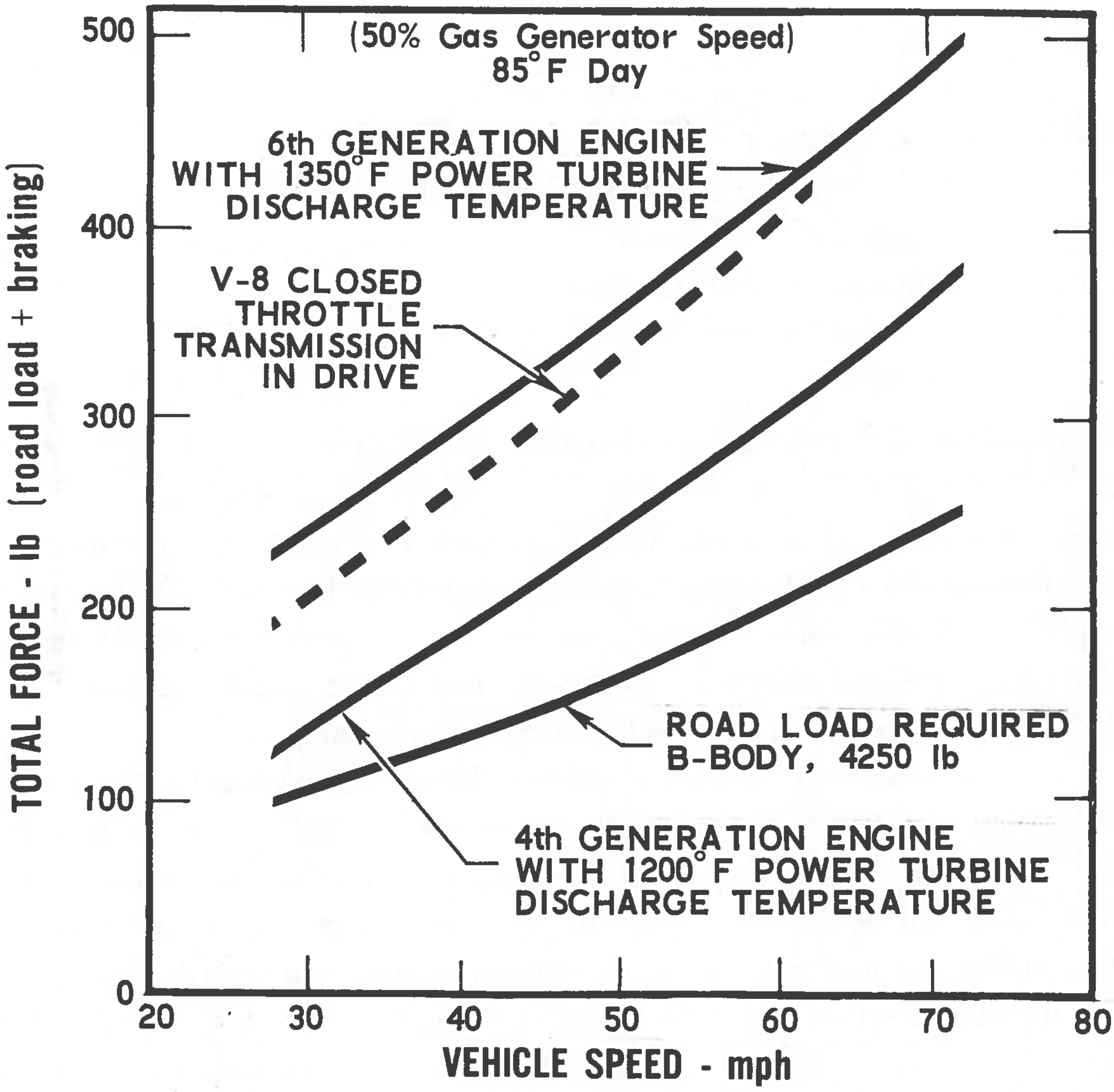


Figure 2-13. Engine Braking Force Characteristics (Ref. 2-28)

2.1.3.6.3 System Controls

System controls involve 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 (Ref. 2-2):

Fuel Control
Turbine Inlet Guide Vane Actuators
Compressor Inlet Guide Vane Actuators
Automatic Starting and Limit Protection Control
Transmission Control
Hydraulic Clutch Control
Power Boost Control
Sensors

Control operation could be hydromechanical or electronic. The major difference between the two systems is in sensors, metering sections, and controller 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.

A closed-loop control system functional schematic for a variable inlet vane, single-shaft, gas turbine-powered vehicle is shown in Figure 2-14 (Ref. 2-2). Driver command and operation would be identical to that for existing automatic transmission vehicles powered by spark-ignition engines. In this design, the engine is coupled to the rear wheels through an infinitely variable traction-type transmission and a forward/reverse-type gearbox. Engine operation with zero vehicle speed is provided by a hydraulic clutch that decouples the drive train from the engine. Essential elements in this system include the engine fuel management components and transmission control components. Although somewhat more complex, fuel management

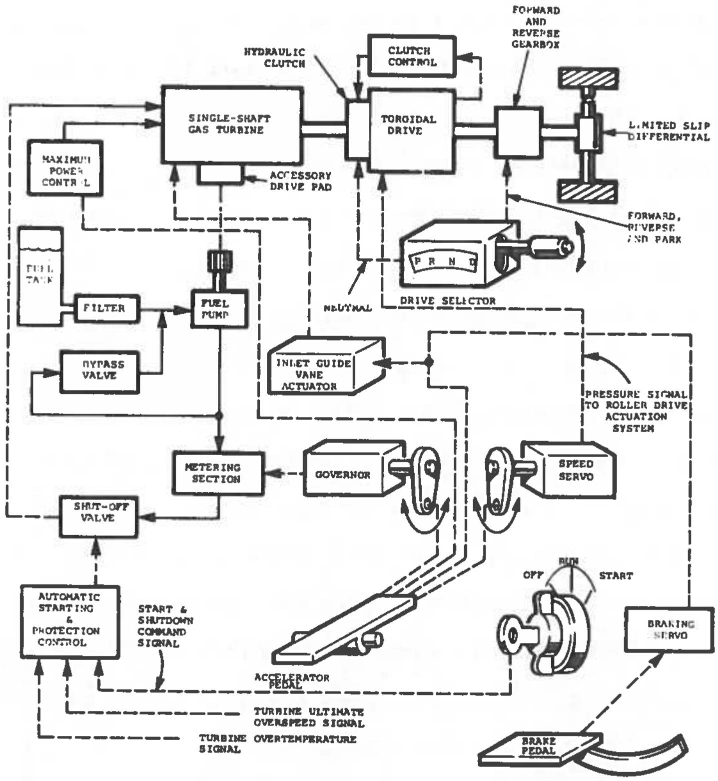


Figure 2-14. Control System Functional Schematic, Single-Shaft Gas Turbine Engine (Ref. 2-2)

of a gas turbine can be compared in function to a carburetor system in a spark-ignition engine. Other controlling elements include items such as the inlet guide vane control and the power boost control (water injection) for maximum acceleration.

The control system functional schematic for a free-turbine powered vehicle is comparable to the single-shaft configuration; the major difference is in the transmission control. This difference is a result of the three-speed automatic transmission considered for this application and the special requirements for preventing free-turbine overspeed.

Ford utilizes two different control systems for their free turbine engine. One system, used in generator set applications, maintains constant engine speed over a wide range of loads by sensing and adjusting the fuel flow rate and the position of the power turbine nozzles. Alternatively, a double closed-loop control of engine speed and turbine inlet temperature is employed in those applications where both shaft power and engine speed are varied (e.g., automotive applications). In this control system, predetermined schedules of first-stage turbine speed versus power level and turbine inlet temperature are built into the control system. The system senses first-stage turbine speed and turbine inlet temperature and regulates the power turbine nozzle angle to match the prescribed temperature. Optimum part-load fuel economy is maintained by operating at the highest turbine inlet temperature consistent with the required compressor surge margin. By adjusting the nozzle vane position, the design point turbine inlet temperature can be maintained for engine speeds as low as 85 percent of the design value. Below that point, the turbine inlet temperature is reduced to avoid compressor surge (an unstable flow condition).

Engine braking is achieved by releasing the throttle, which automatically sets the power turbine nozzle into the retard position. The gasifier (first-stage turbine) shaft speed is then increased by a commensurate increase in fuel flow to provide the gas flow rate required for effective braking. At 80 percent of design speed, the braking power of the engine is about 75 percent of the maximum positive power of the engine.

The engine idle speed can be adjusted by means of a switch to 55 percent or 45 percent of design speed. The higher idle speed is normally selected if a more rapid acceleration of the engine is desired.

In case of overtemperature, the fuel supply to the engine is shut off. Overspeed protection is provided by reducing the fuel flow and by adjusting the nozzle vanes to the braking position.

Chrysler's sixth-generation free turbine engine utilizes an open-loop hydromechanical control system selected for cost reasons. Under its current EPA contract, Chrysler will investigate closed-loop electronic fuel control (EFC) system approaches. The principal advantage of closed-loop EFC is its capacity to improve system response. In addition, the turbine inlet temperature and the position of the power turbine nozzle can be optimized in this system to provide minimum engine fuel consumption at all operating conditions. Chrysler prefers EFC systems, but is concerned about the life of the temperature sensors (a problem not present in the open-loop hydromechanical system). In its 50-car program, the sensors failed after about 5000 miles as a result of oxidation of the thermocouple beads and/or erosion of the shields. Imbedded thermocouple configurations are not feasible because of the lack of response time.

The General Motors GT-404 engine employs a start and monitoring system designed for use with hydromechanical control of fuel flow and its own power transfer system (see Section 2.1.4.1.3). The start and monitoring system provides automatic starting and automatic engine shutdown when certain limits are exceeded.

2.1.4 Current Engine Concepts

This section of the report provides a review of automotive gas turbine engine types and design concepts under consideration by the automobile industry and by engine manufacturers.

2.1.4.1 Automobile Manufacturers

2.1.4.1.1 Chrysler Corporation

Research and development on the automotive gas turbine has been underway at Chrysler since 1950. Their current sixth-generation engine is the result of these efforts. The engine is a free-turbine regenerative design, consisting of the following basic components: (1) a single-stage radial compressor (4.1:1 design pressure ratio, 44,600 rpm design speed) driven by a single-stage axial turbine, (2) two rotating regnerators, and (3) a separate variable nozzle, single-stage axial power turbine (45,700 rpm design speed). The engine is connected to the vehicle transmission through a reduction gear arrangement. Axial turbine wheels were selected by Chrysler for a number of reasons, including improved packaging and low inertia.

The current engine is a modification of Chrysler's fourth generation engine used in their 50-car test program. The principal new feature of the current engine are a higher first stage turbine inlet temperature (1850°F vs 1750°F during maximum steady-state operation; 2000°F vs 1850°F during maximum acceleration), a higher power output (150 hp vs 133 hp) and a redesigned accessory drive arrangement. On this current engine, major accessories (power steering and alternator) are driven by the power turbine. In the fourth-generation engine, all accessories were driven by the gas generator. The shift of major accessories to the power turbine resulted in a faster response for the engine as shown in Figure 2-15. This change reduced the first-stage turbine load, permitting a reduction in the size and number of high-speed bearings required.

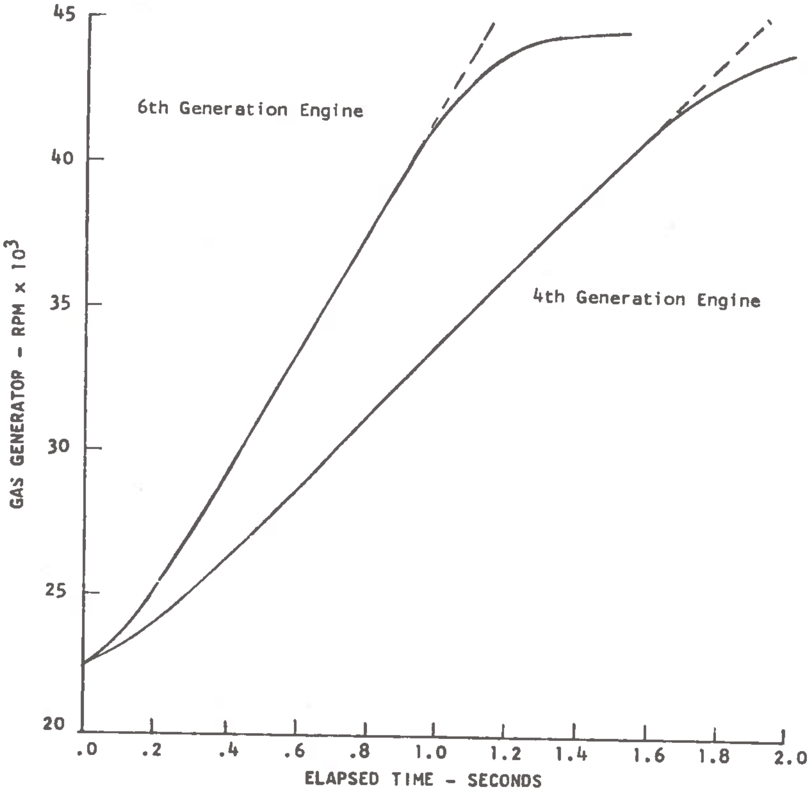


Figure 2-15. Gas Generator Response Comparison for Chrysler Engines, 85°F Day (Ref. 2-28)

The sixth-generation engine, shown schematically in Figure 2-16, is a research and not a production engine. The engine's main characteristics are listed in Table 2-1; Figure 2-17 shows engine power vs gas generator and power turbine speeds. The fuel economy and the power output of the engine were increased from the fourth-generation values by increasing the first-stage turbine inlet temperature by 100°F. This was accomplished by fabricating the turbine wheels from INCO 713C (70 percent nickel).

Table 2-1. Chrysler Sixth Generation Engine Characteristics, 85°F Day (Ref. 2-28)

	Gas Generator Speed (percent)	
	100	50
Gas Generator Speed (rpm)	44,600	22,300
Maximum Power Turbine Speed (rpm)	45,700	-
Regenerator Speed (rpm)	22	11
Compressor Pressure Ratio	4.1	1.5
Compressor Air Flow (lb/sec)	2.3	0.8
First Stage Turbine Inlet Temperature (°F)	1850	1430
Exhaust Temperature (°F)	590	340
Compressor Efficiency	0.77	0.77
First Stage Turbine Efficiency	0.86	0.76
Second Stage Turbine Efficiency	0.70	0.67
Regenerator Effectiveness	0.87	0.90
Pressure Loss Sum (percent)	13	5

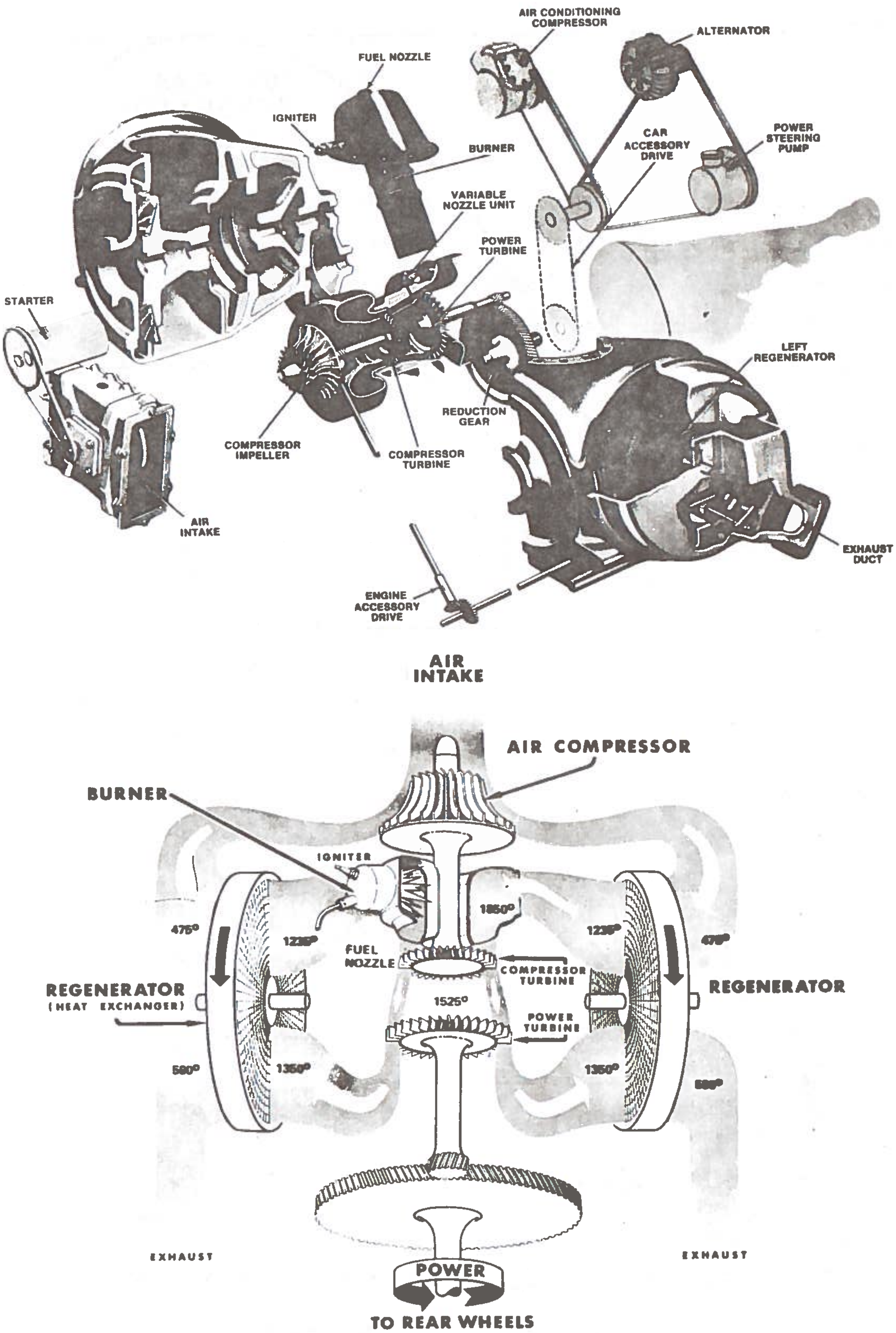


Figure 2-16. Chrysler Sixth-Generation Gas-Turbine Engine Schematic (Ref. 2-28)

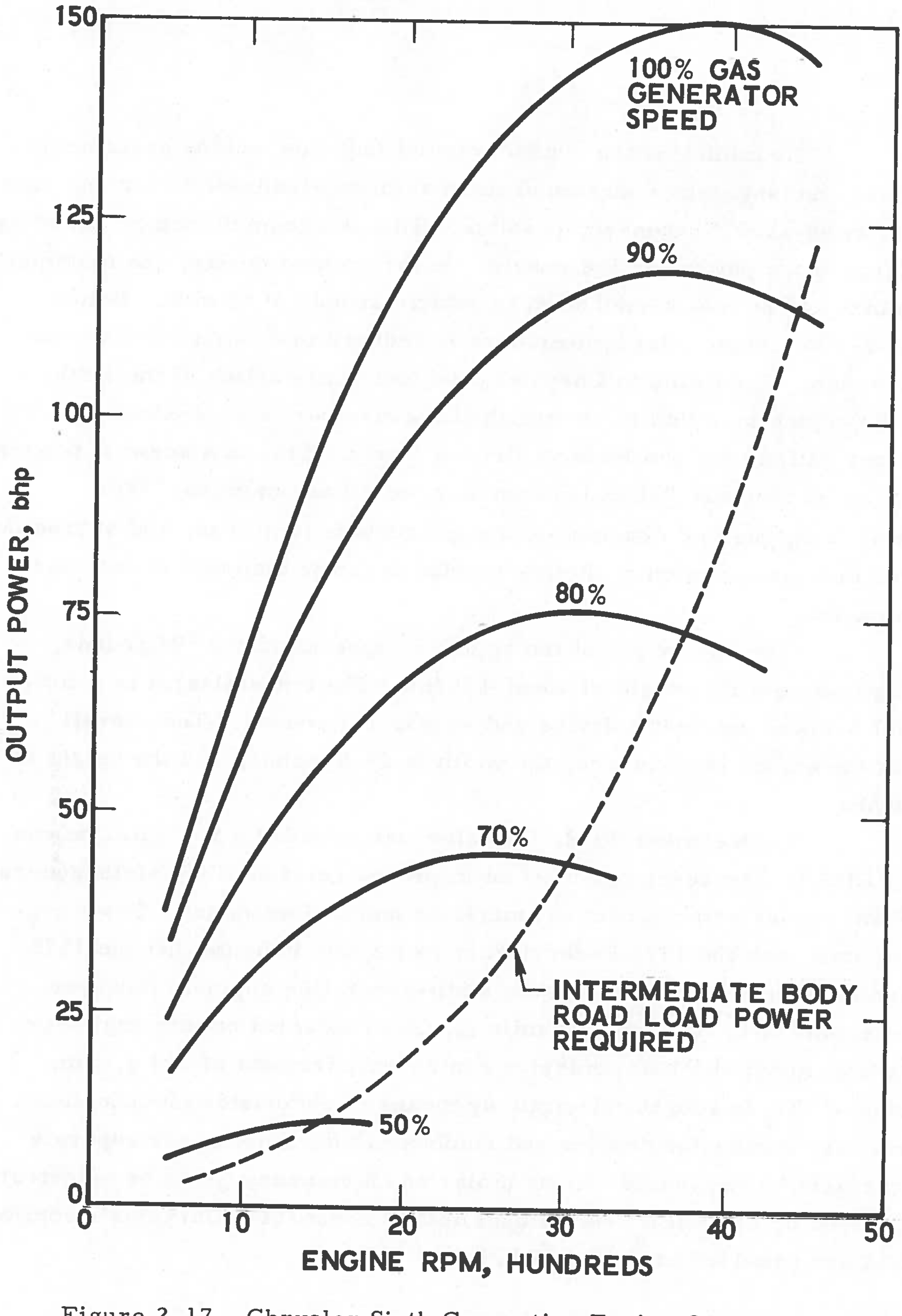


Figure 2-17. Chrysler Sixth Generation Engine Output Power, 85°F Day (Ref. 2-28)

To minimize the consumption of fuel (low-octane gasoline or diesel fuel), the engine is operated at the maximum steady-state turbine inlet temperature of 1850°F whenever possible. This is accomplished by adjusting the position of the power turbine nozzle. In the present design, the maximum temperature can be maintained down to vehicle speeds of 35 mph. Below this speed, the turbine inlet temperature is reduced in order to avoid compressor surge. According to Chrysler, the fuel consumption of the sixth-generation engine installed in an intermediate size car is approximately 8 miles per gallon over the Federal Driving Cycle. This is somewhat poorer than that of current spark-ignition engine-powered automobiles. With increasing load, the fuel economy of the gas turbine improves, and at freeway speed the fuel consumption of the gas turbine is lower than that of the spark-ignition engine.

The dry weight of the engine is approximately 594 pounds, resulting in a specific weight of about 4 lb/hp. The transmission is a conventional 3-speed automatic device and weighs 137 pounds. The overall length of the engine is 37 inches, the width is 29.5 inches, and the height is 27.5 inches.

In December 1972, Chrysler was awarded a $6.5 million contract by EPA for the development of an improved version of the sixth-generation gas turbine engine with respect to emissions and fuel economy. Tests conducted to date with the 1972 Federal Test Procedure indicate that the 1975 emission standards can be met by the sixth-generation engine. However, NO_x emissions of 2.7 gm/vehicle mile (g.v.m.) obtained on this engine are considerably above the 1976 emission control requirement of 0.4 g.v.m. Reduction of NO_x is sought primarily by means of combustor modifications. Both in-house combustor designs and combustors designed under separate EPA contracts by two outside firms (Solar and a company yet to be selected) will be tested by Chrysler. (Additional details concerning Chrysler's contract with EPA are provided in Section 4.2.1.)

2.1.4.1.2 Ford Motor Company

Ford does not have a gas turbine passenger car in development but research work is currently underway to determine the design and feasibility of a gas turbine engine for automobiles. This effort has a substantial base of prior activity represented by Ford's experience with the development and manufacture of the 707 family of industrial and (for 1974) truck engines. This experience will undoubtedly influence Ford's choice of engine and component designs for the passenger car.

The 707 engine is a split-shaft (free turbine) configuration which was designed by Ford for minimum cost and ease of servicing and installation (Ref. 2-12). Engines in this family are rated from 325 to 525 horsepower. Each engine has a total of 740 parts; the number of moving parts are 75 percent fewer than those of a typical diesel engine. A cutaway

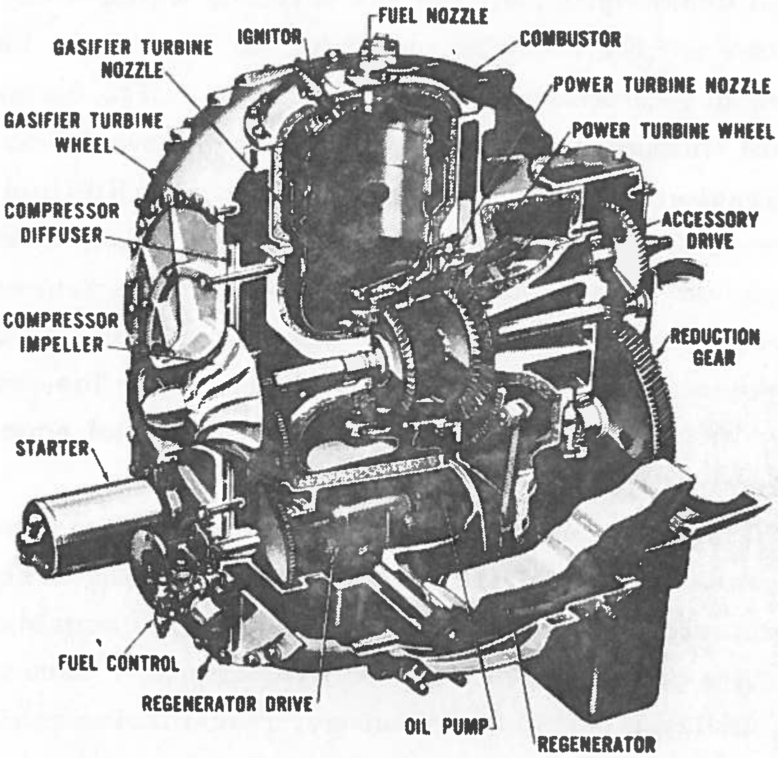


Figure 2-18. Cutaway of Ford 707 Engine (Ref. 2-12)

of the engine is shown in Figure 2-18. There are five self-contained subassemblies : gasifier, power turbine variable nozzle, power turbine and gear box, combustor, and regenerator. Each of these subassemblies, except for the power turbine nozzle, can be removed from the engine housing as a unit.

Important design point operating parameters of the 707 engine family (Ref. 2-12) are gasifier turbine speed ranging from 37,500 to 45,300 rpm, turbine inlet temperature of 1900°F and pressure ratio of 4.4:1 to 4.6:1. The basic engine is rated at about 450 horsepower. Exclusive of alternator, oil cooler, control box, fuel pump, and stator, it is 40 inches long, 35 inches wide, and 42 inches high, which is considerably smaller than an equivalent industrial diesel engine. The weight of the engine is 1700 pounds, approximately 50 percent of the weight of comparable diesels.

Ford claims that at present, the 707 engine matches the fuel economy of equivalent diesel engines. Ford would like to see a 10-percent improvement in fuel consumption for the gas turbine, which would make the engine very attractive for the trucking industry. In Ford's opinion, operating costs are so important to truckers that they would switch to the use of gas turbines if their fuel consumption were even 2-percent lower than that of diesels with comparable maintenance costs and operating lifetime. Since direct-injection diesels have a NO_x emission problem, Ford feels that the injection timing of these engines must be retarded in order to meet the 1975/76 emission control requirements. This would result in some loss in power and a 5 to 7-percent loss in fuel economy. Although the power loss could be compensated for by increasing engine size and cost, the fuel economy loss would not be affected by this approach.

With regard to passenger car applications, the free-turbine engine design is currently Ford's first choice in engineering design studies, although single-shaft gas turbine configurations are being considered in research studies. If a passenger car gas turbine program were to be initiated today, Ford would utilize a current-technology, free-turbine engine design similar to the 707 series in order to meet the engine response and braking characteristics of current automobiles. The 707 engines require an initial 5 seconds after engine start before engagement of the shift lever. For automobile gas turbines, this time period could probably be reduced to 2.5 seconds or slightly less by using small diameter (low inertia) turbomachinery components.

Ford feels that the fuel economy of its current gas turbines could be further improved by increasing the compressor and turbine efficiencies and by minimizing the parasitic losses in the engine. Part-load fuel consumption of a passenger car gas turbine could be improved by reducing the design point power to the lowest level commensurate with acceptable vehicle acceleration.

2.1.4.1.3 General Motors

General Motors has a 20-year experimental background in gas turbine engines for vehicular applications (see Section 4.2.3). All of the GM engines have been free-turbine types with pressure ratios between 3.5 and 4.2. None of these experimental engines were installed in test vehicles except the GT 309 (heavy duty) engine.

The GT 309 was a 280 hp regenerative cycle engine using a variable coupling or clutch (power transfer system) between the gasifier shaft and power turbine. A modified version of this engine is the GT 404, which is currently undergoing road tests in a Greyhound bus (Ref. 2-13). This engine is in the pilot stage of production by the Detroit Diesel Allison Division. Table 2-2 (Ref. 2-13) shows the design point objectives of the engine. The engine speed is about 37,000 rpm, the peak power output is 325 bhp, the turbine inlet temperature is 1700°F, and the compressor pressure ratio is 4.2. The design SFC value is 0.475 which is slightly better than that for a comparable diesel engine.

General Motors is currently in the process of evaluating the gas turbine engine for passenger car applications. A new division, called the Passenger Car Turbine Development Division, has been created to investigate the preliminary design for gas turbine automobiles. A 2-year program of research has been defined in which both single-shaft and free-turbine engine designs will be evaluated. The main effort, called the

Table 2-2. General Motors Gas Turbine Engine, GT-404 Design Point Objectives (Ref. 2-13)

Gasifier speed (rpm)	37,103
Power turbine speed (rpm)	30,830
Output shaft speed (rpm)	2873
Brake horsepower	325
Torque (ft-lb)	595
Fuel flow (lb/hr)	154
Sfc (lb/hphr)	0.475
Turbine inlet temperature (°F)	1700
Compressor airflow (lb/sec)	4.31
Compressor pressure ratio	4.2
Compressor efficiency (percent total-to-static)	77
Gasifier turbine efficiency (percent total-to-total)	89
Power turbine efficiency including exhaust diffuser (percent total-to-static)	85
Regenerator effectiveness (percent)	88
Regenerator leakage (percent)	4.2
Burner efficiency (percent)	99.6
Burner pressure drop (percent)	4
Gasifier rotor mechanical loss (hp)	8
Reduction gear loss (hp)	10
Internal leakage (percent)	1.6

Standard conditions: 59°F and sea level.

225A Program, is an investigation of the free-turbine engine which is the favored design. All engine design information is proprietary.

In general, the 225A Program will, with the exception of combustors, utilize state-of-the-art components. The program will pursue the following design philosophy:

- Free turbine design
- Twin regenerators
- Conventional transmission
- Low inertia components

General Motors feels that many iterations will be required to produce a design which will compete with the internal combustion engine.

2.1.4.2 Gas Turbine Engine Manufacturers

Most of the recent automotive gas turbine cycle analyses/design concept studies by engine manufacturers have been sponsored under the EPA/AAPS Brayton cycle project. These programs were initiated by EPA in consideration of the fact that much of the automotive industry's past investments in gas turbines have been put into the free-turbine regenerative system, while more recent studies performed by gas turbine engine manufacturers indicated the potential for improved design by the use of single-shaft engines. Accordingly, EPA sponsored a number of contract efforts intended to define an advanced engine concept and to give comparative performance and cost figures. Study efforts in these two categories were divided as follows: engine optimum configuration studies were conducted by AiResearch, United Aircraft, and General Electric; economic analyses were conducted by Williams Research Corporation and United Aircraft.

As directed, the three contractors involved in the engine optimization effort used state-of-the-art technology to define the optimum engine for a gas turbine automobile meeting EPA baseline specifications for weight, capacity, and performance. The optimization criteria included emissions, performance, cost of ownership, mean operational life and installation volume. All pertinent types of gas turbine configurations were considered. A representative sample of the scope of these studies is given by the configuration summary in Table 2-3 taken from the AiResearch final study report (Ref. 2-2).

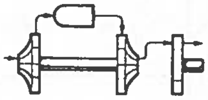
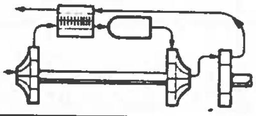
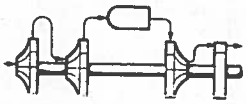
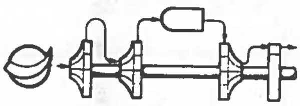
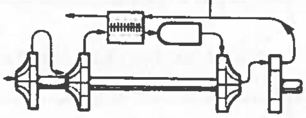
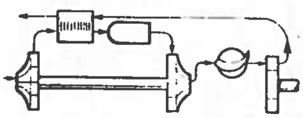
For each configuration in Table 2-3, the optimum engine pressure ratio is shown, as well as the effectiveness of the regenerative heat exchanger, where applicable. The maximum design shaft horsepower required to satisfy the vehicle performance specifications and the fuel economy estimated for the Federal Driving Cycle (FDC) and Uniform Simplified Emission Driving Cycle (USEDC) are also tabulated.

As indicated, both free-turbine and single-shaft arrangements were considered. It is noted here that the torque characteristic of the free-turbine design permits the use of conventional three- or four-speed transmissions, whereas the single-shaft engine requires a transmission with many speeds or with continuously variable speed ratios. (Transmission requirements for these engine types are discussed in Section 2.2.)

Configurations 7 and 11 provide an approximate comparison in performance between the single-shaft and free-turbine arrangements. In these two configurations, pressure ratio and regenerator effectiveness are the same, but the maximum engine design power is different. Even though the power requirement is indicated to be larger for the free turbine arrangement, the fuel economy is better than for the single-shaft design. The power requirement is influenced by engine inertia because engine response time to generate peak power has a direct effect on vehicle acceleration; a low-inertia engine could have a lower power rating to meet a given vehicle acceleration specification.

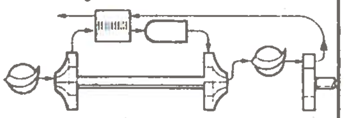
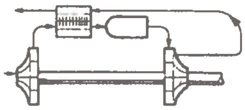
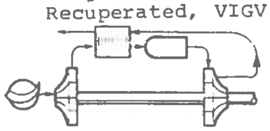
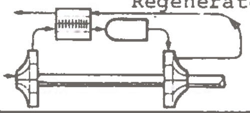
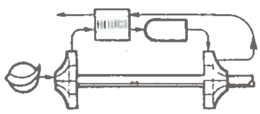
An advanced design concept that is incorporated in several of the configurations in Table 2-3 is the use of water injection. Water injection augments the engine power output and reduces the maximum design point power level (see Section 2.1.5). The effect is shown for Configuration 7, where the design power requirement is indicated to be reduced from 175 hp without water injection to 135 hp with water injection.

Table 2-3. Gas Turbine Engines Analyzed by AiResearch (Ref. 2-2)

Engine Configuration	Maximum Cycle Pressure Ratio	Design-Point Regeneration Effectiveness, ε_R	Design Point shp, 60°F	FDC mpg, 85°F	USEDC mpg, 85°F	Comment
1. Free-Turbine 	8.0	--	150^+	5.0	--	
2. Free-Turbine, Recuperated 	8.0	0.85	150^+	8.4	12.2	
3. Single-Shaft 	12.0	--	160	6.3	8.0	
4. Single-Shaft, VIGV* 	12.0	--	160	6.3	8.0	IGVs do not improve unregenerated cycle. Idle W_F decreased by 6 percent.
5. Free-Turbine, Recuperated, Bypass 	10.0	0.70 at 60 percent power	150^+	7.9	--	MPG based on min sfc vs shp curve compared with Cycle 2.
6. Free-Turbine, Recuperated, VPTN** 	6.7	0.75	175^+	10.0	12.7	
		0.85	175^+	13.6	17.1	

*Variable inlet guide vanes
**Variable power turbine nozzles

Table 2-3 (continued). Gas Turbine Engines analyzed by AiResearch (Ref. 2-2)

Engine Configuration	Maximum Cycle Pressure Ratio	Design-Point Regeneration Effectiveness, ϵ_R	Design Point shp, 60°F	FDC mpg, 85°F	USEDC mpg, 85°F	Comment
7. Free-Turbine, Regenerated, VIGV, VPTN 	4.6	0.90	175	16.4	19.9	No power boost.
			135	18.1	21.6	Power boost† for maximum acceleration.
8. Single-Shaft, Recuperated 	6.4	0.80	165	6.0	9.5	
		0.80	120	8.1	12.6	Power boost† for maximum acceleration.
9. Single-Shaft, Recuperated, VIGV 	6.4	0.85	125	14.3	20.0	Power boost† for maximum acceleration.
10. Single-Shaft, Regenerated 	4.6	0.90	108	9.6	14.9	Power boost† for maximum acceleration.
11. Single-Shaft, Regenerated, VIGV 	4.6	0.90	108	17.0	22.1	Power boost† for maximum acceleration.
			155	14.0	19.7	
12. V-8 Spark Ignition	-	-	175	12.5	14.8	

† refers to use of water injection

Accordingly, the engine size is reduced and it operates more frequently at a higher fraction of peak power output, thereby improving overall performance. The performance effect is indicated by the fuel economy values for Configuration 7. With water injection at maximum power level, the overall fuel economy improves by over 10 percent.

With regard to other hardware improvements, the variable turbine nozzle feature was considered by each of the three investigators. In addition, AiResearch employed compressor inlet guide vanes and General Electric considered the use of compressor variable diffuser blades. The performance effect of some of these improved hardware features may be noted in Table 2-3. Adding a recuperator (with an effectiveness of 0.85) to the simple cycle improves the fuel economy by 68 percent. The effect of adding a regenerator may be observed by comparing free turbine Configurations 1 and 2. The same regenerative cycle with variable power turbine nozzles (Configuration 6) provides a 170 percent improvement in fuel economy. Increasing regeneration effectiveness to 0.9 and adding compressor variable inlet guide vanes (Configuration 7) provides a fuel economy improvement over the simple cycle of 228 percent. Finally, with water injection added, the fuel economy improvement is 262 percent.

It is important to recognize that while hardware sophistication, as illustrated in Table 2-3, tends to improve performance, the engine becomes more complex and more difficult to control and manufacture. Increased complexity is generally accompanied by increased cost, reduced reliability, and additional maintenance problems. Accordingly, the final selection of optimum engine configurations by the three EPA study contractors was based on an appropriate balance among these and other criteria. These recommended choices, cycle descriptions, concept arrangements and important parameters are shown in Table 2-4 (Refs. 2-2, 2-14, 2-15).

Table 2-4. Gas Turbine Estimated Optimum Configuration Recommendations

Parameter	General Electric (Ref. 2-15)	United Aircraft (Ref. 2-14)	AiResearch (Ref. 2-2)
	Single Shaft, Regenerated with Variable Compressor, and Turbine Geometry	Single Shaft, Simple Cycle	Single Shaft, Regenerated with Variable Inlet Guide Vanes and Water Injection
Pressure Ratio	3.2	10	4.6
Shaft Speed (rpm)	40,000	106,000	83,050
Horsepower rating at 85°F	150	150	108 Without Water Injection
Horsepower rating at 105°F Ambient	134	135	135
Fuel Economy over FDC (mpg)	12.7	7.5	13
Engine Weight (lb)	484	330	425
Air Flow Rate (lb/sec)	1.96	1.15	1.22
Fuel Flow Rate (lb/hr)	75	84	60
Compressor Efficiency (%)	82	81	82
Turbine Efficiency (%)	85	87	89
Regenerator Efficiency (%)	85	No Heat Recovery	90
T_{t_1} (°F)	1900	1900	1900
Transmission Type	Infinitely Variable	Infinitely Variable	Infinitely Variable
Transmission Design used in vehicle performance calculations	Tracor (Traction)	GE HMT (Hydromechanical)	Tracor (Traction)
Acceleration 0 to 60 mph for 4600-lb vehicle test weight (sec)	12.2	15.8	12.5

The results of these studies were summarized by EPA (Ref. 2-16) as follows:

1. Two of the contractors selected a single-shaft, regenerated engine with different degrees of variable geometry in the compressor and turbine areas.

2. One contractor selected a single-shaft, simple cycle engine as its top choice.

3. The cost predictions between free-turbine and single-shaft concepts varied over a very large range. For example, one contractor predicted the initial cost ratio of free-turbine to single-shaft turbine to be 1.65, while another predicted 0.89 on the assumption that an infinitely variable transmission (IVT) could be made for the same cost as a standard automatic transmission. If a 40 percent increase in the IVT cost were assumed, the ratio changed to 1.52 and 0.82 respectively.

4. At peak fuel economy one contractor predicted 30 mpg while two others were in the range of 17 to 18 mpg for the single-shaft, regenerative engine, using variable geometry. The free-turbine, peak-fuel economy was predicted as 17 mpg by one contractor and 23 mpg by another. These predictions were made for vehicle curb weights ranging from 3800 to 4000 pounds.

As a result of the large variances between estimates for cost and for fuel economy, it was not possible to draw accurate conclusions on what comprised an optimum advanced gas turbine concept. EPA felt that the cost of the IVT for the single-shaft engine could play a predominant role in the future selection of gas turbine concepts and was the probable reason that the free turbine was selected earlier by the automobile industry.

EPA concluded that the potential of lower initial cost exists with the single-shaft engine, but that significant advances would have to be made in techniques to improve part-load fuel economy and to develop infinitely variable transmissions before proceeding to a development program on the single-shaft engine system. Accordingly, it was felt that the results of these studies confirmed EPA's decision to use a free-turbine engine as a baseline for further development in the AAPS Brayton cycle project.

In the Williams Research Corporation cost-of-ownership economic analysis for EPA (Ref. 2-17), the basic design employed in the WR 26 gas turbine prototype engine (presently installed in a Hornet vehicle) was extrapolated to 1975 technology and the costs associated with the ownership and operation of a gas turbine-powered medium-size automobile were evaluated. The WR 26 is a free-turbine engine with centrifugal compressor and axial turbine, rated at 80 shp. In the study for EPA, the size of the engine was increased to provide 130 shp, but the basic elements of the WR 26 design, with some improvements, were utilized. Improvements in the design relative to the WR 26 system are variable turbine nozzles and an increase in turbine inlet temperature from 1700°F to 1900°F.

2.1.5 Advanced Concepts

2.1.5.1 Combustors

Development work conducted on gas turbine combustors has indicated that sufficiently low HC and CO emission levels can be achieved with conventional combustors to meet the 1975/76 Federal emission control requirements for light duty vehicles. However, the levels of NO_x emitted by these combustors are considerably higher than the 1976 requirement. In conventional combustors, the fuel is injected at high pressure through fuel injectors, and fuel atomization is achieved in the dome section of the cylindrical or annular combustion chambers by means of jet impingement. Combustion of the fuel takes place in the near-stoichiometric fuel vapor/air region surrounding the individual fuel droplets. As a result, the combustion temperatures are very high, especially in the case of regenerated or recuperated gas turbine engines. Since the kinetically controlled NO_x formation rate increases exponentially with temperature, the NO_x emissions from a conventional droplet-burning type combustor are also very high. For instance, Chrysler's sixth-generation gas turbine installed in a medium-size vehicle has NO_x emissions of about 2.7 g.v.m. over the FDC. The NO_x emissions of non-regenerated gas turbines with conventional combustors tend to be somewhat lower, because of the lower temperature of the incoming air.

In order to obtain satisfactory fuel economy in gas turbines, some degree of regeneration appears to be required. Since conventional gas turbine combustors are inherently high NO_x emitters it appears that new combustors would have to be developed if the gas turbine automobile is to meet the 1976 NO_x requirements. In view of current industry efforts in the development of high-temperature gas turbines utilizing ceramic components, the need for low NO_x combustors becomes even more important.

The NO_x concentrations computed from kinetic theory increase with increasing flame temperature and residence time. In gas turbine combustors, the residence time is of the order of 5 milliseconds. Negligible NO_x concentrations are obtained for that residence time by operating the primary zone of the combustor in the lean regime at a temperature of about 3000°F or less. However, all fuel must be burned at that temperature, and this requires complete vaporization of the fuel and a uniform air/fuel mixture distribution at the primary zone inlet.

Based on these considerations, it is concluded that the concept of lean combustion of fully vaporized and premixed air/fuel mixtures offers a potential solution to the NO_x emission problem with current gas turbine engines. New combustor designs which are based on this particular concept 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. A number of these advanced configurations are briefly described in the following paragraphs.

Solar, under contract to the EPA, has been involved in the development of a low NO_x, jet-induced circulation (JIC) combustor concept for potential use in automotive gas turbines (Ref. 2-18). In this design, shown schematically in Figure 2-19, the fuel and the primary zone air are premixed before entering the primary combustion zone through a nozzle-like opening. The air/fuel vapor jet emanating from this nozzle acts as a jet pump and entrains a portion of the combustion gases which then raise the temperature of the air/fuel mixture sufficiently to ignite the fuel. The chemical reactions which continue inside the cylinder of this combustor (JIC-1 design) are essentially complete when the gases reach the combustor dome. At the design point, the NO_x emissions are quite low. However, at off design, NO_x increases substantially because of the enrichment of the primary zone air/fuel mixture. By incorporating variable area primary nozzles in their JIC-3 design, Solar was able to sufficiently extend the low NO_x regime of the combustor and meet the contractual emission goals of 1.75 gm NO_x/kg fuel, 14.9 gm CO/kg fuel, and 1.8 gm HC/kg fuel.

In the Ford external vaporizing combustion (EVC) concept, which is illustrated in Figure 2-20, the fuel enters the premix/vaporization chamber through a coaxial nozzle and is then atomized and premixed by the high velocity primary air flow (Refs. 2-4 and 2-5). The fuel droplets are vaporized in the chamber which is sufficiently large to ensure complete vaporization and small enough to prevent pre-ignition. Then the homogeneous air/fuel mixture enters the primary combustion zone through a set of six ports. Secondary air is added in the dilution zone to obtain the desired turbine inlet temperature. The air/fuel ratio in the primary zone is maintained between about 30:1 and 40:1 by means of a sleeve-type flow control device which adjusts the primary air flow in accordance with a predetermined schedule. Based on initial test results, Ford feels that the 1976 emission control requirement can be met with a gas turbine utilizing the lean premixed/prevaporized EVC concept. However, a number of potential problem areas must be solved before the

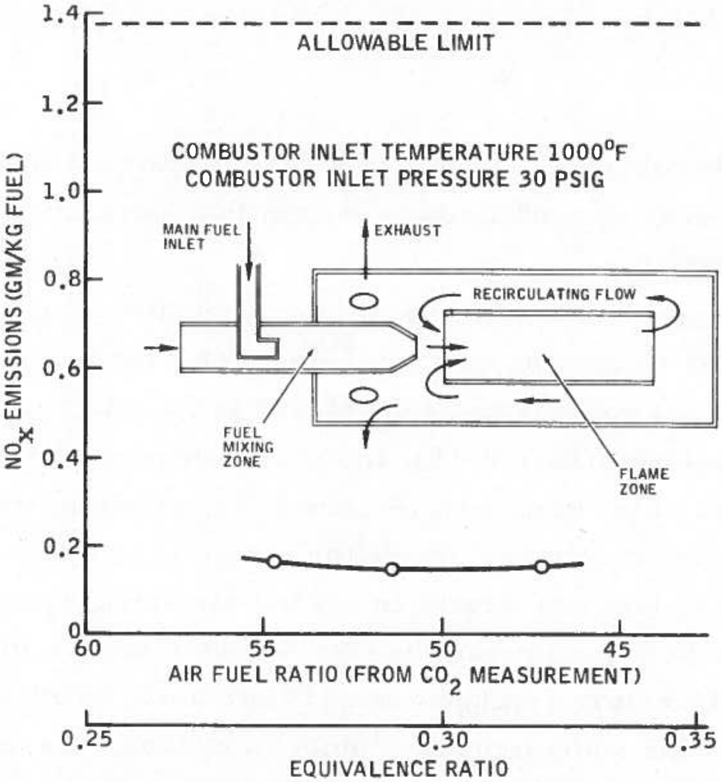


Figure 2-19. Solar High Recirculation Stabilized Lean Primary Zone Combustor, NO_x Emissions Expressed as NO_2 (Ref. 2-18)

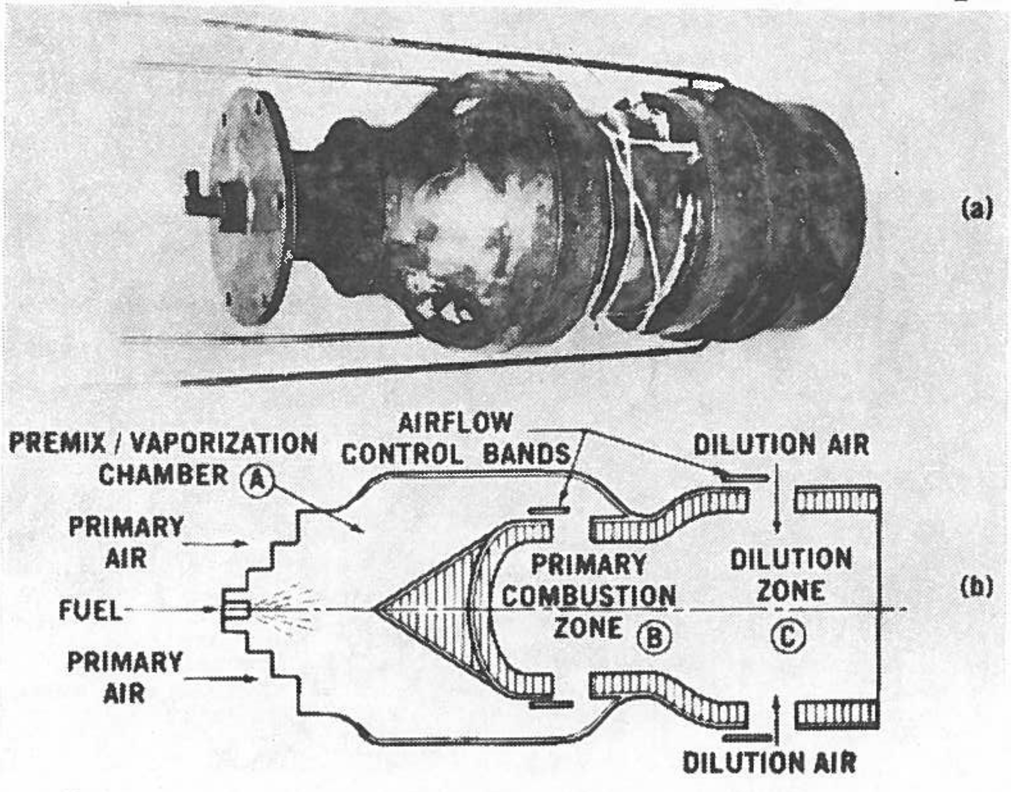


Figure 2-20. Ford Experimental Externally Vaporizing Combustor Showing Airflow Control Rods and Fuel Atomizer with a Schematic Representation of the Internal Flow Arrangement (Refs. 2-4, 2-5)

combustor is ready for use. These include combustor stability and response under transient operating conditions, pre-ignition, durability, and cold start emission characteristics.

Aerojet has designed a novel combustor for potential use in the EPA automotive gas turbine program. This combustor is based on their platelet premixer concept originally developed for use in rocket engine combustors. In this concept (Ref. 2-19), the conventional fuel spray nozzles are replaced by the premixer hardware (Figure 2-21) which distributes the initially liquid fuel and injects it into the combustor air through a large number of very small orifices. The fuel evaporates in the hot air stream and is completely mixed with the air before entering the combustion chamber primary zone at the exit of the platelet/venturi arrangement. Dilution air is injected into the chamber downstream of the short primary combustion zone. Based on analytical

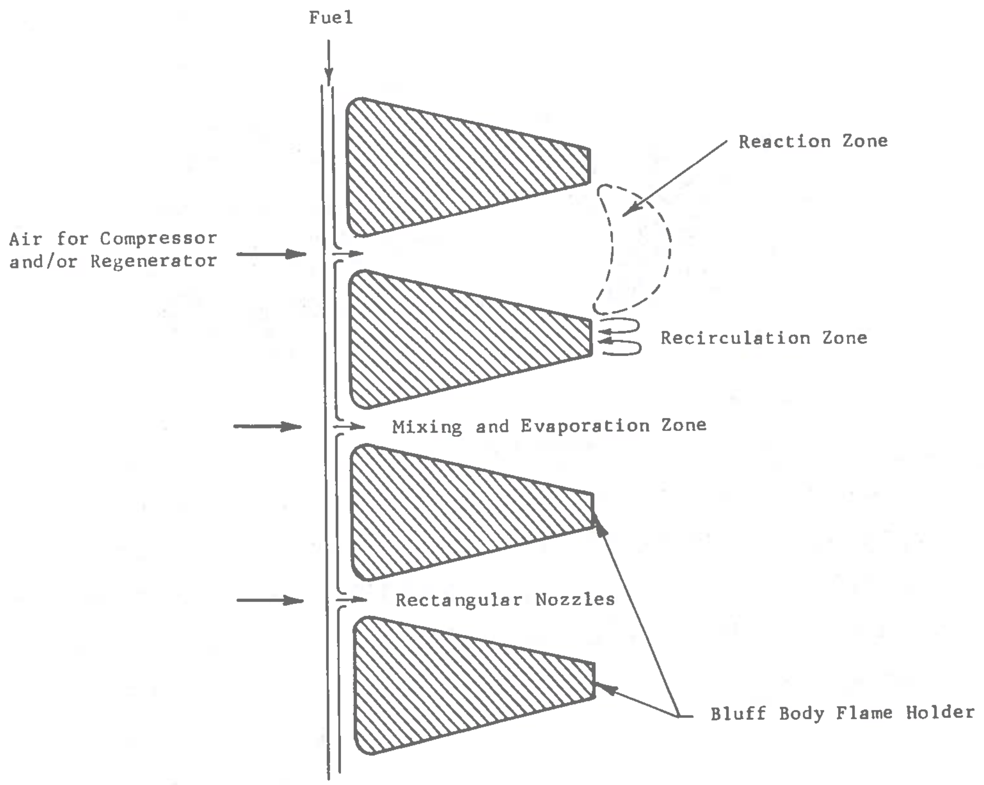


Figure 2-21. Schematic Diagram of Aerojet Platelet Premixer Concept (Ref. 2-19)

work on flow mixing and combustion kinetics, Aerojet feels that the 1976 Federal emission control requirement can be met with the platelet combustor.

AiResearch, under contract to EPA, has been involved in the development of low NO_x combustors utilizing recuperator bypass (Ref. 2-20). As shown in Figure 2-22, part of the recuperator bypass air is injected through the staged dome section of the combustor. The remainder of the bypass air and the fuel are injected in an upstream direction through an L-shaped pipe located downstream of the dome. Although the emissions of this vaporizer combustor with bypass are rather low, further reduction of NO_x is required before the 1976 requirement can be met in a gas turbine automobile.

General Electric is under contract to EPA to develop a low-emission porous plate combustor for use in automotive gas turbine engines. In this concept (Ref. 2-21), illustrated in Figure 2-23, the fuel is prevaporized and the air/fuel mixture is then discharged through the porous combustor plate and ignited at the front face of the plate. A portion of the heat of combustion is transferred back into the plate from where the heat is re-radiated or transferred into imbedded cooling tubes. As a result the adiabatic flame temperature is never reached and therefore the NO_x emissions are low. The heated cooling air is then mixed with the dilution air before being injected into the secondary zone of the combustion chamber. Based on preliminary test results, General Electric feels confident of meeting their emission goal which is 25 percent of the 1976 Federal requirement, i.e., 0.1 g.v.m rather than 0.4 g.v.m.

In catalytic combustors a catalyst material, deposited on a suitable ceramic substrate, is used to promote and sustain the oxidation reactions at very lean air/fuel ratios. Preliminary test data indicate catalytic combustors are inherently low NO_x, CO, and HC emitters. However many potential problems remain to be solved. These include catalyst and substrate life, catalyst poisoning characteristics, temperature capability, transient response, maximum heat release rate, and air/fuel mixture preparation.

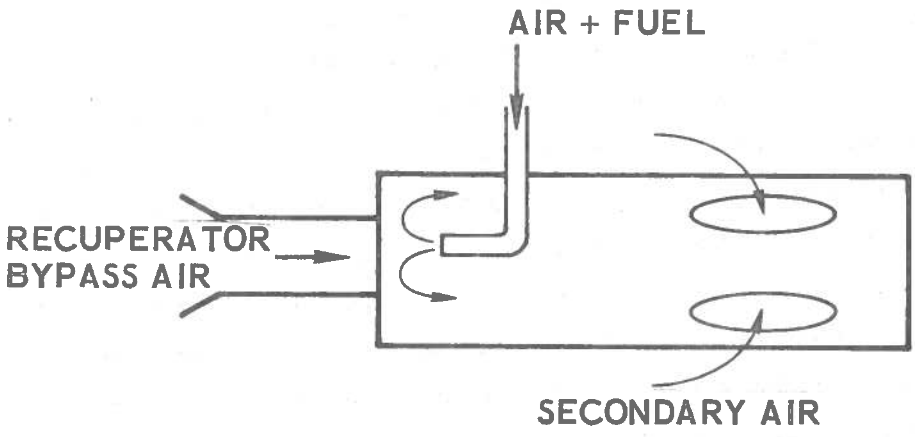


Figure 2-22. AiResearch Vaporizer Combustor (Ref. 2-20)

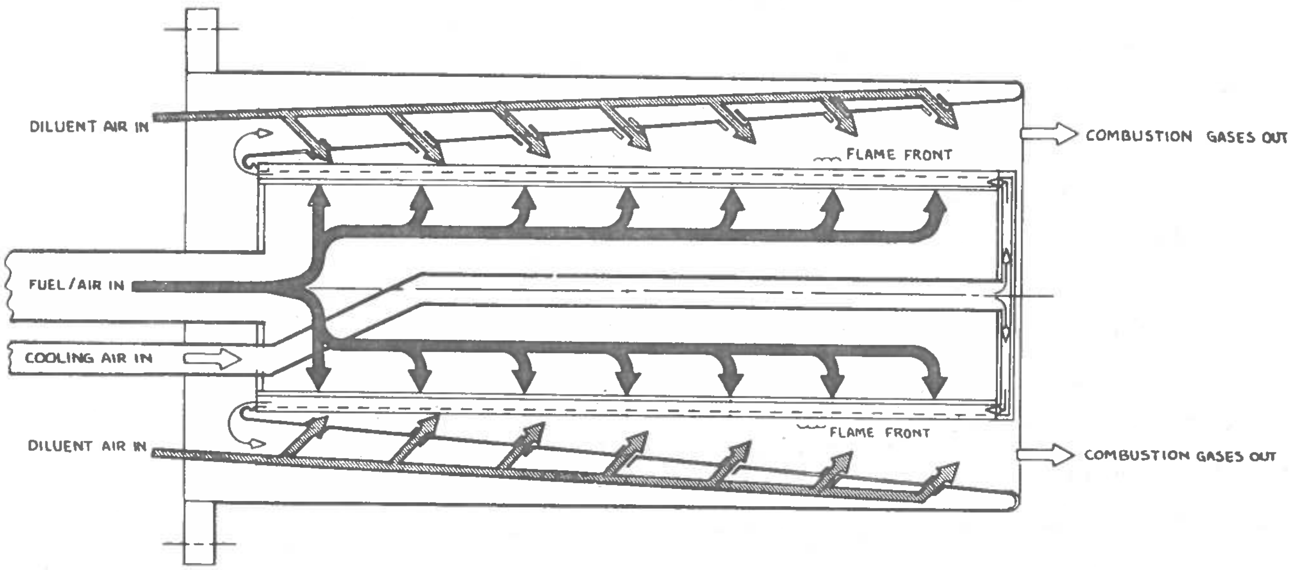


Figure 2-23. General Electric Low NO_x Porous Plate Gas Turbine Combustor (Ref. 2-21)

2.1.5.2 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 by increasing the turbine inlet temperature from 1800°F to 2500°F. Based on current materials technology, turbine inlet temperatures are limited to about 1800°F to 1900°F using nickel alloys. Higher temperatures can be achieved with transpiration-cooled, veil-cooled, or internally cooled turbine blades. However, these approaches are limited to turbine inlet temperatures of about 2300°F and are not currently considered feasible for automotive gas turbines because of high manufacturing costs. For these reasons, gas turbine manufacturers have been interested in ceramic turbine nozzles and rotors for some time. Although initial acceptance of these brittle materials has not been good, there are indications that the properties of ceramics have now been improved to a point that a number of manufacturers are seriously interested in the use of these materials in their gas turbines.

No serious difficulties are foreseen in the use of ceramics for stationary components of the engine such as combustor liners, nozzles, shrouds, heat exchangers, and insulation. However, the design of rotating components such as ceramic turbine wheels represents a very difficult challenge. The wheel must be capable of withstanding the high thermal and centrifugal loads and must be sufficiently light to provide adequate engine response. But the lack of ductility of ceramics leaves very little room for error, requiring extreme care in defining boundary conditions and loading. The large difference in thermal expansion characteristics between ceramics and metals indicates the need for a novel rotor/shaft attachment approach. Ford has developed a "folded-bolt" configuration in which the bolt is prestressed in the cold condition in order to offset its thermal expansion during operation (Ref. 2-22). This bolt is probably the most critical component of the engine because it controls the heat flow from the ceramic rotor which in turn controls the thermal stress distribution in the rotor.

In June 1971, Ford with Westinghouse as subcontractor was awarded a $10.3 million ARPA-sponsored contract to demonstrate that brittle materials can be successfully used in high-temperature gas turbine components such as turbine inlet nose cones, nozzle vanes, turbine wheels, and combustor liners. Under the terms of the contract, which is monitored for ARPA by the Army Materials and Mechanics Research Center, Ford is concentrating on the development of ceramics for use in a small automotive gas turbine vehicle, and Westinghouse is investigating the applicability of ceramics to large stationary gas turbines (Ref. 2-23).

To date, Ford has concentrated its efforts in the areas of materials technology, turbine component development, and stress analysis. In the material technology area, Ford has initiated a program to determine the physical properties of various ceramics, including hot-pressed silicon carbide, hot-pressed silicon nitride (Si_3N_4) and injection-molded silicon nitride. Based on these evaluations, Ford feels that hot-pressed silicon nitride and silicon carbide are candidate materials for turbine rotors.

Three different turbine rotor manufacturing processes are currently being evaluated by Ford. These include injection molding of silicon nitride, hot pressing of separate silicon nitride blades and discs, and vapor deposition of silicon carbide. Currently the vapor deposition process appears to be the most promising approach. Other rotor manufacturing techniques such as ultrasonic and electric discharge machining of parts from billets are also being considered. Hot pressed Si_3N_4 is being considered for other stationary components.

Although very encouraging results have been achieved to date in the ceramics area, considerably more development work is required before these ceramics can be considered feasible for use in the manufacture of rotating components for applications to the automotive gas turbine engine.

2.1.5.3 High Temperature Alloys

The high-temperature components of gas turbines are the combustor and the turbine wheel(s). In the combustor, two superalloys are used extensively: Hastelloy-X, a nickel-base alloy, and L-605, a cobalt base alloy. Hastelloy-X is a good high-temperature and oxidation-resistant alloy and is applicable to turbine wheels for gas temperatures up to 2200°F. It is easily fabricated and can be welded (Ref. 2-11).

For turbine wheels, the material used for nozzles and stators is cobalt base alloys such as Haynes 31 or WI-52. Both of these alloys can be vacuum melted. In recent years, a series of cobalt base alloys developed by Martin Metal Company have shown more promise, especially Mar-M322 which has very high rupture strength at high temperatures (Ref. 2-11).

Integral turbines (disc and blades) are usually made of a one-piece investment casting and the high-temperature materials used are nickel-based alloys IN 713LC (a low carbon modification of Alloy 713C) and IN 100. A-286 is an iron-base alloy with 25.5 percent nickel that is used extensively for the first-stage disc of high-temperature turbines.

Additional discussion on high temperature alloys can be found throughout Section 3.

2.1.5.4 Water Injection

By injecting water or other suitable fluids into the engine air flow, the thermodynamic and physical properties of air are altered so that more work is derived from each pound of air. Injection could occur at the compressor or combustor inlets.

Injection of liquid at the compressor inlet cools the air resulting in higher mass flow rates. In addition, because of an increase in density, the pressure ratio will increase. Likewise, injection of water in the combustor increases the mass flow and alters the thermodynamic properties of the medium, thereby resulting in an increase in turbine power. With water injection (water-to-air mass ratio of 0.06) at an ambient temperature of about 80°F, the power increase is 35 percent. However, this power increase is obtained at the cost of a reduction in compressor efficiency. At a water-to-air mass ratio of 0.06 the ratio of compressor efficiency with water injection to the compressor efficiency without water injection is 0.83, a substantial drop in compressor efficiency (Ref. 2-24).

Water injection is to be operative only for the higher power output requirements of the engine. In a normal vehicle driving cycle, the engine operates only for a short time at high power output. Therefore, the change in efficiency due to water injection which occurs during periods of higher power operation does not have a significant effect on overall fuel consumption. A positive result of the power boost feature is that the engine size can be reduced, resulting in an improvement in part-load operating efficiency.

2.1.5.5 Gas Bearings

The successful operation of oil-lubricated bearings is dependent on the temperature and purity of oil. Current lubricating oils are limited to a temperature of 400°F. With the high operating temperatures of gas turbines 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 (i.e. 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. AiResearch (Ref. 2-25) and others have successfully used gas bearings in a number of turbomachinery configurations.

2.2 TRANSMISSION SYSTEMS DESIGN APPROACH

The gas turbine engine, as described in previous sections, generally operates at speeds above 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 drive. This is accomplished by a fixed-ratio reduction gear box installed ahead of the transmission.

The function of the transmission is to convert the energy output of the engine to useful levels of torque at the vehicle wheels. Ideally, the transmission should have the following characteristics (Ref. 2-2):

- High efficiency over the normal operating range
- Control simplicity for optimum performance
- Low volume for compactness
- Low noise
- Low weight/power ratio
- Reverse-power and braking capability
- Capability of absorbing road shocks
- Low power consumption during engine start and at idle

The gear ratio requirements for the gas turbine/transmission powertrain are dependent upon the torque-speed characteristics of the particular engine type used. In general, satisfactory vehicle operation demands high torque at low speeds to provide rapid start-up acceleration, while less torque is needed at the higher vehicle speeds used for cruising. The transmission speed ratio range and step size has to be selected so that these desired vehicle performance characteristics are achieved.

The transmission requirements for different engine types may be understood by referring to Figure 2-24 which shows the trend of torque versus speed for the free turbine engine and the single-shaft gas turbine engine as compared with the conventional internal combustion reciprocating engine. It may be seen that the torque curve for the free turbine approximates

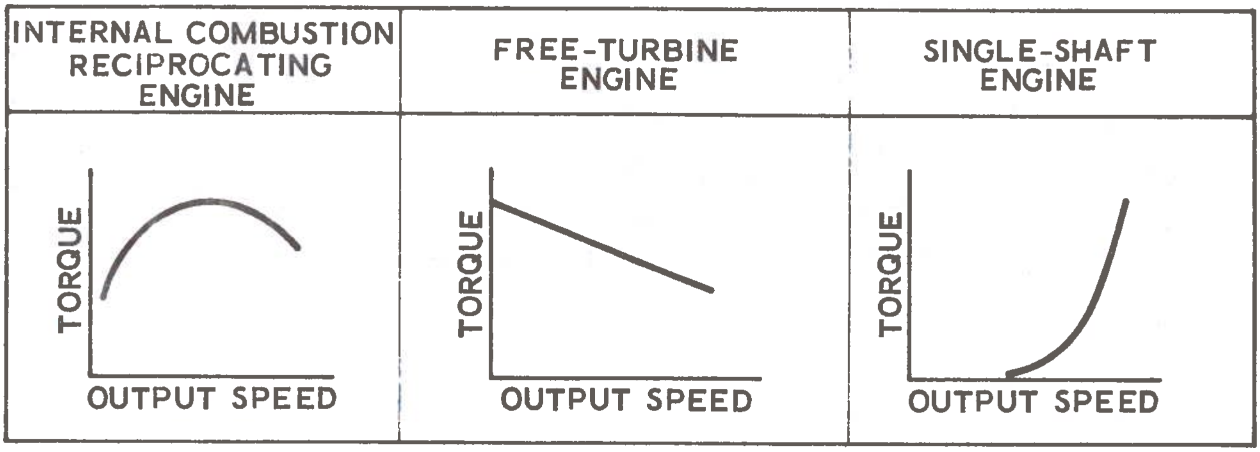


Figure 2-24. Engine Torque-Speed Characteristics

an ideal characteristic, providing maximum torque at low speed while maintaining a relatively high level of torque over the speed range. The general characteristics of this curve are similar to the internal combustion engine characteristics. Hence, conventional two-, three-, or four-speed transmissions may be used with this engine.

The characteristic for the single-shaft engine, on the other hand, shows a very steep rise in torque over a narrow speed range. To satisfy vehicle torque requirements with this engine demands the use of a transmission with a wide range in gear ratios; a range of up to 10 to 1 in eight or more steps may be required.

There are four major types of wide speed-ratio range transmissions under consideration for use with the single-shaft engine: the hydromechanical, the 8-speed mechanical drive, the traction, and the belt drive transmissions. The mechanical drive is a stepped variable speed device; the other transmissions are stepless variable speed transmissions. These other transmissions are considered to be more practical than the 8-speed mechanical drive for the single-shaft engine and are discussed below.

2.2.1 Hydromechanical Transmission

General Electric proposes to use a hydromechanical transmission (HMT) (Ref. 2-26) that is designed so that 60 percent of the torque is transferred hydraulically and 40 percent is transferred mechanically. The mechanical portion contains a planetary gear system which drives the input to the hydraulic unit. The output of the hydraulic unit drives a ring gear and the ring gear, in turn, drives the transmission output shaft.

The operation of the transmission is predetermined as a function of the design speed-load schedule. The transmission control receives an input from the accelerator position and engine speed. With an increase in acceleration requirement, the transmission control calls for an increase in engine speed. As the engine speed increases, the transmission selects the gear ratio that results in the best torque at the lowest SFC possible.

The efficiency of the General Electric hydrodynamic transmission is shown in Figure 2-25 (Ref. 2-15). The efficiency of the system peaks at 80 percent, which is below the 85 percent efficiency of transmissions currently used by the automobile manufacturers with the internal combustion engine.

2.2.2 Traction Transmission

Although traction transmission devices have been used in toys and small power equipment, they are currently not commercially available

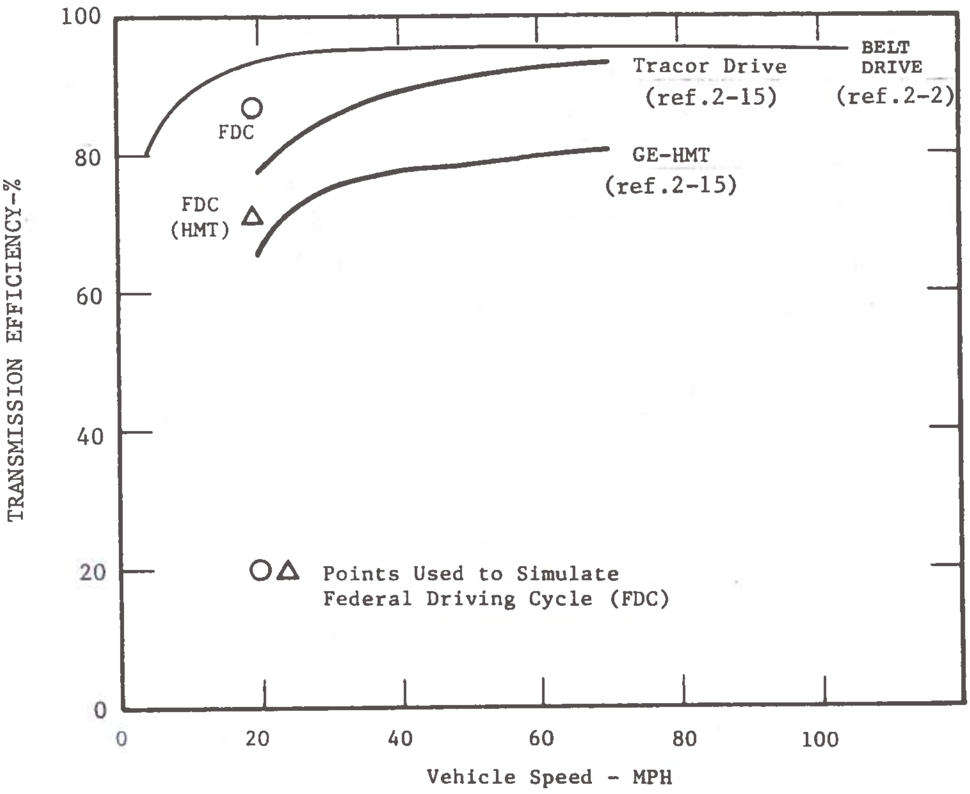


Figure 2-25. Transmission Efficiency at Cruising Conditions for Different Drives, Single-Shaft Engine (Refs. 2-2, 2-15)

for large power output devices. A recent development effort in this area by Tracor, Inc. has resulted in the design of a special metal traction device for transmitting torque at the high power levels associated with automotive drives.

The Tracor design uses toroidal discs and rollers, special hydrostatic thrust bearings, and a specially prepared lubrication oil (Monsanto's Santotrac 30). This device is presented schematically in Figure 2-26. As shown, the roller position is controlled so that the transmission can operate in a speed step-up, in a speed step-down, or in a direct-drive mode. According to Tracor, the favorable features of the traction transmission include low noise, high-speed operation (up to 10,000 rpm input speed), compact size, a wide speed range capability, and comparatively low cost.

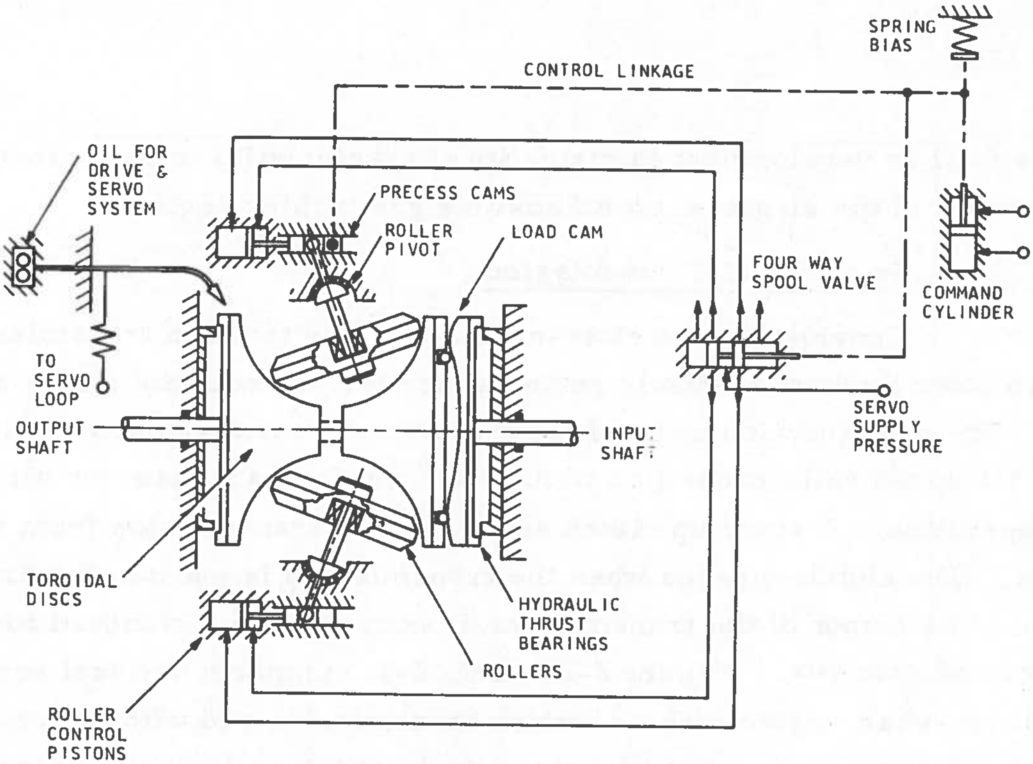


Figure 2-26. Tracor Traction Drive Schematic

The estimated efficiency of the Tracor traction transmission serving a 250-hp engine is shown in Figure 2-25. Over a wide range of vehicle speed, the transmission efficiency is between 85 and 90 percent. Comparison with the General Electric hydromechanical transmission indicates superior performance of the Tracor transmission.

2.2.3 Belt Transmission

The belt drive used for high-torque transmissions benefits from a recent development in high-strength rubberized composites (Ref. 2-2), and is based on a unique bent-axis concept that affords nearly optimum design. Estimated efficiency versus speed performance of this type of transmission is presented in Figure 2-25 (Ref 2-2). As can be observed, the belt-drive transmission has very high efficiency (substantially higher than the toroidal traction drive). In general, the belt drive transmission operates at lower absolute speeds than the toroidal traction system. This type of transmission requires further development to match its characteristics with the torque requirements of the single-shaft automotive gas turbine engine.

2.2.4 Selection of Transmission

Considering the state-of-the-art, the traction transmission seems to offer the best available performance for use with the single-shaft engine. One configuration of the Tracor traction transmission is capable of a total of 9:1 speed ratio range (3:1 to 0.33:1), which is adequate for single-shaft engine operation. A start-up clutch separates the transmission from the gear box. The clutch engages when the transmission is put into the drive position. The output of the transmission is connected to a standard torque converter and gear box. Figure 2-27 (Ref. 2-2) compares the fuel economy of the single-shaft engine with a traction transmission and with a four-speed automatic transmission. The advantage of the traction device is especially evident at low speeds; for example, at 10 mph, the traction transmission shows a 25 percent improvement in performance. However, the design feasibility has to be proven in extensive tests before a single-shaft engine can be selected for an automobile powerplant.

2.3 ENGINE/VEHICLE PERFORMANCE

Weight, volume, fuel economy, exhaust emissions, durability, safety, and noise are important vehicle-related engine performance parameters. These parameters are discussed in the following sections.

2.3.1 Engine Size and Weight

The size and weight of the engine impacts the power train packaging, chassis suspension, and other vehicle design elements. In general, both specific weight and specific volume of gas turbine engines are lower than for equivalent spark-ignition engines. Weight and volume data for a number of gas turbine engines are provided in Table 2-5. The specific weight and specific volume values for a family of engines, when plotted versus horsepower, may be expected to decrease as the horsepower increases. However, variations in the data shown in Table 2-5 do not permit such a trend to be

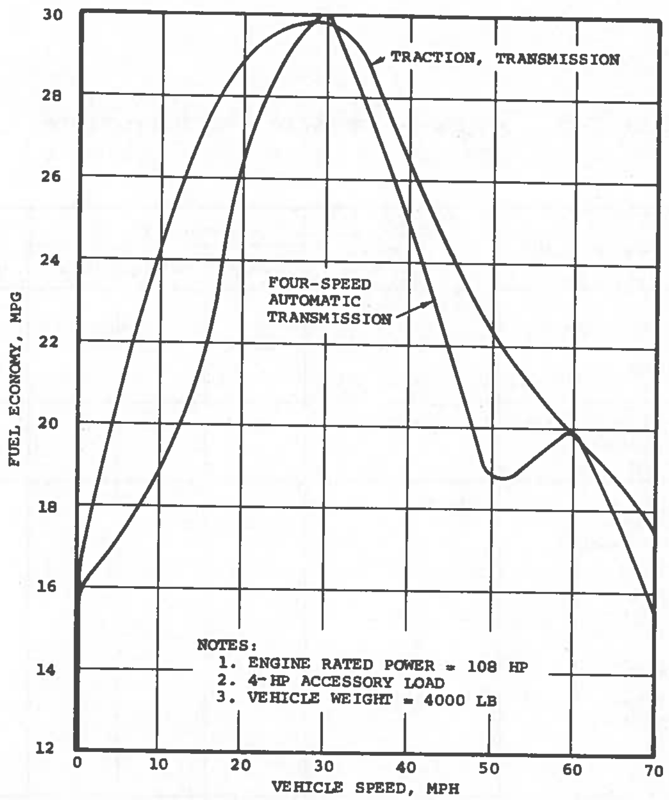


Figure 2-27. Estimated Road-Load Fuel Economy of Single-Shaft Regenerated Engine, 85°F Sea-Level Day (Ref. 2-2)

delineated. Note that the simple cycle engines are lighter than the regenerative engines. Table 2-5 shows a range of specific weights of 1.07 to 1.33 lb/hp for the simple cycle engines and of 1.4 to 5.31 lb/hp for the regenerative engines.

The dimension data available do not permit an accurate calculation of engine volume; therefore, only the overall engine dimensions are shown in Table 2-5. As can be seen, the simple cycle engines are relatively compact as compared to the regenerative engines. In each category the engine size appears to be inversely related to peak operating speed.

Table 2-5. Engine/Vehicle Performance

Manufacturer	Type of Engine	HP	Peak Operating Speed, rpm	Dimensions, in.			Specific Weight lb/HP	SFC lb Fuel/ HP Hr
				Length	Width	Height		
Ford	Regenerative Cycle with Ceramic Regenerator	320	45,300/38,200**				5.31	0.41
		450	37,500/31,650	40.8	34.6	41.8	3.78	0.41
		525	37,500/31,650				3.23	0.43
GM	Regenerative Cycle with Metal Regenerator	325	37,103/30,830	47	28	42	5.23	0.475
AiResearch	Single-shaft Regenerative Cycle with Metal Regenerator	155*	70,230	-	-	-	2.2	0.41
	Single-shaft Regenerative Cycle with Ceramic Regenerator	125*	83,600	-	-	-	3.2	0.434
	Free Turbine Regenerative Cycle with Ceramic Regenerator	175*	67,500/55,200	-	-	-	2.5	0.423
United Aircraft	Simple Cycle Single-shaft	150*	130,000	17	-	19	1.07	0.51
	Simple Cycle Free Turbine	150*	130,000/40,000	21	-	17	1.33	0.51
	Regenerative Cycle with Regenerative Single-shaft	163*	112,000	26	-	21	1.78	0.45
	Regenerative Cycle with Regenerative Free Turbine	166*	66,500/71,300	27.5	-	28	2.95	0.53
Williams Research	Regenerative Cycle with Regenerative Free Turbine	130*	-	-	-	-	1.4	0.40
Chrysler	Regenerative Cycle with Regenerative Free Turbine	150	44,600/45,700	33	27.5	29.5	4.42	0.60

*Design Engine, not built or under test

**Two speeds shown for dual-shaft (free turbine) engines; first figure for first stage turbine, second figure for power turbine

2.3.2 Fuel Economy

The estimated SFC for design point operation of the engines discussed in Section 2.1.4 is also tabulated in Table 2-5. SFC values ranging from 0.4 to 0.6 are shown. However, since automobiles operate over a range of part-load conditions, the performance indicated at the design point is only crudely representative of engine fuel economy over a normal driving cycle.

Fuel economy can be evaluated more realistically when engine operation is simulated for an automobile run over the FDC. In the engine optimization studies performed for EPA, the fuel economy of several gas turbine engines were evaluated and compared with the fuel economy of a representative V-8 spark-ignition engine.

The United Aircraft estimated fuel economy values for a 150 hp vehicle are shown in Table 2-6 (Ref. 2-14). The conclusion was that the fuel economy of a regenerative engine was superior to a spark-ignition engine and that the fuel economy of a simple cycle was inferior to a spark-ignition engine. The fuel economy predicted by United Aircraft for regenerative engines varies between 11 and 12 miles per gallon, depending on the effectiveness of the heat exchanger. The spark-ignition engine had a fuel economy of about 9.5 mpg and a single-shaft gas turbine of 7.5 mpg.

AiResearch predictions of fuel economy are shown in Table 2-7 (Ref. 2-2). Calculated results for two free-turbine regenerated cycle 135 hp and 175 hp engines, operating with three-speed automatic transmissions, are compared with a spark-ignition engine. Both FDC and fixed operating speed results are indicated. The fuel economy over the FDC is highest for the small 135 hp engine. This engine requires water injection to meet the maximum engine power requirements. The fuel economy of the 175 hp regenerative engine, while less than that of the 135 hp engine, shows a 31 percent improvement over the spark-ignition engine.

Table 2-6. United Aircraft Estimated Fuel Economy, Baseline Vehicles (Ref. 2-14)

Ambient Temperature 59°F

Fuel Economy (mpg)

Engine	FDC	20 mph	30 mph	40 mph	50 mph	60 mph	70 mph	Vehicle Test** Weight (lb)
RGSS-6 (Regenerative Single Shaft)	12.16	15.06	18.02	18.65	17.96	16.59	14.70	4000
RCSS-8 (Recuperative Single Shaft)	11.20	13.73	16.59	17.33	16.73	15.42	13.79	3950
SSS-10 (Single Cycle)	7.51	8.68	11.21	12.51	12.63	12.22	11.47	3700
OC-70* (Otto Cycle)	9.49	10.65	12.62	14.10	13.71	12.91	11.48	4300

*For reference purposes
**Simulated

However, existing gas turbine automobiles show lower fuel economy. The average fuel economy of the Chrysler sixth generation gas turbine engine installed in an intermediate-size car is approximately 8 miles per gallon over the FDC. The peak fuel economy of the same car is 18 miles per gallon at 40 miles per hour (Ref. 2-28). The AMC Hornet with the Williams Research W-26 engine rated at 80 horsepower had a fuel economy performance range of 5.1 to 8.1 miles per gallon during several tests conducted for exhaust emission evaluation using the FDC (Ref. 2-29).

2.3.3 Exhaust Emissions

Both Chrysler and Williams Research have tested their gas turbine automobiles over the FDC. The results of these tests are presented in Table 2-8. In these tests, the engines were equipped with conventional state-of-the-art combustors. The Chrysler results meet the CO and HC standards, but not the NO_x standard. The two Williams Research gas turbine engines (WR-25 and 131-Q) installed in a 1971 Hornet and a 1965 Volkswagen showed a high level of exhaust emissions. These data were extracted

Table 2-7. AiResearch Estimated Fuel Economy of Free-Turbine Regenerated Cycle (4000-lb Test Weight Vehicle,* 4-hp Accessory Load, Three-Speed Automatic Transmission) (Ref. 2-2)

Rated Power Level at 59°F Without Boost, shp	Fuel Economy, mpg							
	Ambient Temper-ature, °F	FDC (1.3-hp Accessory Load)	20 mph	30 mph	40 mph	50 mph	60 mph	70 mph
175	85	16.4	20.6	23.2	23.3	23.4	22.3	20.6
135	85	18.1	23.3	23.8	25.9	25.8	24.3	21.1
175	59	12.5	16.1	18.2	18.2	17.2	15.5	13.7

*Simulated

Table 2-8. Exhaust Emission Data using Federal Driving Cycle

Engine/Manufacturer	Emissions (gm/mi)			Remarks
	CO	HC	NO_x	
a. Conventional Combustor				
UARL RGSS-6	0.53	0.15	2.72	Ref. 2-14. Calculated values based on emission data from GM engine GT-309 (Ref. 2-13).
UARL SSS-10	1.86	0.31	1.03	Ref. 2-14. Calculated values based on emission data from GM engine T-56 (Ref. 2-13).
Chrysler Engine	3.4	0.3	2.7	Ref. 2-28, test data, single bag, 1972 Federal Test Procedure
Williams Research/ WR26/AMC Hornet	7.43 6.92	0.62 0.72	2.8 2.5	Cold start Hot start } Ref. 2-29, test data, 1975 Federal Test Procedure
Williams Research/ 131Q/Volkswagen	4.5	0.34	1.81	Ref. 2-30, test data, 1972 Federal Test Procedure
b. Advanced Combustors (current test results)				
Solar	0.898	0.105	0.169	Calculated values based on advanced combustor data
AiResearch	1.6	0.67	0.44	Calculated values for recuperated engine with 10 percent bypass
c. Federal 1976 Requirements	3.4	0.41	0.4	-

from References 2-29 and 2-30. The computed performance of other conventional combustors operated over a simulated FDC are also listed in Table 2-8; none of these meet the 1976 NO_x requirement.

As discussed in Section 2.1.5.1, a number of EPA contractors, have been working on advanced-design combustors. Based on experimental component testing, the emission levels for engines equipped with these devices are predicted as shown in Table 2-8. The exhaust emissions are generally close to or below the 1976 requirements. The AiResearch data, which simulates the use of an advanced combustor in a recuperative engine with 10 percent recuperator bypass, meets the CO and HC standards but is slightly above the NO_x requirement. These laboratory tests have proven the feasibility of reducing exhaust emissions to meet the 1976 requirements.

2.3.4 Driveability and Safety

2.3.4.1 Driveability

Driveability may be defined as the responsiveness of the vehicle to driver commands. In the case of the conventionally powered vehicle, criteria such as stall, stumble, hesitation, standing-start response (lag from idle to required power level), transient acceleration, and warmup apply to the evaluation of driveability. In the gas turbine vehicle, the principal driveability considerations involve standing-start acceleration response and braking behavior.

In general, the gas turbine car does not have the standing-start response of a piston-powered vehicle, circa 1970. This is exemplified by the performance characteristics shown in Figure 2-28 (Ref. 2-2), where the standing-start acceleration performance for a regenerated free turbine engine vehicle and a single-shaft turbine engine vehicle are compared with a spark-ignition engine vehicle. As shown, 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 starting delay; the pre-controlled emission spark-ignition engine has a delay of less than 0.1 second.

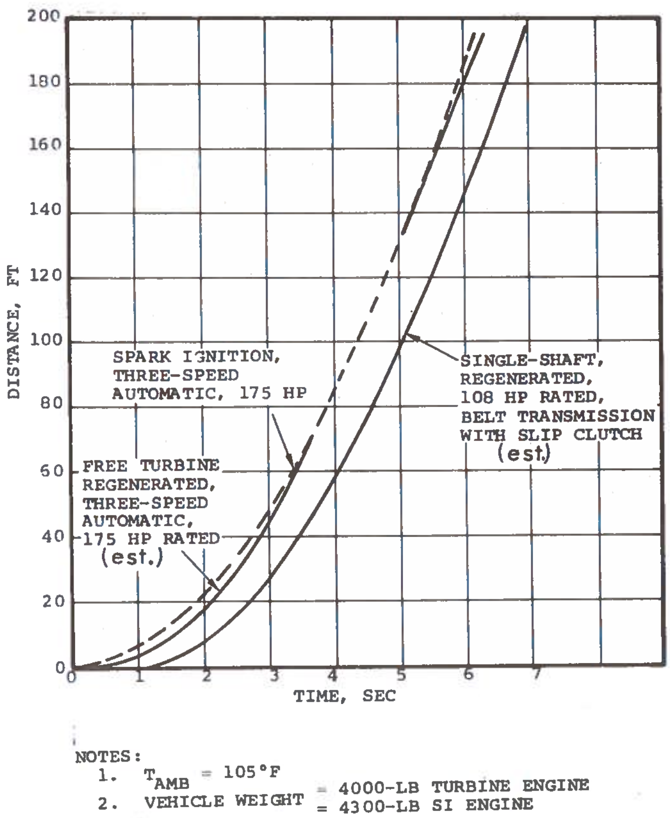


Figure 2-28. Standing-Start Acceleration Performance (Ref. 2-2)

Ford reported that driveability tests of a 1966 Thunderbird equipped with a 706 gas turbine engine (a forerunner of Ford's current 707 industrial engine) showed acceleration performance that was slightly better than that with the standard 428 CID spark-ignition engine.

Some comments on drivability by the drivers participating in the Chrysler 50-car test program as noted in Ref. 2-27 are as follows: (1) The operation of the engine was smooth and vibrationless. Passengers felt a gliding sensation at all speeds, which was particularly pleasant on long trips. (2) Starting ability was said to be superior to the internal combustion engine. Users consistently stated that the turbine car was superior to conventional cars in providing fast and sure ignition. (3) Other superior operating features mentioned were good engine power, quietness of operation, low vibration, and non-stalling characteristics. (4) The main negative comment was lack of acceleration, primarily when starting from standstill. Chrysler attributed this to the relatively low engine design power level in this automobile (130 hp).

Chrysler improved the acceleration and braking response characteristics of their sixth-generation engine, relative to the fourth-generation engine performance, by shifting major accessories from the first-stage turbine shaft to the power turbine shaft. Braking response characteristics were improved with an increase in turbine inlet temperature, providing additional braking power at negative turbine nozzle blade incidence. These improved characteristics are displayed in Figures 2-13 and 2-17.

2.3.4.2 Safety

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.

Aircraft and stationary gas turbine engines have an excellent record of safety performance, due largely to the practice of employing regularly scheduled preventive maintenance and overhaul. In the passenger car application, systematic maintenance cannot be guaranteed. Accordingly, these special safety provisions have to be incorporated into the basic design of the system to prevent severe damage in the event of catastrophic failure:

- Containment has to be provided so that in case of engine runaway or turbine blade failure, the rotating elements of the engine are safely confined.
- Limit controls must be designed so that engine operation does not exceed allowable limits.

- Backup provisions such as engine packaging and installation arrangements must be made so that the vehicle occupants are not subjected to heat or other hazards in the event that primary safety provisions fail under high-impact accident or other catastrophic conditions.

No fundamental difficulties in meeting these objectives for the passenger car turbine are anticipated.

2.3.5 Engine Noise and Vibration

The noise level of a gas turbine engine tends to be higher and composed of different frequencies, than that of the internal combustion engine because of the high-velocity flow of air at the compressor inlet, high idle speeds, and interference effects due to the 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 engine because the heat exchanger in the regenerative case absorbs part of the sound energy in the exhaust.

A number of investigators expect that the automotive gas turbine engine system will require exhaust noise silencers (particularly for simple cycle engines). United Aircraft suggests the use of fixed ceramic core or fiberglas mufflers as a possible cheap and simple installation approach. The present Chrysler engine package is reported not to require exhaust mufflers.

Chrysler expects that a number of design modifications would be required in the gas turbine vehicle chassis and frame. These include a new suspension system, a new exhaust system arrangement, and a new front end. The new suspension would be of the rubber-insulated type to provide a quieter ride. This modification is felt to be necessary because the noise due to bumps in the road would no longer be masked by the noise level of the piston engine.

The gas turbine engine has been demonstrated to operate with significantly less vibration than the conventional piston engine. This is directly attributable to the pure rotary motion of the engine.

2.4 PACKAGING AND INSTALLATION

Generally, the specific volume (ft^3/hp) of gas turbine engines tends to be lower than that of spark-ignition reciprocating engines. Therefore, there should be no problem in fitting the engine package into a conventional sized engine compartment unless combustor or regenerator volumes were to increase substantially. The engine could be located either in the front or in the rear of the vehicle. A front installation with front-wheel drive or a rear installation with rear-wheel drive would provide improved road traction and would eliminate the long driveline required in conventional car designs. A rear installation would also eliminate the long exhaust ducts and the resultant chassis redesign required to accommodate the duct volume. Although the engine itself is compact, the air intake and exhaust ducts are large (the gas turbine has five times the air flow of an internal combustion engine), and these 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 gas turbine engines in conventional vehicles required tearing up of the car floor pans. (Were the engine less sensitive to exhaust back pressure, smaller ducts could be used.) Williams Research indicated that the exhaust system for the turbine car could cost twice as much as for the conventional car.

Chrysler agrees that the size of the exhaust ducts will be considerably larger than for internal combustion engines. In their current installations, the exhaust pipes terminate slightly ahead of the rear axle. No exhaust mufflers are required with this installation. The larger exhaust ducts would require some design modification in the underbody and seat arrangement in the gas turbine car, unless a rear-engine installation is used (however, Chrysler does not at present favor a rear-engine car). Chrysler indicated that the front end of the turbine car would have to be strengthened because the radiator yoke which provides part of the front end support in current automobiles would not be available for use in gas turbine cars.

Chrysler feels that the incorporation of these changes into an existing design might be rather difficult and expensive. Therefore, they are 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 about every 3 to 5 years.

2.5 MAINTENANCE AND DURABILITY

Modern piston engines operated in normal passenger car service are expected to accumulate 75,000 to 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 fewer parts, may, assuming proper care and maintenance, provide even higher durability. The potential durability of the engine may be gauged from the fact that the AiResearch Industrial Division, manufacturer of turbo-superchargers, recommends the overhaul of their diesel engine turbo-superchargers on a schedule that coincides with the overhaul of the diesel engine itself at over 300,000 miles.

The contractors involved in the EPA-sponsored engine configuration optimization study 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. AiResearch estimated that engine-related repairs, although different in nature, would occur at about the same frequency among the aggregate of service or repair items for both engine types. United Aircraft assumed that the average service station would not be capable of working on the gas turbine engine, but that a facility similar to an automatic transmission repair and maintenance service, using specialized equipment, would be required. Williams Research concluded that random failure rates associated with the automotive piston engine would not be exceeded by the automotive turbine engine.

In the Chrysler 50-car program, 1.1 million vehicle miles were accumulated in a period slightly over two years. In the beginning of this program, the lost time due to engine malfunction was about 4 percent; this was eventually reduced to one percent as familiarity with repair problems was acquired. The Chrysler experience suggests that the training of mechanics in maintenance and repair of gas turbines will not present unusual problems.

Vehicles in the 50-car program were equipped with two pleated-paper intake air filters to avoid problems with ingestion of material leading to compressor and turbine blade erosion. Under normal operating conditions of the engine, the filters had to be cleaned every 25,000 miles. As with internal combustion engines, dirty filters result in lower gas turbine engine power output. Filters of this type also would be used in future Chrysler gas turbine engines.

Chrysler anticipates that production gas turbine engines will require less maintenance than their internal combustion engine counterparts. This judgment is partly based upon experience with the sixth-generation prototype engine, which was serviced after 3500 hours of operating time, corresponding to a mileage accumulation of about 170,000 miles.

In an automotive gas turbine designed for mass production, Chrysler would favor the independent subassemblies approach, which allows the rapid exchange of complete subassemblies, instead of replacing individual worn or defective parts. Chrysler is also contemplating the use of an onboard diagnostic system, which would facilitate overhauling the engine at the dealer's repair shop. In this case, the training of mechanics would have to be extended. However, Chrysler feels that this would not create a problem because the gas turbine is a less complicated machine than the internal combustion engine, with fewer parts to malfunction.

According to Ford, one service problem that will have to be faced, if ceramics are used in gas turbine engines, is how to re-train service personnel to be able to handle brittle materials. Modularization for ease of maintenance will be considered, but this increases the initial cost of the gas turbine engine because of the increased labor needed to assemble bolted and flanged components in the engine. According to Ford, training service personnel is part of the product development lead time requirement associated with the gas turbine automobile.

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.

A discussion of maintenance costs is included in Section 3.2.4.7.

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SECTION 3

SECTION 3

POTENTIAL FOR MASS PRODUCTION MANUFACTURING

3.0 INTRODUCTION

The production potential of gas turbine engines is dependent on the types, cost, and availability of materials as received at the engine plant and on the processes used to manufacture the engine. These factors are reflected in production rates, equipment design, facilities, and the eventual production cost of the engine. The following section discusses the availability of raw materials and the requirements of processed materials as well as their impact on supply industries, engine manufacturing processes, equipment tooling and facility requirements, engine production costs, and possible means for reducing production costs. Most of these items are compared to current and future emission controlled piston engines in order to provide a basis for assessing effects incurred by a changeover to gas turbine engine manufacture.

3.1 CRITICAL FACTORS ASSESSMENT

3.1.1 Raw and Processed Materials

The piston engine without 1976 emission controls has temperature/stress requirements that can be readily satisfied by the use of low-alloy carbon steels, cast iron, and aluminum, but the piston engine with 1976 emission controls, as presently conceived, does require a certain amount of high-temperature metal in the exhaust system. In contrast, the gas turbine engine operates continuously at high temperatures and stresses and therefore requires a significant amount of materials which have high-strength properties at elevated temperatures. These considerations govern the difference in basic material selection between the different engines noted.

The manufacturer of an engine receives practially all of his materials in some type of processed form. The succeeding discussion reviews raw material requirements for gas turbine engines and examines the effect this will have on processed materials as they are received at the engine factory.

3.1.1.1 Raw Materials

Table 3-1 provides an approximate comparison of the types and weights of materials used for contemporary and future piston engines as well as a low-pressure ratio regenerative gas turbine. This comparison is based on data provided in Reference 3-1. Data regarding the use of Inconel 718 and 738 have been deleted from Table 3-1 because, by comparison with Inconel 713, Inconel 718 contains much greater levels of niobium, and Inconel 738 contains much greater levels of tungsten and tantalum. Most manufacturers have elected not to use these potentially critical elements for their engine designs. It should be noted also that there are considerable variations in material weights for gas turbines proposed by a number of manufacturers. However, compared to piston engines, all concepts use relatively large amounts of high-alloy steel, Inconel, and Hastelloy.

Table 3-2 compares the 1969 U.S. consumption of potentially critical materials with the material needs for production of 10 million engines (the approximate quantity of passenger automobile engines produced annually in the United States in recent years). These data were extracted from various sections in Refs. 3-1, 3-2, 3-9, 3-10 and 3-11 and are based on initial quantities of materials required with fabrication scrap recycling. As can be seen, some of the material requirements for the gas turbine engine when contrasted with 1969 U.S. consumption levels would appear to present a significant impact on future availability of these materials. However, some lessening of the impact is anticipated. First, inquiries to stainless steel producers have revealed that there has been a significant increase in availability of chromium and nickel since 1969. Second, a further expansion in production is expected in order to meet the requirements for the 1976 piston engine, unless some drastic changes in the present emission control concepts occur. Therefore, cobalt, niobium, and molybdenum are the only materials that may be critical in availability.

The above analysis for Table 3-2 considered the initial demand for critical elements but did not include the recycling of scrapped engines to extract the critical elements. It is estimated that for the current annual engine

Table 3-1. Engine Material Content and Weight

Material	lb/engine (scrap weight not included)		
	Piston Engine		Gas Turbine
	Circa 1970	Circa 1976 (Est.)	4:1 Regenerative (Est.)
Gray Cast Iron	220	224	
High-Temp Cast Iron		28	23
Ductile Cast Iron	20	20	252
High-Alloy Steel	5	5	65
Low-Alloy and Carbon Steel	189	226	68
Copper	19	19	15
Brass	25	25	
Stainless Steel		5	14
ACI Type HU Steel		25	
Aluminum	20	21	4
Inconel 713			8
Hastelloy-X			4
Cercor (Al_2O_3)			20
Platinum/Palladium/Ruthenium		0.007	
Total	498	598	474

Table 3-2. Estimated High-Temperature Metal Element Requirements for 10 Million Engines*

(Millions of Pounds)

Element	Annual Needs			Usage and Availability		
	Piston Engine		Gas Turbine	United States		World
	Circa 1970	Circa 1976	4:1 Regenerative	1969 Annual Consumption	1972 Stockpile	1970 Reserves
Chromium	8	147	54	481	5331	1,550,000
Nickel		141	124	283	79	150,000
Cobalt			1.4	15	74	4,818
Molybdenum			8.5	52	43	11,000
Tungsten			2.4	16	129	2,800
Niobium			1.6	3	9	13,000
Platinum Type		0.1		0.1	0.14	31

*Amounts contained in the engine after fabrication production rates, the quantities of high-temperature material elements to be obtained from ore could be eventually reduced by a factor of 2 to 3 by recycling all of the scrapped engines. Since the introduction of gas turbines would probably build up from initial production quantities of approximately 250,000 engines per year to the full potential in excess of 10 million, the material requirements in Table 3-2 eventually would not have to be obtained from ore alone if recycling were to prove profitable.

Aside from problems of availability, consideration must be given to (1) potential effects on cost of the high-temperature elements due to supply/demand factors, and (2) the balance of trade effect on the U.S. economy due to the requirements of increases in purchases of ore or refined metals from foreign countries.

3.1.1.2 Processed Materials

The major processed forms in which materials are received at plants manufacturing piston and gas turbine engines are presented in order to allow an evaluation of the changes required in the materials processing industry as a result of presently conceived gas turbine requirements. The materials received at the engine plant may have been processed at foundries, at steel rolling mills, at the engine manufacturer's subcontractor or at separate divisions of the automobile manufacturer.

3.1.1.2.1 Types of Processed Materials

The following discussion is based on information summarized from Ref. 3-3.

3.1.1.2.1.1 Castings

a. Mold Type

The most widely used casting process for metals uses a permanent pattern of metal or wood around which an expendable mold is formed, with a refractory material. The pattern is then removed, the metal is poured, and the refractory material is broken away from the casting after cooling. The resulting casting must usually be machined.

b. Diecastings

This process is most widely used for large volume requirements of zinc, aluminum, brass, and magnesium castings of intricate shape. Castings are formed by forcing molten metal at relatively high pressure into an accurately machined die. The die is held in position in a hydraulic press during filling with metal and solidification of the casting. Dies are usually made from hardened tool steels but refractory metals are being used for casting higher melting temperature metals.

c. Investment Castings

This process conventionally uses both an expendable pattern and an expendable mold. Patterns of wax or plastic are manufactured by injecting these materials into permanent injection dies. Expendable molds are then formed around the pattern by repeated dipping into refractory slurries and drying. After formation of the mold, the expendable pattern is either burned or melted from the mold, the mold is preheated, and metal is poured into the mold. After controlled cooling, the mold is broken away and the casting is removed and cleaned by sandblasting or leaching. The finished casting is usually quite accurate and requires a minimum of machining.

3.1.1.2.1.2 Forgings

Forging is accomplished by plastic deformation of ductile material either by a squeezing pressure or by sharp blows on an ingot, billet, or powdered metal shape in a die to produce a desired shape. Forging stock is generally heated to increase plasticity.

3.1.1.2.1.3 Sheets

Heated slabs are progressively reduced in size as they move through a series of rolls.

a. Hot-Rolled Sheets

These are the product of the first stage of the rolling process. The available common dimensions are: 0.18 to 0.23-inch thick for

12 to 48-inch width, and 0.05 to 0.18-inch thick for greater than 48-inch width. The shipping configuration is usually in coiled form, but can be a flat sheet.

b. Cold-Rolled Sheets

These are made from hot-rolled coils which are chemically processed to remove scale and then cold rolled to the desired thickness. The available common dimensions are: 0.014 to 0.082-inch thick for 2 to 12-inch width, and 0.014-inch thick and up for greater than 12-inch width. The shipping configuration is usually in coiled form but can be flat sheet.

3.1.1.2.1.4 Strips

The manufacturing process is the same as for "sheet" except for closer dimensional tolerance.

a. Hot-Rolled Strips

Common dimensions are: 0.025 to 0.23-inch thick for 0.5 to 12-inch width. Shipping usually occurs in coiled form.

b. Cold-Rolled Strips

Common dimensions are: 0.025 to 0.25-inch thick for 0.5 to 24-inch width. Shipping usually occurs in coiled form.

3.1.1.2.1.5 Plates

These are produced in the form of rectangular plates or coils by hot rolling directly from the ingot or slab. Usual dimensions are: 0.15 inch and thicker for less than 48-inch width, and 0.23 inch and thicker for greater than 48-inch width. Widths range from 8 inches minimum to 200 inches maximum.

3.1.1.2.1.6 Bars

These are produced from blooms or billets in a variety of cross-sections and sizes, in straight lengths or, for some sizes and sections, in coils.

a. Hot-Rolled Bars

Common size ranges are: rounds, squares, and hexagons from 3/8 inch to 3 inches; flats to 8 inches wide and thicknesses over 0.2 inch but not over 12 square-inch cross-sectional area or 40.8 pounds per linear foot; structural shapes (angles, I-beams, etc.) with the greatest cross-sectional dimension under 3 inches.

b. Cold-Finished Bars

These are produced from hot-rolled bars by machining, cold drawing and cold rolling or a combination of these operations. Common size ranges are: rounds to 9 inches in diameter; squares to 4 inches; hexagons to 3-1/8 inches; flats from 1/8 inch and thicker up to 12 inches wide.

3.1.1.2.1.7 Wires

Steel wire is made from hot-rolled rods produced in continuous length coils. Most wire is drawn by pulling the rod through a series of dies having holes progressively smaller than the original diameter of the wire rod. Common sizes are 0.004 inch to 0.999 inch.

3.1.1.2.1.8 Pipes and Tubings

Welded tubular products are made from hot-rolled or cold-rolled flat steel coils by forming a cylindrical shape and welding. Seamless tubular products are made by hot piercing, extrusion or drawing of hot metal. Sizes for tubing range from 1/4 inch to a maximum (normally) of 10 inches in outside diameter. Pipe sizes vary from a nominal 1/8 inch to in excess of 30 inches in diameter.

3.1.1.2.1.9 Fabricated and Purchased Parts

These are defined as components previously fabricated, assembled, and tested plus such items as fasteners and filters. Examples of components for a piston engine are fuel pumps, coolant pumps, carburetors, etc. For gas turbines, examples are turbine and compressor rotors and stators, fuel controls, and ceramic regenerators.

3.1.1.2.2 Summary of Processed Materials

The approximate form and relative weights of the materials for the 1970 piston engine and the 1976 piston engine as compared to the gas turbine engine are indicated in Table 3-3 to show the changes required in the materials processing industries. The quantities of the different forms of materials used were derived mainly from Refs. 3-1, 3-2, and 3-4.

When compared with the piston engine, it can be noted that considerably more ductile iron castings are required for the gas turbine engine. Ductile iron castings are not as available as gray iron castings and are somewhat more difficult to produce. More expensive materials and closer refined process controls are necessary; the foundry yield and production rate is also lower than for gray iron. The production of large quantities of ductile iron would probably require some changes in current gray iron foundries. This relates to finer control of material purity and furnace temperatures.

Whereas the piston engine uses no investment castings, the gas turbine would need an appreciable number of investment castings, using both Inconel and aluminum alloys. This would require the development of a new investment casting industry supporting the passenger automobile field and could cause a considerable impact on the implementation of mass production of gas turbine engines, as discussed in Sections 3.1.3 and 3.1.4.

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. Therefore, the cost of forgings would increase for gas turbine engines.

Sheet, plate, wire, tube, bars, and extrusions would remain relatively constant in weight but the materials list would 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%) amounts required. It is probable that the required amounts of high-nickel-content steel would have to be produced by the large steel producers, such as U.S. Steel. This situation is similar to that posed by the stainless steel requirements for the 1976 emission-controlled

Table 3-3. Processed Material Form and Weight (Refs. 3-1, 3-2, 3-4)

Form or Material	Weight/Engine (lb)		
	Piston Engine		Gas Turbine
	Circa 1970	Circa 1976 (Est.)	4:1 Regenerative (Est.)
Castings			
Mold Type			
Gray cast iron	220	224	
Ductile cast iron	5	5	209
Aluminum	14	15	
High-alloy steel	2	2	
High-temp cast iron		28	23
Inconel			1.1
Die Castings			
Aluminum	6	6	2.1
Investment Castings			
Inconel			7
Aluminum			2
Forgings			
High-alloy steel	3	3	31
Low-alloy steel	90	98	
Sheet, Plate, Wire, Tube, Bar Extrusions			
Low-alloy steel	48	63	55
Hastelloy-X			4
Stainless steel - 304/310/321		5	14
ACI Type HU		25	
High-alloy steel			3
Fabricated and Purchased Parts			
Ductile cast iron	15	15	43
Low-alloy steel	51	65	14
Copper	19	19	15
Brass	25	25	
Cercor			20
High-alloy steel			30
Total	498	598	474

piston engine (Ref. 3-5). The placement of large orders would require that the carbon 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. This requires that scale be removed from the steel billets prior to rolling and that scale be removed from the hot-rolled sheets after rolling. Necessary equipment consists mostly of grinding equipment for removal of scale from billets and pickling equipment to remove scale from sheets. Additionally, some special sheet-rolling equipment is required to provide the desired gauge, width, and surface conditions. It can be assumed that most of this capacity will have been acquired to meet the stainless steel requirements of the 1976 emission-controlled piston engine.

3.1.2 Production Processes

In order to evaluate the production processes involved in the mass production of gas turbine engines, a comparison with piston engine mass production was made. Since gas turbine engines will probably not be mass produced until the 1980's, the comparison was conducted with respect to the 1976 emission-controlled piston engine, since it can be anticipated that this type of engine will be in production prior to and during this period.

3.1.2.1 Piston Engine

The production of 1976 piston engines with emission controls involves engine-related manufacturing operations outside the engine plant, as well as within the plant.

3.1.2.1.1 Pre-Mass Production Operations

The following major operations are performed prior to arrival of parts at the engine manufacturing and assembly plant:

1. Foundry. Manufacture of unfinished mold-type castings for engine block castings, intake manifolds, cylinder heads, exhaust manifolds, pistons, and piston rings.
2. Forge Shop. Manufacture of unfinished valves, connecting rods, crankshaft, flywheel, camshaft, gears, and drive parts.

3. <u>Fabricated and Purchased Parts</u>. Manufacture of coolant pump, fuel pump, radiator, fuel control system, alternator, voltage regulator, starting motor, coil distributor, spark plugs, wires, muffler, catalytic converter(s), exhaust and exhaust gas recirculation system, bearings, valves, valve lifters, valve springs, valve guides, rocker arms, filters, fasteners, etc.

3.1.2.1.2 <u>Mass Production Operations</u>

After arrival of the processed and purchased materials at the engine plant, these parts are machined as necessary and then used in assembly operations for approximately 150 engines per hour. (The time from start of machining of the first part of an engine until the engine is assembled and tested is approximately 3-1/2 hours.) The various operations for this assembly rate require from three to five parallel lines, depending on the time for each major operation. The following description of machining and assembling processes for the engine blocks and crankshaft is presented as an example of engine manufacturing operations.

The raw engine blocks have locating surfaces machined on them and are then conveyed to a broaching machine. The tops of the blocks (to be mated with the heads) and the sides of the blocks (to be mated with the exhaust manifolds) are then broached. The blocks are then transferred to a machine which bores the cylinders. Further conveying brings the blocks to a machine which drills and taps holes for attaching mating parts to the blocks. The block is then transferred to a honing machine where the cylinders are honed to obtain final finish and dimensions. This operation is followed by measurement of the cylinder diameters. The size of each cylinder is marked and teletyped to the assembly station where graded pistons with rings are set aside to selectively mate with the designated cylinder bore. The blocks then enter the assembly area where other machined parts of the engine are joined.

One of the most critical items is the machining of the crankshaft. The raw forging is machined and then ground on various centers to provide smooth surfaces for the piston connecting rod bearings. Tolerances are approximately 0.0002 inch.

It should be noted that, in general, the manufacturing process requires the machining of a large number of surfaces to relatively close tolerances and the removal of relatively large amounts of metal from raw castings, forgings, and other processed materials. Since each engine has from 4 to 8 cylinders, a large number of operations are identical and are performed simultaneously on multiple-spindle machines. Additionally, a large number of components for each engine such as pistons, piston rings, connecting rods, valves, valve lifters, rocker arms, springs, and spark plugs are identical and can be produced at high speeds with repetitive operations. In general, the majority of parts are made from gray cast iron or low-alloy steel which can be machined at high speed without regard to excessive tool wear. More importantly, most parts are cylindrical or have regular surfaces that can be machined with high accuracy without requiring very complex machining operations.

For the 1976 emission-controlled piston engine, the most critical item is the catalytic converter system. At the present time, mass production processes for this system are being developed, particularly for processes related to production of the ceramic substrates. The problems in producing substrates have a degree of similarity to the problems of producing ceramic cores for the gas turbine regenerator system; i.e. maintaining uniformity in high-speed fabrication to ensure retention of structural strength when the material is exposed to high-temperature gases.

3.1.2.2 Gas Turbines

At this time gas turbine engines for automotive use have only been produced in limited quantities. In order to describe mass production of these engines, mass production techniques for similar hardware were observed and evaluated. One case in point is the line of turbosuperchargers for diesel engines which are made by the AiResearch Industrial Division in quantities of 800 to 1000 per day. Like the piston engine, the production of gas turbine engines involves both pre-mass production operations and mass-production operations.

3.1.2.2.1 Pre-Mass Production Operations

The following major operations would be performed prior to arrival of parts at the engine manufacturing plant:

1. Foundry. Manufacture of unfinished mold-type castings for compressor scroll, turbine inlet scroll, turbine stator housing, turbine plenum, regenerator housing, gear box housing, combustor cover, and vane support ring for the variable geometry nozzle.
2. Precision Investment Casting Facility. Manufacture of compressor wheel, turbine wheel(s), turbine nozzles, and variable geometry vanes.
3. Die Casting Facility. Manufacture of compressor diffuser.
4. Forge Shop. Manufacture of raw forgings for compressor/turbine shaft and gears for the compressor/turbine shaft, starter, turbine drive, reduction, and accessory drive.
5. Fabricated and Purchased Parts. Fuel control system, seals, gaskets, electrical system, ceramic regenerator, finished gears, fasteners, and bearings.

3.1.2.2.2 Mass Production Operations

After arrival of the above materials at the engine plant, it is assumed that these parts must be machined and assembled at rates approximating the piston engine in order to be competitive in usage of labor, equipment, and facilities. This means that rates approximating 150 engines per hour must be reached, and that the time from start of machining of the part requiring the longest time until completion of assembly and test is in the range of 3 to 4 hours.

The unfinished castings are machined by using conventional machine tools similar to those used on piston engines. While the ductile iron parts are relatively easy to machine, some of the higher-alloy cast parts will probably require either more expensive tooling or will result in faster tool wearout than experienced with piston engines. It is assumed that this will cause a relatively insignificant difference in cost or time. The precision investment castings for turbines will require only minor machining at the blade tip and on the face of the hub. The machining and assembly process for the compressor/turbine rotating assembly is presented as an example.

The investment cast compressor wheel is machined at its periphery to tolerances of about ±0.002 inch after the center of the impeller is finished, bored and splined to receive the shaft. It is then balanced, x-rayed for internal flaws, and Zyglo (dye penetrant) inspected for external flaws, e.g., surface cracks or dimples. The turbine wheel is similarly machined at its periphery and hub to tolerances of about ±0.001 inch, balanced, x-rayed for internal flaws, and Zyglo inspected for external flaws. The shaft is finish-machined on a lathe and subsequently ground at the bearing surfaces. It is then inertia-welded to the turbine wheel. The inertia-welded interface is annealed and the weld flash is machined off. The compressor wheel is then fastened to the shaft using the spline to hold the compressor circumferentially and a threaded bolt to hold the compressor axially against a machined shoulder on the shaft. The completed assembly is then balanced.

3.1.2.3 Critical Factors in Mass Production Processes

In comparing the gas turbine manufacturing process to the piston engine, the following items stand out.

For high-volume manufacture of the gas turbine engine, new handling, loading, unloading, machining and transfer equipment will be required. Basic materials are generally composed of higher-temperature alloys and are more difficult to machine than materials used 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 as opposed to the large number of duplicate parts in the piston engine (e.g., in a V-8 engine there are 8 pistons, 8 intake valves, 8 wrist pins, etc.). The gas turbine engine also has about the same tolerances as the piston engine, but the number of close tolerances is less (e.g., the number of operations to machine to better than 0.001 inch for gas turbines is estimated at 377 as opposed to

514 for piston engines). To some degree the larger number of unique parts along with a lower number of close tolerances in gas turbines may eventually balance the duplication of parts and higher number of close tolerances in piston engines, from a mass production point of view. Assembly of the gas turbine is also visualized as less complex than assembly of the piston engine due to fewer parts involved in the process.

Critical production factors exist mainly in the fabrication of components and parts prior to delivery to the engine plant; these elements of the engine include: ceramic regenerator cores, fuel control units, and investment castings or alternate processes.

3.1.2.3.1 Ceramic Regenerator Cores

Even though the first ceramic cores for regenerators were built about 1950 by Chrysler, the mass production technique for ceramic cores must still be developed. Uniformity of fabrication was not reliable in Chrysler's 1950 efforts, and problems arose in cracking, leakage, and heat transfer effectivity. Chrysler then proceeded 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 of the technical problems.

3.1.2.3.2 Fuel Control Units

The technology of fuel control units for automotive gas turbines is still 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 although the mass production of electronic components is not yet commonplace practice in the automotive industry. System selection and design must be directed at reducing the present high cost of fuel control units for gas turbine engines.

3.1.2.3.3 Investment Castings

The present processes used in the U.S. to produce precision investment castings are complex, time consuming, and expensive. While this process has been found to be cost effective for aircraft-type engine parts and diesel engine turbosuperchargers, it is considered to be one of the most critical cost factors in developing gas turbine engines for passenger automobiles.

For mass production of compressor or turbine wheels and nozzles in the U.S., a metal die (Fig. 3-1) is made to produce a wax pattern by the injection molding process (Ref. 3-6). The wax patterns are then manually dipped into successively coarser ceramic slurries to form a surrounding ceramic mold (Fig. 3-2). An average of seven dips and drying cycles is required to form the ceramic mold. The mold is then cured in an oven and the wax is burned out. Upon completion of this phase, the mold is preheated to within 300°F of the melting temperature of the metal to be poured. The mold is then brought to a vacuum furnace operating at approximately 2-micron vacuum, and the molten metal is poured into the mold. After cooling, the ceramic mold is knocked off the periphery of the casting by pneumatic hammering. The casting is then manually sandblasted to remove any remaining ceramic and is ready for inspection. Inspection involves dipping into a fluorescent dye penetrant (Zyglo) to discover surface flaws, visual inspection by gaging for specified profiles, x-raying for internal flaws, and flow checks on a balance bridge for proper pressure drop of gas flow across the unit.

A typical current production rate for such a process ranges from 3 to 5 parts per hour and the time cycle from mold making through casting is approximately 70 hours. This rate can be contrasted with production rates for sand castings of V-8 piston engine blocks that have reached levels of about 155 parts per hour per line with a total process time in the foundry of about 3 hours. Increased production rates for investment castings can be obtained by enlarging facilities and equipment and by automating many parts of the process. For example, the manual dipping of the wax pattern into the ceramic slurries can be automated. Additionally, parts can be produced in multiple units by placing the wax patterns on a "tree," dipping them simultaneously, and forming a multiple ceramic mold.

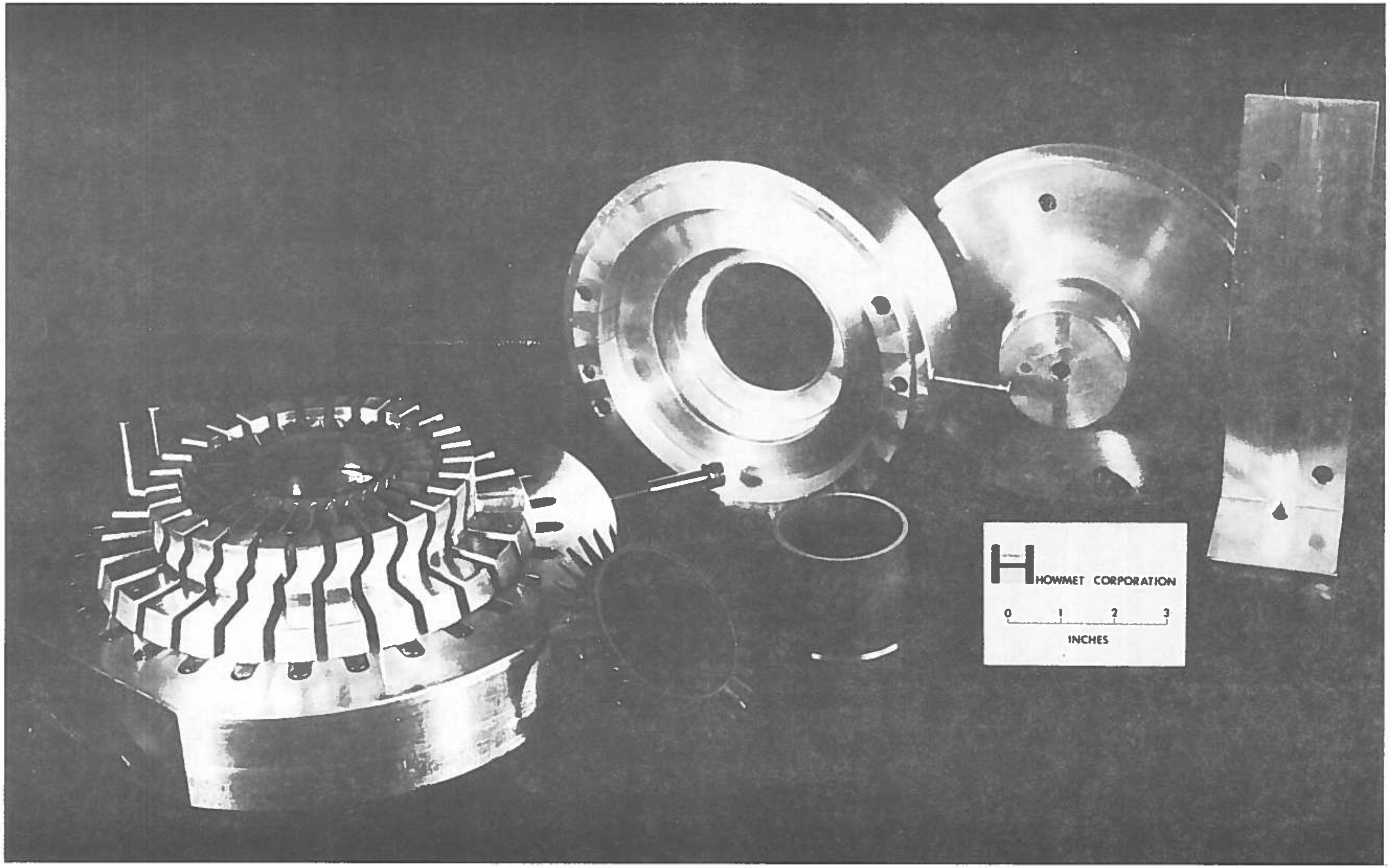


Figure 3-1. Single Injection Wax Pattern and Tooling (Ref. 3-6)

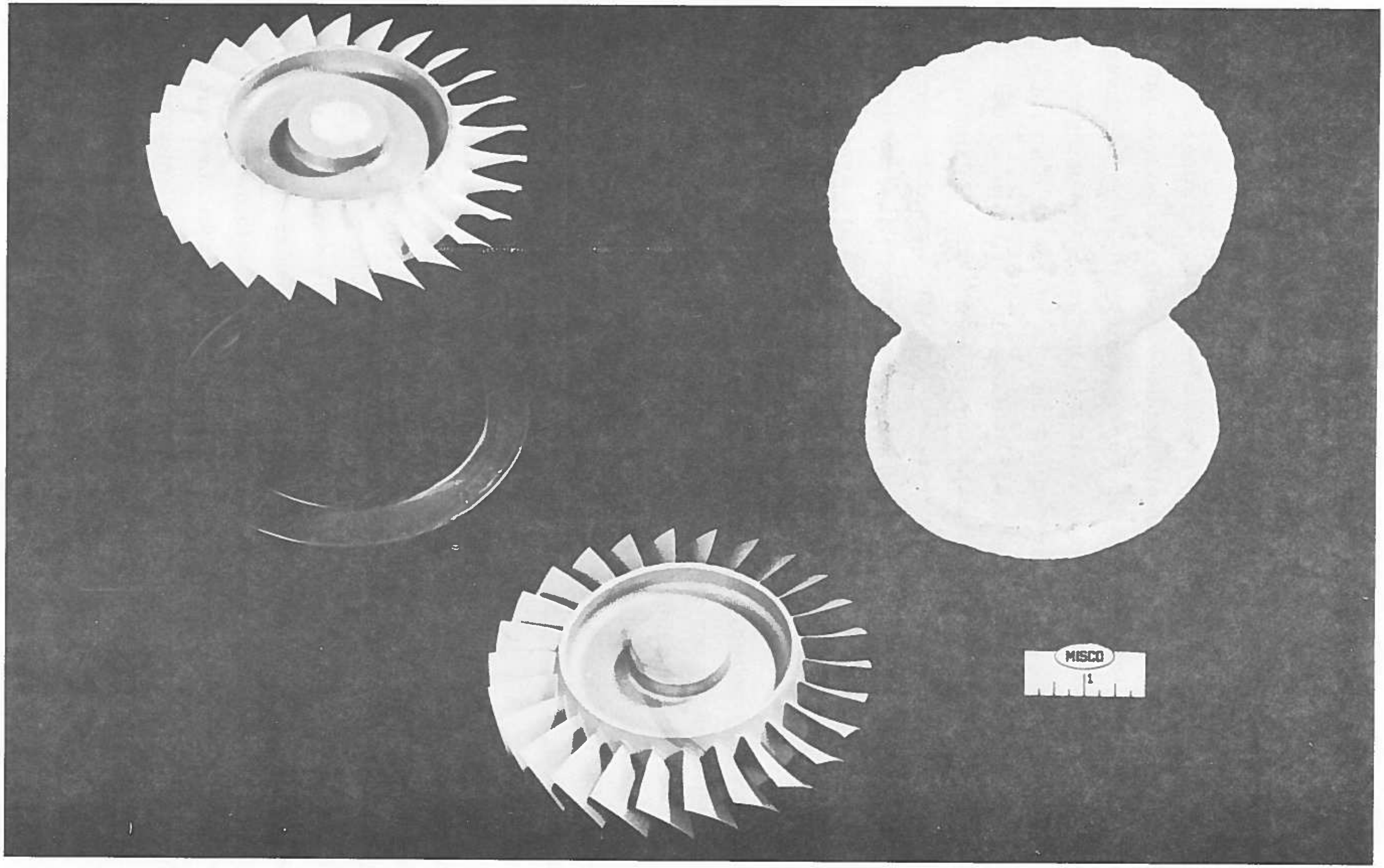


Figure 3-2. Axial Compressor Rotor Vehicular Turboshaft Engine 17-4 PH (Ref. 3-6)

It should be noted that the investment casting of superalloys required for high-temperature components imposes special requirements as opposed to the casting of low-temperature components. Whereas the investment molds for nonferrous alloys (such as aluminum) generally use gypsum as both binder and aggregate, molds for melting high-temperature materials use a separate aggregate and binder (aggregate consists of fused silica, mullite, or zircon; binders are generally ethyl silicate and phosphates). Additionally, air melting is generally used for low-temperature alloys (such as aluminum), while the superalloys are usually vacuum melted to control impurities, oxidation, and grain structure. Vacuum melting increases the complexity and cost of the operation due to the additional cost of the furnace and the time to produce the required vacuum. However, it is possible to air-melt superalloys if a high-quality casting is not required. The major factor controlling overall process time is the period required for drying the ceramic casting molds.

The USSR has developed the investment casting process to mass-produce parts for automobiles, tractors, airplanes, sewing machines, bicycles, and motorcycles (Refs. 3-7, 3-8). Through use of new technology plus automation, the mold making-casting production cycle has been reduced from about 70 hours to 24 hours.

In the USSR process, the pattern wax material is saturated with air to reduce pattern shrinkage and the injection molding process to produce patterns is automated by using multistation machines which produce patterns automatically with injection cycles of 10 to 20 seconds. The patterns are then assembled into a cluster, or tree, consisting of a multiple number of patterns. Assembled pattern trees are then conveyed to the mold preparation where they are dipped successively and dried between dips using automated dipping and drying equipment. Mold curing, wax pattern removal, mold preheat, metal pouring, mold breakup, and cleaning of castings are all done by automated equipment.

Aside from automating the operation, the USSR has developed some new technology. Refractory materials which have a short drying time have been developed. The molds are supported in beds of heated sand during the preheat and pouring operation to relieve thermal stresses and patterns are made from water soluble wax. 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). Since the metals poured were apparently not Inconel or other high-temperature alloys, it is not clear whether major modifications to the process are required to permit use of these materials. Additionally, the degree of precision in the casting is not known and data on cost per unit produced are lacking.

The Industrial Chemicals Department of E.I. DuPont is developing a new process for forming investment casting molds. The DuPont Colal (TM) shell formation process consists of dipping the wax or plastic pattern into each of three chemical types of slurries. These slurries are chemically reactive and solidify around the wax form. The dipping sequence into Tanks 1, 2, and 3 follows this pattern: 1, 2, 3 — 2, 3, — 2, 3, — 2, 3 — etc., for a total of about seven or eight dipping series in a 15-minute period. The initial dip in Tank 1 is for acquiring a very fine silica grain coating on the wax form in order to establish a precision inner shell surface after firing. Successive dippings in Tanks 2 and 3 provide consecutively coarser grain structure in the slurry as the thickness of the coating is built up. Tank 1-type slurry is designated as Colal M, a colloidal silica. Tank 2-type slurry is designated as Colal P, a colloidal alumina silica. Tank 3-type slurry is proprietary and the designation remains undefined at this time.

The main advantage of the DuPont process is that no drying is required between dips. About a 2-day drying period is required after all dips have been made. This time might be reduced by resorting to some degree of stage drying during this 2-day period. In fact, if the shell could sustain rapid firing while wet (never accomplished to date), the drying time could be reduced to about 1 hour or less. Since drying times for the older processes (using ethyl silicate) are also about 2 days, the DuPont system is mainly a factory routing improvement and a labor saver in terms of shell handling.

DuPont has spent 4 years developing its shell fabrication process in-house, followed by 2 years working with industry. TRW is currently evaluating under Air Force contract the DuPont process and other processes for shell fabrication and casting of superalloys. TRW uses an Elliott Machine (a programmed pneumatic device made by G E C-Elliott, Kent, England) for automatic dipping to improve coating consistency over that achievable by hand dipping. They have used an autoclave dewaxing process in the past, but are now examining an automated microwave oven technique.

DuPont has not yet examined recovery of the ground-up shell after the casting has been made. However, it feels that there should be no problem in reuse, since the chemical composition of grain and binder is very similar. At this time, DuPont is developing a price structure for bulk purchase of materials and expects that material costs plus in-plant operating costs associated with shell formation will be competitive with existing systems.

3.1.2.3.4 Diecasting

Diecasting of compressor and turbine parts is not considered practical at this time. In general, diecasting is used to produce components from low-melting-temperature alloys such as zinc, lead, aluminum, magnesium, and copper. While aluminum is the material considered for compressor impellers, no evidence is available to demonstrate the successful diecast of compressor impellers required to operate at the stress levels encountered in gas turbine engines. It was reported by the Withrow Die Casting Company, Los Angeles, that attempts have been made in the past to develop diecasting for high-speed aluminum impellers, but the components failed under stress. The problem seems to be related to obtaining the necessary grain structure and metal fluidity for the type of aluminum alloy required. Development work is reportedly being performed by General Electric to produce diecastings from stainless steel using tungsten dies.

An additional problem with diecasting is the flashing that occurs on the product at the parting surface of the die. This flashing is detrimental to the aerodynamic performance of impellers and would require special machining operations for removal.

3.1.2.3.5 Centrifugal Casting

Williams Research Corporation is considering the permanent mold centrifugal casting of aluminum compressor impellers (Ref. 3-9). In this process, a permanent metal mold is filled with the molten metal. The mold is then spun about its axis, allowing centrifugal force to distribute the molten metal within the mold. The current development status of this process is not available.

3.1.3 Equipment, Tooling, and Facility Requirements

The criticality of equipment and tooling needs for gas turbine engine manufacture is directly related to the type of processed materials and manufacturing processes previously discussed.

3.1.3.1 Castings

Foundries would have to be modified and new equipment installed to produce ductile iron castings 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 similar to those discussed for the USSR and DuPont. 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 as well as 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. If it is assumed that technology advancements are successful, the time cycle to procure this equipment would depend on business conditions (i.e., industry backlog and growth capability); however, it is questionable whether the normal 18-month lead time cited for automotive applications (Ref. 3-5) would be sufficient unless foreign sources can be relied upon.

The procurement of diecasting equipment does not appear to present any appreciable problems.

3.1.3.2 Steel Mill Equipment

As explained previously, additional grinding, pickling, and rolling equipment would be required for the high-alloy materials (Section 3.1.1.2.2).

3.1.3.3 Fabricated and Purchased Parts

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 core manufacturers would require facilities and equipment similar to those contemplated for catalytic converter substrates.

3.1.3.4 Engine Manufacture

New equipment and tooling to manufacture the gas turbine engines would be required to set up a mass production facility. The number of machine tools, their cost, and total capital investment are shown in Table 3-4 for production of 1 million engines annually (Ref. 3-1). 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 load is compounded even more if consideration is given to the 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.

Table 3-4. Machine Tool Investment for Gas Turbine Engine Manufacturing Plant* (Ref. 3-1)

(Annual Production: One Million Units with Two-Shift Operation)

Machine Type	Number	Total Investment ($ Million)
Milling machines	224	42.5
Multispindle drill	99	19.8
Deburring facilities	33	1.2
Grinding machines/gear cutters	229	27.4
Welding machines	61	6.1
Tube cutters	32	1.3
Metal blanking press	4	0.6
Automatic lathe	5	0.3
Automatic hole tapper	7	0.5
Hole breach/reamer	19	3.7
Boring machines	98	18.6
High pressure tube expander	2	0.2
Sheet metal necking machine	2	0.1
Sand blaster	2	0.1
Contour spindle chucker	39	5.3
Carburizing facilities	5	0.1
Metal bending/forming	26	3.9
Miscellaneous		7.6
Total		139.3

*This does not include machine tools for purchased or prefabricated components

3.1.4 Capital Investment

The total capital investment for gas turbine engine manufacturing plants alone was estimated in Ref. 3-1; an investment of approximately 400 million dollars would be required to produce 1 million engines annually after a gradual production build-up. This compares with approximately 320 million dollars if new facilities were required to produce the same number of piston engines. Since facilities for manufacture of piston engines are available, the only new capital investments for piston engines are those involved with producing emission controls. The cost of this change is estimated at about 50 million dollars for 1 million cars.

The 400 million dollars for production of 1 million gas turbine engines per year 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 costs. It should be emphasized that $400 million is solely the capital investment for the engine manufacturing plant. Additional capital investment of unknown but relatively high amounts is estimated to be required for equipment to produce processed materials and also for fabricated and purchased parts received at the engine manufacturing plant. The $155 million capital investment for engine manufacturing machining tools cited in Ref. 3-1 was reduced by approximately $16 million to a total of $140 million by removing the requirement for 16 Gatorizing forge machines. This is based on the rationale that these machines would not be used at the engine manufacturing plant but rather would be used at another plant to prefabricate compressor and turbine rotors. Additionally, it is not yet clear whether these parts would be Gatorized or investment cast. Either way, the machine tool cost for these components would be a part of the prefabricated component/part equipment cost.

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 automobiles. This cost includes the 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, then this cost would increase.

3.2 ESTIMATED UNIT COST FOR ENGINES

3.2.1 Impact of Production Volume

The automotive industry characteristically employs machines particularly suited for high-volume, specialty operations. These machines are relatively inflexible with respect to configuration changes but, when combined with automatic transfer equipment for repetitive fixed operations, they are capable of producing parts with relatively low labor requirements.

The production processes for gas turbine engines being currently produced are generally geared to relatively low volume and fabrication flexibility for a variety of configurations. This type of production usually involves considerable labor for both the manufacturing process and quality control. In steps taken to reduce the labor involved with changes in machine setup, tape or numerically-controlled machines are very often used since these lend themselves to quick changes in operation sequence and rate. Nevertheless, the cost of labor and production equipment is currently a relatively high factor in the total production cost.

Total production cost (C_T) is defined as follows:

$$C_T = \text{Direct Manufacturing Costs} + \text{Labor Overhead Costs} + \text{Capital Cost Amortization} + \text{Administrative Costs}$$

where:

Direct Manufacturing Costs = Raw Material Costs + Processed Material Costs + Cost of Purchased Parts + Direct Labor Costs

An estimate of the relationship between direct manufacturing cost and production volume is given below. The direct manufacturing cost-to-volume relationship was based on the assumption that material costs are the dominant factor and that labor costs are a relatively small percentage of the direct manufacturing cost for a highly automated plant. Although it would have been desirable to also estimate such a relationship for total production cost (C_T), it was felt that too many variations exist in the methods and factors used by various manufacturers to determine labor overhead, capital cost amortization, and administrative costs. Furthermore, the precise impact of production volume on unit cost is not available from manufacturing sources since this type of information is considered proprietary.

If the direct manufacturing unit cost is equal to "C_1" for a given volume "V_1" the direct manufacturing unit cost "C_2" for a larger volume "V_2" decreases in accordance with the following formula:

$$C_2 = C_1 \left(\frac{V_1}{V_2} \right)^n$$

where n is a fractional power. As a hypothetical example, if the direct manufacturing unit cost of a gas turbine engine is \$850 at a volume of 100,000 per year, and if n = 0.125, the unit cost at a volume of 1 million units per year is:

$$C_2 = \$850 \left(\frac{100,000}{1,000,000} \right)^{0.125} = \$640$$

The above example is in general agreement with the relationship between cost and volume as estimated by United Aircraft Corporation (Ref. 3-4) for two production volumes: 100,000 and 1 million units per year.

The decrease in direct manufacturing cost with production volume is based on the following rationale. As noted previously, direct manufacturing cost is made up of raw and processed materials, purchased parts, and direct labor costs. The basic premise is that as production volume increases, the extensive use of highly automated equipment becomes cost effective and labor costs can be decreased. The additional capital investment for automation and larger facilities must be amortized; cost effectiveness is realized when the increase in the additional cost per unit due to amortization becomes less than the reduction in cost per unit resulting from a reduction in the labor force.

The absolute value of "n", generally labeled as "the learning power" is difficult to derive and would probably show a relatively broad band of variability for various manufacturers, type of design, and prevailing economic conditions. The range of volume over which a given learning power holds also is subject to high variability. For example, if the demand exceeds the full capacity of a given multi-shift operation facility, a decision must be made whether it would be feasible and more economical to speed up the production process by changing production procedures and equipment, whether an additional similar facility is more economical or whether the old facility should be scrapped and a new facility to handle the new volume should be built.

Traditionally automobile manufacturers have used pilot plants for low production levels with a minimum of automation. After the new design has been proven and it has been determined that the demand exists, a full volume engine production plant (multi-shift ultimate capacity of say 700,000 annual units) is set up with 200,000 to 300,000 engines considered a minimum annual production level. From that point, the tendency is to retain existing equipment and facilities. If demand exceeds the capacity of the existing high volume plant, it can be assumed that additional facilities will be added without scrapping the old one.

3.2.2 Impact of Design Approach

The following discussion covers some of the ramifications of four different engine design approaches.

3.2.2.1 Single Shaft, Non-regenerative, 10:1 Pressure Ratio

The apparent simplicity of this concept can be deceiving. The inlet diffuser and compressor operate in the supersonic regime and this design requires that sharp edges and close tolerances be obtained (and maintained) to retain high efficiencies. The high operating pressures require use of a titanium compressor impeller and a Hastelloy-X combustor can. Both of these materials are costly and they are foreign to the automotive industry. Due to the lack of a regenerator, fuel economy is relatively poor. Additionally, since the noise is not muffled by a regenerator, the vehicle might require a muffler at additional cost. The single-shaft engine requires an infinitely variable speed or 8-speed transmission, both of which are not yet developed.

From a positive standpoint the engine is lightweight, relatively small, requires fewer components and could be packaged into a small engine compartment. These features would aid in decreasing vehicle initial cost.

3.2.2.2 Free Turbine, Non-regenerative, 10:1 Pressure Ratio

This engine appears to offer very few relative advantages except for the fact that a standard transmission can be used. The fuel economy would also be relatively poor due to lack of a regenerator.

3.2.2.3 Single Shaft, Regenerative, 3.2:1 to 7:1 Pressure Ratio

All of the contractors arrived at relatively lower manufacturing costs for this type of engine than for the free turbine--regenerative engine. The basic problem is again the need for a new transmission with a very broad speed ratio. The problem with this approach is that automobile manufacturers appear to be reluctant to accept the risk of developing two basically new design concepts.

Since the engine does not contain a power turbine, it can be made relatively smaller and from fewer parts at lower cost, and it can be packaged in a smaller engine compartment than the free turbine. The fuel economy of this type of engine is considered superior to the free turbine--regenerative type since the efficiency loss from the power turbine is not involved.

3.2.2.4 Free Turbine, Regenerative/Recuperative, 4:1 to 6.6:1 Pressure Ratio

This engine has the highest manufacturing cost indicated for all concepts considered. It also is generally the largest and heaviest. Since it has a relatively low pressure ratio, the compressor materials used are cheaper than those for higher pressure ratios. Also, the free turbine concept allows the use of a standard transmission. Since practically all automotive gas turbines designed in the past have been free turbine--regenerative types, a considerable amount of historical data is available and the automobile manufacturers feel that less risk is involved in its development.

3.2.2.5 Additional Considerations

The large exhaust ducts for the gas turbine engine will require that existing automobile frames and bodies be modified to provide sufficient room for the ducts while maintaining the necessary clearance between the ducts and the ground. Thermal insulation and special alloys might also be required for the ducts of non-regenerative engines whose exhaust temperatures are expected to be higher than for current piston engines.

Within each of the engine concepts, a number of variations exist that impact on cost. These include variable versus fixed geometry compressors and turbines, hydromechanical versus electronic fuel controls, regenerative versus recuperative heat exchangers, ceramic versus stainless steel cores for heat exchangers, and standard 3-speed versus infinitely variable speed transmissions. Each one of these features has an effect on performance and cost. At this time, the development status of many of these items is insufficient to permit a comprehensive tradeoff analysis.

3.2.3 Impact of Materials Selection

Table 3-5 shows the materials selected by the contractors that performed manufacturing cost estimates for EPA (Refs. 3-4, 3-9, 3-10, 3-11). Two types of engines are illustrated: a single-shaft regenerative engine and a free turbine--regenerative engine. A comparison shows that in general the material selection by the various contractors is quite similar. Exceptions are materials for the compressor impeller where two of the contractors selected steel in place of aluminum due to higher operating pressures for their design. The components exposed to high temperatures are generally all made from high-nickel-content alloy steels. It appears that large differences in cost estimates (See Section 3.2.4) are mainly the result of different estimates for labor costs, quantities of materials, material processes and basic engine design. The selection of materials for the concepts considered is mainly governed by structural, dynamic, strength and lifetime requirements.

3.2.3.1 Compressor Impellers

The selection of materials for cast compressor impellers is mainly a function of strength-to-density ratio. The following materials are required at the approximate maximum pressure ratios indicated:

Maximum Pressure Ratio	Material
4:1	Aluminum
6:1	Steel
16:1	Titanium

A tradeoff exists between the positive aspects of size reduction and gain in efficiency at higher pressure ratios and the negative aspects of increased cost of materials and processing. Whereas aluminum compressor impellers can possibly be centifugally cast, steel or titanium impellers do not lend themselves to this process and require more expensive processing such as precision investment casting or precision forging (Gatorizing Process).

Table 3-5. Materials for Major Components in Gas Turbine Engine

Component	Single Shaft, Regenerative			Free Turbine, Regenerative			
	UA	GE	AiResearch	UA	GE	AiResearch	Williams
Compressor Shroud	Ductile Cast Iron	Aluminum	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron
Compressor Impeller	Steel	Aluminum	Aluminum	Aluminum	410 SS	Aluminum	Aluminum
Shafting	SAE 4340	SAE 4340	SAE 4340	SAE 4340	SAE 4340	Steel	Steel
Diffuser Case	Ductile Cast Iron	Aluminum	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Aluminum
Burner Liner	Hastelloy-X	Hastelloy-X	SAE 1018 Chromized	Hastelloy-X	Hastelloy-X	SAE 1018 Chromized	Hastelloy-X
Combustor Scroll	HS-188	304 SS	Ductile Cast Iron	Hastelloy-X	304 SS	Ductile Cast Iron	310 SS
Turbine Nozzle	Coated WI 52 or INC 738	INC 713	INC 713	Coated WI 52 or INC 738	INC 713	INC 713	INC 713
Turbine Rotor	Udimet 700	INC 713	INC 713	Udimet 700	INC 713	INC 713	INC 713
Turbine Shroud	INC 738	304 SS	310 SS	Coated WI 52 or INC 738	Hastelloy-X	310 SS	Hastelloy-X
Exhaust Diffuser	Coated Ductile Cast Iron or INC 738	304 SS	Ductile Cast Iron	Ductile Cast Iron	304 SS	Ductile Cast Iron	Insulated Steel
Regenerator/Recuperator	Cercor Ceramic	Cercor Ceramic	Cercor Ceramic	Cercor Ceramic	Cervit	Cercor Ceramic	Cercor Ceramic
Nozzle-Power Turbine	-	-	-	INC 738	CMR-60	INC 713	Hastelloy-X
Rotor-Power Turbine	-	-	-	INC 100	CMR-60	INC 713	INC 713
Shroud-Power Turbine	-	-	-	Coated Ductile Cast Iron or INC 738	304 SS	321 SS	Hastelloy-X
Main Housing	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron

AiResearch - AiResearch Mfg. Co. (Ref. 3-10)
GE - General Electric Co. (Ref. 3-11)
UA - United Aircraft Corp. (Ref. 3-4)
Williams - Williams Research Corp. (Ref. 3-9)

3.2.3.2 High Temperature Components

3.2.3.2.1 Turbine Wheels

In general, the temperature of the air at the turbine inlet is in the areas of 1800°F to 2000°F. For these conditions, the creep-rupture life of the materials governs the design stresses and leads to the selection of special materials for turbine wheels. It is of interest that most contractors selected Inconel 713 as the material for turbine wheels. This material has good creep-rupture strength at temperatures up to 2000°F and good oxidation resistance.

3.2.3.2.2 Combustors

Most contractors selected Hastelloy-X for the combustor liner since this material also has high strength at the temperatures encountered. An exception is AiResearch which proposes to use chromized SAE 1018 steel. This is a carbon steel with a diffusion coating of chrome for oxidation resistance. It is the AiResearch contention that the combustor operates at maximum temperatures for only short periods of time and that most of the time temperatures are relatively low. This condition allows the use of chromized SAE 1018 steel which is estimated to cost 20¢ per pound versus $5 per pound for Hastelloy-X. It should be noted that the maximum burner temperature used by AiResearch for the single-shaft regenerative turbine is 2360°F, and that for the free turbine is 2310°F. These temperatures are lower than those used by some other contractors.

3.2.3.2.3 Exhaust Diffuser

Some contractors are using low temperature insulated materials for the exhaust diffuser. However, General Electric and AiResearch use a 300-grade stainless steel.

3.2.4 Summary of Estimated Costs

3.2.4.1 Introduction

Cost data presented in this section are based upon information contained in the automotive gas turbine studies conducted by United Aircraft, Williams Research, AiResearch, and General Electric (Refs. 3-4, 3-9, 3-10, 3-11 respectively).

Manufacturing and consumer retail costs for four basic types of automotive gas turbine engines have been examined. These included the simple cycle-single shaft, the simple cycle-free turbine, the single shaft with regenerator and the free turbine with regenerator. Where applicable, comparisons have also been made between costs associated with the conventional V-8 piston engine vehicle and the gas turbine-powered vehicle.

3.2.4.2 Pricing Techniques

Examination of the pricing techniques employed by each of the reference contractors revealed that rather widely varying procedures were employed in arriving at both the direct manufacturing cost and the retail price to the consumer. This frequently resulted in the anomalous situation of engine A having a lower manufacturing cost but a higher retail cost than engine B.

The pricing techniques used by each contractor have been summarized in Table 3-6. It will be noted that AiResearch is the only one of the four to apply an overhead burden on the direct manufacturing labor charge. The net effect of this is to add approximately $58 to the manufacturing cost of the regenerated free turbine and $27 to the regenerated single-shaft turbine. Retail prices are seen to vary from 1.728 to 3.47 times the direct manufacturing cost. The reasons for this, of course, stem from the fact that actual pricing structures within the automotive industry are highly proprietary and, as a result, numerous assumptions had to be made.

Table 3-6. Pricing Techniques of EPA Study Contractors

Contractor	Manufacturing Cost	Retail Price
AiResearch Mfg Co.	Direct Labor = \$ 4.40/hr Fringe Benefits = 1.60/hr Mfg Overhead = 4.00/hr Total Mfg Labor = \$10.00/hr Mfrd Mat'l = \$/lb Purch. Mat'l = Vendor OEM*	1.2 × Factory Cost = Distributor Cost 1.2 × Distr. Cost = Dealer Cost 1.2 × Dealer Cost = Consumer List 1.728 × Factory Cost = Consumer List Consumer Price = Consumer List + Sales Tax (4%) + Shipping (\$156.00) + Advertising (\$20.00) Consumer Price = Factory Cost × (1.728)(1.04) + \$176.00
General Electric Co.	Direct Labor = \$ 5.00/hr Mfg Mat'l = \$/lb Purch. Mat'l = Vendor OEM	Manufacturing Overhead = 20% Manufacturer's G&A Expense = 20% Manufacturer's Profit = 13% Dealer Markup = 23% Consumer Cost = 1.2 × 1.2 × 1.13 × 1.23 = 2.0 × Factory Cost
United Aircraft Corp.	Direct Labor = \$ 4.00/hr Mfg Mat'l = \$/lb Purch. Mat'l = Vendor OEM	Direct Mfg Cost + 130% = Dealer Cost Dealer Cost + 23% = Sticker Price Consumer Price = Sticker Price - 10% Consumer Price = $(1 + 1.3)(\frac{1}{1-0.23})(1-0.1)$ = 2.7 × Mfg Cost
Williams Research Corp.	Direct Labor = \$ 4.00/hr Mfg Mat'l = \$/lb Purch. Mat'l = Factored* Vendor OEM *Labor & Mat'l = 0.41 × OEM Mat'l:Labor ratio = 80:20	Direct Mfg Cost × 2.0 = Transfer Price Transfer Price × 1.2 = Distr. Price Distr. Price × 1.2 = Dealer Cost Dealer Cost × 1.2 = Retail Price Retail Price = 3.47 × Mfg Cost

*OEM - Original Equipment Manufacturer

3.2.4.3 Basic Engine Costs

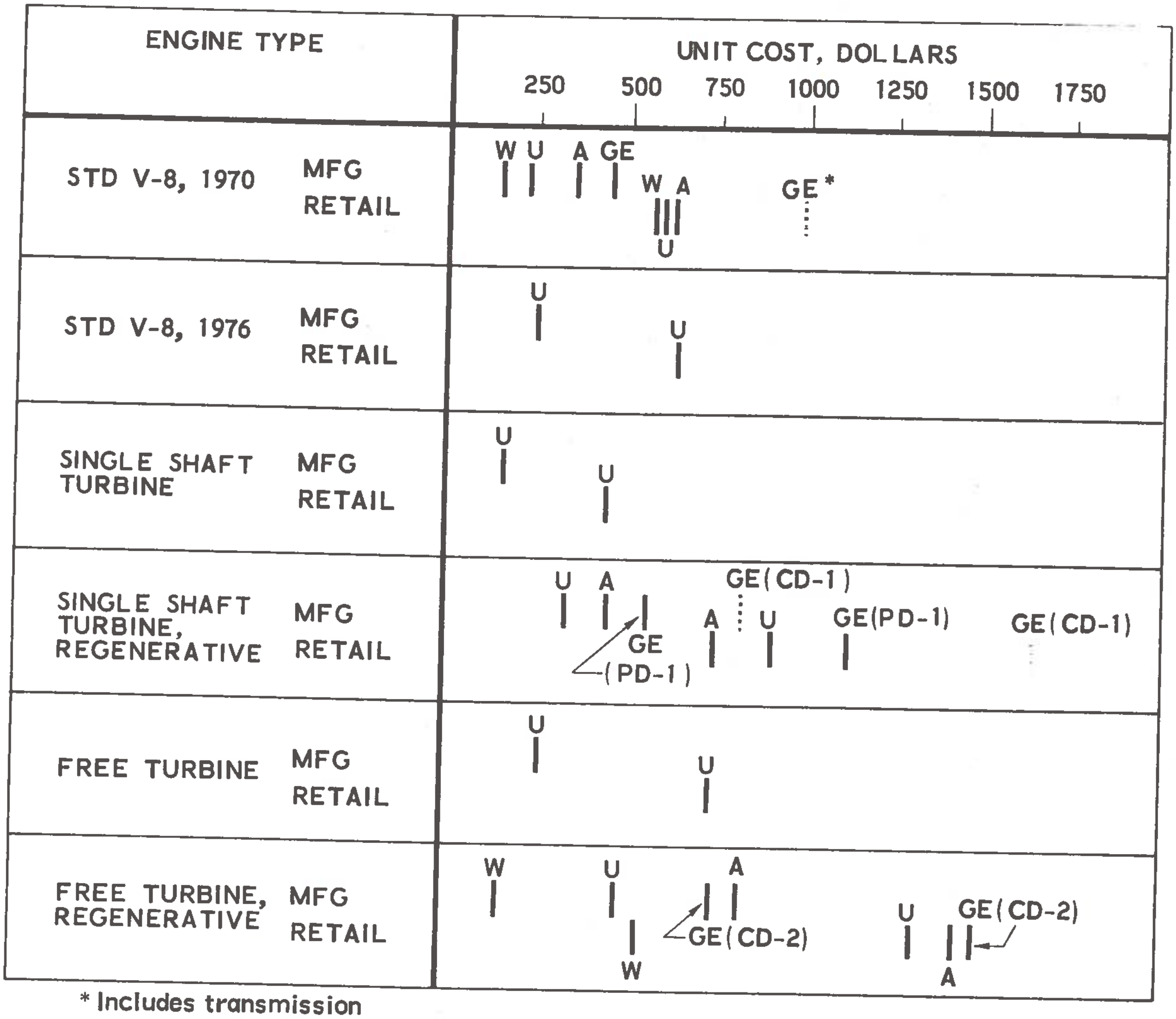
Manufacturing and retail cost estimates for each of the four gas turbine engines are shown in Figure 3-3. As illustrated in Table 3-6, AiResearch adds sales tax, shipping, and advertising costs to the consumer list price to arrive at the consumer cost. However, in the basic engine cost data being presented, for purposes of commonality with other estimates, the added costs have not been included in the AiResearch consumer list price.

It will be noted that two prices are shown for the General Electric single-shaft regenerated engine. The CD-1 is the conceptual design engine while the PD-1 is a refined, preliminary design engine. Technical differences between the two are discussed in Section 2.1 and are not to be presented here. Essentially, cost reductions were achieved through the replacement of nodular iron castings with diecast aluminum. Regenerator core costs were also reduced by $10.

The reasons for the relatively low costs indicated by Williams Research for the regenerated free turbine are not known.

As an additional piece of information, it is of interest to note, that, although Chrysler was unable to provide an accurate cost figure for mass-produced gas turbines, because of uncertainties in the cost of precision castings and the regenerator, its opinion is that a manufacturing cost of $250 is a reasonable goal at this time. This figure was arrived at by assuming that the material cost was 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 piston engine are also shown. It should be pointed out that the 1970 piston engine costs include controls and engine-mounted accessories. In the case of General Electric, the cost of the engine and transmission was reported as a single value; hence, its engine price includes the transmission while the others do not. In the case of the 1976 piston engine, United Aircraft includes accessories in the basic engine cost.



* Includes transmission

A	AiResearch Mfg Co.
GE	General Electric Co.
U	United Aircraft Corp
W	Williams Research Corp
CD-1, CD-2	Conceptual design
PD-1	Preliminary design

Figure 3-3. Engine Manufacturing and Retail Cost Estimates

As a matter of general interest, Ford built six passenger car turbine engines in the 1964/67 period. At that time, the manufacturing cost of this 706 series gas turbine engine was of the order of three times that of the Ford 428 CID piston engine. The cost difference was attributed primarily to the use of high-temperature alloys and to the type of machining operations required for the gas turbine engine.

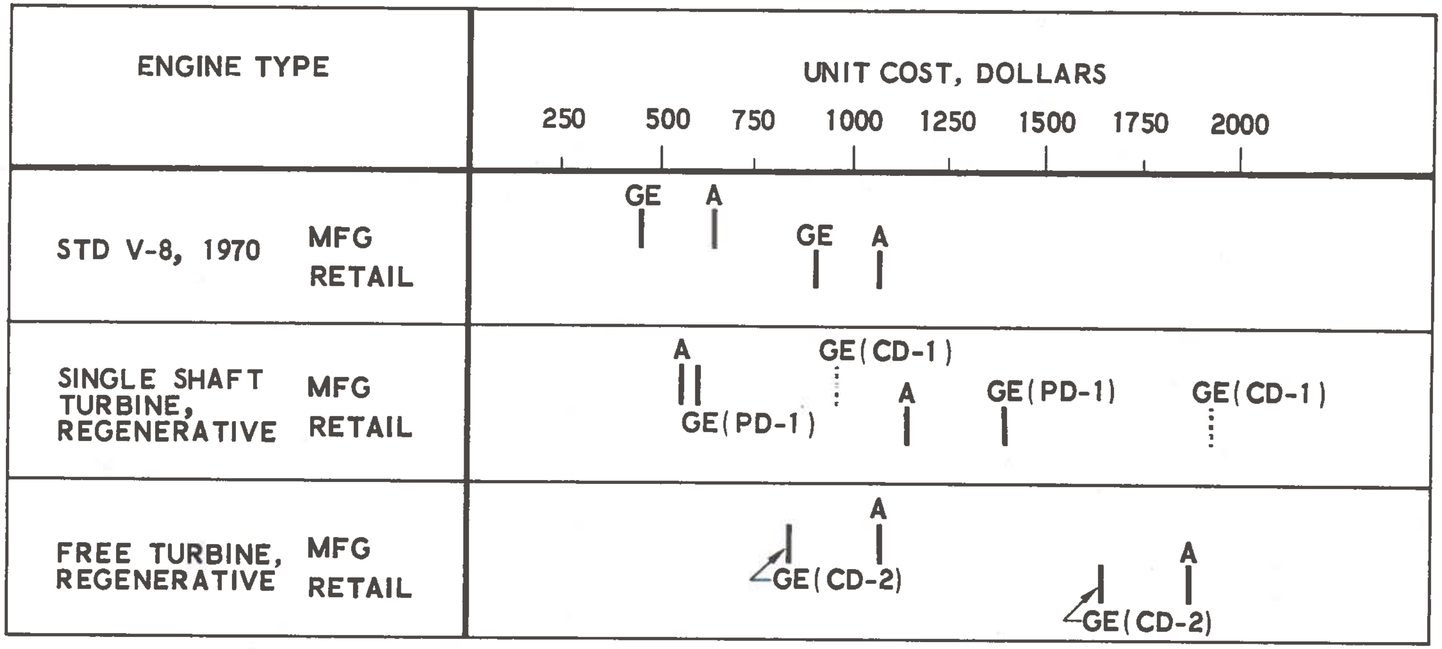
3.2.4.4 Transmission Costs

Transmission cost estimates were not reported separately for each of the four gas turbine engine types. United Aircraft, for example, because their pricing structure was based on engine/vehicle weights, did not separately cost out the transmission but rather included it in the cost of the residual vehicle which includes drive line, body, tires, etc. As previously mentioned, General Electric quoted a combined price for the engine and transmission.

The cost of the engine/transmission combinations for which data are available is shown in Figure 3-4 as reported by general Electric and AiResearch. As was the case with basic engine cost, a considerable spread is evident in the cost figures available.

3.2.4.5 Total Vehicle Costs

Total vehicle cost estimates are summarized in Table 3-7 and shown graphically in Figure 3-5. Here, the combined effect of any uncertainties in estimates of mass production costs for gas turbine engines, the variations in overhead estimates, and the mark-up used to arrive at a consumer cost (see Section 3.2.3.2) are evident. For example, the 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



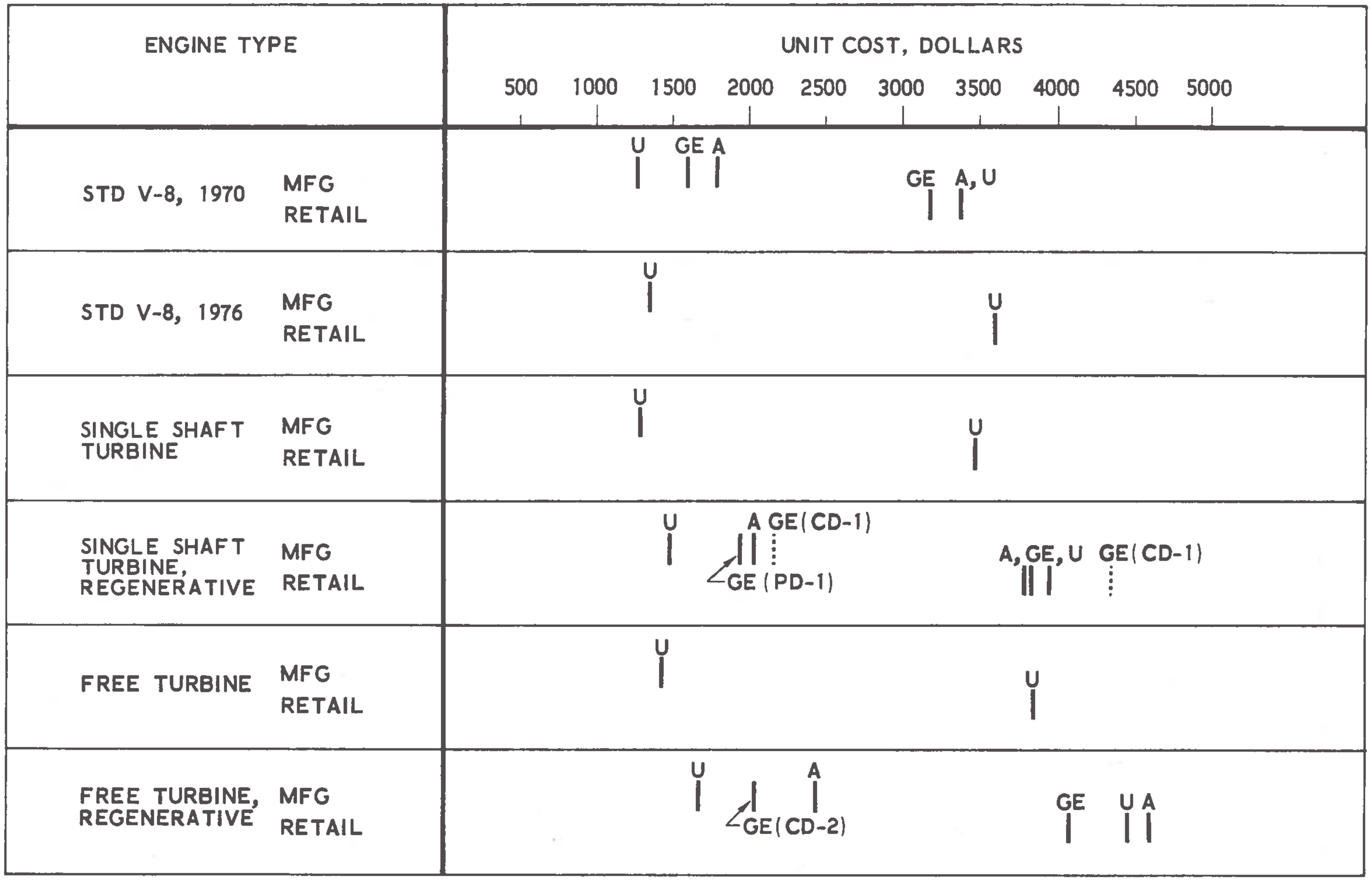
A AiResearch Mfg Co.
GE General Electric Co.
CD-1, CD-2 Conceptual design
PD-1 Preliminary design

Figure 3-4. Engine Plus Transmission Manufacturing and Retail Cost Estimates

Table 3-7. Manufacturing and Consumer Cost Estimates

Component	Engine	Controls	Accessories	Transmission	Drive Line, Body, etc. (Residual Vehicle)	Total Mfg. Cost	Cost to Consumer	Remarks
1970 OC Engine with Automatic Transmission								
AiResearch	$356	-	-	$267	$1157	$1780	$3185	C&A included in engine cost
United Aircraft	220	-	-	-	1030	1250	3374	C&A included in engine cost Transmission included in vehicle cost
General Electric	450	-	-	-	1142	1592	3185	C&A and transmission included in engine cost
Williams Research	166	-	-	NR	NR	NR	NR	C&A included in engine cost
1976 OC Engine with Automatic Transmission								
United Aircraft	239	37	-	-	1055	1331	3595	Transmission included in vehicle cost Accessories included in engine cost
Single Shaft								
United Aircraft	158	75	43	-	1007	1283	3460	Transmission included in vehicle cost
Free Turbine								
United Aircraft	271	112	43	-	993	1419	3830	Transmission included in vehicle cost
Single Shaft, Regenerated								
AiResearch	429	137	61	233	1150	2010	3788	
United Aircraft	334	75	43	-	1007	1459	3920	Transmission included in vehicle cost
General Electric (PD-1)	558	50	22	140	1142	1912	3825	
General Electric (CD-1)	817	50	22	140	1142	2172	4344	
Free Turbine, Regenerated								
AiResearch	820	161	61	267	1150	2458	4595	
United Aircraft	483	110	43	-	1007	1643	4440	Transmission included in vehicle cost
General Electric (CD-2)	739	50	22	84	1142	2037	4074	
Williams Research	151	38	31	NR	NR	NR	NR	

C&A Controls and accessories
CD-1, 2 Conceptual design
PD-1 Preliminary design
NR Not reported
OC Otto cycle



A	AiResearch Mfg Co.
GE	General Electric Co.
U	United Aircraft Corp
CD-1, CD-2	Conceptual design
PD-1	Preliminary design

Figure 3-5. Total Vehicle Manufacturing and Retail Cost Estimates

for a manufacturer to arrive at an accurate estimate of engine costs. Because of differing distributions between labor and material costs for the engine and for the entire vehicle, the ratio of retail price to manufacturing cost differs somewhat from that seen in Figure 3-3.

3.2.4.6 Major Component Costs

An attempt has been made to evaluate the cost of most of the components of the gas turbine engine system. However, because of the varying degree to which costs were detailed by the contractors, a certain amount of caution should be exercised in making a direct comparison between various types of engines or between contractors' estimates for the same type of engine. They are, however, indicative of the trends between the various engines and constitute 60 to 90 percent of the total component and hardware costs, including controls and accessories.

The major component costs are summarized in Table 3-8. Both the manufacturing costs as well as the retail, or consumer prices, are given, with the retail price calculated in accordance with the mark-up procedures used by each contractor as delineated in Table 3-6.

The least expensive component is seen to be the compressor impeller, with a manufacturing cost ranging from $5 to $24, which represents 0.6 to 3.8 percent of the total cost. Turbine wheels and nozzles, by comparison, are seen to constitute approximately 11 percent of the cost of both the single shaft and free turbine (without regenerator) and 16 to 20 percent of the cost of the regenerated engines.

The cost of castings includes all major castings except the regenerator housings which are, wherever possible, included in the regenerator costs.

While it has been estimated that metal regenerators are cheaper than ceramic regenerators for low production quantities, the reverse is felt to be true for high production quantities. Breakthroughs in production processes may provide some revision to these estimates.

Table 3-8. Major Component Cost Estimates

Component	Single Shaft		Free Turbine		Single Shaft, Regenerated						Free Turbine, Regenerated					
	United Aircraft		United Aircraft		AiResearch		United Aircraft		General Electric		AiResearch		United Aircraft		General Electric	
	Mfg	Retail	Mfg	Retail	Mfg	Retail	Mfg	Retail	Mfg	Retail	Mfg	Retail	Mfg	Retail	Mfg	Retail
Turbine Wheels	$ 10.50	$ 28.35	$ 27.52	$ 74.29	$ 40.20	$ 69.47	$ 12.29	$ 33.19	$ 41.25	$ 82.50	$ 72.70	$ 125.63	$ 38.59	$ 104.20	$ 49.62	$ 99.24
Turbine Nozzles	20.10	54.27	42.73	115.38	21.20	36.63	21.72	58.64	51.00	102.00	102.50	177.12	89.12	240.63	NSI	NSI
Total - Wheels & Nozzles	$ 30.60	$ 82.62	$ 70.25	$ 189.67	$ 61.40	$ 106.10	$ 34.01	$ 91.83	$ 92.25	$ 184.50	$ 175.20	$ 302.75	$127.71	$ 344.83	-	-
Compressor Impeller	9.27	25.03	9.27	25.03	4.80	8.29	8.79	23.74	23.75	47.50	6.50	11.23	9.11	24.60	12.06	24.12
Regenerator, including Core, Housing, and Drive Motor	-	-	-	-	82.80	143.08	118.30	319.41	82.11	164.22	82.15	141.96	150.10	405.27	NSI	NSI
Regenerator Core	-	-	-	-	30.00	51.84	NSI	NSI	60.00	120.00	37.00	63.94	37.00	99.90	70.00	140.00
Casings	40.53	109.43	82.62	223.06	163.65	282.79	92.73	250.36	90.58	181.16	166.50	287.71	99.51	268.69	142.28	284.56
Controls	75.00	202.50	112.00	302.40	137.00	236.74	75.00	202.50	50.00	100.00	161.00	278.21	110.00	297.00	50.00	100.00
Accessories	43.00	116.10	43.00	116.10	61.00	105.41	43.00	116.10	22.00	44.00	61.00	105.41	43.00	116.10	22.00	44.00
Other Expensive Parts" (Inconel and Hastelloy-X)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	169.45	338.90
Miscellaneous	22.21	59.97	35.02	94.55	41.40	71.54	15.72	42.43	NSI	NSI	61.00	105.41	26.62	71.86	NSI	NSI
Total, Components	$220.61	$595.65	$352.16	$ 950.83	$552.05	$ 953.94	$387.55	$1046.39	$360.69	$ 721.38	$ 713.35	$1232.67	$566.05	$1528.34	$515.41	$1030.82
Total, Engine and C&A	276.00	745.20	426.00	1150.20	627.00	1083.46	452.00	1220.40	630.00	1260.00	1042.00	1800.58	636.00	-	811.00	1622.00
Components, Percent of Total	79.9	-	82.7	-	88.0	-	85.7	-	57.3	-	67.7	-	89.0	-	63.6	-

C&A Controls and accessories

NSI Not separately identified

Engine control system costs vary considerably, due apparently to the differing degrees to which cost details were provided. On the single-shaft regenerated engine, for example, manufacturing costs for this element ranged from 8 to 22 percent while on the generally more expensive free turbine regenerated engine, they ranged from 6 to 17 percent.

3.2.4.7 Operating Costs

Lifetime operating costs were developed by each of the 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. Component costs included 100 percent depreciation of the automobile less salvage allowance for expensive materials, estimated repairs and maintenance costs over the life of the vehicle, fuel costs based on the average fuel consumption calculated over the composite driving cycle, and such vehicle related costs as tires, insurance, garaging, parking, and taxes (excluding fuel).

With regard to major maintenance and repair costs requirements over the life of the vehicle, an example of the comparison with a piston engine automobile service schedule is provided in Tables 3-9 and 3-10, taken from the AiResearch final study report (Ref. 3-10). Engine-related repairs are different in nature, but are shown to occur at about the same frequency among the aggregate of service or repair items for both engine types. Primarily due to yearly tune-ups and a valve and ring job assigned to the piston engine, AiResearch concluded that repair and service costs for the gas turbine car would range from 50 to 60 percent of the costs for a piston engine car, considering a 7-year, 105,000-mile lifetime for both vehicles. (While these results are based on a 7-year lifetime, other contractors elected to use a 10-year lifetime.)

For the same reasons, United Aircraft concluded that the repair and maintenance costs for the gas turbine car would appear very attractive when compared with the costs for conventional vehicles. It assumes that

Table 3-9. Repair and Maintenance Cost Estimates for 105,000 Miles, 7-year life, 1970 V-8 Spark-Ignition Engine and Vehicle (Ref. 3-10)

Maintenance or Repair Item	Average Interval, (mi or yr)	Average Cost for Each Repair or Service, (Dollars)	Years in Which Repair or Maintenance Required	Cost/Year, Dollars							Seven Year Totals (dollars)
				First Year	Second Year	Third Year	Fourth Year	Fifth Year	Sixth Year	Seventh Year	
Front end alignment	20,000	12.00	2, 3, 4, 6, 7	--	12.00	12.00	12.00	--	12.00	12.00	
Engine tune-up	20,000	40.00	2, 3, 4, 6, 7	--	40.00	40.00	40.00	--	40.00	40.00	
Transmission service	24,000	26.00	2, 4, 5, 7	--	26.00	--	26.00	26.00	--	26.00	
Flush and fill radiator	2 yr	15.00	2, 4, 6	--	15.00	--	15.00	--	15.00	--	
Reline brakes	30,000	50.00	2, 4, 6	--	50.00	--	50.00	--	50.00	--	
Replace radiator hose	3 yr	5.00	3, 6	--	--	5.00	--	--	5.00	--	
Replace water pump	40,000	24.00	3, 6	--	--	24.00	--	--	24.00	--	
Replace battery	3 yr	30.000	3, 6	--	--	30.00	--	--	30.00	--	
Grind valves and replace rings	60,000 - 80,000	250.00	5	--	--	--	--	250.00	--	--	
Starter brushes and commutator	50,000	15.00	4	--	--	--	15.00	--	--	--	
Replace alternator	60,000	30.00	4	--	--	--	30.00	--	--	--	
Maintenance yearly	15,000	69.50	1, 7	69.50	69.50	69.50	69.50	69.50	69.50	69.50	
Miscellaneous (alternator belt, wiper)	15,000	--	1, 7	3.50	6.00	10.00	12.00	12.00	10.00	10.00	
TOTALS (dollars)				73.00	218.50	190.50	269.50	357.50	255.50	157.50	1522.00

the average service station would not be capable of working on the gas turbine engine, but that a facility similar to an automatic transmission repair and maintenance service, using specialized equipment, would be required.

Because of fewer moving parts, reduced vibration levels, a simplified ignition system, the elimination of the engine cooling system, and no add-on emission control devices, Williams Research reasoned that the cost of these repairs would favor the turbine engine.

In a review of the analyses conducted by the EPA contractors, it was found that operating costs were not reported on the same basis. For example, assumed fuel costs were found to range from 31¢ to 36¢ per gallon, residual vehicle costs were frequently included as part of the engine-related costs, and transmission costs were either included in the engine depreciation cost, the vehicle depreciation cost or not reported at all.

Table 3-10. Repair and Maintenance Cost Estimates for Gas Turbine Powered Automobiles, 105,000 Miles, 7-Year Life (Ref. 3-10)

Maintenance or Repair Item	Average Interval, (mi or yr)	Average Cost for Each Repair or Service (Dollars)	Years In Which Repair or Maintenance Required	Cost/Year (Dollars)							Seven Year Totals, (dollars)
				First Year	Second Year	Third Year	Fourth Year	Fifth Year	Sixth Year	Seventh Year	
Front End Alignment	20,000	12.00	2, 3, 4, 6, 7	--	12.00	12.00	12.00	--	12.00	12.00	
Reline Brakes	30,000	50.00	2, 4, 6	--	50.00	--	50.00	--	50.00	--	
Battery	3 yr	30.00	3, 6	--	--	30.00	--	--	30.00	--	
Starter Brushes and Commutator	50,000	15.00	4	--	--	--	15.00	--	--	--	
Alternator	60,000	30.00	4	--	--	--	30.00	--	--	--	
Ignition Coil, Lead and Ignitor	55,000	15.00	4	--	--	--	15.00	--	--	--	
(1) (2) (3) Transmission Fluid	55,000	4.50	4	--	--	--	(1) (2) (3) 4.50	--	--	--	
(2) (3) Transmission Belt	25,000	12.50	2, 4, 5, 7	--	(2) (3) 12.50	--	(2) (3) 12.50	(2) (3) 12.50	--	(2) (3) 12.50	
(1) (2) (4) Regenerator Seals	55,000	27.50	4	--	--		(1) (2) (4) 27.50	--	--	--	
(1) (2) (3) Water Hose	3 yr	5.00	3, 6	--	--	(1) (2) (3) 5.00	--	--	(1) (2) (3) 5.00	--	
Transmission Service (4)	24,000	26.00	2, 4, 5, 7	--	(4) 26.00	--	(4) 26.00	(4) 26.00	--	(4) 26.00	
Maintenance Yearly	15,000	52.00	1, 7	52.00	52.00	52.00	52.00	52.00	52.00	52.00	
Miscellaneous (Alternator Belt, Wiper Blades, etc.)	15,000	--	1, 7	3.50	6.00	10.00	12.00	12.00	10.00	10.00	
TOTALS (DOLLARS)											
(1) Single-Shaft, Regenerated, Water Injection, Traction Transmission				57.50	120.00	109.00	218.00	64.00	159.00	74.00	801.50
(2) Single-Shaft, Regenerated, Water Injection, Belt Transmission				57.50	132.50	109.00	230.50	76.50	159.00	86.50	851.50
(3) Single-Shaft, Recuperated, Water Injection, Belt Transmission				57.50	132.50	109.00	203.00	76.50	159.00	86.50	824.00
(4) Free-Turbine, Regenerated, Three-Speed Automatic Transmission				57.50	146.00	104.00	239.50	90.50	154.00	100.00	891.00

Therefore, in order to provide a common baseline for comparison, certain arbitrary assumptions and reallocations of specific operating costs were applied to the cost data as reported. A basic ground-rule adopted was to utilize existing cost estimates where no basis for projecting costs to the future was available. The assumptions made were as follows:

1. Gasoline was priced at 35¢ per gallon. This is consistent with prices quoted in the Oil and Gas Journal of February 5, 1973.

2. From this selection, the price of fuel for the gas turbine engine was set at 33¢ per gallon on the basis of statements by both AiResearch (Ref. 3-10) and United Aircraft (Ref. 3-4) that a 2¢-per-gallon price differential exists between gasoline and JP fuel.

3. All fuel costs were based on 105,000 miles using the reported fuel consumption for each engine. In this regard, it should be pointed out that the fuel consumption data in miles per gallon for each engine have been tabulated in the event it is desired to use different fuel prices.

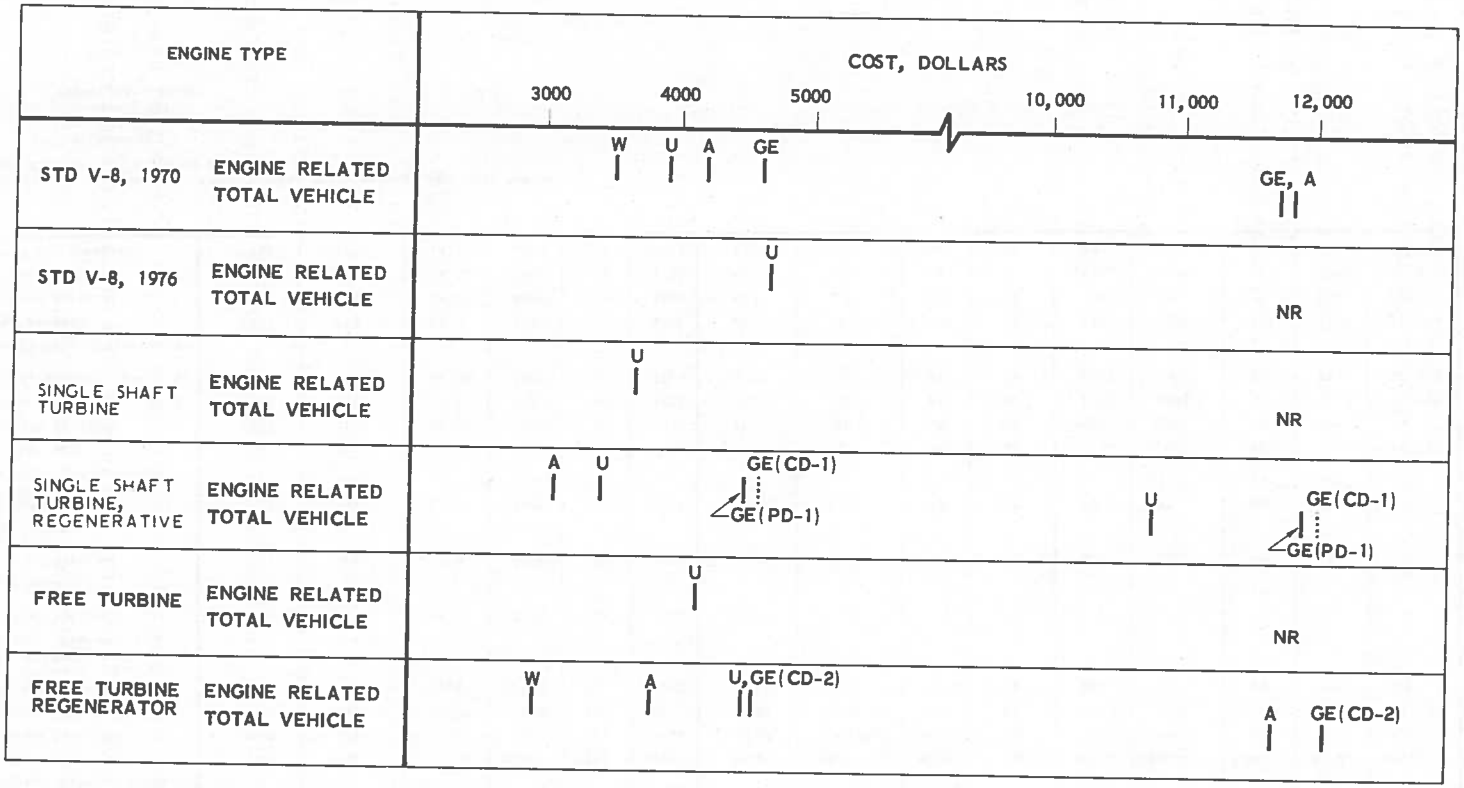
4. Operating costs have been broken down between engine-related costs and vehicle-related costs since many of the vehicle costs were not always reported and the resulting totals were not comparable.

5. Transmission repair and depreciation costs should be included in the engine-related costs. However, United Aircraft included the cost of the transmission in the residual vehicle and did not separately identify the transmission costs while Williams Research did not include transmission or residual vehicle costs at all. Therefore, the arbitrary decision was made to include the transmission in the vehicle-related costs so that all engine-related costs could be shown on the same basis. The only exception is the General Electric engine depreciation cost shown for the 1970 V-8 engine. In this case, the engine and transmission were priced as a single unit and transmission costs could not be separately identified.

6. Controls and engine mounted accessories have been included in the engine-related costs.

Based on the above assumptions, the calculated 105,000-mile operating costs for each engine/vehicle are shown graphically in Figure 3-6. Tabular results are shown in Table 3-11. The engine-related costs of the turbine-powered vehicles are seen to be no higher than those for a standard 1970 V-8, although an extensive spread exists in the range of costs. Examination of the elements of the engine-related costs for the turbine engines (Table 3-11) reveals that engine depreciation costs (essentially the same as the engine retail price) account for as much as $700 out of the total cost spread for the single-shaft regenerated engine, with fuel costs accounting for most of the remaining cost spread. A similar situation is found for the regenerated free turbine.

Fuel costs are seen to 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.



A	AiResearch Mfg Co.
GE	General Electric Co.
U	United Aircraft Corp
W	Williams Research Corp
CD-1, CD-2	Conceptual design
PD-1	Preliminary design
NR	Not reported

Figure 3-6. 105,000-Mile Operating Cost Estimates

Table 3-11. 105,000-Mile Operating Cost Estimates

Component	Engine Related						Vehicle Related								Total
	Net Depreci-tion	Repair and Main-tenance	MPG	Fuel	Oil	Total	Depreci-tion	Repair and Main-tenance	Tires	Acces-sories	Insur-ance	Garaging Parking	Taxes	Total	
1970 OC Engine with Automatic Transmission															
AiResearch	$ 637	$891	14.8	$2483	$158	$4169	$2548	$631	$385	NR	$1722	$1805	$557	$7648	$11,817
United Aircraft	590	494	13.8	2663	161	3908	2780	NR	NR	NR	NR	NR	NR	NR	NR
General Electric	900	961	14.38	2556	160	4577	2285	560	423	28	1722	1805	327	7150	11,727
Williams Research	634	641	16.63	2214	NR	3490	4577	NR	NR	NR	NR	NR	NR	NR	NR
1976 OC Engine with Automatic Transmission															
United Aircraft	745	820	12.5	2940	161	4666	4577								
Single Shaft															
United Aircraft	745	313	13.4	2586	40	3684	4577	NR	NR	NR	NR	NR	NR	NR	
Free Turbine															
United Aircraft	1150	441	13.4	2586	40	4177	4577	NR	NR	NR	NR	NR	NR	NR	
Single Shaft, Regenerated															
AiResearch	1083	268	20.1	1721	0	3072	4577	532	385	NR	1722	1805	557	7706	10,778
United Aircraft	1200	512	20.6	1682	40	3434	4577	NR	NR	NR	NR	NR	NR	NR	NR
General Electric (PD-1)	1245	670	13.6	2550	40	4505	4577	560	423	28	1722	1805	327	7430	11,935
General Electric (CD-1)	1737	670	16.06	2157	40	4604	4577	560	423	28	1722	1805	327	7430	12,034
Free Turbine, Regenerated															
AiResearch	1801	258	19.8	1747	0	3806	4577	632	385	NR	1722	1805	557	7895	11,701
United Aircraft	1720	720	16.8	2008	40	4488	4577	NR	NR	NR	NR	NR	NR	NR	NR
General Electric (CD-2)	1595	670	15.39	2251	40	4556	4577	560	423	28	1722	1805	327	7318	11,874
Williams Research	741	296	18.1	1914	0	2951	4577	NR	NR	NR	NR	NR	NR	NR	NR

Transmission maintenance is not included in the engine costs provided by United Aircraft and Williams Research.

NR — Not reported
OC — Otto cycle
CD-1, 2 — Conceptual design
PD-1 — Preliminary design

Vehicle-related costs, as shown in Table 3-11, are seen to vary by up to approximately $500 for the various systems. These variations are due primarily to differences in the transmission and residual vehicle costs, with only minor differences attributed to vehicle-related repair and maintenance costs.

Total operating costs (where available) are seen to be quite similar at about $11,800 for each engine type except for the single-shaft regenerated engine which was estimated at about $10,800 or about $1,000 less; this saving is essentially the result of differences in engine-related costs.

3.3 POSSIBLE TECHNIQUES FOR COST REDUCTION

The cost sensitivity to production volume was discussed previously (Section 3.2.1) and it was indicated that purchased and fabricated parts plus engine production costs are reduced appreciably as volume increases. In some cases, a tradeoff between reduction in material costs and increase in fabrication costs exists. In other cases, the reverse situation exists, i.e., reduced fabrication costs might involve higher materials costs. Some means of reducing costs by changing designs and materials are being investigated and some of these are supported by government programs as discussed in Section 4.4 of this report.

3.3.1 Compressors

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.

3.3.2 Combustors

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 requirements for this type of air/fuel mixing still exist.

3.3.3 Turbines

The NASA 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. A possible method of fabrication would be to use a brazing and machining process to permit the hub to mate with the basic wheel and then incorporate "fingers" that fill in the gaps between the base of the blades and the hub. NASA has not yet proved that high-temperature alloys can be stamped or coined and has not yet determined how such processes will change material properties.

The United Aircraft Gatorizing process is also under consideration for the production of turbine wheels; the use of high-alloy metal powder is being considered for this process. At the present time United Aircraft is developing this process for turbine blades in commercial and military aircraft applications. At the present time these blades must be individually machined. There is still a question whether turbine wheels that are "Gatorized" can be finished completely by this process or whether some machining will still be required.

3.3.4 Fuel Controls

The engine control system is generally an intricate design requiring many pieces of precision hardware because of the many inter-related sensing and control functions that must be performed accurately and simultaneously. Briefly, these include provisions for insuring, 1) smooth, uniform engine response to driver commands, 2) safe, reliable operation, 3) good fuel economy, and 4) low exhaust emissions. The need for component compactness and accuracy requires precision fabrication, careful calibration, and thorough inspection in an extensive quality control program. It is these factors that increase labor time in manufacture and result in a high unit cost for mechanical, hydraulic or electronic elements of the system. The evolution of design simplicity (offering the prospect of less parts) and the introduction of automation to both fabrication and inspection should aid in reducing unit costs.

By way of example, the cost of a fuel control system for aircraft engines is estimated to be 25 to 30 percent of the total engine cost. To reduce this 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 10. It provides higher loop gain control and more stable operation than the original system. The system senses compressor inlet and outlet pressures and shaft speed; these variables are fed back into the control system. (It should be noted that for automotive gas turbine engines, regenerator or recuperator temperatures may also have to be sensed.)

3.3.5 Ceramic Components

3.3.5.1 Development Programs

Development of ceramic components could offer both cost reduction and performance improvement. Because of high strength, 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¢ 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 15¢ to 18¢ per pound. Considering the fact that a significant portion of the total cost of a mass-produced automotive gas turbine would be in the superalloys, it becomes quite apparent that ceramics offer a potential cost advantage for these engines. However, initially not all the potential cost savings could be realized for several reasons. First, there would not be an immediate replacement market for gas turbine parts and this would tend to increase the cost of vendor-supplied materials and components. Also, more skilled labor might be required for the assembly of the delicate ceramic turbine parts and this would tend to raise unit cost.

Ford is working on a 2500°F ceramic turbine design which has the potential of increasing fuel economy and costing less than present 1900°F turbine design. Ford is also considering ceramics for other hot-flow-path components such as stators and shrouds. Work in this area has been funded by ARPA, who also funds Westinghouse Corporation's development of ceramic components for large industrial power turbines.

Norton Company is working on its own to develop ceramic components. The results have been encouraging at this time although the process is not fully developed. Production processes include hot processing by consolidation of fine particles, chemical vapor deposition by depositing solid on a heated substrate, reaction bonding by consolidation of fine particles to achieve a new compound, and sintering to consolidate fine particles by applying heat. The machining of ceramic components is also under development; the techniques being tried include laser beams, diamond grinding, ultrasonics, and electric discharge machining.

3.3.5.2 Physical Properties of Ceramic Materials

The physical properties of silicon nitride (Si_3N_4) and silicon carbide (SiC) are listed in Table 3-12 (Ref. 3-12). As indicated, the density of these materials varies between 2.4 for the reaction bonded Si_3N_4 and 3.2 for the hot-pressed Si_3N_4 and SiC materials. Although Si_3N_4 and SiC have excellent thermal shock characteristics, the modulus of elasticity and the coefficient of thermal expansion are lower for Si_3N_4 whereas the thermal conductivity is much higher for SiC.

Table 3-12. Properties of Silicon Nitride and Silicon Carbide (Ref. 3-12)

	Hot Pressed Si_3N_4	Reaction Bonded Si_3N_4	Hot Pressed SiC	Direct Bonded SiC
Density (gm/cc)	3.2	2.4	3.2	2.6
Modulus of Elasticity (psi at 25°C)	46×10^6	25×10^6	64×10^6	30×10^6
Coefficient of Thermal Expansion per °C	3.2×10^{-6}	3.2×10^{-6}	4.8×10^{-6}	4.8×10^{-6}
Thermal Conductivity (BTU/hr °F at 25°C)	10	8	47	25
Specific Heat at 25°C	0.17	0.17	0.15	0.15

Hot-pressed Si_3N_4 is formed by hot die pressing a mixture of Si_3N_4 powder and a catalyst, such as magnesium oxide, at temperatures up to 1750°F and pressures up to 5000 psi. In this approach the material is formed into high-density blocks which are subsequently machined using diamond tools. Although this process is expensive, the Si_3N_4 produced in this manner is of interest to gas turbine manufacturers because of its high strength at temperatures up to 2550°F. The effect of impurities on the strength of Si_3N_4 is depicted in Figure 3-7 (Ref. 3-12). For 1 percent impurities, the strength of Si_3N_4 at 2500°F is over 50,000 psi, and improvements might be obtained by further reducing the impurities in the materials. At lower temperatures the strength of hot-pressed Si_3N_4 increases significantly. For instance, at 1850°F the strength is about 120,000 psi.

Although lower in strength than hot-pressed Si_3N_4, reaction-bonded Si_3N_4 has great appeal because of its more versatile fabrication capabilities. This material is manufactured by compacting silicon powder into the desired shape by means of conventional powder metallurgy. The various process routes are illustrated in Figure 3-8 (Ref. 3-13). The silicon compact is then converted to Si_3N_4 by reacting it with nitrogen at temperatures up to 2640°F. If machining of the work is necessary, this is done in the "green" state by means of carbide-tipped tools prior to final nitriding. Also, components can be joined in the green state by using a flame-spraying technique.

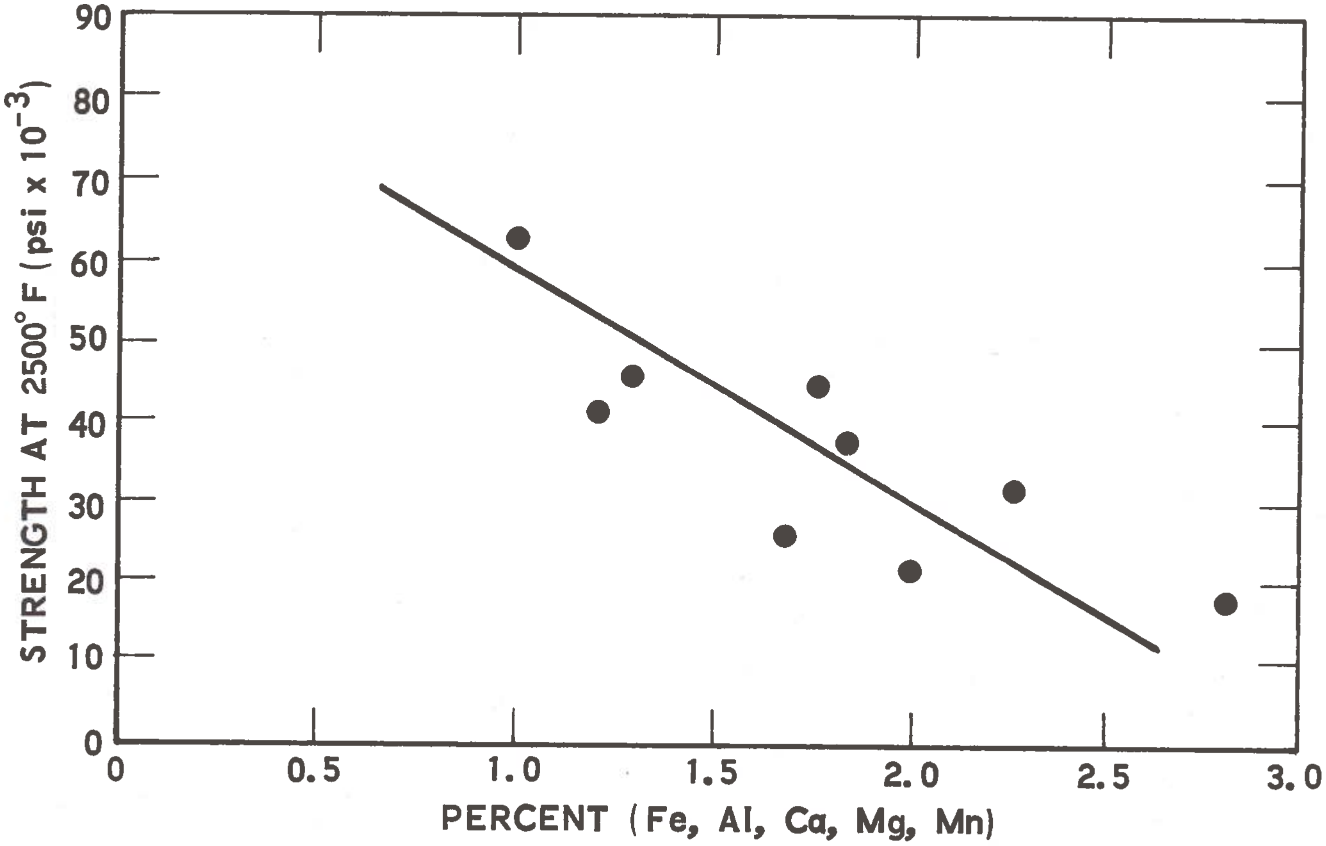


Figure 3-7. Flexural Strength of Hot-Pressed Silicon Nitride at 2500°F vs Impurities (Ref. 3-12)

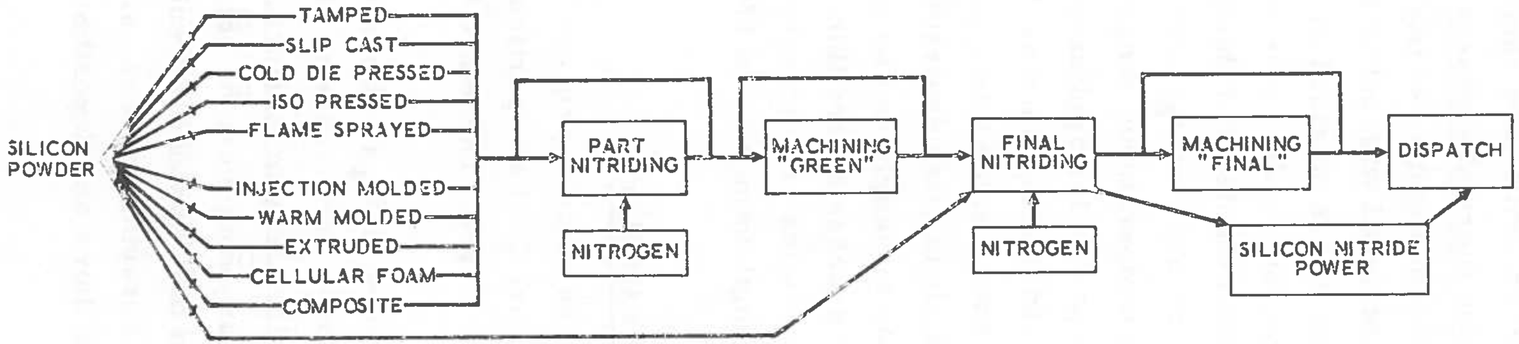


Figure 3-8. Process Routes for Turbine-Quality Silicon Nitride (Ref. 3-13)

Hot-pressed SiC is very appealing because of its excellent oxidation resistance. However, until very recently, the material was not strong enough to withstand the thermal stresses occurring in large gas turbine stators. As indicated in Figure 3-9 (Ref. 3-12), very high flexural strength has recently been achieved with hot-pressed SiC material.

Direct-bonded SiC is obtained by crushing and milling SiC (99 percent minimum purity), suspending it in water, and casting the mixture into plaster molds. When the desired thickness build-up on the walls of the mold is reached, the excess material is removed. After drying, the "green" shapes are fired to temperatures ranging between 1950°C and 2500°C, depending upon the particular application. This procedure allows fabrication of very thin-walled pieces, such as duct inserts for use in high-temperature environments. Since this type of SiC has a relatively high porosity of about 18 percent, it is often desirable to enhance its strength characteristics. This can be accomplished by means of a chemical vapor deposition process. In this process a very thin layer (0.003 to 0.030 inch) of dense, sub-micron SiC particles are deposited on the surface of the direct-bonded piece. Flexural strength values up to 170,000 psi have been achieved with this method.

3.3.5.3 Silicon Nitride Grades

A number of the various process routes used in the manufacture of turbine-quality Si_3N_4 (Figure 3-8) are particularly well suited to advanced technology applications (Ref. 3-13). These are briefly discussed in the following paragraphs.

Isostatic pressed Si_3N_4 is obtained by compacting silicon powder isostatically in a flexible membrane tooling to form a billet of uniform density. Machining of the billet may be performed in the partially nitrided "green" condition. Almost any shape can be obtained by this technique. However, this process is rather slow and not suitable for mass production.

In the flame-spraying process, silicon particles are passed through an acetylene/oxygen flame and deposited onto a tool which is shaped

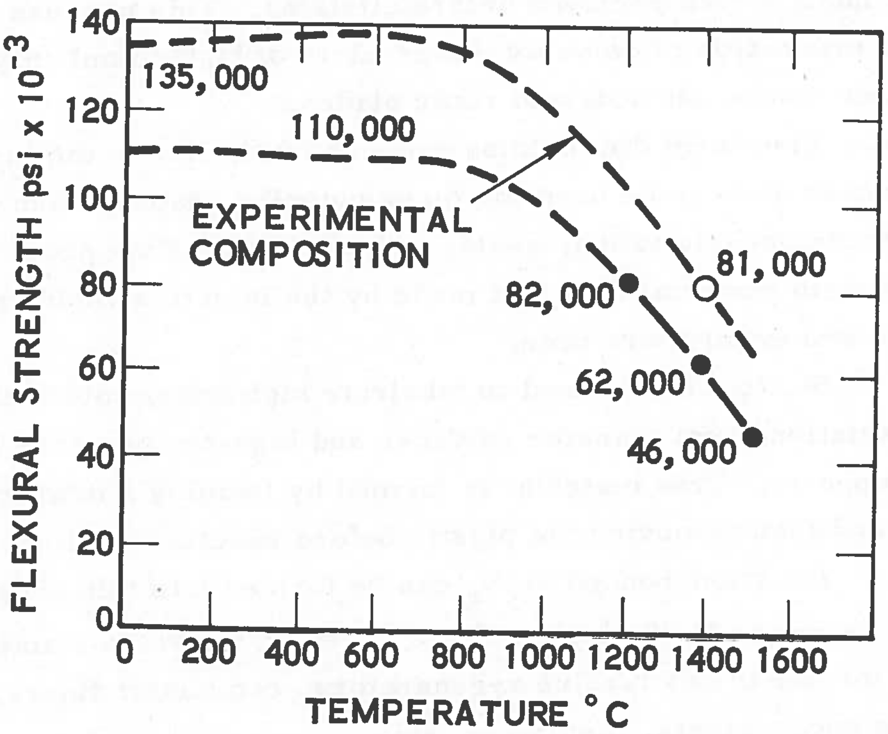


Figure 3-9. Flexural Strength of Hot-Pressed Silicon Carbide (Ref. 3-12)

to give the desired form. When the required material thickness has been reached, the "green" compact is cooled and then removed from the tool. This process is applicable to the manufacture of thin-walled components such as turbine nozzle shrouds.

Injection-molded components are manufactured by injecting a hot viscous stream of silicon combined with a plastic binder into a cooled die. The binder is then removed before nitriding. This process is applicable to the mass production of close tolerance parts of high complexity, such as turbine nozzle vanes, shrouds and rotor blades.

The warm die molding process is similar to the injection-molding process and can be used for many complex shapes, such as turbine blades, shrouds, nozzle vanes, seals, and bearings. This process makes a higher strength material than that made by the injection-molding process but requires somewhat more time.

Si_3N_4 foam is used to fabricate high-temperature thermal and acoustic insulation, heat transfer surfaces and high-temperature lightweight structure supports. This material is formed by foaming a mixture of silicon and plastic and then removing the plastic before reaction bonding.

Reaction-bonded Si_3N_4 can be formed into thin sheets having a thickness as low as 0.004 inch. These sheets can then be stamped and corrugated for use in gas turbine regenerators, combustor liners, high-temperature encasements, insulation, etc.

3.3.6 Transmissions

The key to use of a low-cost single-shaft turbine is the development of a low-cost infinitely variable speed transmission. A transmission under development by Tracor Company that uses a traction-drive principle shows promise. Other transmissions suitable for potential use with single-shaft turbine engines are discussed in Section 2.2.

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SECTION 4

SECTION 4

PRODUCT DEVELOPMENT PROGRAMS AND SCHEDULES

4.0 INTRODUCTION

If the gas turbine automobile is eventually introduced to the American market, it will be accomplished on a gradual basis, 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 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 of the report will treat the status of industry progress in gas turbine technology and production development, the potential for converting this experience into development of gas turbine automotive systems, and the prospects for implementing mass production of the gas-turbine car in a near-term time frame. Steps and activities comprising the product development cycle for conventional piston-engine-powered automobiles will be reviewed first in order to provide a vantage point for better understanding of the issues involved in scheduling the development and production of gas turbine automobiles.

4.1 AUTOMOTIVE PRODUCT DEVELOPMENT CYCLE

4.1.1 Fundamental Definitions

It is useful at the outset to define several terms that will be employed in the discussion that follows: product development lead time, car line production program, and production lead time.

- Product Development Lead Time: 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 model-year production run of automobiles to come off the assembly line.

- Car Line Production Program: that part of the product development cycle involving the design of the production prototype vehicle and the development and implementation of the mass production manufacturing process for a given car model.
- Production Lead time: the time reserved by the automobile manufacturer to (a) detail the product configuration for mass manufacture; (b) analyze the manufacturing processes; (c) design or plan the equipment and facilities needed to perform these processes; (d) erect facilities and construct, install, and check out the production equipment; and (e) escalate the manufacturing process to full-volume output.

The production lead time activities may consume 95 percent of the resources spent in a car development program. The following overview of the product development cycle will serve to provide a suitable framework within which these and other car-program activities may be examined in detail.

4.1.2 Product Development Cycle Overview

For purposes of this discussion the automotive product development cycle should not be viewed in terms of the action required to produce any given model in any given year. In the aggregate of products offered by the manufacturer, one or more car lines may undergo substantial changes in the design of functional systems or body structure. In other lines, which do not undergo major modifications, a substantial percentage of component parts may be newly designed. Regardless of the degree of change from the previous model, however, car development proceeds according to a planned cycle of events that is common to all lines being introduced into production.

A representative product development cycle may be considered to consist of eight different phases:

- Research and Advanced Development
- Product Conceptualization
- Car Concept Development/Preliminary Design
- Car Program Approval
- Production Engineering/Car Prototype Testing
- Parts Procurement/Tool Construction, Installation, and Tryout
- Pilot Assembly
- Production Buildup

The timing and typical duration of these phases are illustrated in Figure 4-1. It is noted that the data shown are broadly representative of practice throughout the automotive industry; however, specific details in any given manufacturer's schedule may differ considerably from these values.

Referring to Figure 4-1, the schedule for Research and Advanced Development is unbounded because of the broad range of possible options associated with new invention activity. This phase, though not strictly part of a car-development program, is an essential prerequisite to the introduction of new functional components or features in a vehicle. Some items may undergo Research and Advanced Development lasting for 5 to 10 years or more.

Excluding Research and Advanced Development, the overall product development cycle has a duration of approximately 48 months. The milestone marker shown in the chart identifies the Production Lead Time reference point, representing 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; historical data from individual manufacturers indicate a range from 24 to 28 months (Ref. 4-1).

Details of the individual phases of the product development cycle are presented in the following paragraphs and in Table 4-1, which shows typical phase activities and significant schedule milestones.

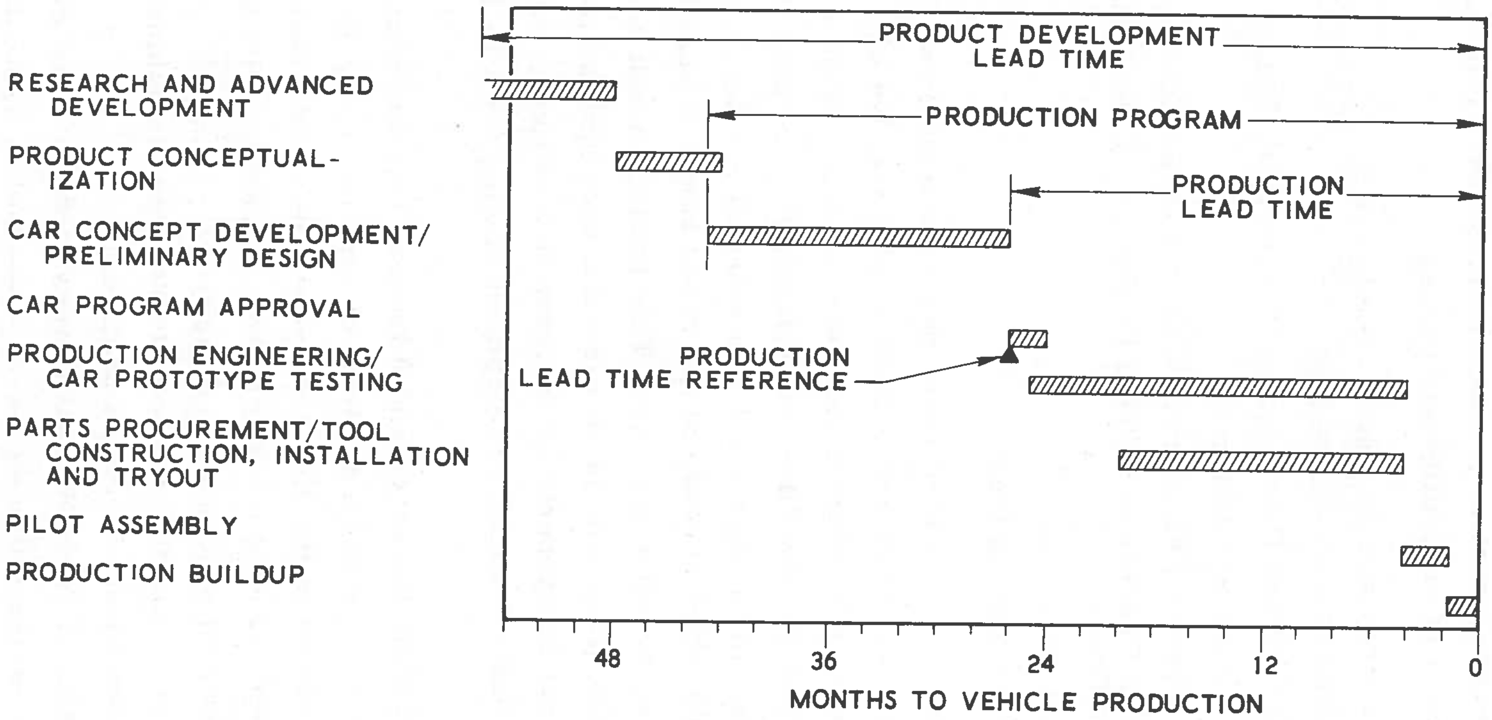

Figure 4-1. Automotive Product Development Phases

Table 4-1. Phase Activities and Significant Milestones

Phase	Typical Activities	Significant Milestones
Research and Advanced Development	Invention Proof-of-Principle Testing Research Prototype Testing	Research Hardware Build Feasibility Demonstration
Product Conceptualization	Options Identification Alternative Design Evaluation	Tentative Car Line Proposal Definition
Car Concept Development/ Preliminary Design	Car Line Proposal Reviews Cost/Producibility Studies Interface/Interaction Studies Car Systems Selection Mechanical Prototype Design	Car Plan Selection Long Lead Time Facilities Commitment
Car Program Approval	Commitment of Program Resources	Production Design Preliminary Approval
Production Engineering/Car Prototype Testing	Mfg Process Analysis & Decisions Tooling Design & Commitment Detail Drawings & Release Systems/Vehicle Testing	Tooling & Facilities Approval Clay Model Approval Drawing Release EPA Certification Tests
Parts Procurement/ Tool Construction, Installation, and Tryout	Make/Procure All Parts Install & Test Production Equipment	Parts/Equipment Contracts Complete Tool Tryout Build/Submit Last Samples
Pilot Assembly	Volume Test Production Process	Start Pilot Part Program
Production Buildup	Accelerate Operations to Full Rate	Full Component Production Start Vehicle Production

4.1.3 Product Development Phases

4.1.3.1 Research and Advanced Development

Normally, every major automotive innovation undergoes a period of research, experimental development, and testing before being introduced to production. As mentioned earlier, the Research and Advanced Development phase can precede a car development program by 5 to 10 years or more. For example, the energy-absorbing, or collapsible, steering column underwent a 6-year period of research and development before being put into a production program (Ref. 4-1).

In this initial phase, the new device or invention is subjected to a variety of basic proof-of-principle tests, followed by experimental prototype development and demonstration tests. The experimental prototype incorporates the functional features of the new invention in a (hand-built) preliminary-concept version of the production hardware configuration. The platform adapted for test purposes usually consists of an existing vehicle, modified as required to accommodate the new device at its interfaces with other vehicle components. The test program may continue for an indefinite period; several designs or design modifications may evolve before a suitable configuration is achieved. At this point, the new device would be turned over to a car program advanced engineering group for refinement, modification into a design suitable for mass production, and additional testing.

The new device or modification is frequently introduced on a single model as a limited-production, low-volume option for a period of evaluation in customer use before being adopted for use throughout one car line or in several car lines. To cite an example of this practice, disc brakes were first introduced in the United States on the Chevrolet Corvette; they are now available as standard or optional equipment on 60 percent of the domestic automobile production (Ref. 4-2).

It is noted that the recent effort by the automotive industry with respect to the accelerated introduction of catalytic converter emission control systems on all 1975 model year vehicles is in sharp contrast with the conventional procedure described above.

4.1.3.2 Product Conceptualization

The first few months preceding initiation of a car line production program is spent in styling, engineering, and product-planning activities which explore the alternative approaches to the design of the new model. The factors shaping the selection of these alternatives include the status of research and advanced development projects, manufacturing costs, competitive pressures, and the projected market for the features and options under consideration. Potential modifications and improvements are delineated, and tentative proposals for each car line are selected from available alternatives for presentation to management. This phase may have a duration of 6 months, as indicated in Figure 4-1.

It should be noted that experimental testing of new car systems begun earlier may continue throughout this phase and succeeding phases. The extent of such testing is dependent on the need for continued development of safety devices or emission control equipment required to meet standards imposed by statutory regulations targeted to a given model year. Normally at this juncture, new functional features that are imperfectly developed, or which would involve excessive cost penalties to incorporate, are deferred to subsequent model year production programs. In contrast, non-functional vehicle image features are seldom if ever deferred because of incomplete development.

4.1.3.3 Car Concept Development/Preliminary Design

The car production program commences in this phase of the product development cycle. For several manufacturers, this begins at about 43 months prior to Vehicle Job No. 1. The events which occur in the production program are typified by Figure 4-2, which shows the timing and major schedule milestones for Fords 1975 Car Line Program. (Ref. 4-3).

In the beginning months of this phase, the available alternatives and tentative proposals for the individual car lines are reviewed, and an overall package plan for each line is selected. At this point the broad objectives for the car development program are established, including such

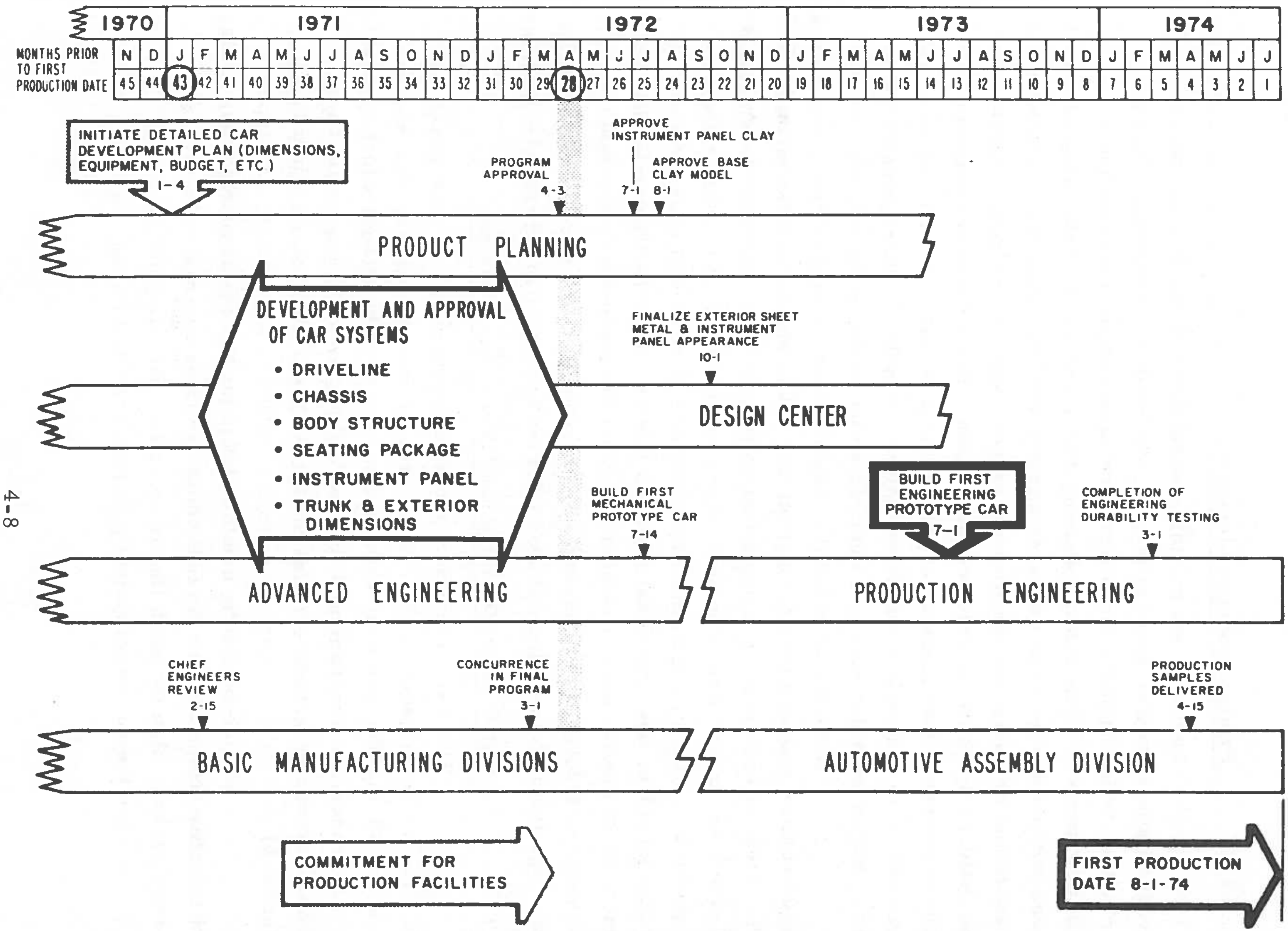

Figure 4-2. Ford 1975 Car Line Program (Ref. 4-3)

factors as the number of models to be offered, performance levels sought, budget to be assigned, equipment to be included, overall size and weight, styling goals, and seating capacity. Cost tradeoffs, technical feasibility studies, and producibility investigations are carried out; interface/interaction studies involving chassis, body, and powertrain are performed; facility requirements are checked against available resources. Changes to the initial assumptions are made as required for compatibility among all of the program objectives. Procurement activities related to long lead time facilities acquisition may be initiated in this period.

Vehicle design studies begin: body styling, space envelope definition, and occupant packaging are initiated; full size clay models are developed. Exterior and interior dimensions of the vehicle are defined. Driveline, chassis, and engine compartment dimensions are finalized. Body structure, instrument panels, and front compartment designs are completed. Emission devices/systems are selected.

Vehicle testing and modification of new car systems will continue throughout this phase if required. A number of such test-fleet programs were recently conducted in connection with the planned introduction of catalytic converters for 1975 model year vehicles. Typical examples are Ford Motor Company's 5-vehicle experimental development durability test fleet and Riverside test fleet programs. Schedule timings for these programs are illustrated in Figure 4-3 (Ref. 4-3).

4.1.3.4 Car Program Approval

The car system selection/preliminary design effort described earlier undergoes management review and approval on a periodic basis. Final management review of the entire car program package, finalized in terms of performance characteristics, features, equipment, and appearance, occurs at about the 26-month point prior to vehicle production. This phase may last from 1 to 1-1/2 months.

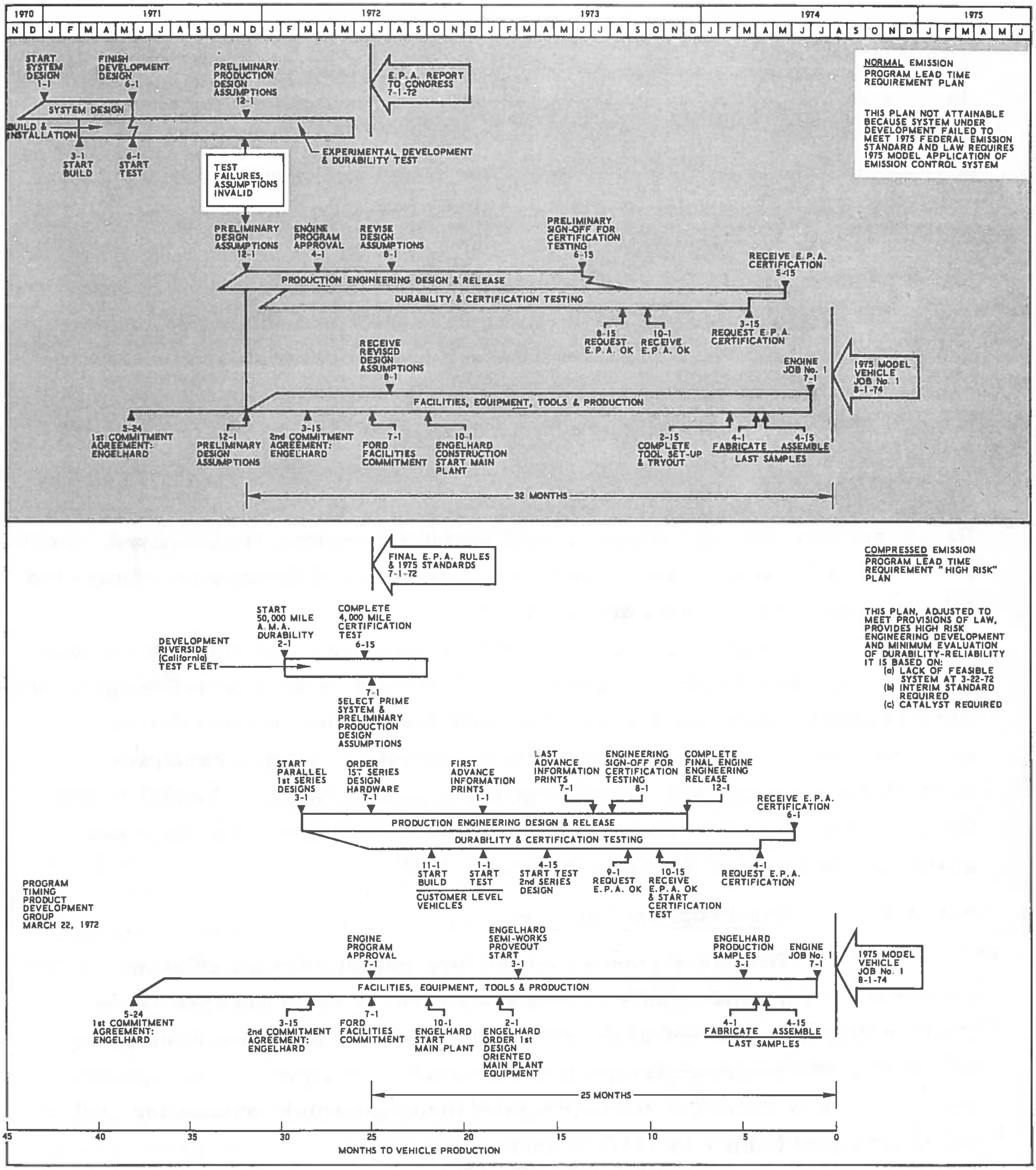

Figure 4-3. Ford 1975 Model Federal Emission Program and Passenger Car Timing Plan (Ref. 4-3)

The program approval phase is a key point in the product development cycle for two significant reasons. First, in a normal development program, it fixes the key parameters and specifications in the vehicle design which form the basis for much of the technical effort that follows. Second, it signals the commitment of major program funds. Up to this point in the Product Development Cycle, perhaps 5 percent of the total program resources for production are utilized; the balance is expended in the remaining 26 months before Job No. 1 -- primarily on facilities, major items of equipment, tooling, and parts and material procurement.

Because of the surge of activity and resource expenditures on production-oriented functions beginning at or immediately following this point, the program-approval milestone is commonly used as a convenient reference point for identifying the production lead time requirement, most frequently in reference to the major automobile manufacturer. (The lead time for the supplier of parts or equipment generally is referenced to a contractual commitment from the automobile manufacturer.) It should be recognized, however, that the various phases of the product development cycle overlap. Accordingly, some initial capital commitments and some manufacturing operations may begin as soon as a probable design has been identified.

4.1.3.5 Production Engineering/Car Prototype Testing

After Car Program Approval, the next major phase of activity is the Production Engineering/Car Prototype Testing phase, which has a duration of 21 months (Figure 4-1). Within the interval indicated, sustained peak-level production engineering activity may have a duration of about 12 months. Car testing activities may start prior to the initial release of detailed production drawings and may continue some months after final engineering drawing release.

Production engineering involves all process engineering and parts design operations required to convert the complete car program package plan into mass produced and assembled components and subsystems. Manufacturing processes and techniques are investigated, and the details of the manufacturing and assembly operations and material and parts flow are delineated. Part and assembly drawings are detailed; facilities, plant layout, equipment, and tooling requirements are defined. These are submitted for management approval and subsequent release to manufacturing or to purchasing for procurement. In this period, the full-scale clay model of the vehicle is approved, and die patterns for the body panels are constructed.

Testing operations in this phase fall into three categories: mechanical prototype tests, engineering prototype tests, and EPA certification tests. The mechanical prototype is a vehicle test bed that utilizes an existing body structure to test the frame, underbody, powertrain, suspension, brake, and other systems planned for the production vehicle. Design of these parts and functional systems may start several months before Car Program Approval. Mechanical prototype testing may include hot weather, cold weather, altitude, performance, economy, and other road tests as well as laboratory tests. Several mechanical prototype-series vehicles may be built, incorporating successive refinements in subsystem design, until production level versions are evolved.

Engineering prototype vehicles are totally representative of the final car product. The engineering prototype is used to test sheet metal and structural features of the final design as well as to continue the test and development of mechanical features. The test program is comprehensive, encompassing all of the conditions expected to be met in customer operation, including rough-road, city traffic, high-altitude, etc.

The EPA certification tests involve two groups of vehicles: emission data (4000-mile) vehicles, involving as many as four cars per engine family, and durability data (50,000-mile) vehicles, one per engine family. The durability test fleet (which is assembled and tested first) and the emission data vehicles are constructed from hardware similar in all material respects to production vehicles. The certification test procedure involves road mileage accumulation on a prescribed (modified AMA) duty cycle, with dynamometer tests of emissions at 4000 miles (emission test vehicles) and at successive 4000-mile intervals up to 50,000 miles (durability test vehicles).

As an example, durability testing for 1975 vehicles is scheduled by the various manufacturers to start in the September/October period of 1973 (11 and 10 months before Vehicle Job No. 1), and to continue for about 6 months. Testing of emission data vehicles is scheduled to start in the period from November 1973 to March 1974 and may involve durations of from 2 to 4 months, depending upon the extent of modification required and retesting encountered.

A representative timing plan for these tests is given by the Ford schedule shown in Figure 4-4 (Ref. 4-3).

4.1.3.6 Parts Procurement/Tool Construction, Installation, and Tryout

The activities accomplished in the Parts Procurement/Tool Construction and Installation phase may encompass the detailing of process or parts specifications; the preparation of requests for vendor quotes; the selection of suppliers and fabricators; and the operations of design, construction, and installation of process machinery, equipment, and tools fabricated in house or by selected vendors. Some automobile manufacturers have a substantial in-house tooling capability; others do not. As indicated in Figure 4-1, this phase may overlap considerably with the Production Engineering/Car Prototype Testing phase. A duration of 12 to 16 months is possible; the longer duration has been selected for illustration in Figure 4-1.

Decisions to buy a part, or to make it are generally accomplished in the Production Engineering phase on the basis of the combined judgment of engineering, purchasing, cost estimating, manufacturing, and (in some instances) outside vendor consultations. Parts having the longest procurement or longest tooling construction lead times are detailed for release first. Sufficient lead time must be provided for vendor capital equipment procurement and facilities construction requirements, as typified by the needs associated with catalytic converter production for 1975 automobiles. Representative of such provisions are those made by Ford

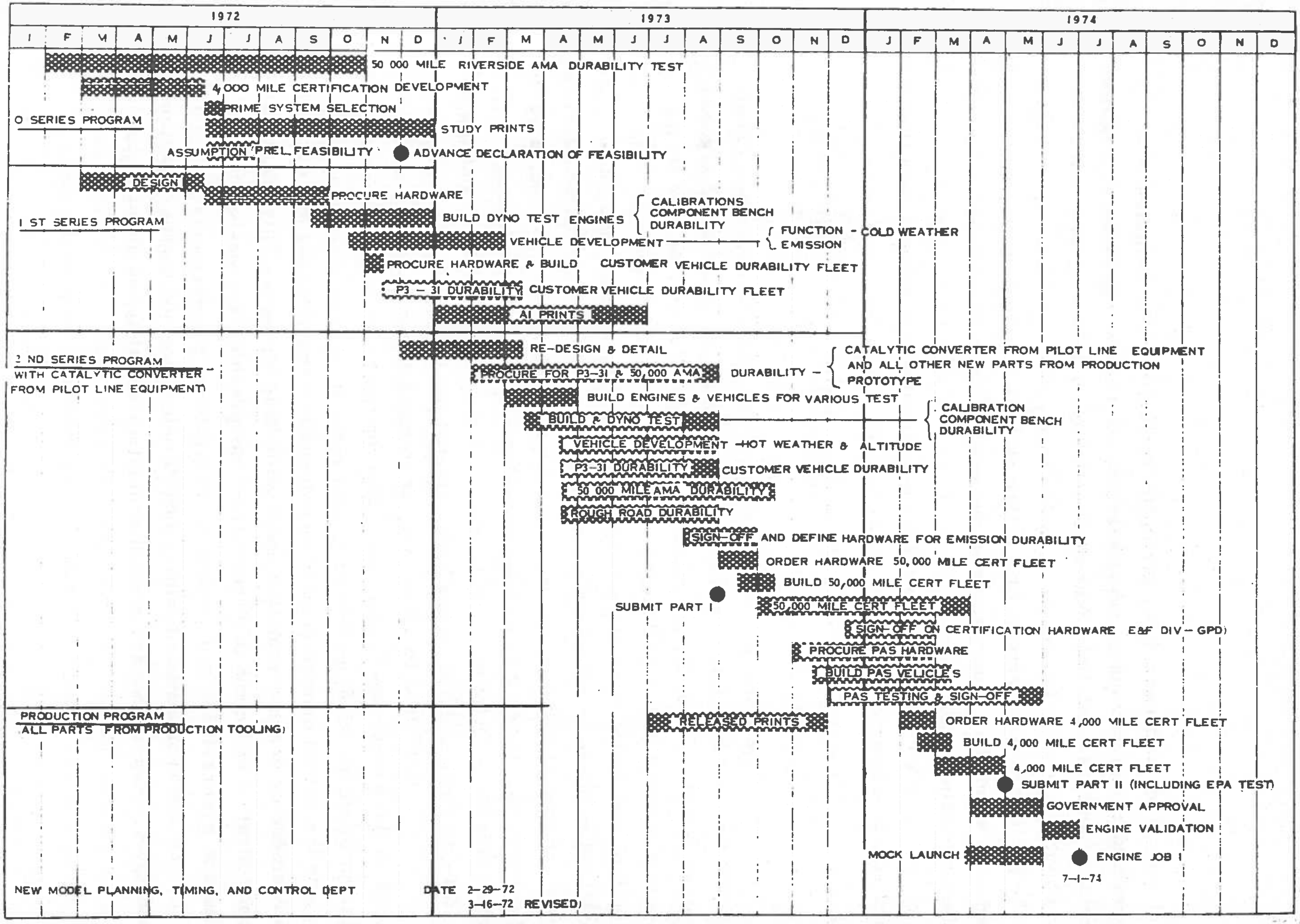

Figure 4-4. Ford Engine/Emission Hardware Testing and Scheduling (Ref. 4-3)

and indicated in Figure 4-3 by the notations referring to Engelhard agreements/commitments. A breakdown of Ford's vendor facility timing requirements for catalytic converter production is shown in Figure 4-5 (Ref. 4-3).

With regard to production equipment, the long lead-time items are typically the large, assembly-line process equipment pieces such as transfer lines for automatic-sequential machining operations and high-capacity, multiple-action presses for cold-metal working operations (forming, blanking, piercing, etc.). Lead time for these machines from receipt of order to installation and checkout may range from 13 to 30 months, in the case of transfer lines, and from 10 to 15 months in the case of presses. Other specialized devices, such as General Motors' electron-beam welding equipment (for use in fabricating catalytic converter containers), may also involve long lead times. Representative lead time requirements for such equipment are illustrated in Figures 4-6 and 4-7 (Ref. 4-3).

Checkout of specialized machinery such as discussed above is first accomplished at the vendor facility. A number of pieces are produced and examined for compliance with parts specifications. The equipment is then disassembled, shipped, re-erected, and rechecked at the automotive assembly plant. Installation times for these large pieces of equipment may range from 3 to 6 weeks; initial tryout after installation may involve another 3 to 6 weeks. To these specialized equipment items must be mated jigs, fixtures, conveyor equipment, and other assembly apparatus.

4.1.3.7 Pilot Assembly

The objectives of Pilot Assembly are to identify and correct basic problems in the fabrication and assembly processes. This phase may have a duration of from 2 to 4 months; a 3-month interval is selected for display in Figure 4-1.

Typically, machinery and tooling setup and tryout operations at supplier facilities and at automotive plants are completed about 4 months prior to Vehicle Job No. 1. First-piece or sample parts made from production tooling are checked for approval against detailed part drawings,

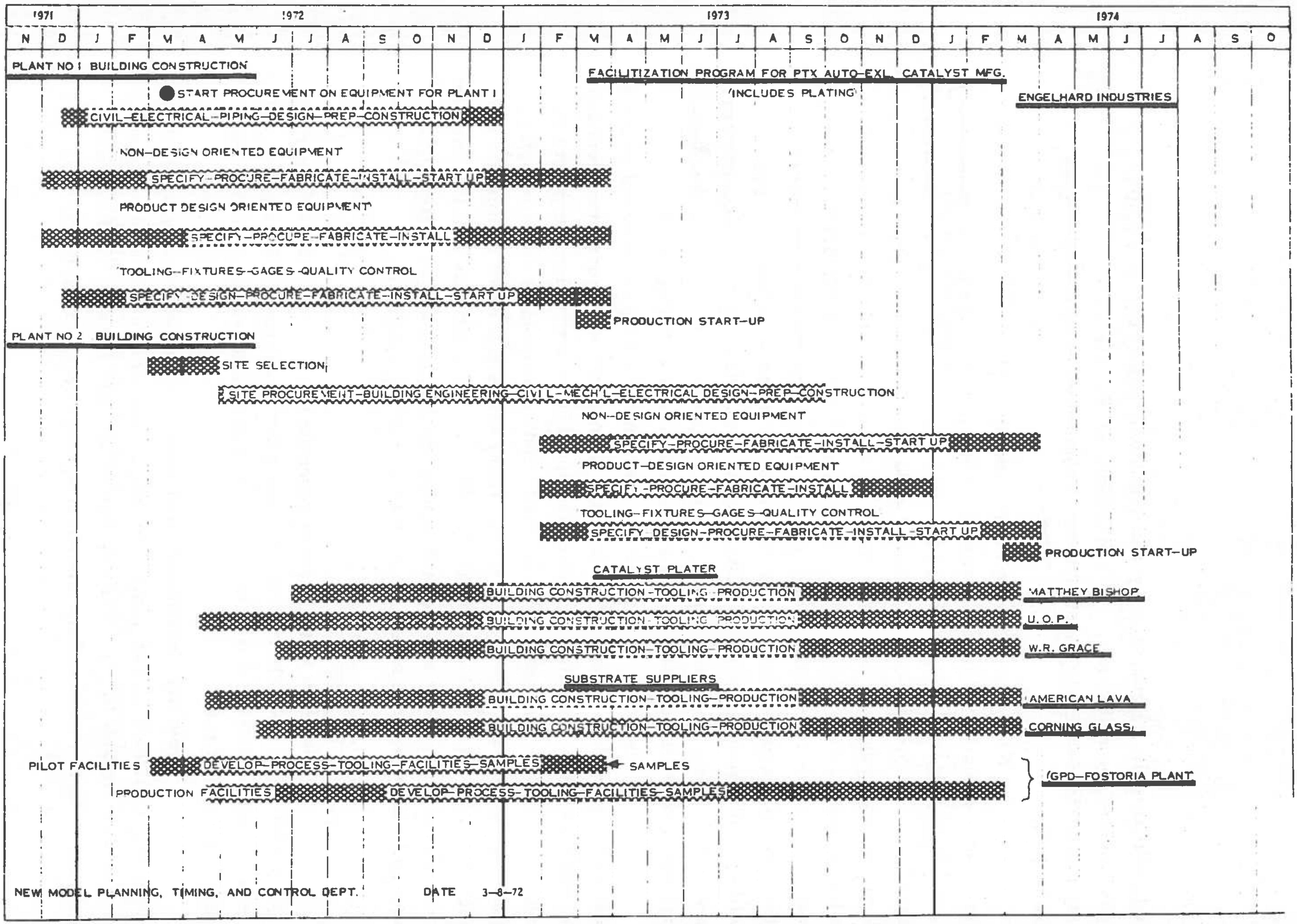

Figure 4-5. Ford's Vendor Timing Requirements (Ref. 4-3)

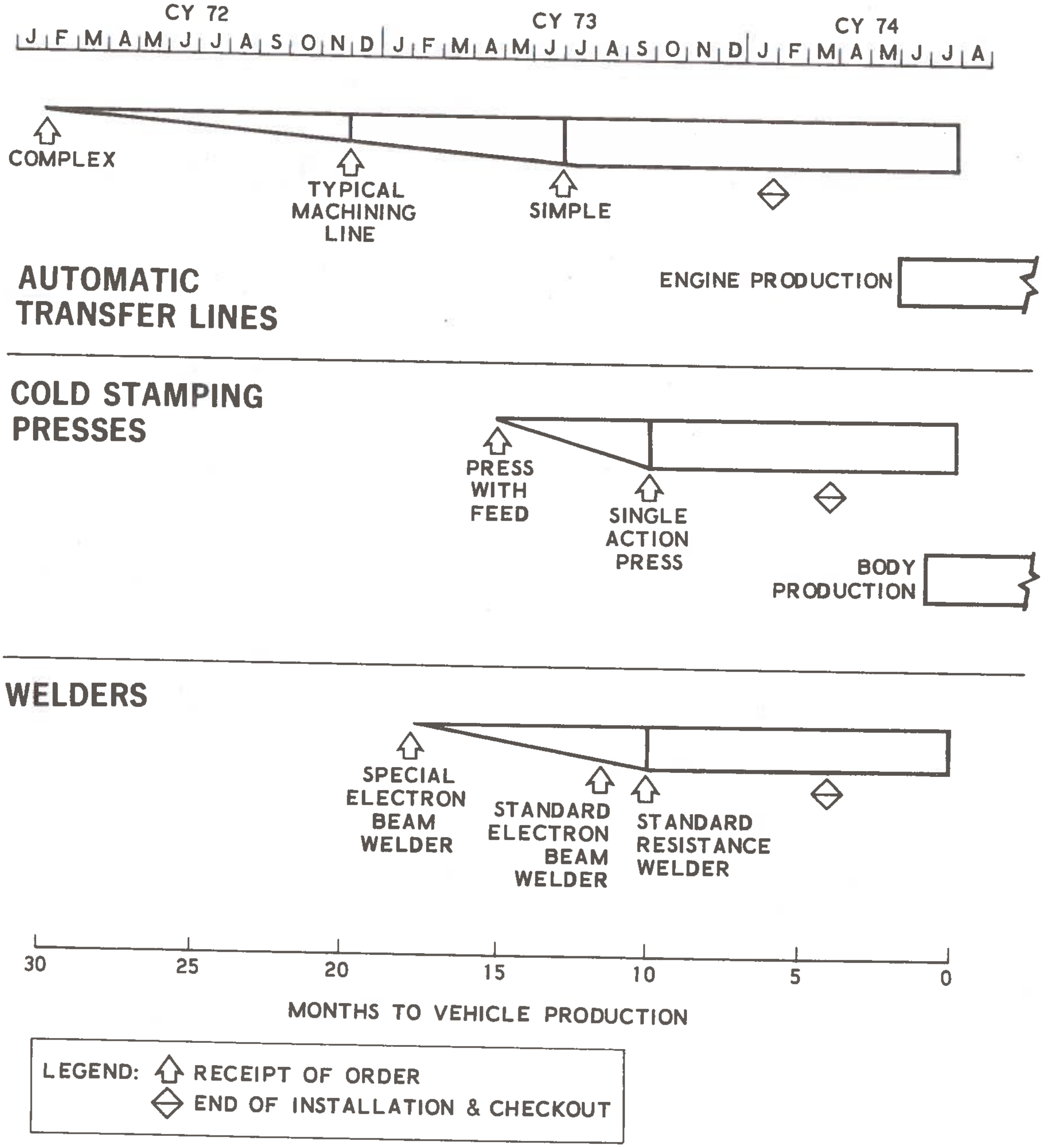

Figure 4-6. Production Equipment Manufacturers' Overall·Lead Time (Ref. 4-3)

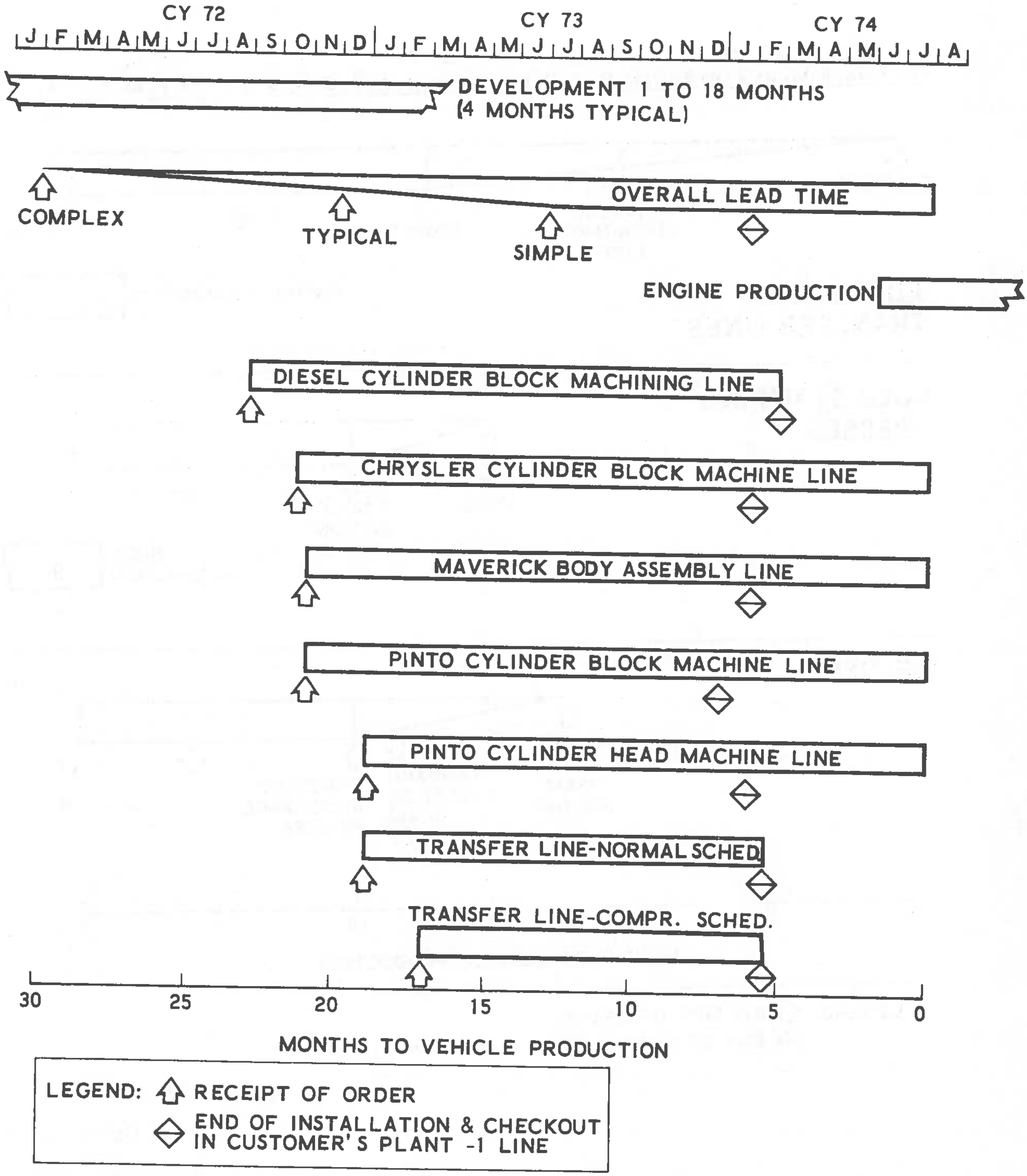

Figure 4-7. Automatic Transfer Line Lead Time (Ref. 4-3)

templates, and specifications. These production samples are made available to the automotive assembly plant for check of functional fit and performance in a vehicle sample assembly. Necessary modifications to tooling and equipment are made during this period.

Following this production sampling, one or more pilot assembly runs are made to check out the volume fabrication and assembly processes. Several assembly runs may be necessary, depending on the modification requirements that are revealed during these production trials.

4.1.3.8 Production Buildup

A 1-1/2 month interval is assigned to the Production Buildup phase. By the beginning of this interval, vendors and part suppliers have completed their initial production runs, and parts are made available in the automotive assembly plants to start stocking the production line. In this period, component production at the automotive plant facilities is accelerated toward full-volume output rates. For example, engine production and other subassembly production will be started in advance, with a target date for first production output 1-month earlier than Vehicle Job No. 1. All of this stockpiling for inventory will precede the production buildup of the vehicle assembly line, which will generally commence in the last few weeks of this period.

4.2 SUMMARY OF MANUFACTURERS' GAS TURBINE PROGRAMS AND SCHEDULES

4.2.1 Chrysler/Development/Production Programs

4.2.1.1 Background

Chrysler has been involved in the development of a number of automotive gas turbine engines since 1950. By 1956, Chrysler's development efforts on their fourth-generation gas turbine had been completed, and the well-known 50-car gas turbine test program was launched. At the conclusion of the 50-car program, Chrysler decided to abandon their original idea of a low-volume-production, gas turbine vehicle because of a number of deficiencies uncovered during that program. These included poor fuel economy, inadequate engine response and braking, insufficient engine power, and excessive noise. In addition, Chrysler felt that reduction of engine size and weight was desirable to reduce fuel consumption. Development work on the fourth-generation gas turbine engine was terminated in 1966. At that time, the engine consisted of about 1400 piece parts.

Research on the automotive gas turbine has since been continued by Chrysler with in-house funding. Their current sixth-generation engine is the result of these efforts. The fourth- and sixth-generation engines are similar in design. The engines incorporate a single-stage radial compressor driven by a single-stage axial turbine, two rotating regenerators, and a separate variable nozzle, single-stage axial power turbine, which is connected to the vehicle transmission through a reduction gear arrangement. The principal differences between the two turbine engines are the higher turbine inlet temperature and power output (150 hp vs. 133 hp) of the sixth-generation engine and the accessory drive arrangement. On the current engine, all vehicle accessories are driven by the power turbine instead of the first-stage turbine, which was used as accessory drive in the fourth-generation design. Additional data on the sixth-generation engine are provided in Section 2.1.4.1.1.

4.2.1.2 Current Programs

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 power plant 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:

a. Manufacture of seven Chrysler sixth-generation automotive gas turbines, and installation of three of these engines into three 1973 intermediate-size research vehicles,

b. Evaluation and development of engine components and vehicles.

c. Incorporation of improved components in the engines and vehicles.

d. Final engine and vehicle performance and durability testing using 1973 and 1975 vehicles.

The tie-in of the Baseline Development Program with other EPA/AAPS Gas Turbine Component and Technology Programs is shown in Figure 4-8 (Ref. 4-4).

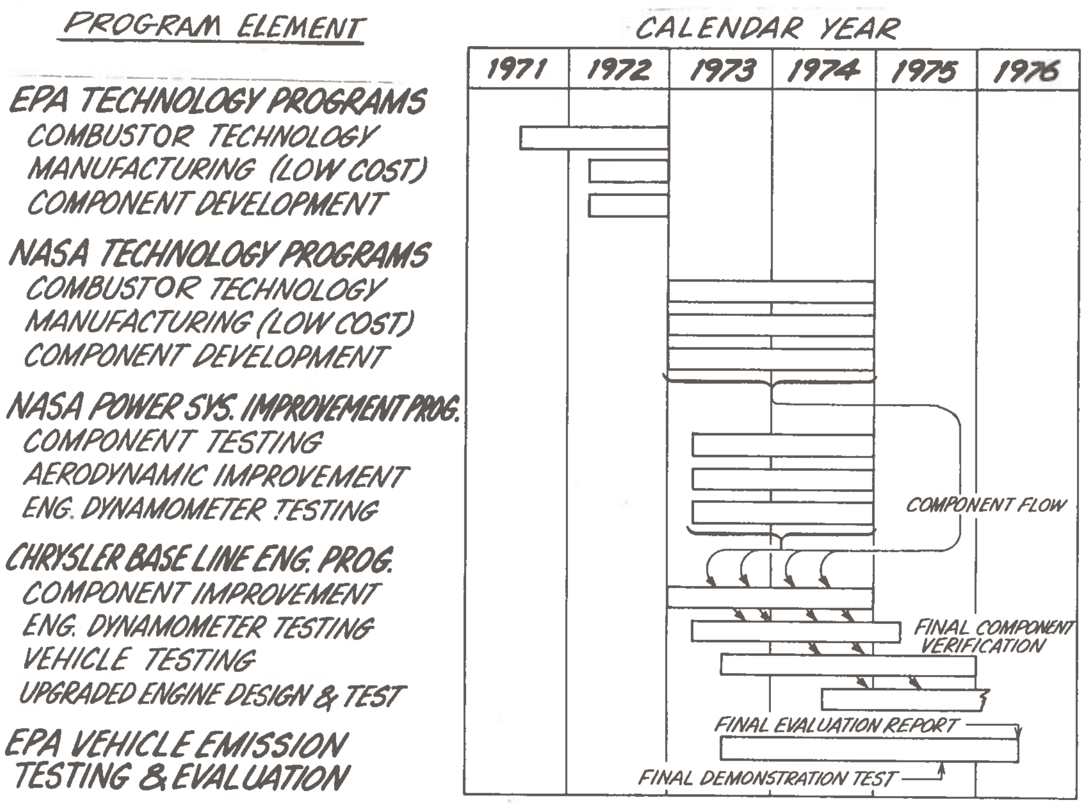

Figure 4-8. Gas Turbine Power System Program (Ref. 4-4)

4.2.1.3 Product Development Schedules

The baseline gas turbine development schedule for Chrysler's EPA sponsored program is presented in Figure 4-9 (Ref. 4-5). This 42-month program is divided into 9 tasks:

Task 1 Build and checkout seven baseline engines. Chrysler will loan the program three of its existing engines to get evaluation and development work started while program parts are being procured.

Task 2 Build and checkout three baseline vehicles.

Task 3 Support NASA and EPA engine and vehicle programs as well as other government contractors in their baseline engine components efforts.

Task 4 Evaluate endurance of baseline engine as well as upgraded components as they become available.

Task 5 Develop and evaluate upgraded components:

a. A contract will be issued for improving the engine by cost/benefit optimization of the control system as well as for meeting the control requirements of other upgraded components.

b. The following will be furnished by EPA from other technology contracts for evaluation and development:

1. Two combustors

2. Ceramic regenerator

3. Turbine wheels manufactured by experimental low cost concepts.

c. The result of Chrysler's proprietary combustor work will be evaluated.

d. Chrysler will design, evaluate, and develop:

1. An advanced concept metal regenerator

2. A rotary power turbine nozzle which is potentially faster-acting, lower-cost, better-packaged, and has less linkage.

3. An overrunning clutch or torque converter lockup device for preventing accessory cut-out due to low-power turbine speed during the engine-braking, vehicle-coastdown mode.

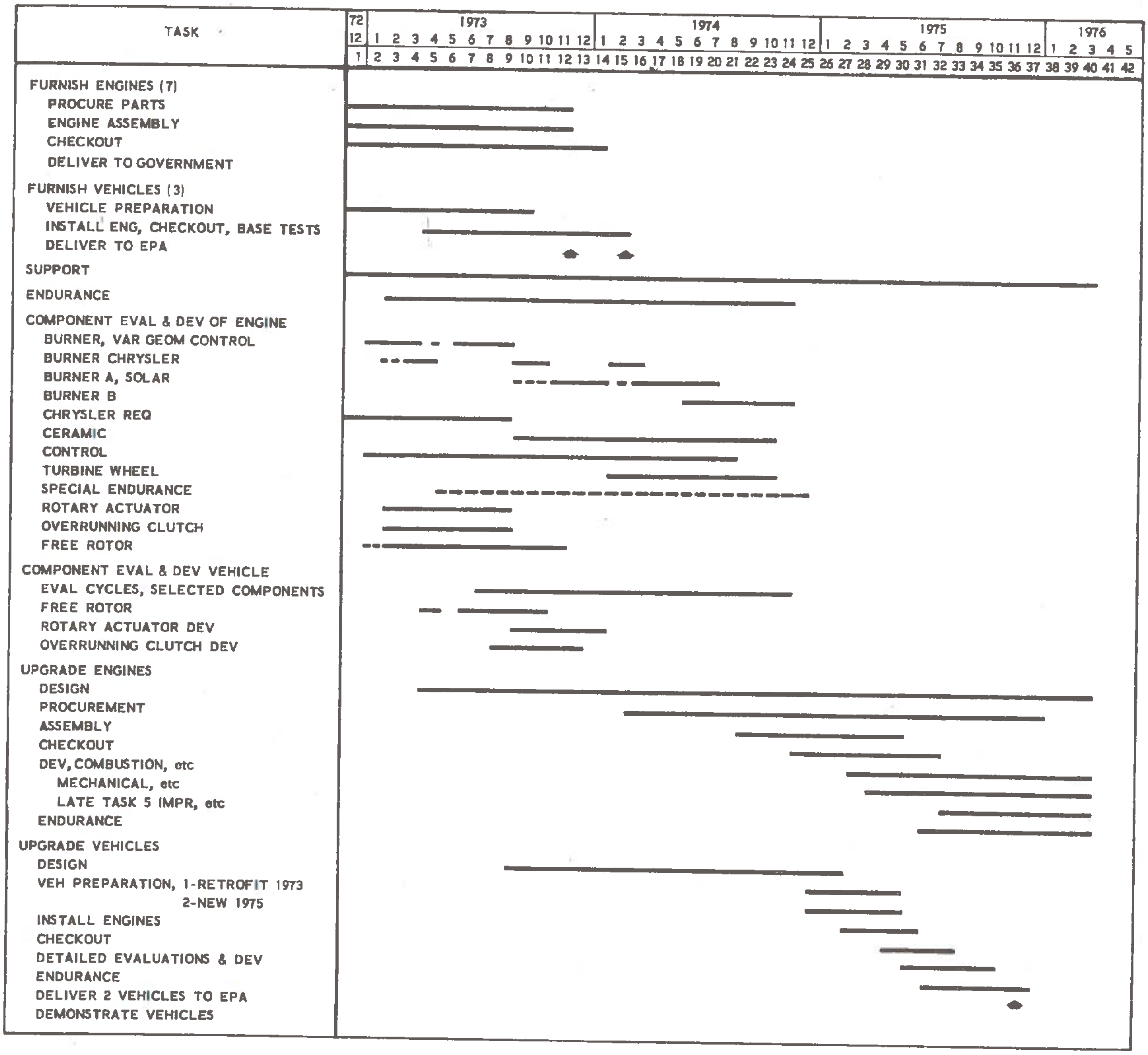

Figure 4-9. Chrysler Corporation Baseline Gas Turbine Development Program (Ref. 4-5)

4. A free rotor concept in which all of the engine accessories would be run from the power turbine along with the vehicle accessories. Potential advantages of this system are:

- faster gas generator response
- improved fuel economy
- quieter operation
- faster cold starting
- improved engine configuration
- ability to incorporate a gas-bearing rotor.

Task 6 Evaluate and develop Task 5 improvements in a vehicle.

Task 7 Upgrade engine design, procurement, and development.

Task 8 Upgrade vehicle design, build and demonstration.

Task 9 Reporting.

Upon completion of this program, Chrysler feels that the engine would basically be ready to be introduced into a new car model program. The current EPA contract does not provide for funding of any pilot production development effort. But Chrysler believes a program of this type is necessary as a checkout for new production procedures associated with gas turbine engines, particularly for regenerators and precision castings. Approximately $1 to $2 million would be required initially for a program to check out equipment and tooling. Subsequently, a low-volume (10,000 to 20,000 engines per year) pilot plant could be built. Construction could be started and machine tools ordered in about two years, with some attendant risk because the baseline development program would not be complete. However, some substantial redesign efforts on the engine might be required in order to reduce production costs.

A number of design modifications are required on the vehicle chassis and frame. These include a new suspension system, a new exhaust system arrangement, and a new front end. The new suspension would be of the rubber-insulated type to provide a quieter ride. The large exhaust ducts required for the gas turbine engine would demand some design modification in the underbody and seat arrangement of the vehicle, unless a rear engine installation were to be utilized (currently, Chrysler is not in favor of a rear-engine car). The design of the front end of the turbine car would have to be strengthened because the radiator yoke providing part of the front-end support in current automobiles would not be used in gas turbine cars.

Chrysler feels that these modifications can be easily incorporated in a new vehicle design. However, incorporation of these changes into an existing design might be rather difficult and expensive. For these reasons, Chrysler would design a special vehicle for the gas turbine and would introduce the car at the time of a normally scheduled major model change. This is done usually, about every 3 to 5 years (the cost is at least $50 million). Construction and installation of the pilot plant would require about 20 to 24 months, and debugging would take another 24 months to build up to a production rate of 20,000 units per year. Some automatic transfer equipment would be utilized in this plant, but most of the equipment would be of the numerical control type. The experience gained from the operation of the pilot plant would be applied to the construction of a mass-production facility. A total of 24 to 36 months would be required for this effort, followed by an additional 24 months to build up to a mass production rate of 300,000 units per year.

The mass production plant would be designed for a single-shift annual production rate of about 300,000 engines, which represents minimum capacity from an economic point of view. Currently, Chrysler's largest engine manufacturing facility has an annual capacity of 800,000 units. Originally, this particular plant was designed for a single-shift capacity of 500,000 engines per year; it was then modified to the 800,000-unit level by using some 2-shift operations and by improving plant operations.

Chrysler feels that mass production of gas turbine powered automobiles would have a very significant impact on the steel and tooling industries. Since the steel industry lacks sufficient cold rolling capacity for production of the high nickel alloy required for turbine wheels, Chrysler feels that the automakers might have to form joint ventures with the steel industry to provide this capability. However, the large steel firms might do it themselves in order to increase their profit margin. According to Chrysler, the tooling industry would be swamped if all automakers were to suddenly decide to mass produce automotive gas turbines. Even at a relatively low annual production level of 300,000 turbine cars, the tooling industry would see some tight spots. Nevertheless, Chrysler feels that 300,000 turbines might be feasible for the first year.

Most likely, gas turbines would be introduced in a specialty car at the rate of about 20,000 to 25,000 vehicles per year. The cost of the gas turbine specialty car would probably be of the order of $15,000, compared to about $10,000 for a new specialty car equipped with an advanced piston engine. With success in this line the turbine would be gradually phased into other model lines.

4.2.2 Ford/Development/Production Programs

4.2.2.1 Background

In 1969, Ford decided to construct a small production facility for industrial-class gas turbines for truck, bus, marine, engine-generator and other applications. In order to minimize capital investment requirements, they chose to modify an existing engine storage facility located in Toledo, Ohio, instead of building a completely new plant. The Toledo facility was gutted to the walls, and production line equipment for the gas turbine was designed and installed in the building. This task was completed in 1971.

In its present form (Phase I), the Toledo plant has an annual production capacity of about 1000 gas turbines. The plant has numerical control equipment procured from outside specialty vendors, such as Excello. This type of equipment is feasible for production rates up to 3000 per year. To reach this capacity (Phase II), additional numerical control machinery would be installed. For annual production rates above 3000 units, Ford would utilize automatic transfer equipment, which is more economical at higher production rates. Expansion of the production to about 15,000 gas turbines per year (2 shifts per day) is considered a Phase III effort by Ford and would require a capital investment of the order of $60 to $80 million. Beyond that, an additional $30 million would be required to reach an annual engine production capacity of 40,000, which would be the minimum projected production rate to justify the additional expenditures. The cost breakdown for such a plant is considered proprietary data by Ford.

These cost data are exclusive of foundry investment costs. Ford plans to procure all castings for the gas turbine from outside vendors, because their own foundry is not interested, for cost effectiveness reasons, in production levels below about 100,000 units per year. Furthermore, the housings of the projected Ford gas turbines (285 to 550-hp output) are bigger than the castings normally handled by their foundry operations. The engine accessories are also purchased from vendors. These components, all engineered by Ford in cooperation with the vendor, are proprietary to Ford and manufactured exclusively for them. The electronic fuel-injection system, selected by Ford in 1968, is being supplied by a European company; at that time, domestic firms showed little interest in the manufacture of components for small industrial gas turbines.

The gas turbines to be manufactured at the Toledo facility are designed to compete with diesel engines. Studies conducted by Ford indicate that the gas turbine offers great potential in a number of applications including boat drives, electric power generation, oil field power units, and trucking. Based on these considerations, Ford selected the 707 gas-turbine engine family for production. This engine family, which represents the seventh engine design completed by Ford since 1951, consists of three different-size units, with shaft horsepower outputs ranging from 320 to 520 hp. The 710 gas turbine family, which consists of at least four different engine sizes, is being considered for initial production in the 1975/76 time period. To minimize unit cost, all Ford gas turbines are designed to use as many common parts as possible. If both the 707 and 710 engine series were to go into production, the capacity of the Toledo plant would have to be expanded from its current level. Since Ford owns an additional 15 acres of land adjacent to this facility, plant expansion is possible.

In the 1964/67 period Ford built six passenger car, gas turbine engines designated as the 706 series design. This engine was quite similar to the 707 and 710 engine family designs. One of these engines was tested in a 1966 Thunderbird automobile. The fuel consumption of the turbine was 10-percent higher in urban and suburban driving and about 15-percent lower on cross-country routes. In some respects the driveability of the turbine-powered Thunderbird was better than the standard vehicle. The car's acceleration, for example, was slightly better than cars equipped with the standard 428 CID spark-ignition engine.

4.2.2.2 Current Programs

The 707 engine is currently in production at Toledo. Two hundred engines were manufactured in 1972; 400 are projected for 1974. These engines are all hand-assembled. Development work on the 710 engine will run through 1973.

Currently, the 707 engine is guaranteed to operate continuously for 2500 hours, although many components actually last much longer. By September, 1973, the warranty period will be increased to 3000 hours; by 1974 to 5000 hours. Ultimately, the durability of the engine will be 10,000 hours.

Research on a gas turbine for a passenger car is currently being conducted by Ford. If this concept becomes a reality, the engine would also be built at the Toledo facility. In this case, the research model of the engine would be redesigned for optimum producibility and packaging in the car. Ford's Industrial Engine and Turbine Division would be responsible for the redesign and prototype development effort.

4.2.2.3 Product Development Schedules

Ford's minimum critical-path timing estimate for mass production implementation of a current-technology, gas-turbine automobile is presented in Figure 4-10. As indicated in the chart, a minimum time period of 9 years is required between the start of the Vehicle Applications Study and Production. The chart is based on a turbine production volume equal to 10 percent of Ford's current annual automobile production rate. An additional 10 years might be required to tool up for 100-percent production.

The Vehicle Application Study covers a 9-month period. At the end of that period, Ford will be in a better position to make a decision regarding continuation of the program. This phase is currently being conducted by Ford.

The Design and Dynamometer Test Development phase will be initiated upon completion of Vehicle Application Study. Twenty-seven months are required for this work. Of these 27 months, 12 months will be required for completion of the engine and tooling drawings, an additional 6 months will be needed for engine manufacture, and the engine will be dynamometer tested during the remaining 9 months.

The Vehicle Development and AMA Durability test phase of the schedule covers a time period of 12 months. At the end of this phase, Research Feasibility will have been established, if all problem areas have been resolved. This phase concludes the Concept Program.

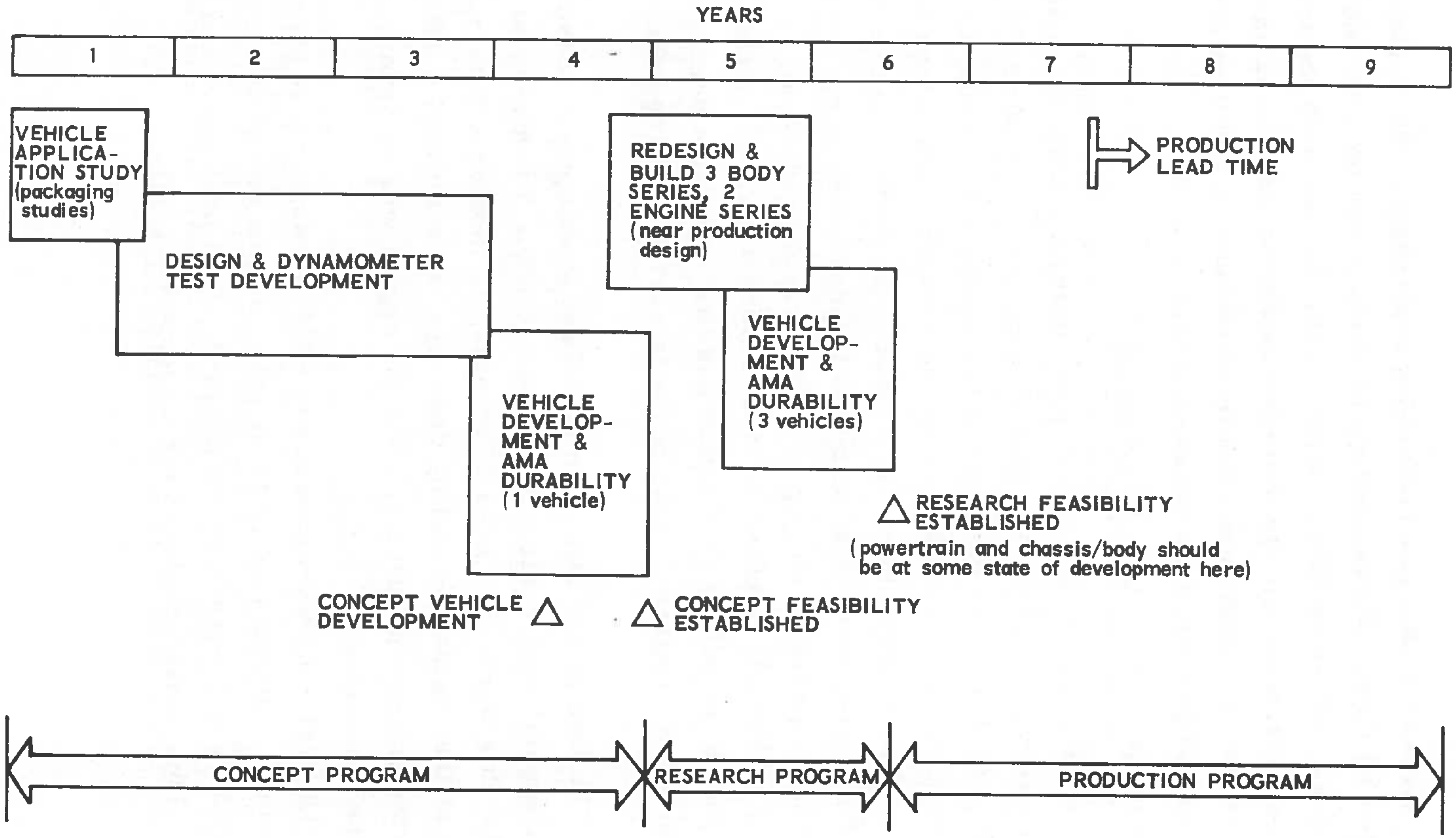

Figure 4-10. Ford's Minimum Critical Path Timing Estimate

Based on results from the previous phases, the gas turbine engine/vehicle will be redesigned and 3 new engines will be built and installed. An additional 18-month effort is projected for this phase, with the initial 3 months overlapping the Vehicle Development and AMA Durability phase.

AMA durability testing of the three vehicles will be conducted over a period of 12 months. This phase overlaps the Redesign and Build phase and concludes the Research Prototype Program. At this point the powertrain and chassis should be at the same state of development.

The 42-month Production Program follows these efforts. The last 26 to 28 months of the Production Program represents the time period commonly called Production Lead Time. Near the beginning of the Production Program and continuing for a period of about 15 months, a large fleet of turbine-powered automobiles would be road-tested. In the case of established internal combustion engines, only one or two vehicles would be tested.

The indicated timing assumes that no problems would be encountered and is largely based on Ford's experience with conventional vehicles. Since Ford has had no experience with gas-turbine automobiles, the estimate cannot be viewed with any great reliability. Indeed, according to Ford, the overall program for a gas-turbine-powered vehicle might have a 13-year duration, rather than the 9 years indicated.

Because of capacity limitations of the tooling industry, only about 10 percent of Ford's annual vehicle production could be converted to gas turbines each year. A large increase in production orders has a major impact on the tooling industry usually resulting in longer lead times than normally encountered. As an example, lead time of the tooling manufacturers increased by 2 months during 1972 as a result of General Motors' decision to use quick-heat manifolds on their 1975 model year vehicles. The requirement of skilled labor for assembly of the gas turbine engines might impose additional constraints on production conversion.

Initially the gas turbine would probably be limited to a single vehicle model. Most likely, this vehicle would be a new design that would be offered for sale with a gas turbine as an option in place of the conventional internal combustion engine. Compared with current designs, this vehicle would have many new features, including a redesigned body and frame (to accommodate the much larger ducts in the exhaust system for the gas turbine) and a new suspension system. In addition, all vacuum-operated components used in present automobiles would have to be replaced by either pressured-pneumatic units or by hydraulic units. The air-conditioning system would not require modification, except that a condenser fan would have to be provided in the absence of a conventional radiator fan.

4.2.3 General Motors/Development/Production Programs

4.2.3.1 Background

General Motors' activities in the automotive gas turbine field began over 20 years ago in an experimental and developmental program targeted toward the evolution of a commercial gas turbine engine for heavy-duty vehicles. This program culminated in the GT-404 engine, a regenerative split-shaft design with a rated output of 325 hp. The GT-404 is currently in pilot production, with full production scheduled for the near future (Ref. 4-6).

Experimental engine/vehicle systems were tested as early as 1953, beginning with an experimental car (Firebird I) which was powered by a nonregenerative 370-hp engine. Also in 1953, an experimental bus (Turbo-Cruiser I) powered by the same engine was produced. In 1955, Firebird II, a passenger car with a 200-hp regenerative engine was evolved. A heavy-duty truck (Turbo-Titan I) using the same engine was built and tested in 1956. Another experimental car, Firebird III, was produced in 1958; and a second heavy-duty truck (Turbo-Titan II) was produced during the following year, both using improved versions of the regenerative-engine design (GT 305). A fifth-generation engine, the GT 309, was field-tested in several heavy-duty vehicles: GMC's Turbo-Cruiser II bus in 1964, Chevrolet's Turbo-Titan III truck in 1965, and other vehicles in this same period. The GT 309 is a split-shaft, regenerative engine rated at 280 hp. The more advanced GT 404, rated at 325 hp, has been operating in a number of heavy-duty test vehicles including Turbo-Cruiser III, a GMC coach, and a Greyhound coach.

The GT 404 engine has been classified as the first of a family of industrial power units planned for development by GMC (Detroit Diesel Allison Division). Work has been initiated on larger and smaller engines, while improvements to the GT 404 have continued as field service experience is acquired. General Motors expects that regenerated gas turbine engines will comprise about 25 percent of Detroit Diesel Allison's production by 1980.

4.2.3.2 Current Programs

In addition to the continuing development of heavy-duty engines, General Motors is presently conducting a passenger-car turbine development program. According to General Motors, this effort has been given high priority involving over 300 employees from 22 GM divisions. Their efforts have progressed to the early phases of preprototype engineering design and manufacturing technique evaluation; no final engine selection has been made. Both a two-shaft and a single-shaft regenerative engine are being evaluated, and both axial and radial flow components are under consideration.

The main effort in GM's turbine passenger car program is concentrated on the 225A system, a two-shaft, twin regenerator, state-of-the-art engine designed for use with a conventional 3-speed transmission. Techniques for braking this two-shaft design are still under investigation; a variable geometry power turbine and power transfer technique, which couples the driving wheels to the compressor on deceleration, are being evaluated. Other hardware development problems remaining to be resolved include their low-emission combustor, rotating components with low inertia and improved efficiency, and suitable routing and packaging for the exhaust system.

The current development effort is envisioned to evolve one or more preprototype engine designs, from which a best configuration would be selected for eventual field testing in a taxicab fleet. Ultimately, the selected design would be introduced into a car-product line on a limited basis for further evaluation in customer use. It is likely that the engine would be offered in an existing car chassis; the cost of a new vehicle coupled with the unknowns regarding public acceptance of the new engine is, in General Motors' view, too great a risk to accept.

4.2.3.3 Product Development Schedules

Schedule data for General Motors' passenger-car turbine development program are not available. The principal schedule-pacing considerations that must be addressed in a gas turbine production development program relate to new and difficult fabrication processes. These include vacuum melting and casting of exotic, high-temperature alloys for the turbine wheel. GM views this as the first invention needed in order to break the gas-turbine manufacturing cost barrier.

One specific manufacturing problem pertaining to GM's current prototype development concerns their combustor design. This is comprised of 120 separate piece parts. The design must be simplified to make it acceptable for mass production.

4.2.4 Solar/Development/Production Programs

4.2.4.1 Background

The Solar Division of International Harvester produces a wide range of industrial gas turbine models ranging from 10 to 2500 kW generating capacity. These are used for industrial drives, emergency power units, and peakload electric power operation. All models are of the simple-cycle, single-shaft design. Gas turbine models of the lower-power levels ranging from 10 to 225 kW have radial turbomachinery components; two high-capacity units have axial components. All major components of these units, except the casting parts, are made at Solar. The three small models have 500 to 600 parts each; the two large models have 1500 to 1600 parts per unit. (The production rate of each gas-turbine model is less than 1000 units per year.)

In the period from 1964 to 1969, Solar undertook the development of a 300-hp gas turbine engine targeted for use in International trucks in the 30,000-lb (gross vehicle weight) class. (Vehicles of this size are normally equipped with diesel engines.) The objective was to produce 10,000 units per year of a system which would be competitive with diesel engines in terms of fuel economy and cost (0.5 lb/bhp-hr, $15/lb). The engine was a recuperative, free-turbine design with a pressure ratio of 4:1. The free turbine was a novel coaxial design with all power-driven systems geared to the cold (compressor) side of the engine. The recuperator was a Solar-manufactured heat exchanger of annular design, which enveloped the power turbine section of the unit.

Insofar as possible, materials selected for this unit were chosen on the basis of cost, as dictated by the high production-rate goal. The housing was made of cast iron. The compressor was a precision casting made of 17-4 ph (precipitation hardened) stainless steel. The compressor diffuser was made of nodular iron. The power-turbine nozzle and wheel were integral investment castings of Inconel 713 LC. Nodular iron with high nickel content was used for the turbine exhaust housing. The recuperator was made of stainless steel foil. High-nickel alloy sheet was used for the combustor.

Projected costs for the compressor and turbine investment castings were finally determined to be too high to be compatible with the goals of the program.

Seven of these engines were built and three trucks were manufactured. These trucks were operated for about 20,000 miles. The project was abandoned in 1969 because of the high cost of manufacturing and the poor fuel economy observed in operation. The manufacturing cost based on production of 10,000 units a year was estimated to be 20-percent higher than diesel engines; fuel consumption was about 20-percent higher than the diesel baseline figure.

4.2.4.2 Current Programs

Solar has been involved since May 1971 in developing a low NO_x gas turbine engine combustor for EPA. The basic goals of this program are to achieve low emissions and good fuel economy simultaneously. Features of the Solar combustor include lean operation with high turbulence in the primary zone produced by Solar's Jet Induced Circulation (JIC) design. The operation of this combustor with a simulated FDC resulted in emission levels below 1976 requirements. This performance resulted in a follow-on contract for Solar in January 1973. This program will run for 18 months, and its goal is to deliver a suitable combustor for use in the EPA/Chrysler Baseline Engine Program.

4.2.4.3 Product Development Schedules

Solar's estimate of the timing involved in developing and producing a passenger car gas turbine engine is shown in Figure 4-11. This estimate is largely an extrapolation of Solar's experience in the aborted truck engine development program discussed previously.

As shown, an optimistic estimate for the duration of the engine development phase would be 5 years, extending beyond the termination point for the truck engine program. Development could last as long as 7 years, depending on the program objectives with respect to performance, emissions, and manufacturing costs. Experimental (preprototype) engine tests in vehicle test beds might commence at a point 3 years into the development program.

Solar considers that a 50-vehicle fleet test program would be necessary in order to statistically demonstrate the suitability of the engine design. This requirement seems to be compatible with current automotive-industry practice employed in connection with introducing new functional equipment on car-product lines.

Production planning would require a minimum of 1 year and could extend to a duration of 3 years. At least 2 years would be required for tooling and equipment development, installation, checkout, and assembly line startup; but this effort could run as long as 4 years. Engine Job #1, the first mass-produced engine off the assembly line, would occur at the 8 to 10-year point in the program.

A critical and possibly pacing factor in creating a gas-turbine production capability is the requirement to develop techniques for making investment castings in the quantities, and at the rates, required. Also, if present procedures are used, machining of some of the hard alloys used for gas turbine components may be both slow and expensive. New techniques are required for these operations. Solar encountered few problems in machining hubs and grinding blade tips for the truck turbine engine, but the quantities fabricated in this program do not provide a good basis for judging impacts on timing for a high-volume/high-rate production program.

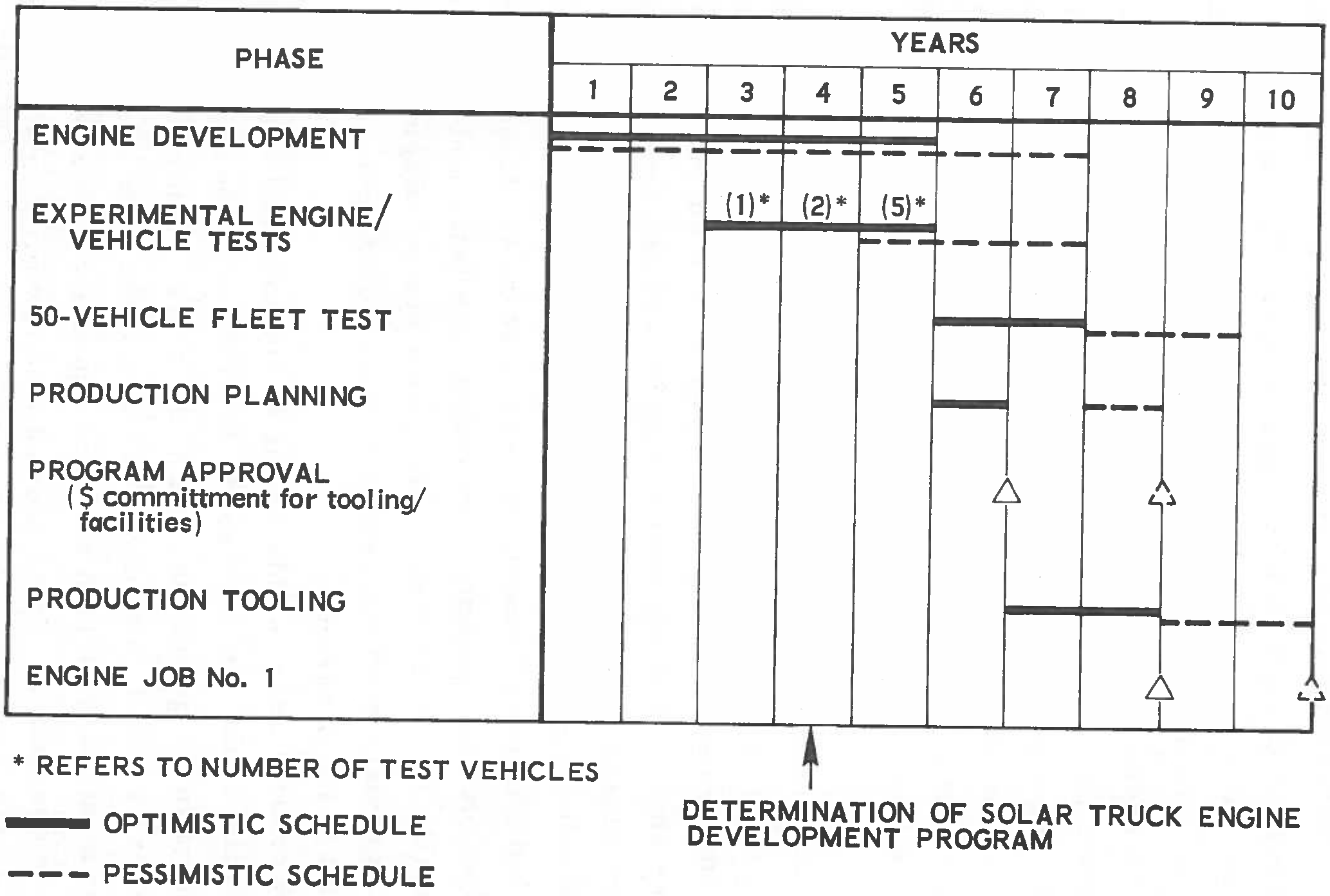

Figure 4-11. Projected Schedule for Development and Production of Vehicular Gas Turbine Engine (Solar)

4.2.5 United Aircraft Corporation/Development/Production Programs

4.2.5.1 Background

Though well know for work in the aircraft engine field, United Aircraft has had limited hardware experience applicable to automotive gas turbines. United Aircraft of Canada, Limited, has carried out a series of research programs aimed at providing advanced components for small gas turbines for aircraft since 1961. The technology base acquired here was utilized in a United Aircraft manufacturing cost study of automobile gas turbines sponsored by the National Air Pollution Control Administration (NAPCA) in FY 1970 (Ref. 4-7). Subsequently, another study concerned with automotive gas-turbine configuration optimization (Ref. 4-8), was sponsored by EPA in FY 1972.

The manufacturing-cost studies examined several potential gas-turbine design concepts. A simple-cycle, high-pressure-ratio, single-shaft design using radial components was selected, based primarily on cost and complexity considerations. Highlights of the studies include: (1) the use of high-ductility forging techniques to produce the titanium centrifugal compressor and the alloy-steel radial-turbine impeller, (2) the use of an 8-speed automatic transmission, and (3) the estimate that initial engine and total automobile costs would be approximately equal to those of a 1976 piston engine vehicle.

The objective of the optimum-configuration study for EPA was to define an advanced gas turbine engine design configuration having the best potential for solving the problems of part-load fuel economy and cost in a short-term development program. A large number of candidate gas turbine cycles were reviewed for application to automobile propulsion. Following a preliminary evaluation on the basis of total lifetime costs for each design, three leading candidates were chosen for more detailed analysis: (1) a simple cycle, (2) a regenerated cycle, and (3) a recuperated cycle; all of which were single-shaft concepts. Further analysis led to the final selection of a single-shaft, simple-cycle design with a pressure ratio of 10:1, a shaft speed of 106,000 rpm, and a horsepower rating of 135. For additional details concerning the results of this study, see Section 2.1.4.2.

With regard to the fabrication of this engine, United Aircraft proposed to use a UAC-patented, high-ductility forging process called "Gatorizing". This process, developed at the Florida Research and Development Center, Pratt & Whitney Division of United Aircraft, utilized appropriate combinations of pressure and temperature to create a high ductility condition in metal preforms, thereby permitting them to be forged inside precision dies into thin, highly convoluted parts with near-finished dimensions. At the present time, United Aircraft is using this process to forge turbine wheels for the F-15 and F-14B jet engine planes made by Grumman Aircraft Corporation. Furthermore, United Aircraft is presently studying this process for its possible application to commercial engines, replacing the presently used numerically-controlled flank milling of turbine wheels. For the compressor forging, United Aircraft would use titanium sheet metal as the base raw material, as opposed to the powdered metal form proposed for the high-alloy steel turbine wheels.

4.2.5.2 Current Programs

United Aircraft Corporation, under contract to EPA, worked on the development of a low-emission, gas turbine combustor (Ref. 4-11). The basic approach was to work with the best conventional combustor components and combustion techniques in a design aimed at very lean mixtures in the primary zone. The approach taken was to minimize flame temperatures and to achieve rapid quenching for minimizing residence time at peak temperature. Combustors for both simple-cycle engines and regenerative/recuperative engines were examined.

Another EPA-sponsored program in effect at this time involves the further development of United Aircraft's Categorizing Process as applied to automotive gas turbines.

4.2.5.3 Product Development Schedules

Based on the results of the United Aircraft manufacturing-cost study, a gas turbine design and manufacturing development program was recommended. As indicated in Figure 4-12, this program was timed so as to meet the EPA target date for prototype engine production in 1976. The proposed program was based on the assumption that the simple-cycle, single-shaft, high-pressure-ratio engine would be adopted for development, since the United Aircraft study indicated that it had the best potential relative to manufacturing cost, operating cost, and NO_x emissions.

The program, as shown, is divided into two phases. Phase I would be devoted to concept validation, basic component research, fabrication, and test of several demonstrator engines; development and demonstration of suitable transmissions; and preliminary vehicle demonstration. This phase

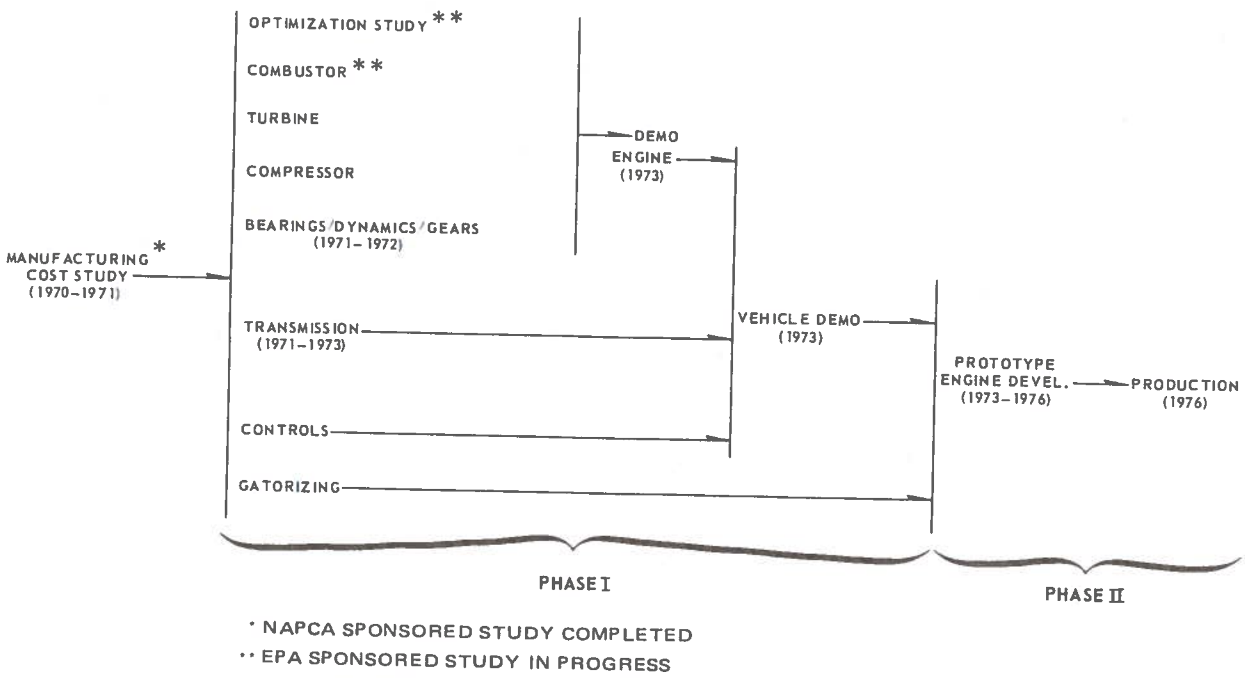

Figure 4-12. United Aircraft Recommended Development Program for Gas Turbine Engine (Ref. 4-7)

would encompass about 2-1/2 years. Phase II would include the design, development, and test of prototype engines, as well as a more extensive vehicle demonstration (fleet-test) program, and would require an additional 2 to 2-1/2 years.

The Phase I program would consist of three parts. The first part would encompass an engine Optimization Study, a transmission feasibility study, and research, development, and demonstration of the following engine components: combustor, compressor, turbine, gear box, bearings, and fuel control. It would also include a feasibility demonstration of high-ductility forging for this application. The second part would consist of engine and transmission design, fabrication, and test. The third part of the Phase I effort would be on the demonstration of engines, with two or three suitable transmissions, in automobiles. The first two parts would be accomplished concurrently to meet the 1976 prototype engine production date.

The Phase II program would consist of three parts: production prototype development, fleet tests of gas turbine-powered vehicles, and production planning. The fleet testing phase was indicated by United Aircraft to be rather extensive and was proposed to be carried out by various government agencies under the supervision of EPA's Office of Air Programs.

Some key milestones in this program identified by United Aircraft are as follows: Assuming the program had started in 1971, key components would have been on test in 1972. First run of a demonstrator engine on a test stand would have taken place late in 1972; feasibility would have been demonstrated by the end of that year. Vehicle testing with demonstrator engines would commence late in 1973. Design, fabrication, and first run of production prototype engines would occur in 1974; extensive vehicle tests would commence in 1975 and continue into 1976. Engines would be placed in initial volume production in the period between mid-1976 and mid-1978. If the latter figure is taken, the overall program would have a duration of 7 years, according to the United Aircraft figures.

The engine production shown to begin in 1976 (Figure 4-12) refers to initial prototype production that would grow to 10, 000 to 20, 000 units per year. Another 2 years or more would be required to produce engines in quantities of 100,000 units per year or more. Thus, a program lasting perhaps 8-1/2 years would appear to be United Aircraft's estimate for this production level.

A detailed breakdown of the Phase I Development and Demonstration program was provided in the United Aircraft configuration-optimization study (Ref. 4-8). This schedule is shown in Figure 4-13. United Aircraft proposed a total of five preproduction prototype engines to be built and installed in three demonstration vehicles. The demonstration would consist of proof of approximately 100 hours of essentially trouble-free operation with each automobile.

In evaluating these timing schedules with reference to schedules proposed by other manufacturers, it is important to recognize that the United Aircraft program does not include a vehicle development or production design effort. According to United Aircraft, the vehicles used for demonstration purposes would be "off the shelf". The Vehicle Development activity indicated in Figure 4-13 pertains only to the modifications required to make the chassis and drive train components suitable for gas turbine packaging and operation.

4.2.6 Williams Research Corporation/Development/Production Programs

4.2.6.1 Background

Williams Research Corporation's gas turbine products fall primarily in the small power unit category with primary application to propulsion of military surveillance and target drones. The company has entered the automotive gas turbine field and is now performing development work for such firms as General Motors and Volkswagen.

The Williams automotive gas turbine engine, WR 26, was developed about seven years ago. The unit is a moderate-pressure-ratio (4:1), regenerative free-turbine engine developing 80 shp. The unit is currently installed in an American Motors Hornet vehicle, driving the rear wheels

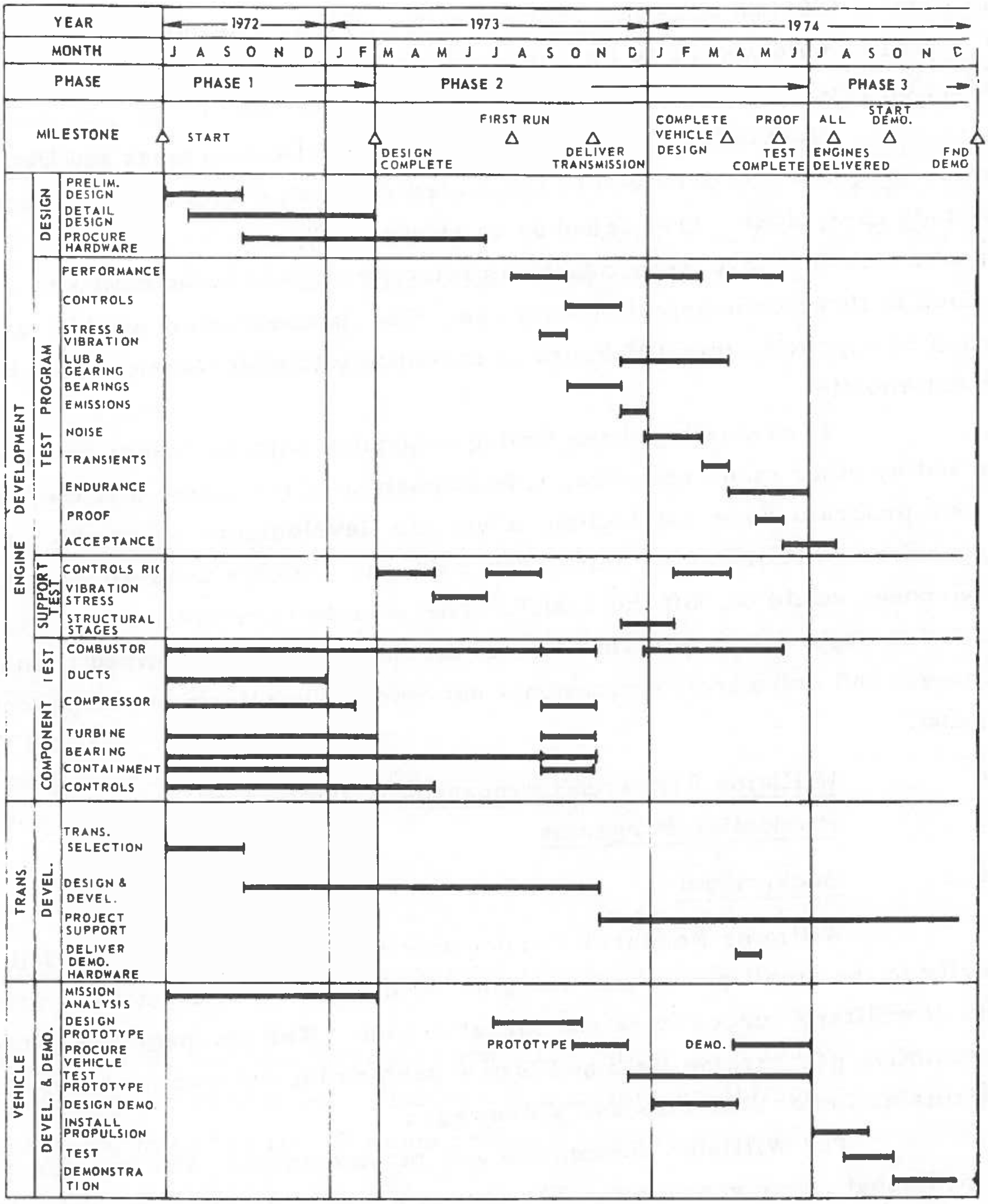

Figure 4-13. Recommended Gas Turbine Engine Development and Demonstration Program, United Aircraft (Ref. 4-8)

through a conventional torque converter and three-speed automatic transmission. In late 1971, this automobile was submitted to the New York City Environmental Protection Administration for testing and evaluation. A number of mechanical problems were encountered, and the vehicle was subsequently returned to Williams. The unit is now undergoing tests at EPA. Another unit, designated 131Q, has been installed in a Volkswagen and has been tested by EPA (see Table 2-8, Section 2.3.3).

In 1972, under EPA contract, Williams performed a cost-of-ownership economic analysis for a gas turbine-powered automobile, using the WR 26 engine as a prototype baseline for estimating the costs of a 1975 state-of-the-art configuration (Ref. 4-9). This analysis indicated that the net cost for ownership of gas turbine-powered automobiles would be substantially lower than current and future piston-engine-powered passenger cars.

4.2.6.2 Current Programs

Williams has an EPA contract to investigate the cost of investment cast turbine wheels and to evaluate processes leading to cost reductions. They developed a conceptual investment casting process and plant suitable for volume production of automotive turbine wheels. A cost summary has been prepared to show the costs associated with raw materials, manpower, and facility capitalization.

4.2.6.3 Product Development Schedules

A timing schedule for product development was not provided by Williams Research.

According to the Williams economic analysis (Ref. 4-9), the basic mass production machining and fabrication techniques and processes currently used in the automotive industry could be utilized to produce nearly all of the components for the automotive turbine engine. New handling, loading, unloading, and transfer equipment would be required. However, Williams feels there is nothing significantly unique about turbine engine components that would prevent the machine tool industry from designing and building this equipment in approximately the same time frame as that required to produce similar equipment for piston-engine parts. Williams estimates this time frame to be not more than 18 months from the beginning of design to the start of production.

Williams notes several exceptions to the use of current processes and techniques. These include the mass production of ceramic regenerator cores, fuel control units, and precision investment castings (or other turbine-wheel production processes). An additional area of concern, according to Williams, is the cost of high-alloy sheet metal parts in the burner components. Williams concludes that process development in these areas is necessary but that the accomplishment of these goals is well within the state-of-the-art for the industry.

4.2.7 AiResearch/Development/Production Programs

4.2.7.1 Background

The AiResearch Manufacturing Company of Arizona, a division of the Garrett Corporation, produces a wide range of gas turbine systems for marine, industrial, auxiliary power and aviation applications. The total number of gas turbines produced from 1945 to 1972 are shown in Figure 4-14. Total production of 17 different models with power outputs ranging up to several hundred horsepower is shown to be about 27,000 units over the 27 year period. Although production of gas turbines has been in effect for some time, the total annual production has never exceeded about 2000 units for any given model; the average annual production for a given model is generally closer to about 300-400 units.

In July, 1972, AiResearch completed an automobile gas turbine optimization study for EPA (Ref. 4-10). The study objective was to determine the optimum gas turbine power plant for a standard 6-passenger automobile

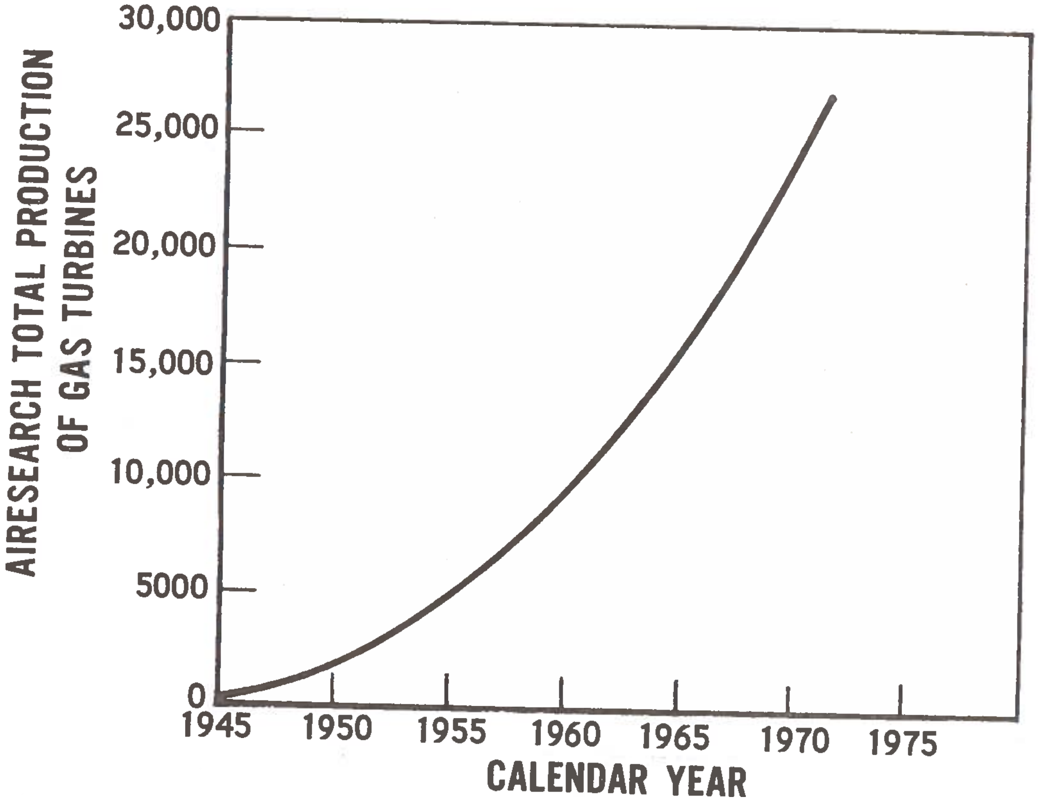

Figure 4-14. Total Number of Gas Turbines Produced by AiResearch From 1945 to 1972

which would meet 1976 exhaust-emission control requirements as well as acceleration, performance, fuel economy, and cost specifications representative of conventionally powered automobiles. The study examined a total of 11 gas turbine configurations, including single-shaft, free-turbine, and multispool configurations with both simple and regenerative cycles. From this array, three prime candidate systems representing the single and split-shaft arrangements were selected. These were examined in detail with respect to design optimization, manufacturing cost, and operating cost. The optimum system was found to be a low-pressure ratio (4.6:1), 108-shp, regenerative, single-shaft design featuring water injection.

The powertrain arrangement proposed for use with this engine would utilize a two-stage gear train driven from the compressor end of the engine, an on/off clutch, and an infinitely variable traction-type transmission (for example, the Tracor design discussed in Section 2.2.2). The transmission output shaft would drive a conventional torque converter coupled to a forward and reverse gearbox.

The AiResearch Industrial Division (AID) in Los Angeles, manufactures a complete line of turbosuperchargers for large diesel engines and for aircraft. At the present time, their annual production comprises about 200,000 units of various types; production rates as high as 1000 units a day are achieved (two-shift operation). The maximum production for any one model is 90,000 units per year.

One high-volume production model is the T04 (40,000 units per year), a design that operates at a low-pressure ratio (3:1 to 4:1), 135,000 rpm, and delivers about 50 hp. The schedule for a crash development program on this unit is discussed in Section 4.2.7.3.

4.2.7.2 Current Programs

AiResearch has been under contract to EPA for some time to develop low-NO_x emission combustor configurations. Since June 1972, AiResearch efforts were concentrated in the area of pneumatic-impact combustors with air bypass and three different types of vaporizer combustors using recuperator bypass.

With their own funding, AiResearch has also been active for some time in the development of a Reusable Investment Pattern (RIP) method of casting. Briefly, the process consists of casting a plaster or ceramic mold from a reusable rubber pattern. The rubber pattern is removed from the mold and can be used many times over. The compressor or turbine wheel is then cast from this mold. The applicability of this casting process is limited to rotor and stator designs that permit removal of the rubber pattern.

The principal advantage of this procedure is low manufacturing cost of turbine wheels, which is estimated at 25 percent of that of an equivalent precision investment casting.

Although this method has been perfected to some degree, a number of problems related to blade distortion and control of leading-edge and trailing-edge thickness remain to be solved.

4.2.7.3 Product Development Schedules

To prove the feasibility of the engine/transmission system selected in the Automobile Gas Turbine Optimization Study, (Ref. 4-10), AirResearch proposed a 33-month demonstration program, which would proceed as depicted in Figure 4-15. The timing schedule for this program is shown in Figure 4-16.

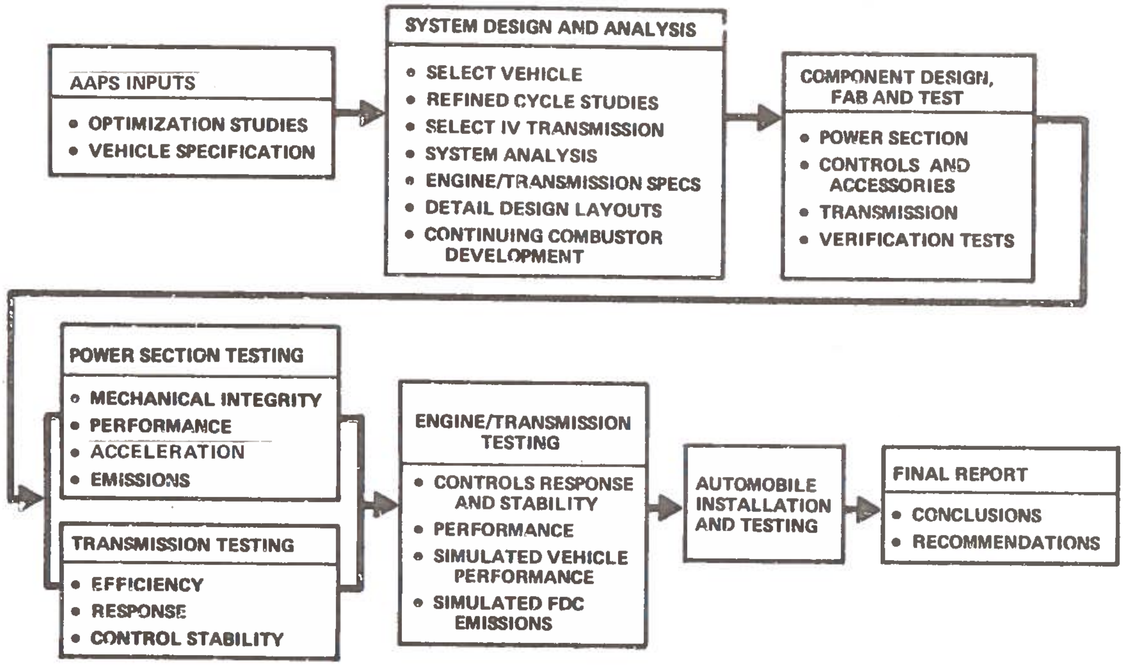

Figure 4-15. Advanced Gas Turbine Automobile Demonstration Program, AiResearch Condensed Logic Chart, Single-Shaft Engine, Infinitely Variable Transmission (Ref. 4-10)

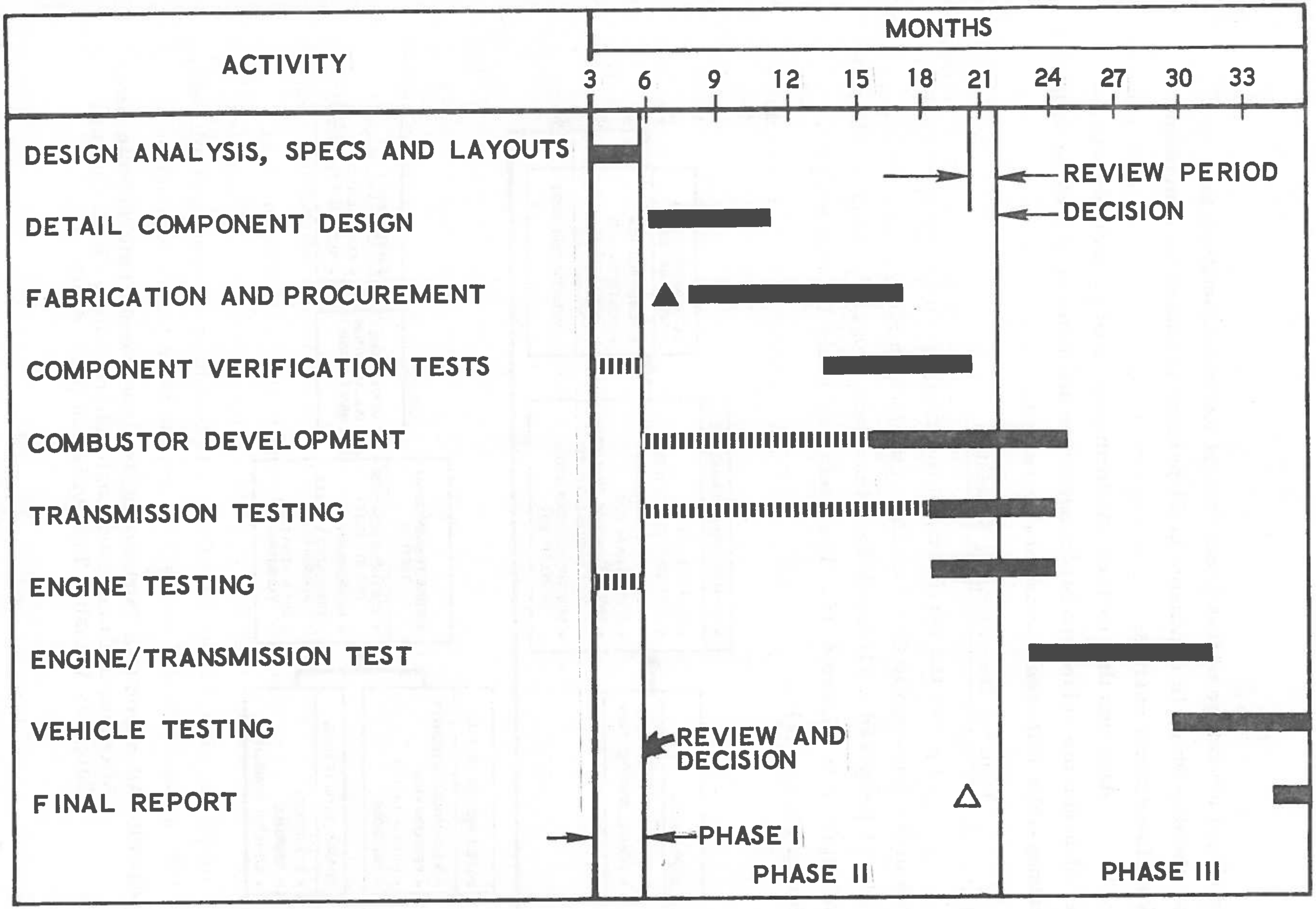

Figure 4-16. AiResearch Advanced Gas Turbine Automobile Demonstration Program Schedule (Ref. 4-10)

Referring to the logic chart of Figure 4-15, the AAPS inputs refer to component developments by other contractors working under the EPA/AAPS Brayton cycle program (e.g., advanced combustor designs for low NO_x). Accordingly, AiResearch proposes to carry out refined cycle analysis studies that would account for the influence of such possible cycle changes as pressure drop, combustor temperature, etc. Following this, engine and transmission specifications would be written. Detailed design activities would then commence; and the engine, transmission, and control system components would be built. This would be followed by component testing, then engine and transmission testing for mechanical integrity, performance, response, control stability, and emissions. The transmission and engine would then be mated for dynamometer tests of the complete system. Following this, the system would be installed in the automobile for demonstration and final verification.

These activities would proceed according to the AiResearch schedule shown in Figure 4-16. Three months have been allotted for design analysis. Detailed design, fabrication, and testing of components would largely be accomplished in the 16-month Phase II period. Engine/transmission/vehicle tests would be accomplished in Phase III, which has a duration of 14 months.

AiResearch has consulted with automobile firms regarding the initial production of from 2000 to 10,000 engines of the type proposed to be demonstrated. During the early phases of the program, AiResearch proposes to split engine production with the automobile manufacturer; later, all production would be taken over by the automobile manufacturer, and AiResearch would only produce engine components. The requirements for getting such an engine ready for production would involve 30,000 to 50,000 hours of dynamometer and vehicle testing, 30 to 40 engines, and 15 to 20 vehicles (engines may cost $150,000 each). Once this test base had been established, it would take a minimum of 5 years to reach the point where production drawings could be released, considering the combined requirements of AiResearch and the automobile manufacturer. A program structured for a more reasonable pace might be 6 to 6-1/2 years in duration.

With regard to turbosupercharger production by the AiResearch Industrial Division (AID) the T04 turbosupercharger unit was developed on a crash basis for the John Deere Corporation. Within 6 months from the start of design layouts, production tooling for castings had been ordered and installed (a $100,000 investment) and about 100 T04 units had been produced and delivered for customer field testing and evaluation. This evaluation took 18 months. At this point, a production purchase commitment from the customer was received, and production machine tools (turret lathes, grinders, etc.) were ordered. Nine months were required for tooling delivery (a normal lead-time requirement for such equipment). AID then went into low-volume production of the unit. Three and one-half years from the start of this program AID was producing 10,000 T04 units. This production buildup rate was governed primarily by the growth in unit sales.

It must be noted that the T04 design involved relatively simple changes from an existing production unit; accordingly, the 6-month design and production development effort should not be regarded as a representative minimum requirement for new units of this type.

4.3 GAS TURBINE MASS PRODUCTION IMPLEMENTATION

In Figure 4-17, each of the manufacturers' product-development schedule estimates discussed in the previous section have been translated into a common format, permitting individual estimates to be readily compared.

With regard to treatment of the manufacturer's data, it is emphasized that in each case where a manufacturer provided upper and lower limits for the duration of a given schedule phase based on considerations of risk or uncertainty, the average of both durations, or the mean chronological position of the milestones involved, was selected for display in Figure 4-17. In a few cases, estimates were made (based on data in Ref. 4-3) concerning the identification of activities in schedule intervals that were not completely defined.

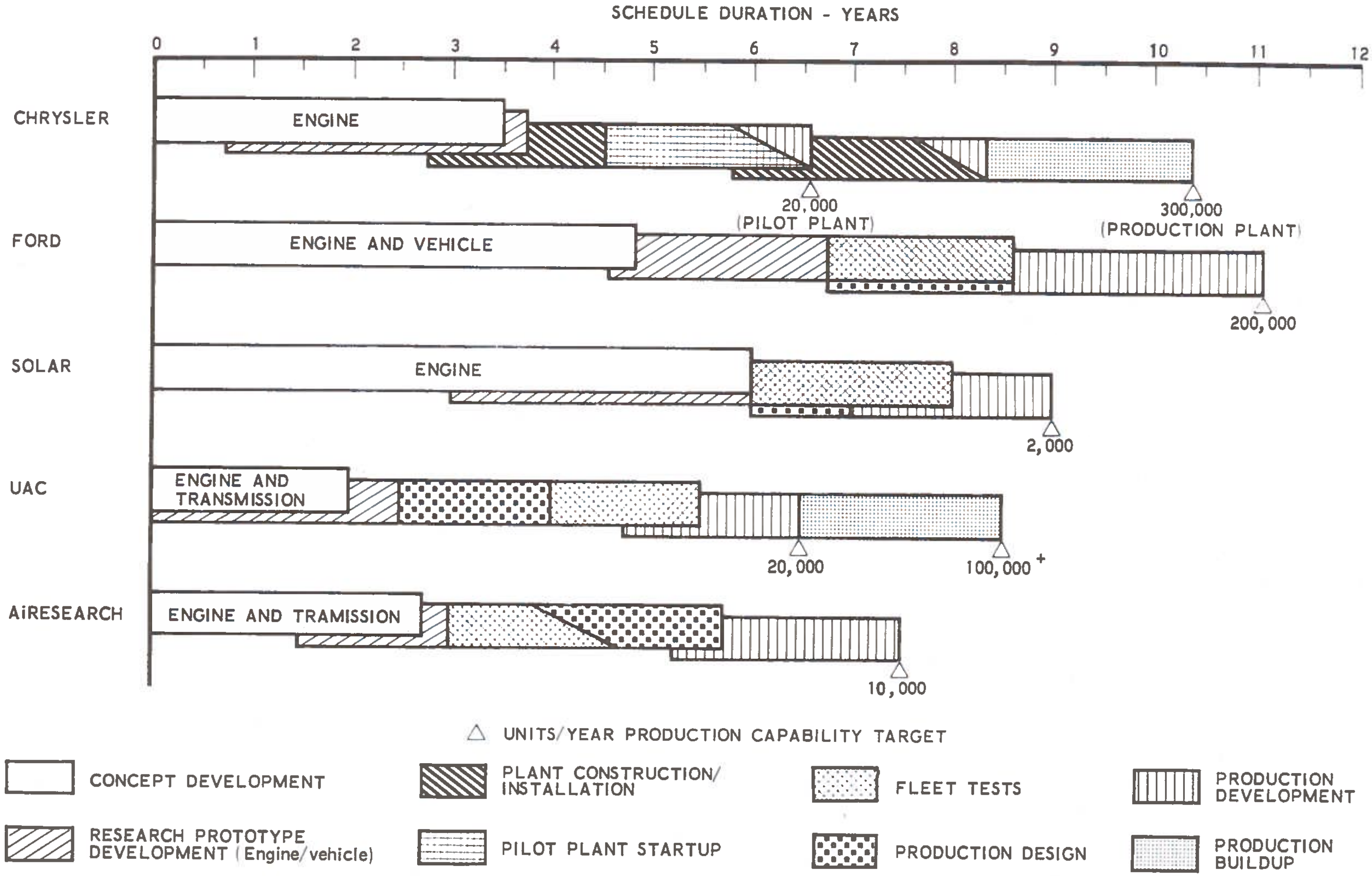

Figure 4-17. Comparison of Manufacturers' Product Development Schedules

Several important noncommon characteristics are observed in the timing plans shown. One of these is that the individual programs differ in scope: the Chrysler and Solar schedules are addressed to engine development; the United Aircraft and AiResearch schedules encompass both engine and transmission development; the Ford schedule reflects the timing effects of both an engine and car development program. Differences in production volume objectives may also be observed. These objectives range from 2,000 to 300,000 units per year among the five manufacturers represented. These schedule-comparison factors are summarized in Table 4-2.

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 militated against a straightforward consensus of the manufacturers' schedule estimates. Instead, the following approach was used:

a. A composite engine/transmission/vehicle product development program targeted to a production volume of 300,000 + units per year was selected as the objective for evaluation.

b. Appropriate schedule elements in each manufacturer's program were compared and evaluated in the light of past automotive industry experience.

Table 4-2. Schedule Comparisons

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^+

c. A best-judgement selection of the duration required for each element of the proposed program was made.

The resulting schedule is shown in Figure 4-18. A total program duration of slightly over 11 years is indicated. This schedule is designed to provide adequate durations for development and test periods so as to diminish the manufacturer's risk in proceeding with successive phases of the product development program. A discussion of the rationale supporting the selection of the various program components is provided in the following paragraphs.

It was assumed that the manufacturer would be starting in a position characterized by a background of experience in turbine-engine development and manufacturing for truck, industrial, and/or other nonpassenger-car applications but would lack actual prototype hardware for an automobile design. On this basis, a duration somewhat longer than 4 years was assigned to the schedule phase identified in Figure 4-18 as Concept Development. This duration is longer than the Chrysler Gas Turbine Development program because it takes into consideration the additional timing requirements for vehicle and transmission development activities. In this phase of the program, vehicle application studies would be made and experimental prototypes of the engine, transmission, other powertrain components, and the vehicle would be designed, fabricated, assembled and tested for performance (e.g. emissions, fuel economy, acceleration, braking, and durability). This would be accomplished at the 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.

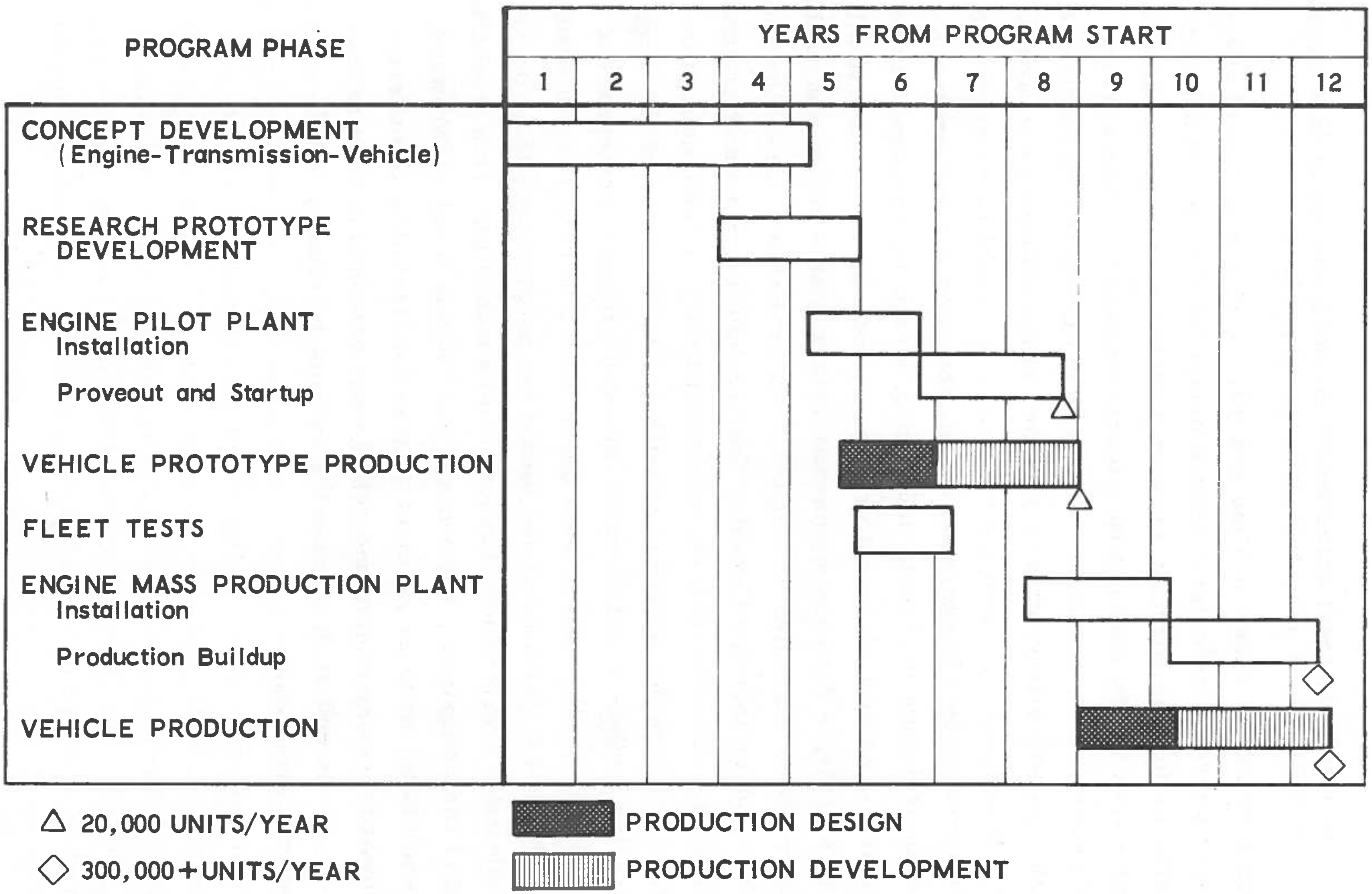

Figure 4-18. Best Estimate of Gas Turbine Automobile Mass Production Implementation Schedule

At a point about 3 years into the Concept Development work, and based on the progress and results achieved up to this point, the engine/vehicle system would be redesigned and upgraded to reflect problem solutions and improvements. Several 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 from both activities. A duration of slightly over 2 years is assigned to this phase, in consonance with an estimate made by Ford.

Concurrent 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 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 (Ref. 4-3). 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-production volume output of about 20,000 units per year (as suggested by Chrysler; see Section 4.2.1). (It is noted that Ford took 3 years to develop its Toledo industrial gas turbine facility, now producing at a rate of only 1000 units per year (see Section 4.2.2).

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 systems.

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 4-18 represents normal timing for conventional internal combustion engine car line production programs (Ref. 4-3).

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; initial activity to develop a plant with a $300,000^{+}$ units/year capacity would then begin. The start of this phase is shown to precede the end of the Pilot Plant Phase by 6 to 8 months; this lead is selected on the basis of minimum-risk considerations, and it agrees with the Chrysler schedule as well as the Engelhard/Ford program for catalytic converter production.

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 4-18 to be of a normal 42-month duration which, in this case, would represent a parallel development of production facilities for several car lines.

The previous discussion was based on development of only one type of mass produced gas turbine automobile. One additional timing factor that must be considered in estimating a practical production implementation schedule is the need to provide a variety of engine sizes to support a given manufacturer's mix of car lines. Table 4-3 shows, for example, the distribution of various piston engine sizes among different cars produced by the Ford Division of Ford Motor Company. This current practice of marketing cars would imply that gas turbine engines would also have to be produced in various sizes. Quantitative information regarding the impact of a multi-engine product line on development schedules was not available from the automobile manufacturers; there were only general indications that this factor would likely extend the schedule duration.

Table 4-3. Matrix of Engine Size Distribution, Ford Division, 1973 Model Year

Engine Type and Displacement (cu. in.)	Car Line					
	Pinto	Maverick	Mustang	Torino	Custom 500, Galaxie, LTD	T-Bird
4 cyl. 97.6	X					
4 cyl. 122	(X)					
6 cyl. 200		X				
6 cyl. 250		(X)	X	X		
V-8 302			X	X		
V-8 351			(X)	(X)	X	
V-8 400				(X)	(X)	
V-8 429				(X)	(X)	X
V-8 460					(X)	(X)

X designates standard
(X) designates option

4.4 SCHEDULE COMPRESSION CONSIDERATIONS

The lead time required for automotive product development is sometimes quite fluid and may be influenced by numerous factors such as tolerable financial risk, product complexity, extent of design modifications from prior models, and production volume objectives. The risk factor is predominant because the financial implications are tremendous for investments of the magnitude involved in automobile manufacture. Accordingly, major new functional components and systems are subjected to extensive research, advanced development, and demonstration test efforts before being introduced into car line production programs. Again, for the purpose of limiting risk, new car systems are first offered to the public on a limited-volume basis to test consumer reaction and system operation under customer driving conditions before committing the device to mass production across several car lines. In general, the rate at which a new device proceeds through the product development cycle is a risk-oriented decision influenced by considerations of available resources, competitive pressures, the potential for increased sales, and other incentives and disincentives.

With regard to the production phase of the product-development cycle, a reduction in the normal schedule time is possible through three practical approaches identified by the automobile industry: increase the degree of overlap between the various phases in engineering development and manufacturing development, extend the use of overtime, or increase the number of working shifts. However, the greater the amount of schedule-phase overlap, the greater the chance for making costly errors through premature decisions. Another factor to be considered in regard to compressing the production-phase schedule is the limited capacity of the tooling industry to provide quick response to short-term schedule objectives when several manufacturers need them simultaneously. Chrysler, for example, indicated that their schedule could be compressed to 8 years by telescoping various schedule tasks. However, they stated that this would increase the risk of costly built-in design flaws and would add to the cost of production. The ultimate financial risk is characterized by potential problems with recall, warranty, lack of adequate sales volume, etc.

A detailed review and assessment of the compression potential of these and other cycle-schedule influences was beyond the scope of this study. The subject should be investigated in depth in order to identify those approaches and schedule phases that would yield a maximum payoff in reducing the product development cycle duration for the gas turbine car. In general, the greatest benefits for schedule reduction appear to lie within the research and advanced development phases of the cycle, since they are the longest by reason of their criticality to the fundamental objectives of the product program. At the same time, these phases presently offer the least incentive to the manufacturer for acceleration because of the risks involved and the lack of any compelling market demand or other forcing function.

One approach to compressing the development schedule of the gas turbine car is to provide additional government support and sponsorship of programs in gas turbine technology, hardware, and manufacturing-process development, similar to the programs that are currently being sponsored and/or monitored by EPA and NASA under the EPA/AAPS Brayton Cycle program. The current programs, with emphasis on technology (primarily improvements in exhaust emissions and fuel economy), have stimulated automotive industry interest in gas turbine engine development. If the Federal government wished to accelerate progress toward gas turbine automotive production, these programs and others like it would warrant continued and perhaps expanded support. Additional emphasis might also be put on manufacturing-process development programs which show promise of significant advancements in solving the current manufacturing problems discussed in Section 3.

The scope of the AAPS Brayton Cycle Program and the participating organizations are illustrated in Figure 4-19 (Ref. 4-12). The funding level available for this project has varied from about \$4.5 million in FY 73 to \$2 million in FY 74. A brief description of these programs is presented in Appendix C.

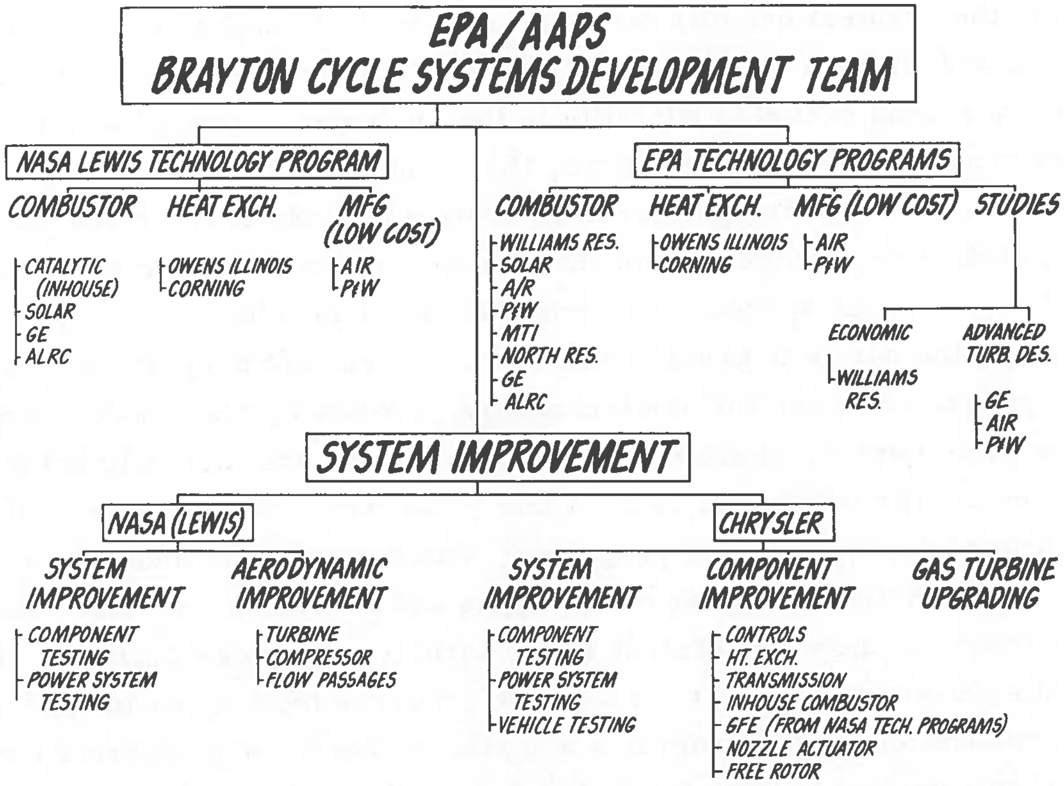

Figure 4-19. EPA/AAPS Brayton Cycle Systems Development Team (Ref. 4-12)

4.5 REFERENCES

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SECTION 5

SECTION 5

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

5.0 INTRODUCTION

This section of the report discusses several significant impacts which relate to the conversion of present-day automotive mass production facilities to the manufacture of gas turbine automobiles. These impacts include the economic effects on the base industry and its suppliers, effects on the labor market serving the industry, and effects on the general public pertaining to air quality, vehicle operation and services, and cost of vehicle ownership and operation. The economic effects have been studied by International Research and Technology Corporation under a program sponsored by the Department of Transportation (Ref. 5-1) and by Hittman Associates, Inc. under a program sponsored by the National Science Foundation (Ref. 5-2). The discussion which follows is largely based upon findings in these two references.

5.1 ECONOMIC IMPACTS

5.1.1 Automotive Industry

The areas of major economic impact on industry of conversion to gas turbine automobiles encompass unit price effects on sales, capital equipment and tooling investment, machine tool and equipment purchase and supply, and material resource and labor skills availability and cost.

With regard to unit price, the projected costs to the consumer for several of the gas turbine configurations under consideration have been presented in Section 3; these costs indicate that the gas turbine vehicle may cost from $200 to $1300 more than a 1970 baseline conventionally powered vehicle. As uncertain as these estimates may be, based as they are on limited manufacturing cost data, they implicitly assume that the gas turbine product development schedule will proceed in a conservative manner. Adequate development and test periods are assumed so as to diminish the manufacturer's financial risk in proceeding with successive phases of the development program. Any significant degree of schedule compression, either in development or in introducing the product to the American public, may tend to increase unit costs even more over those currently projected, since the cost penalties associated with excessive schedule compression must invariably be passed on to the consuming public in the form of higher prices. Historically, many important improvements to automotive products have been made after innovations are first offered for sale. Accordingly, it is standard industry practice to introduce new functional features on a limited production volume basis and to observe the operation and performance of these features under customer-driving conditions for several years before expanding production levels. In addition to the unit cost impact, accelerated industry conversion to gas turbine manufacture would inevitably "freeze in" design deficiencies which may produce adverse public reaction and sales resistance to the new vehicle.

These considerations, coupled with the sensitivity of sales to unit price, argue against an accelerated industry conversion to gas turbine manufacture. The sales impact of price increases comes about as a result of changes in consumer purchasing decisions triggered by the higher cost factor. These decisions encompass a number of options available to the consumer. He may elect to keep his present vehicle longer, to buy an equivalent model of a conventional automobile (offered either as an option or made available by another manufacturer), to purchase a smaller, less expensive vehicle, to buy a used conventional automobile, or to forego the purchase of another automobile and instead to utilize other forms of transportation. It is estimated (Ref. 5-1) that a unit increase in cost as low as 10 percent would reduce the annual demand for automobiles by 13.6 percent and would reduce the industry's gross sales income by $1 billion for the year in which the price change takes effect.

One other sales/price consideration likely to pace the conversion to gas turbine automobile manufacture concerns customer acceptance of the new automobile with regard to performance and other operating features, as well as the general reluctance on the part of some elements of the buying public to switch to new systems.

The total capital investment needed for the annual production capacity of 1 million gas turbine engines has been estimated (Ref. 5-1) at about \$400 million. This investment includes \$140 million for machine tools and \$260 million for facilities, transfer equipment, and other equipment costs. If it is assumed that economies of scale beyond 1 million units do not apply, this investment, extrapolated linearly to a total annual production of 10 million cars, would indicate a capital investment requirement for the industry of about \$4 billion. According to Ref. 5-1, somewhere in the neighborhood of \$0.5 billion can probably be saved from existing facilities, but this would roughly be balanced by a write-down of undepreciated but unsalvageable equipment.

These capital investment figures are roughly supported by a Chrysler estimate that a total capital investment of \$5 to \$6 billion would be required to tool up for an annual engine production capacity of 10 million gas turbine powered automobiles. The Chrysler estimate includes the plants and the tooling required by the automobile/gas turbine engine manufacturers and the tooling industry. Additional costs were indicated to be involved if a mix of gas turbines and internal combustion engines were to be offered with a given vehicle model.

In the short term, the source for 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. Reference 5-1 suggests that conversion to the gas turbine engine could be accomplished without recourse to financial markets by extending the current 3-year model cycle by several years, thereby reducing and conserving the annual model-change outlay, which is on the order of \$1 billion per year. However, the impact of such a course on sales volume may make other alternatives more attractive to the industry.

5.1.2 Suppliers

By reason of changes in the design and material composition of the engine, conversion to gas turbine automobiles will have a significant impact on various supplier industries serving the automobile/engine manufacturing industry. These impacts will occur by the mechanism of changes in the pattern of purchases by the motor vehicle industry, involving tooling and production equipment, manufactured components, spare parts, basic raw materials, and fuel refining requirements. These changes may also impact foreign imports of materials and equipment and may ultimately influence the U.S. balance of payments in international trade.

The principal requirements pertaining to tooling and equipment involve new loading, unloading, handling, conveying, and transfer machine equipment, as well as new tooling materials and techniques needed for high-speed grinding and machining of high-alloy materials required for gas turbine engines. Additionally, heat treating and annealing equipment may be required for use in component assembly facilities after machining operations on temperature/stress-critical components are completed.

With regard to the fabrication of components or subsystems prior to delivery to the engine plants, new sources of supply or new supplier skills and equipment are needed for the mass production of precision metallic castings with near-finished dimensions which are typical of the requirements for compressor and turbine wheels and nozzles. Mass production sources for metallic and ceramic regenerator cores and fuel control units must also be identified or developed. The development of manufacturing skills for new, infinitely variable or other wide speed-ratio range transmissions is another potential supplier-source requirement.

Until such time as a scrap inventory has been built up, the materials consumption for the gas turbine engine will be somewhat greater than for present engine production. The use of high-temperature alloy materials, especially nickel-chrome, will be required. Other critical materials that will be sought include tungsten, cobalt, and titanium (Ref. 5-3). The quantities involved could be significant fractions of current U.S. consumption depending on engine design. Most of these materials are imported, and the new requirements will increase U.S. dependence on foreign sources for several years until the buildup of a new-vehicle scrap inventory permits a recovery cycle for critical materials to be initiated.

Fuel requirements for the turbine engine are considerably more flexible than for the conventional internal combustion engine. No octane or cetane requirements are involved, and a wide variety of fuels from unleaded gasoline through distillate oils may be employed. If phase-in of the gas turbine automobile occurs gradually, standard diesel fuel supplies, augmented in response to increased demand, could be utilized. Ultimately, the refining industry would be compelled by economic pressures to convert refinery outputs to turbine fuels that would permit maximum recovery of useful products from crude oil and would result in the lowest price at the pump. Such fuels could be straight-run distillate No. 2 diesel or furnace oil types, kerosene, naptha, gasoline, or mixtures of these constituents (Ref. 5-1).

5.1.3 Labor Market

In the past, the major automobile manufacturers have adhered to the practice of opening new production facilities by starting production at low levels of output. Employment at new plant facilities is generally built up slowly as workers receive on the job training, and is accelerated gradually, along with output, as the risk of committing larger production volumes to the new labor force diminishes.

As pointed out in Ref. 5-1, a massive, simultaneous shutdown of existing engine production facilities, followed by the mass transfer and training of workers to produce gas turbine engines at new facilities, would create unbearable strains on automotive assembly schedules and may, in any case, be impossible to accomplish in the short term because of new occupational skills and other labor force changes required for the production of gas turbine engines. Foundry workers, machinists, assembly line workers, and workers in after-sales repairs would be particularly affected. Reference 5-1 estimates that a 10 percent increase in direct and indirect production labor requirements (skilled and unskilled) would be needed for gas turbine engine manufacture as compared with the production labor requirements for a conventional (1970) baseline automobile engine. Changes in skill and skill emphasis between the 1970 piston engine labor force and the turbine engine labor force are compared with the projected supply of skilled labor in Reference 5-1. These data suggest that, with regard to the long term, the need for skilled labor generally does not constitute a constraint on gas turbine production implementation. Furthermore, given sufficient time for the conversion to gas turbine manufacture, the present labor force is almost totally salvageable through on-the-job and part-time training. For a given plant labor force, Ref. 5-1 recommends a personnel retraining program spread out over a minimum period of four years.

5.2 IMPACT ON THE GENERAL PUBLIC

5.2.1 Air Quality

Gas turbine automobile production will only be pursued if the vehicle can be shown to compete with the conventional automobile in terms of cost, performance, and fuel economy, combined with demonstrated emission reductions to levels below the 1976 Federal exhaust emission requirements. These requirements call for a 90 percent reduction in HC and CO emissions relative to 1970 model year automobiles and a 90 percent reduction in NO_x emissions relative to 1971 model year cars. These reductions, when referenced to 1968 uncontrolled automobiles, represent exhaust emission control to the level of about 97 percent. Pollutants emitted by mobile sources in 1968 comprised 60 percent of the total HC dump from all sources, 77 percent of the total CO dump, and 43 percent of the NO_x dump. The overwhelming proportion of these mobile source contaminants were emitted by passenger cars.

If it is assumed that the 1976 requirements will be achieved or surpassed by the gas turbine vehicle, the potential exists for improving air quality over 1968 levels, to the extent represented by reductions in these pollutant concentrations, by factors of approximately 58, 75, and 42 percent for HC, CO, and NO_x, respectively, based on a static (1968) vehicle population and no additional benefits due to abatement of other pollutant sources. The rate at which these air quality levels are achieved is dependent upon the rate at which new, low-emission cars are introduced into the automobile population. Historically, this rate has been about 10 percent of the total vehicle population per year. Thus, assuming a static total vehicle population, 10 years of new car production at currently established mass production volumes would be needed before the automobile population would be totally comprised of new-type, stringently controlled vehicles and before the air quality improvements quoted above would be realized.

5.2.2 Vehicle Operation and Services

Aspects of gas turbine vehicle performance and operation in the context of driveability and safety have been discussed in Section 2.3.4. Maintenance and durability issues are addressed in Section 2.5.

In general, the impacts on the general public related to vehicle operation and services primarily concern the reaction of owners to vehicle driveability characteristics relating to standing-start acceleration and response, new engine noise characteristics, lack of vibration, and new schedule requirements for preventive maintenance and repair of the gas turbine engine.

The first owners of gas turbine vehicles will undoubtedly suffer some inconveniences due to unforeseen component attrition effects and the lack of universally available repair or replacement-part facilities. The situation envisioned is not expected to be significantly different from the problems faced by individuals who purchased the first rotary engine systems sold by Mazda in the U.S., and which is still encountered with respect to repair and parts replacement for some of the limited-volume import vehicles sold in the U.S.

An additional inconvenience situation which may exist with respect to gas turbine vehicles when they are first introduced for sale will be the limited availability of fuel grades which may be recommended for best turbine engine performance and response. This situation is not expected to be long-lived; adequate fuel distribution and supply networks will be quickly established as the demand pressures on the petroleum industry are sensed.

5.2.3 Cost Effects

The best projected estimates of vehicle costs indicate that the initial purchase price of the gas turbine vehicle will be greater than the price for the conventional piston engine-powered system. Estimated price increases to the consumer vary widely and range up to $1300. The sales impact of such an increase has been discussed in Section 5.1, indicating that at least a temporary negative response to purchase will be encountered in some segments of the consumer market. Eventually, the price discontinuity between conventional and gas turbine vehicles will diminish in psychological impact on consumer acceptance as the number of conventional vehicles offered for sale is reduced, and as the situation with respect to the new price plateau becomes more familiar with time.

Maintenance and repair costs for the gas turbine vehicle are difficult to estimate with high confidence at the present stage of development. The consensus of estimates by gas turbine manufacturers recently involved in engine optimization and manufacturing cost studies for EPA, 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 will become manifest.

On the basis of a mixed urban-rural driving pattern, fuel economy for improved versions of the gas turbine vehicle is expected to be somewhat better than the conventional baseline (1970) piston engine and considerably better than for 1976 emission-controlled (exhaust gas recirculation/catalytic converter-equipped) conventional vehicles.

5.3 REFERENCES

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SECTION 6

SECTION 6

SUMMARY OF CURRENT AUTOMOTIVE AND GAS TURBINE INDUSTRY ATTITUDES

6.0 INTRODUCTION

A decision to mass produce the gas turbine engine is dependent to a large degree on the viewpoint of many manufacturers as to the desirability of undertaking a relatively new product line. Since there does not appear to be a uniform opinion regarding the many factors bearing on implementation of gas turbine engine mass production, the industry attitudes have been summarized on a company-by-company basis. This summary represents Aerospace Corporation's understanding of the views of each company as conveyed in conversations with company representatives and does not necessarily reflect an official company position regarding gas turbine engines.

The topics covered in this section are not all inclusive, but to some degree include:

1. State-of-the-art technology, design, and performance
2. Material, labor, equipment, and tooling
3. Plant capacity for foundry work, machining, and assembly
4. Provisions for accessory redesign and driveline redesign
5. Fuels and lubricants
6. Cost of manufacturing
7. Capital requirements
8. Consumer market acceptability
9. Development schedules
10. Service after sales
11. Government regulations
12. Government subsidy programs

Although there are numerous contributing factors, it appears overall that the decision to mass produce gas turbine engines hinges on the prospects of capital gains achieved through success in sales (combined with control of manufacturing costs) versus the possibility of capital loss brought about by the risks of marketing uncertainty and unexpected manufacturing costs. Generally, gas turbine engine manufacturers (potential suppliers to automobile manufacturers) appear to be more optimistic regarding risks associated with a new product line whereas automobile manufacturers are more cautious since they assume the ultimate risk in the market place. These distinctions will be brought out in more detail in the succeeding sections.

6.1 AIRESEARCH

AiResearch favors a recuperated version of the single-shaft gas turbine engine with inlet guide vanes used to improve engine fuel economy. The engine would be linked to a hydromechanical transmission. It feels that new traction fluids will be available for the hydromechanical transmission which could increase tractive effort by a factor of three over current designs. An oversized combustor will be needed to accommodate designs leading to reductions in exhaust emission, particularly NO_x.

AiResearch is strongly considering the use of water injection which, it has found, offers a marked boost in power output of the engine and, consequently, would permit a reduction in engine size. This company has had good experience in the use of gas bearings operating at speeds up to 100,000 rpm; hence, there is a strong possibility that this type of bearing will see application in gas turbine engines. Engine braking can be accomplished by reducing power levels to the idle setting which in turn will load the compressor and decelerate the vehicle through power absorption.

AiResearch indicates that the technology is available to proceed with prototype engine tests on a dynamometer within 1 year. These tests would be conducted to verify component performance. Subsequently, the engine would be tested to failure to establish durability levels. Development efforts on the transmission and recuperator must parallel the development efforts on the engine.

During the manufacturing and assembly process the gas turbine engine must be balanced to closer tolerances than piston engines, but balancing can be automated and should not be a significant cost factor. AiResearch estimates that 20 to 25 percent of the engine manufacturing cost is linked to labor;

to achieve this level of labor cost, a significant amount of automated machinery must still be developed.

AiResearch estimates that a "minimum-time program" culminating in release of production drawings would take approximately 5 years (although a more reasonable program might run 6 or 6-1/2 years). During this period, it would expect to accumulate up to 50, 000 engine test hours to verify performance and durability. Following production prototype tryouts, production levels ranging from 2, 000 to 10, 000 engines per year would be achieved. Larger production volumes would be difficult to handle and there would be a gradual transition whereby the automobile companies would use the experience acquired by the gas turbine manufacturers and produce their own engines; subsequently, the gas turbine manufacturers would become suppliers of a number of components to the automobile manufacturers. The initial 5-year program is estimated to cost on the order to $25, 000, 000, including testing. This figure covers development costs and excludes the cost for facilities, equipment, and tooling. With the automobile manufacturer's costs included, the overall program costs could reach a total of $50, 000, 000.

6.2 CHRYSLER

Chrysler favors the design of a dual-shaft (free turbine), regenerated cycle engine. It maintains that with this type of design no muffling of the exhaust is required. The use of metal cores for regenerators is still preferred, designs might be altered if improved performance of ceramic cores is demonstrated in tests (no cracking of cores and good sealing).

Chrysler envisions that in the next 3 to 5 years gas turbine engine designs could achieve a 50 percent improvement in fuel economy. This would be accomplished through improved performance for the regenerator, a reduction in internal heat and leakage losses, a reduction in aerodynamic losses, improved efficiency for compressor and turbines, increased operating temperatures in the engine, and a reduction in engine size (which should result in an improvement in part load efficiency).

Chrysler expects that engine mounting will be normal, with a front-end location preferred. The engine will require a more complicated inlet and exhaust system than is found with the piston engine. A new front end suspension system will have to be designed for installations into existing cars. Modifications will also have to be made to the automobile floor pan and seating arrangements in order to accommodate the exhaust ducts.

Chrysler estimates that it will be 10 years before ceramic components can be considered reliable enough to be used in the turbine section of the gas turbine engine, and some additional years before such components can be put into production. Use of these ceramic components would permit high-temperature operation and could cut current fuel consumption levels in half.

Chrysler feels that currently there is insufficient casting capacity in the country to meet the needs for mass production of turbine wheels and nozzles. These components are precision investment castings which have never been made in large volume and it will be necessary to automate this type of fabrication. An alternative is the use of hot press or powder metallurgy techniques.

Precision machining requirements for the gas turbine engine should be less of a problem than for the piston engine. No tolerance on the gas turbine engine is more difficult than for the piston engine, and there are fewer operations requiring tight tolerances. The worst problem in tolerance is in the machining of reduction gears. (Chrysler feels that there is a need to match gears in order to reduce noise levels in the gear box.) Furthermore, assembly of the gas turbine engine is not as difficult as that of the piston engine. Assembly techniques are quite similar and labor force skills could essentially be the same; however, in the design of tooling and automated production lines the industry would have to essentially start from the beginning since the sequence of machining and assembly operations is quite different.

High-cost items associated with the gas turbine engine are the regenerator and precision investment castings for turbine wheels and nozzles. Chrysler finds that the engine cost is high primarily because of the high cost of raw materials. To reduce this engine cost, it feels that one of the best approaches to take is to reduce the size and weight of the engine.

Starting a production line for gas turbine engines is more difficult than for a new piston engine because of the greater learning process required by the labor force. Chrysler recommends keeping the initial manufacturing plant investment as small as possible because the plant will shortly become obsolete. As the competition learns new processes and benefits from mistakes of the first entrant into the field more efficient plants can be constructed.

Chrysler feels that a pre-pilot production program costing on the order of $1 to $2 million dollars is necessary to get an initial understanding of production costs, in particular those concerning production of precision investment castings and regenerators. Following completion of its EPA contract in about 3 years, Chrysler envisions the possibility of introducing the engine into a new car model program. Because of marketing requirements, it would have to consider a variety of engine families in the design of production operations.

Chrysler estimates an overall 10-year development program effort is required to get gas turbine engine production underway. This period might be reduced to about 8 years on a high-risk basis by telescoping various implementation steps.

The capital investment required for providing engine production facilities for 10,000,000 engines per year would be on the order of $5 to $6 billion dollars.

Engine servicing accomplished at the dealerships would be accomplished by replacement of engine sub-assemblies. Training of service personnel would have to be expanded to meet demands but the degree of training would be no more difficult than current training programs.

6.3 FORD

Ford favors a small, dual-shaft (free turbine), regenerated gas turbine engine operating at high speed for good specific fuel consumption

(SFC). The dual-shaft design with a variable turbine nozzle offers the prospect of well-controlled vehicle braking. The company expects that most of the future gain in SFC will come about through improved component efficiency. This engine will require redesign of the overall driveline (including a modified transmission) and redesign of accessories (since there is no vacuum source available nor a radiator fan for cooling the air conditioner condenser nor hot water from a radiator for use in interior heating of the car). In addition, the large exhaust system associated with gas turbine engines requires a complete redesign of existing floor pans. Ford will probably design a new car to accommodate the gas turbine engine and this would likely form a portion of the Lincoln line.

Ford considers its current effort in the development of ceramics to be in the research phase. Ceramic materials have great appeal because of their inherent low cost; however, ceramics are very susceptible to contamination from salt, sulfidation, and fuel impurities. The stability growth or shrinkage of this material is a great problem. The use of ceramics is more adaptable to fixed nozzle designs for the turbine section. Movement of ceramics during operation is considered a potential problem because of the brittle nature of the material. This problem extends over into the servicing area and service personnel will have to be instructed in the handling of brittle materials.

Ford will consider the design of a variety of engines to satisfy customer requirements, therefore interchangeability from carline to carline is a problem that will eventually have to be faced.

A new program, such as that for the introduction of gas turbine engines, requires running a very large number of test cars through a development program.

Ford favors the use of no-lead fuels with low sulfur content and a high degree of chemical purity.

Ford expects that the cost breakdown between labor and materials is very sensitive to production volume. For high-production rates most of the cost is found in materials, whereas for low-production rates labor costs dominate.

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. Ford has found that great care must be exercised to avoid work hardening, oxidation, and rapid tool wearout from machining superalloys.

Ford feels that the cost of being the first manufacturer to engage in production of gas turbine engines is very high because of (1) the large investment in vendor and supplier facilities, (2) learning new procedures, and (3) the cost of correcting fabrication and design problems.

Ford is now operating at full production capacity. This increased production rate is brought about through the use of improved equipment, more efficient processes, and additional work shifts. Any further increase in production capacity, as may be required for gas turbine engines, would require substantial new investments in facilities

An acceleration in the implementation of gas turbine engine production can be brought about to some degree by Federal assistance in the development of pilot production lines for about 1000 engines per year. This pilot line would be used to uncover special manufacturing problems, e.g., those associated with the use of ceramics for high-temperature turbine processes. If an accelerated program were to be initiated now on a crash basis, it would take until 1979 before an experienced organization like Ford could start mass production of gas turbine engines. It should also be recognized that in any program such as this, the parallel development of the gas turbine-powered automobile is required.

6.4 GENERAL MOTORS

General Motors has conducted an extensive investigation of the dual-shaft (free turbine) engine for industrial and truck applications and is currently investigating both single- and dual-shaft engines for automobiles. The use of a regenerator with both engines is considered essential for achieving acceptable fuel economy. A conventional transmission will be used with the dual-shaft engine. The company has found that performance levels for dual- and single-shaft engines are quite similar. Improvement in fuel economy of the engine is expected by development of more efficient engine components. It also feels that there must be some additional improvement in engine response time.

General Motors derives its incentive to work on the gas turbine engine from the Federal emission control requirements. The company is encouraged by the results of emission control tests which lead it to believe that the engine has good potential for achieving the 1976 requirements. However, it has found that transients in the combustor during engine acceleration or deceleration produce high emission levels and, therefore, the engine must be mounted in a test vehicle to arrive at realistic emission data. It expects to change from the current powerplant only when a superior engine is available.

The engine as currently conceived just fits within the space available in the engine compartment of contemporary automobiles; however, the routing of the exhaust system remains a problem. Current weights of the engine are comparable to those weights associated with piston engines.

General Motors is very concerned about customer expectations for reliability and cost, particularly operating cost in the form of fuel economy. A significant reduction in manufacturing costs for this engine also remains to be accomplished. In this regard, one of the major problems to be overcome is the cost of producing precision investment castings for turbine wheels. It feels that a breakthrough or invention of some type is required to arrive at a means for automating the casting facility and bringing the cost of this component down.

General Motors would eventually introduce a "best engine" design into a limited car line following extensive operational tests in a taxi-cab fleet. The production design would follow the concept of engine installation in an automobile chassis because the cost of developing a new vehicle for the gas turbine engine would be prohibitive if this vehicle/engine combination is not accepted by the public.

General Motors feels that, by the year 1980, performance and efficiency of the gas turbine engine will be comparable to piston engines. To achieve this goal the Federal government can assist in studies on regenerator performance and durability, on means of increasing component efficiency, and on development of new materials such as plastics for compressor wheels.

6.5 SOLAR

Solar feels that a single-shaft engine linked to an infinitely variable speed transmission would be best for automobile applications. It believes this design to be a more responsive powerplant than the dual-shaft engine and there is no need to worry about overspeed protection.

Solar states that future low-emission combustors will have to be much larger in size, designed for variable geometry, and equipped with special control systems in order to meet fuel consumption and emission goals. It is expected that the combustor will become the dominant component in controlling engine packaging. The larger combustor will probably raise the engine cost by 5 to 10 percent at production levels of fewer than 2, 000 engines per year.

The costliest items on the gas turbine engine are expected to be the control system, compressor wheel, and turbine wheel. The company estimates that the control system will represent the largest cost factor; it will represent 25 to 30 percent of the total engine cost at low production volumes and 7 to 10 percent of the total engine cost at high production volume.

An anticipated problem with 1975/76 piston engines will be a decay in the emission performance with time while in the hands of the general public. In contrast, the gas turbine engine should not show any significant decay in performance. Also, since this engine is lighter than the piston engine and has much less vibration, the engine mounts will be lighter. It is expected that the large intake and exhaust pipes will have a major impact on packaging of the gas turbine engine in the automobile.

Solar recommends that leaded gasoline not be used to fuel the gas turbine engine. It expects that synthetic oils will be used for lubrication. Although these oils are more expensive, they do not require changing at maintenance periods and they can operate satisfactorily at the higher temperatures associated with this engine.

Major problems with the gas turbine engine are seen by Solar to be associated with availability of strategic materials and the ability to make low-cost, precision investment castings in large quantities. No problems are anticipated with internal aerodynamics, structural integrity, etc. Exotic materials needed for the gas turbine engine are more difficult to machine, but overall fabrication and assembly of this engine should be no more difficult than for the current piston engine.

Solar feels that major cost items for the gas turbine engine are associated with the control system, compressor wheel, and turbine wheel(s). To bring the gas turbine engine to production status, a breakthrough in cost must come about through the use of new materials or through efficient cooling of high-temperature components to enable the use of low-cost, more conventional materials.

6.6 UNITED AIRCRAFT

United Aircraft favors the design of a high-speed, single-shaft, simple cycle engine. It feels that the high speed increases overall engine efficiency to a level where regenerators are not required and results in a smaller and lighter engine with associated lower costs. No technology development problems are expected with the required, infinitely variable transmission. A muffler will be used in the exhaust system for noise reduction; however, even with a supersonic compressor, overall engine noise should be equivalent to competitive gas turbine engine designs. The only noise area that presents a possible problem is the gear train. With respect to engine exhaust emissions, the company feels that its combustor development work has been very encouraging.

United Aircraft's solution to the high cost of compressor and turbine wheel fabrication is the use of a completely automated "Gatorizing" process. This is a low-cost process with very little scrap loss.

Laboratory tests have been run on a supersonic compressor suitable for an automotive gas turbine engine; this is the most critical element in the company's engine design, since achievement and maintenance of high efficiency has always been a problem with such compressors.

With respect to the transmission, the biggest problem lies in overcoming noise levels and the need for manufacturing costs to be competitive with contemporary 3-speed automatic transmissions. The uncertainty with this transmission is not in its performance but rather in its durability; this durability remains to be proven in comprehensive tests.

United Aircraft prefers the use of no lead, low sulfur fuels to avoid deposits on combustor and turbine wheel surfaces.

No unique tooling requirements are foreseen for the gas turbine engine, except for the particular Gatorizing equipment. The company feels that die life should not be a problem in any contemplated fabrication processes.

United Aircraft believes that there is far less labor associated with fabrication and assembly of gas turbine engines than with piston engines. For example, they state that the piston engine requires 4-1/2 hours of work with assembly of over 1000 parts whereas the gas turbine engine requires 1-1/10 hours of fabrication and assembly with only 250 parts.

It is the company's opinion that simple cycle, single-shaft engines will have a beneficial effect on the energy crisis because they can be introduced into production earlier than regenerative engines and can use less fuel than piston engines. Problems are expected with emissions and regenerator performance and this will delay development of regenerated engines.

United Aircraft would expect to see the initial production of the simple cycle, single-shaft engine by 1978 if its implementation plans were followed.

6.7 WILLIAMS RESEARCH

Williams Research favors the design of a dual-shaft regenerative engine. It prefers the use of a ceramic regenerator core since it maintains that this core is cheaper than a metal core for high production levels. No muffler is required; however, there may be a potential noise problem with the intake system. A catalytic combustor will be required in order to have the engine meet 1976 Federal emission control requirements.

Williams Research considers the severest problems associated with development of the gas turbine engine to be as follows:

1. Development of processes for producing precision investment castings for turbine wheels
2. Durable, low-leakage seals for ceramic regenerators (although this problem does not look as difficult as the seals required for Wankel engines)
3. Fuel control systems

The production of precision investment castings requires the use of sophisticated technology and has never been previously addressed from the standpoint of the low cost methods used in mass production by the automobile industry.

Williams Research expects to see improvements in fuel economy brought about by improved efficiencies for regenerators, improved efficiencies for rotating components (such as compressors and turbines), and higher operating temperatures for the engine.

The company anticipates that the exhaust system may cost as much as two times the cost of conventional exhaust systems and this problem may dictate installation of a mid- or rear-engine design for automobiles.

Williams Research feels that a 4 to 5 year period remains in which to improve technology associated with the gas turbine engine. Following that period, new manufacturing processes must be proven and prototype field test fleets must be run. Even with Federal government assistance, it expects that an accelerated program cannot be completed until the 1980 to 1982 period. It would be some time after that before the automotive industry could be expected to reach a production of 10 million engines per year.

SECTION 7

SECTION 7

ASSESSMENT OF MASS PRODUCTION VIABILITY

7.0 INTRODUCTION

In making any general assessment, it should be recognized that the validity of the conclusions is affected in large part by the quantity and quality of supporting data. For gas turbine engine technology the data are quite extensive, but this is not the case for manufacturing processes and cost estimates. For these latter factors, the automobile manufacturers and gas turbine engine manufacturers have primarily limited their investigations to analytical studies. Before engine costs and development schedules can be viewed with a high level of confidence, actual manufacturing trials on critical components must be conducted.

7.1 CURRENT POTENTIAL FOR PRODUCTION IMPLEMENTATION

7.1.1 Design and Performance Capabilities

In the last 20 years, dramatic improvements made to gas turbine engines for aircraft applications have resulted in significant increases in power output per pound, reduction in maintenance requirements, and improved reliability. In many industrial applications, gas turbine engines with recuperators have met or bettered the operating costs of diesel engines.

In the automotive area, the Williams Research engine has been evaluated in an intermediate-size automobile, and Chrysler's experience with its 50-car fleet demonstration program has led to a sixth-generation engine installed in an automobile that demonstrated performance capabilities for acceleration, braking, and quietness that would satisfy the requirements of a wide variety of consumers. At present, 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, engine response time would have to be improved slightly to match low-speed acceleration capabilities of the current powerplant. High speed acceleration is very good, and 0-60 mph time is as good as the spark ignition engine.

Of prime importance is the prospect for the gas turbine engine-powered car to meet Federal government requirements for exhaust emissions. Current gas turbine engines have demonstrated remarkably low levels of HC emissions with CO emission levels approaching 1976 Federal requirements (and meeting the requirement in the case of Chrysler's car); in contrast the NO_x emission levels are still quite high. However, recent steady-state tests of combustors and associated analytical studies have shown that redesigned combustors with fuel prevaporization and variable geometry might be capable of meeting the 1976 Federal requirement for NO_x; 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.

With respect to the fuel economy of the gas turbine engine powered-car, the current performance is below that of 1970 to 1972 cars powered by internal combustion engines. But it is estimated that future gas turbine engine-powered cars with superalloy turbine wheels can meet or better the projected fuel economy of 1976 spark ignition internal combustion engine-powered cars fitted with all required emission control equipment. Whether this can be accomplished with a concurrent ability to meet 1976 Federal emission requirements 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 internal heat and leakage losses, and more sophisticated fuel control systems. In addition, a significant improvement in fuel economy of about 20% is expected by operating at higher temperatures which is possible with the application of ceramic materials to turbine wheels. By application of all possible techniques, one automobile manufacturer has projected an overall possible improvement in fuel economy of about 50%.

Engine design is, for the most part, founded on well-tested concepts and components. However, each manufacturer's choice is risk dependent. The manufacturers of current gas turbine engines for aircraft or industrial applications may be viewed as potential engine or component suppliers to the automobile manufacturer(s). In this role, the gas turbine manufacturer's risk is not in the consumer marketplace, and the trend appears to be for them to select configurations with the highest performance and lowest manufacturing cost potential. The selection is generally a low-pressure-ratio, single-shaft design with regenerator or recuperator. In one case, a high-pressure-ratio engine is favored with elimination of the regenerator/recuperator, relying on improved components of high efficiency operating at high rotational speed to approach acceptable levels of fuel economy; this engine has potentially the lowest manufacturing cost. These designs have not been subjected to any automotive-oriented testing, and they also require the use of a new transmission design--one with a continuously varying gear ratio (referred to as the infinitely variable transmission).

Conversely, the general attitude of the automobile manufacturers is to adhere to proven, well-tested concepts; the result is the selection of a low-speed, dual-shaft, low-pressure-ratio engine. This design, when contrasted to a single-shaft design, has some inherently higher manufacturing costs due in part to its larger size and an increase in the number of components. The selection of this design is influenced by analytical investigations, as well as by (1) Chrysler's experience with its automotive gas turbine engine, (2) Ford's experience with its industrial, marine, and truck/bus engines, (3) General Motors' experience with its truck/bus engine, and (4) the ability to use a conventional 3-speed automatic transmission. Although this design is currently the first choice of the automobile manufacturers, a thorough, continuing investigation of the single-shaft engine is being pursued by at least one automobile manufacturer to provide a balanced data base for future decisions on a final choice of powerplant.

Both types of engines require the use of variable geometry to come close to matching conventional piston engine response times during acceleration. The single-shaft engine would require variable inlet guide vanes and the free turbine engine would require a variable power turbine nozzle; the latter engine benefits also from the braking effect of the nozzle.

The use of regenerators or recuperators is necessary to bring the fuel economy to acceptable values; the usefulness of these devices is diminished, however, for a high-pressure-ratio engine design.

The nominal power requirement of a gas turbine engine is 150 hp for meeting acceleration specifications for a full-size, six-passenger automobile. At this power level, designers have selected engine speed ranges of 37,000 to 50,000 rpm for the low-pressure-ratio (4:1 to 5:1), dual-shaft engine, and 85,000 to 110,000 rpm for the smaller, high-pressure-ratio (9:1 to 12:1), single-shaft engine. The air flow requirements of the engine result in large exhaust ducts that will require modifications to the vehicle floor pan and overall chassis design in order to retain adequate ground clearance and structural integrity.

In summary, evaluation of recent technical advancements and extension of component data to prediction of engine performance indicates a strong potential for the gas turbine engine to meet both industry and government performance goals within the next 2 to 3 years. Continued Federal government programs in support of engine development for improving fuel economy and exhaust emissions will provide a greater surety for this assessment. Included within such programs is the need to verify engine durability, reliability, and maintenance in both laboratory and road tests.

7.1.2 Manufacturing Technology and Cost

The main roadblock to plans for production implementation of the gas turbine engine is manufacturing cost. Current analyses show that the requirement for using superalloy precision castings in the turbine section, a complex engine control system, and, in most cases, a regenerator or recuperator unit, raises the manufacturing cost above that of the internal combustion reciprocating engine. The cost of exotic materials is responsible for a significant portion of the high engine cost; hence, from one standpoint, the smaller the engine, the lower the cost. Some engine design approaches to reducing costs appear to be quite interesting. These include: (1) increasing engine speed to reduce engine size; (2) using water injection to increase peak power output, thereby permitting a reduction in engine size for the same performance; (3) cooling components with air to reduce material temperatures and, hence, reduce material cost (assuming cooling passages can be fabricated cheaply); (4) using ceramics in place of metal to reduce material costs for regenerators and turbine blades; and (5) using internal insulation of engine housings to maintain lower operating temperatures and permit the use of gray iron castings in place of the more expensive nodular iron castings.

Mass production manufacturing of the gas turbine engine will require scrapping or reassignment of existing machining and assembly equipment. The mix of grinders, lathes, drills, bores, taps, mills, etc., will certainly change, but the basic type of equipment will remain the same. Nonetheless, the machining rates for superalloys will have to be carefully controlled to avoid modification of strength properties or rapid wearout of tooling. Automatic transfer equipment will require a large degree of innovation in design to handle new machining and assembly sequences.

In preparation for casting high-temperature materials, great care is required to assure that the mold does not change shape, size, and surface properties during its forming and that it does not crack during the pour process. To reduce costs, the investment casting of high-temperature superalloys will require some major breakthroughs in production processes to (1) reduce the current fabrication time related to the long drying periods for the ceramic shell molds, (2) reduce the space required for drying, and (3) permit the introduction of automation. A high degree of precision is required in the finished casting to avoid the need for expensive machining of convoluted surfaces associated with turbine blades.

The high cost of labor requires that extensive automation of manufacturing processes be pursued, but always within the framework of acceptable capital costs. An engine design that meets performance specifications and is also readily adaptable to automation in fabrication and (particularly) in assembly will receive the most attention.

The elaborate 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 techniques. These techniques may or may not have been effective at current low production rates, but they could be essential at production levels of 100,000 to 1,000,000 engines per year. There is also the need for new suppliers of major components such as those for regenerators/recuperators and electronic fuel control systems to evaluate low-cost manufacturing techniques for high production levels that historically have not been associated with this type of hardware. Of equal importance is the verification that equipment and tooling can be provided in sufficient quantities to support mass production of engine components.

It is of interest to note that mass production of gas turbine engines ($100,000^+$ units per year) 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 only 300 units per month. This may be compared to rates as high as 35,000 engines per month per assembly line in the automotive industry.

Within the general category of turbo-machinery, however, there are some examples of high production rates. The AiResearch Inudstrial Division currently produces over 200,000 turbo-superchargers per year for automotive and aircraft applications. (The relative simplicity of these small units does not permit a ready comparison with the larger, more complex automobile engine.) Also, certain aircraft gas turbine components are produced in quantities comparable to automotive industry production rates. For example, 3000 turbine blades are used in each of 1500 JT8D engines produced annually by the Pratt & Whitney Division of United Aircraft Corporation for large commercial jet planes. Therefore, a total of 4-1/2 million blades are required to be produced each year. Most of these blades are purchased from a number of different vendors.

In summary, the basic machining and assembly operations for the gas turbine engine should be no more difficult to handle than those used for the piston engine. Of most concern is the need for a significant reduction in manufacturing costs, and, in particular, to provide low-cost precision investment castings for compressor and turbine wheels (and nozzles where applicable to the engine design). While some limited studies are in progress to seek solutions to the problem of manufacturing cost, until the automobile manufacturers have adequate evidence of cost-cutting procedures, the future prospects are poor for replacement of piston engines with gas turbine engines. 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 procedures cannot be over-emphasized.

7.1.3 Manufacturer and Supplier Capacity

The physical ability of the automobile manufacturer to convert to mass production of gas turbine engines is a strong possibility. Initially, new plants would have to be constructed, but, as the conversion from piston engines to gas turbines evolves, current factory floor space will be available after the existing tooling and equipment are scrapped or reassigned elsewhere in the company. The conversion must be accomplished in stages over a period of years. Even without considering capital requirements, this procedure is required for numerous reasons.

First and foremost is the limited ability of the equipment and tooling suppliers to support any large-scale industry changeover. Their capacity is relatively inflexible because of a limited labor force. The supply of skilled machinists/technicians/designers has been shrinking in recent years due to the lack of major model changes as automobile manufacturers have concentrated on the implementation of exhaust emission control systems and safety features. Second, from the standpoint of labor considerations, the automobile manufacturer must have sufficient time to retrain foundry workers, machinists, and assembly line workers.

All 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 number of years, say about 10 years. Even if only 300,000 engines per year were initially manufactured by each firm, it would still be a problem for these supply industries to meet initial demands.

The gas turbine manufacturers would also have to establish new factories for production of a complete engine. Indications are that they could not respond as rapidly as automobile manufacturers to large production volume requirements. Most likely they could supply engines for a pilot production line at volumes up to about 10,000 engines per year and then, as orders from automobile manufacturers increase toward 100,000 units per year, revert slowly to production of engine components only. The dominant inertia factor influencing response time would be implementation of large foundries to handle castings for the engine housings, compressor wheels, and turbine wheels.

The potential problem of supply of cobalt, molybdenum, and niobium 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. In addition, the rolling capacity of the steel industry appears capable of meeting the expanded needs for stainless steel sheet.

No specific concern was expressed by the automobile manufacturers regarding the ability of suppliers of ceramic regenerators or engine control systems to meet mass production levels. However, as designs for these units become more refined, the Federal government should undertake direct discussions with potential suppliers to specifically determine their ability to respond to mass production orders.

In summary, the capacity of manufacturers and suppliers is estimated to be adequate for the mass production of gas turbine engines. However, the rate at which inherent capacity can be converted to the manufacture of this type of engine is still in doubt. Future evaluations of this problem are recommended in order to confirm when the casting industry has made a significant advancement toward plans for automation of precision investment castings and to ascertain when industry and/or government have initiated discussions with foreign suppliers of raw materials.

7.1.4 Plant Capital Investment

A mass production gas turbine engine plant can be considered cost-effective if it is issuing at least 200,000 to 300,000 engines per year. Estimates of the funding requirements for plant renovation (or new plant site), equipment, and tooling are available from two sources. IR&T has projected a cost of $400 million for an annual production rate of 1,000,000 engines per year. Chrysler has estimated a cost or $5 to $6 billion for an annual production rate of 10,000,000 gas turbine engines. This would result in an estimate of roughly $100 to $200 million investment per plant. This level of investment could only be assumed by the largest automakers over a lengthy period and must be justified on the basis of production cost savings of the gas turbine engine over the piston engine. It appears that many gas turbine engine manufacturers could not readily assume this fiscal burden and might have to rely on assistance from the automobile manufacturers. In the past, this assistance has been provided by automobile manufacturers to supporting companies whereby each of the suppliers use tooling and equipment that is owned by the automobile manufacturer.

A continued trend in automation of manufacturing processes can be expected as long as labor costs remain high. The equipment and tooling used in mass production have become more sophisticated and a degree of flexibility in use is thereby lost. Once set up, the automated production line is generally useful for only one engine design. Therefore, to avoid costly changes pre-planning must be very thorough before committing a given design to production. Because of the current extensive applications of automation, the introduction of the gas turbine engine into mass production in a modern plant can be expected to take longer than was the case for the V-8 engine at the time it became the dominant power plant for automobiles.

In summary, if through exhaustive tests and limited manufacturing trials, the gas turbine engine is shown to be superior to the internal combustion, reciprocating engine in fuel economy, exhaust emissions, and cost, the automobile manufacturers might feel compelled to commit major capital funds to mass produce this powerplant. The timing is dependent upon progress in both technology and low-cost manufacturing processes.

7.1.5 Development Schedule

The length of time between concept development and mass production of a new product line is governed largely by the opposing factors of quickly matching or exceeding the competition in sales (with an acceptable profit margin) versus minimizing the financial risks by delaying product line introduction until all significant problems have been resolved. This assumes, of course, that sufficient capital is available for launching a new venture when the time for commitment of production facilities is at hand. Minimizing financial risk in one sense involves assurance of a reliable product that will lend validity to the warranty period and that will not subject the product to recall for defects that arise during consumer use. Financial risk in another sense is found in the spread between estimated and actual production costs where faulty equipment, tooling, inventory control, or labor allocation can easily erase the expected profit margin. These factors are under consideration in every company producing a marketable product, but for the case of a company in mass production, such as the automobile firms, where profit margins are small and acceptable profit is based on achieving large volume sales, the financial risks are even more pronounced.

The automobile manufacturer, being cognizant of these risks, spends an extensive period of time on verification of estimates for both product performance and low-cost production techniques. Verification of performance is sought through a wide variety of test programs that attempt to simulate the product usage in all environments and, as successive degrees of success are met, the test sample size is increased to improve statistical confidence in the test results. Verification of production techniques is achieved through experiments on single-purpose, numerically controlled machines and eventually on pilot production lines with automatic transfer machines.

The mass production implementation schedule would proceed from this time with tests on hand-made pre-prototype gas turbine cars and evolve to prototype tests for a limited car line. Following redesign, as needed, fleet tests would be conducted to gather statistical evidence of performance and durability. Then the manufacturer could enter a low production phase after pilot runs had provided confirmation of manufacturing techniques. Mass production of all models for the entire automobile line might then take up to 10 years from start of the low production phase.

Both technical performance and manufacturing assurance tests form the heart of the development schedule and pace the entire effort. Since the gas turbine engine is a marked departure from previous automobile powerplants (both in design and in certain production processes), the testing period is logically longer than, say, for a new piston engine whose basic design and manufacturing processes are backed by many years of experience that lend early confidence to estimates of performance and production costs. Additionally, this new engine will require design changes to the current automobile and, for the most effective implementation in the marketplace, a new automobile may have to be designed to take advantage of unique or superior features of the engine.

For these reasons, a development schedule based on discussions with the automobile manufacturers covers a period of slightly over 11 years from concept development until full mass production of gas turbine engines is achieved. This schedule is designed to provide adequate durations for development and test periods so as to diminish the manufacturer's 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 for new vehicles will vary from company to company.

The above schedule contrasts with historical experience with piston engine schedules that, without the research and development phase, run about 4 years for minor design changes and about 6 years for major design changes. But it should be understood that even major changes on the piston engine rely on proven technology and manufacturing techniques developed over the last 30 to 40 years.

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. This requires the expenditure of large funds to accelerate the rate of testing. If the government wishes to accelerate the development schedule, and not rely on normal market competition to control engine development, it must appropriate funds for this purpose. Some expenditures are currently underway, with the most significant effort being handled under Chrysler's $6.5 million contract with EPA for development of improvements to its sixth generation gas turbine engine. The program is now weighted heavily toward solution of engine and vehicle performance problems. At some time in the future, the emphasis would have to shift to efforts at development of low-cost manufacturing processes and to their verification in a simulated production line. This program could commence prior to the completion of the technology program. The cost of such a program, however, would be much greater than the cost of the technology program because of the need to provide manufacturing space in a production-type facility and to purchase equipment, tooling, and raw or processed materials.

As a possible supplier to the automobile manufacturer(s), gas turbine manufacturers generally are more optimistic and favor more advanced designs than the automobile manufacturers. Of course they have the potential for marked increase in income without the problems of vehicle/engine integration and eventual consumer marketing of the product. Proposed test programs of gas turbine manufacturers also do not appear to require the large fleet tests that automobile manufacturers consider essential for statistical evidence of satisfactory operation. (In fact, one automobile manufacturer favors taxi fleets that can provide a harsh operating environment with rapid accumulation of mileage.) Therefore, with lower risks and a large profit incentive, the development schedule appears to be viewed in a shorter term context more by the gas turbine engine manufacturer than by the automobile manufacturers.

In summary, it is estimated that automobile manufacturers would consider limited production (10,000 to 20,000 units per year) of gas turbine engines to be feasible anywhere from 5 to 6 years from now and mass production (300,000 units per year) in about 8 to 10 years from now with 10 million annual units in an additional 10 years.

7.2 POSSIBLE GOVERNMENT ROLES FOR ENHANCING PRODUCTION VIABILITY

The role of government in the development of 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. In fact, the current EPA-AAPS programs appear to have stimulated automotive industry interest in gas turbine engine development. However, programs that support development of manufacturing processes would hold some risks for the manufacturers. On the one hand, government funding directed at solutions to engine production would save the manufacturer from expending his own funds and would be 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.

7.3 OTHER CONSIDERATIONS

On the basis that initial production rates of the gas turbine engine will be quite low, introduction is anticipated to take place in limited production runs of a specialty car or a top-of-the-line model (e.g., Cadillac, Lincoln, Imperial). These more expensive automobiles will also provide a cost structure that can more easily absorb some degree of variability in engine costs that may result from unanticipated production problems. Eventually, consideration must be given to the difficulty associated with developing a family of engines to satisfy the current consumer market that tends to prefer a wide diversity in product selection and results in automobile manufacturers offering a large model mix.

It should also 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 can not 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 engine 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 areas. 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.

With the advent of the gas turbine engine in the hands of the consumer, after-sales service at dealerships will be affected both in labor and materials. All the engine parts will have to be stocked nationwide, creating a new inventory problem.

Because the engine has been projected to have low maintenance requirements (no oil, spark plug, or timing changes), most service periods would likely be devoted to (1) ensuring proper operation of fuel inlet jets; (2) cleaning or replacing air intake filters; (3) cleaning or replacing the starting ignition source; (4) inspection of regenerators/recuperators for deposits on core surfaces, for seal wear, and for core cracking; and (5) verification of proper control system operation. Any major work on the engine would probably be handled by removal of a complete subassembly and replacing it with new or reworked parts from a central processing plant.

Most service operations must be handled by skilled mechanics, but training programs will not entail longer or more difficult instruction than for piston engines. An exception may come about eventually when turbine wheels are made of brittle ceramics; the handling problems in that case will be quite different and special instruction programs would be required.

It is essential to point out that some of the information disclosed by this study would bear more detailed examination. The fact that there are problems associated with expanding the capacity to manufacture regenerators and electronic control systems and with automating the manufacture of precision investment castings has already been noted. But details regarding estimates of capital costs and the time required to accomplish these specific tasks should be discussed further with the suppliers themselves; i.e., with those companies that might be involved directly with the implementation effort.

Finally, if low cost, reliable production techniques are not forthcoming for critical hardware in automotive gas turbines within the next 2-1/2 to 3 years, then the postulated 11 year development schedule for gas turbine powered automobiles will likely have to be extended in duration.

APPENDIX A

APPENDIX A

LIST OF PRINCIPAL DATA SOURCES

Agency	Date of Visit	Primary Contact(s)
Ford Motor Company	February 28, 1973	Ivan Swatman, Chief Engineer, Industrial Engine & Turbine Operations Bruce Simpson, Executive Engineer, Emissions Office
Chrysler Corporation	March 1, 1973	George Huebner, Director of Research
Williams Research Corporation	March 2, 1973	Sam Williams, President
Pratt and Whitney Division, United Aircraft Corporation	March 9, 1973	Reeves Morrison, Corporate Technical Staff Edward Wright, United Aircraft Research Laboratories
Solar, Division of International Harvester	March 14, 1973	Charles Gotschalk, Program Manager, Saturn Gas Turbine William Compton, Assistant Director, Research
AiResearch Manufacturing Company of Arizona, Garrett Corporation	March 22, 1973	Edwin Strain, R&D Sales B. Carl Riddle, Engineering Project Industrial Engines
NASA, Lewis Research Center	March 23, 1973	Jack Heller, Head Automotive Power Systems Office Richard Rudey, Combustion & Pollution Research

Agency	Date of Visit	Primary Contact(s)
Advanced Automotive Power Systems Office, Environmental Protection Agency	April 24, 1973	George Thur, Chief Power Systems Branch
General Motors Research Center, General Motors Corporation	April 25, 1973	Tibor Nagey, Director Passenger Car Turbine Development
Austenal Division Howmet Corporation	April 26, 1973	James Boyle, Operations Manager Michael Higgins, Sales Manager
AiResearch Industrial Division, Garrett Corp.	April 30, 1973	John L. Mason, VP, Engineering James Hardy, Director International Operations and Sales

APPENDIX B

APPENDIX B

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APPENDIX C

APPENDIX C

SUMMARY OF EPA/AAPS BRAYTON CYCLE PROGRAM

C.1 EPA/AAPS GAS TURBINE TECHNOLOGY SUPPORT PROGRAMS

C.1.1 Chrysler Baseline Engine Development Program

This contract covers the manufacture, upgrading, and testing of Chrysler's 6th-Generation automobile gas turbine engine, incorporating improved components as evolved at Chrysler and from other elements in the AAPS activity. The goal is to demonstrate emissions below 1976 Federal requirements and fuel economy competitive with conventional vehicles powered by precontrolled spark-ignition engines.

The development logic of the Baseline Engine Program is shown schematically in Figure C-1. Additional details concerning Chrysler's participation in this effort are provided in Section 4.2.1.

C.1.2 NASA/EPA Automotive Gas Turbine Technology Program

NASA-Lewis is conducting an automotive gas turbine technology program in support of the EPA gas turbine program and is managing certain EPA contracts related to gas turbine system and component technology and improvements.

The problem areas to be addressed in the NASA effort include low emissions, low cost, low fuel consumption, and long life. Low emissions are sought by means of improvements in combustor design. Four candidate combustors have been tentatively selected from current EPA programs, and these will be tested by NASA in their gas turbine test facility. One of these designs will be installed and tested in a gas turbine to be manufactured by Chrysler under their EPA contract. Cost reductions will be evaluated by considering (a) different turbine-wheel manufacturing processes

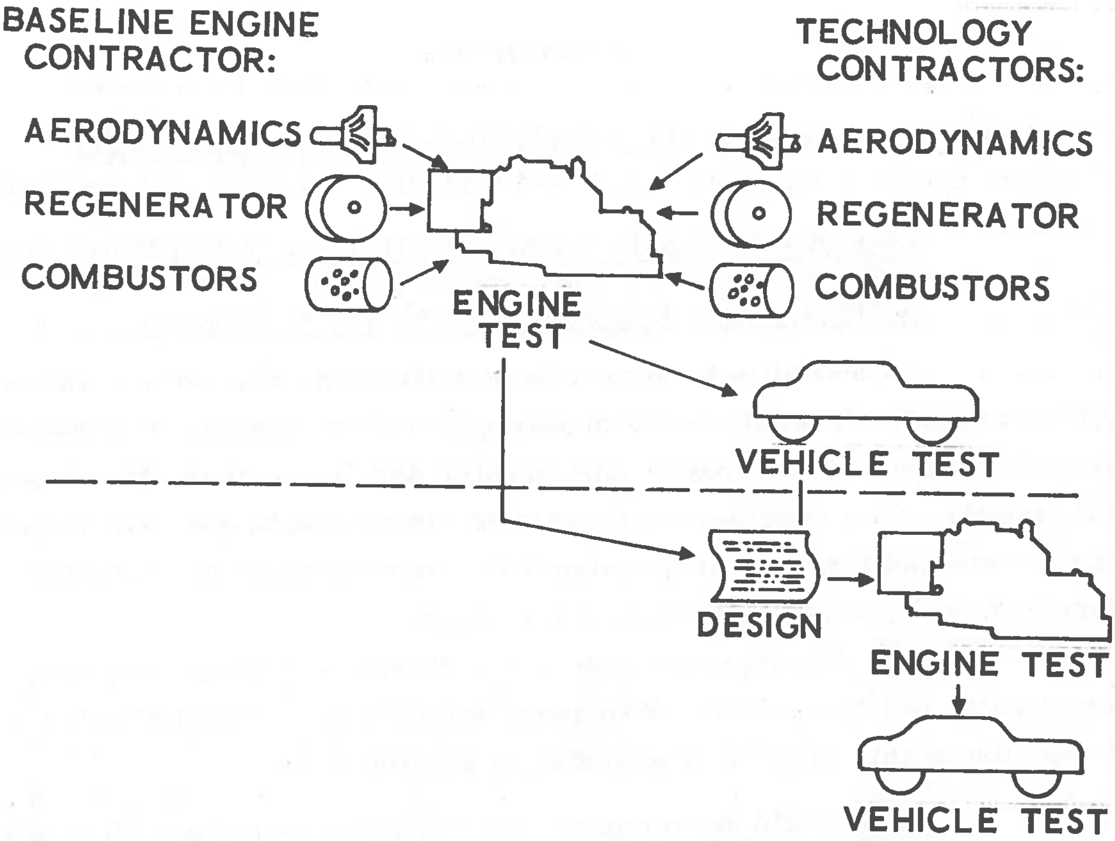

Figure C-1. Development Logic for EPA Baseline Gas Turbine Engine Program (Ref. 4-11)

(integral cast, integral forged, separately forged, or cast discs and blades) which will be experimentally verified, and (b) simplified low-cost control systems. Fuel-consumption reduction will be sought by means of improved aerodynamic design of the turbomachinery components. Engine durability and emission performance will be demonstrated in a 3500-hour (equivalent 105,000 miles) test over the Federal Driving Cycle.

In addition to these efforts, NASA has initiated a turbine regenerator improvement program. The objectives of this program are to fabricate and demonstrate the feasibility of ceramic regenerators as applied to automotive gas turbines and to assess the potential improvements (compared with metallic units) in terms of performance, cost, and driveability. Procurement of current state-of-the-art ceramic regenerators is being performed by Chrysler Corporation; both NASA and Chrysler will evaluate regenerator performance.

NASA will also be involved in the development of a low-emission catalytic combustion system for use in the Chrysler gas turbine. Proposals from potential contractors have been received, and a contract award is scheduled in 1973. This program has a duration of 10 months and consists of four phases: design, fabrication, development testing, and performance demonstration testing. In addition to providing support to EPA, NASA will also perform in-house testing and evaluation of this combustion concept.

C.1.3 Solar JIC-B Combustion System

Solar proposes to continue to work on their jet-induced circulation (JIC) combustor. In their design, a number of angled, variable-area primary ports are arranged around the circumference of the cylindrical combustor in such a manner that the air-fuel mixture injected into the chamber generates a toroidal vortex flow pattern. This injection concept, combined with a lean primary-zone, air-fuel mixture, offers the potential of low-NO_x emissions.

Further work is under way at Solar to simplify and improve NO_x control and to develop a practical variable-area device.

C.1.4 Sundstrand Transmission Study

Sundstrand is conducting a technical and economic-feasibility evaluation of candidate transmissions for use with automotive gas turbine and Rankine engines, and they will make recommendations regarding the selection of an "optimum" transmission type. Transmission efficiency (fuel consumption) and state of development are the principal criteria. The transmission types considered include conventional automatic, electric, hydrostatic, hydrokinetic, hydromechanical, and traction designs.

The hydromechanical transmission has been identified by Sundstrand as the most desirable configuration. The traction type, which is somewhat less expensive, is also considered feasible.

C.1.5 Mechanical Technology, Inc. Transmission Study

Based on the study of many potentially applicable transmission types, Mechanical Technology, Incorporated (MTI) has concluded that the hydromechanical and traction types are the most desirable configurations. The hydromechanical transmission may be better for use in 1974, while the traction types may be superior by 1980. The cost data presented by MTI were developed in cooperation with Ford.

C.1.6 Owens-Illinois Oxide Recuperator

Owens-Illinois is investigating (a) the parametric design of oxide recuperators, (b) the fabrication of four sample flow configurations, (c) the conceptual design of a recuperator for specific engine requirements, and (d) a recuperator cost analysis.

Currently, the seals are considered to pose the most difficult problem. Diaphragm-type seals may be best able to handle the different thermal expansion characteristics of the recuperator core and support materials.

C.1.7 United Aircraft Gas Turbine Study

United Aircraft Research Laboratories (UARL) completed an automotive gas turbine optimum configuration study in May 1972. In this study, essentially all types of gas turbine cycles and configurations were considered including simple cycles, regenerated and recuperated cycles, intercooling and reheat cycles and single-shaft and free-turbine engines. Based on this work, UARL concluded that the single-shaft, simple-cycle gas turbine has the best potential for meeting the 1976 NO_x emission requirement. This engine requires no heat exchangers which UARL feels is a principal problem source in automotive gas turbines.

C. 1. 8 Aerojet Platelet, Premix Combustor

Aerojet has designed a combustor for automotive gas turbine applications, utilizing the platelet premixer concept that had been originally developed for use in rocket engine combustors. In this combustor arrangement, the conventional spray nozzles are replaced by the premixer hardware, which takes the initially liquid fuel and distributes and injects it through a large number of small orifices into the combustion air. The fuel evaporates in the airstream and is completely mixed with the air by the time it enters the combustion chamber at the exit of the platelet/venturi arrangement. Dilution air is injected into the chamber downstream of the primary combustion zone.

To date, Aerojet has conducted an analysis of the mixing and combustion kinetics occurring in their platelet combustor. Based on these results, Aerojet has concluded that the emissions over a simulated version of the Federal driving cycle are below the 1976 emissions requirements by about 50 percent.

C. 1. 9 General Electric Porous Plate Combustor

General Electric is developing a low-emission porous plate combustor for use in automotive gas turbine engines and Rankine engines. In this concept, the fuel-air mixture is discharged through the porous combustor plate and ignited at the front face of the plate. The flame zone is concentrated in a 0.040-in. layer adjacent to the plate surface. A substantial part of the heat of combustion is transferred back into the plate by means of radiation and is picked up by cooling air (gas turbine) or liquid (Rankine engines) passages designed into the plate. As a result, the adiabatic flame temperature is never reached, and the NO_x emissions remain at a very low level.

Although the feasibility of surface combustion has been demonstrated, a number of problem areas remain to be resolved. These include flameout, operation on liquid fuel, liquid fuel cracking in the plate, etc.

C.1.10 NASA/EPA Catalytic Combustor

This effort, which will be managed by NASA/Lewis for AAPS, will be awarded to a contractor as yet unidentified. The objective of this effort is to develop a low-emission catalytic combustor for automotive gas turbine applications. The emission goal selected for this concept, which is similar to the previously discussed General Electric porous-plate surface combustor, is 50 percent of the 1976 Federal requirement. The contract consists of four tasks: design, fabrication, development, and demonstration. Principal design parameters are pressure drop, emissions, efficiency, and response rate. Parallel to this effort, NASA/Lewis will soon embark on an in-house test program of catalytic combustors.

C.1.11 AiResearch Vaporizer and Bypass Combustors

AiResearch has been developing low-NO_x emission combustor configurations for some time. Since June 1972, their efforts have concentrated on pneumatic-impact combustors with air bypass and three different types of vaporizer combustors using recuperator bypass. They have found that the NO_x emissions of the vaporizer combustor with bypass are significantly lower than for the pneumatic-impact combustor. However, further reduction of NO_x is required before the 1976 requirement can be met.

C.1.12 United Aircraft Lean, Bypass Combustor

United Aircraft of Canada has just completed a contract on the development of a low-NO_x automobile gas turbine combustor. The objective of this effort was to develop a simple and reliable combustor using "conventional" design techniques. To minimize flame temperature and NO_x, United Aircraft selected a very lean primary zone combined with very rapid quenching by means of dilution-air injection. For nonregenerated engines, this approach produced low-NO_x emissions but was marginal in HC and CO and had some stability problem. However, the problem might be alleviated by means of heat exchanger bypass (similar to the AiResearch approach).

C.1.13 Williams Research Lean Combustor

Williams had an EPA contract to develop a low-NO_x combustor for automobile gas turbines. Their prototype gas turbine model 131Q meets the 1975 HC requirement and is close to meeting the 1975 CO requirement. However, the NO_x emissions are considerably above the 1976 requirements. The purpose of the EPA-funded combustor program was to reduce the NO_x emissions of the WR 26 engine by means of several different combustor modifications designed to improve premixing and vaporization. This program was terminated in early 1973.

C.1.14 Mechanical Technology, Inc. Rich, Cooled Primary Combustor

MTI was working on the development of a high-pressure, gas-turbine combustor with low-emission characteristics. Based on an evaluation of various combustor concepts, MTI selected a fuel rich, cooled primary combustor design approach as the most practical for this application. In this design, a sufficient amount of heat will be transferred from the primary zone as well as the secondary and tertiary dilution zones by means of radiation and convection in order to inhibit the formation of NO_x. This program was terminated in early 1973.

C.2 EPA/AAPS GAS TURBINE MANUFACTURING SUPPORT PROGRAMS

C.2.1 United Aircraft/Pratt & Whitney Turbine Wheel

United Aircraft Corporation's Pratt & Whitney Division is developing a new hot-die forging process, called the Gatorizing(TM) Process, which simplifies the manufacture of previously hard-to-forge alloys and permits the forging of parts heretofore available only as castings. This isothermal forging process is particularly applicable to turbine-wheel fabrication. The principal advantages of the Gatorizing process are lower cost, lower input pressure, less machining on the forged part, fewer dies, simplified setup, and reduced scrap rate.