SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
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THE CHRYSLER REGENERATIVE TURBINE-POWERED PASSENGER CAR

George J. Huebner, Jr.
Chrysler Corp.

SOCIETY OF AUTOMOTIVE ENGINEERS

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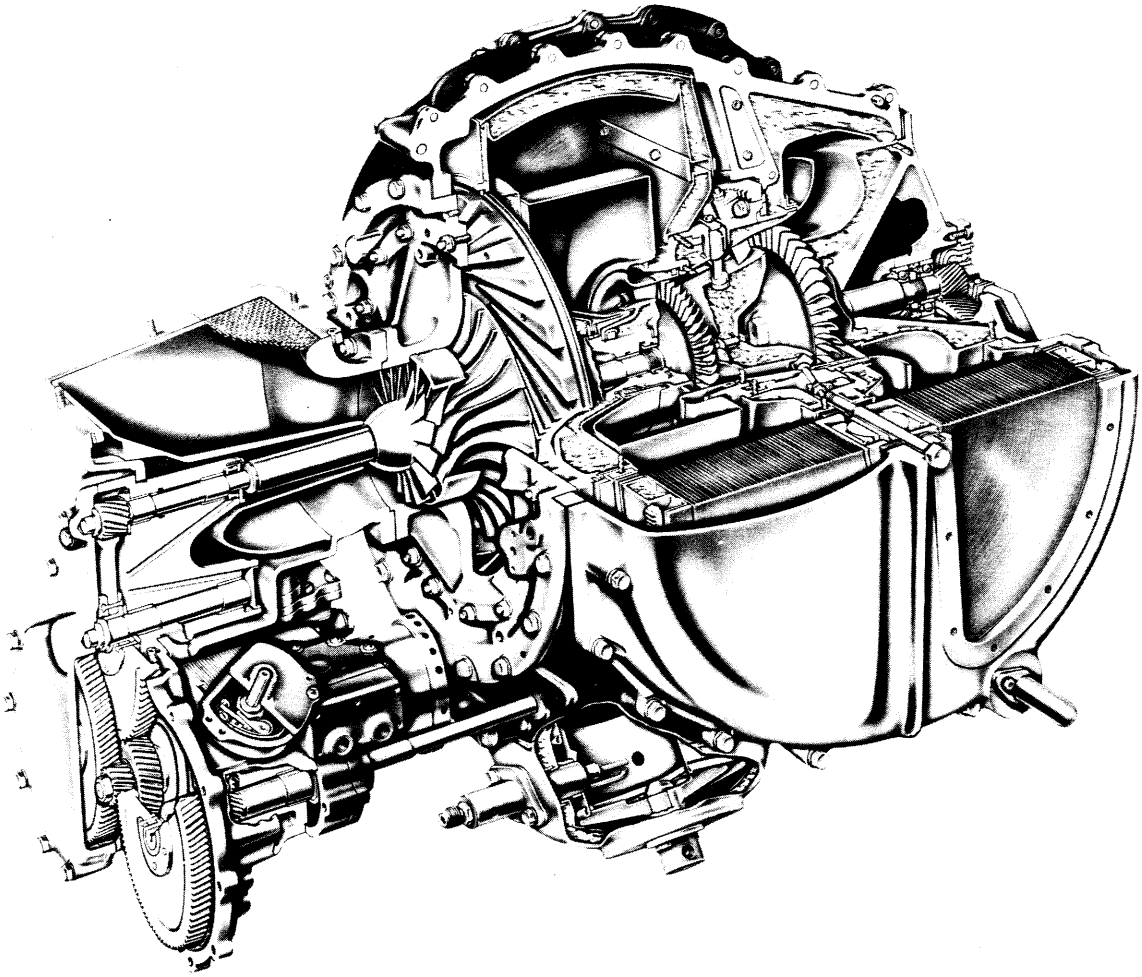


Chrysler Gas Turbine Engine

INTRODUCTION

Gas turbine research and development at Chrysler has been carried on actively and intensively without a break since 1945. During that period only a very small portion of our technical work has been publicly reported. The papers on the Chrysler Corporation gas turbine car which will be presented today are an initial attempt to cover in some preliminary detail a subject in which the technical subtleties are so great and the amount of work done so extensive that these four papers can only serve as an introduction.

Although aircraft turbines had already made their initial military appearance when we started our major work, almost no gas turbine information was publicly available. Much of our earliest work on compressors and turbine wheels was under strict military security and even our original automotive gas turbine moved quickly into another military project, also under strict military control. Consequently, very little of our original work was ever reported. Our papers today will attempt to rectify this to the degree possible in the limited time available. Almost all the information to be given is proprietary, and even the background research was done in-house at Chrysler. It may eventually be found that some of our work has been duplicated by careful and capable workers in other places but, in most cases where the work was published, similar projects carried on at Chrysler were completed long before the publication of results from other sources, and our results applied directly to our own powerplant.

It is difficult to reconstruct the atmosphere in which our early work took place. In the first part of the last decade any discussion of automotive gas turbines, particularly in regard to passenger cars, was a signal for experienced and informed people to deprecate completely the possibility of a successful automotive powerplant. The reasons given for the pessimism of these experts always started with the excessively high fuel consumption of the gas turbine at part load. They proceeded to describe the impossibility of building compressors and turbines in the small size required; the difficulty of achieving reasonable component efficiencies in small size; the impossibility of operating a car without engine braking; the excessive cost of materials; the high volume of gas throughput with resultant difficulty in filtering the inlet air and handling large volumes of high-temperature exhaust gas. Control problems, speed problems, gas generator acceleration lag, transmission problems, etc., etc., etc., etc. The list went on and on, but fortunately for our peace of mind we had already achieved solutions for some of the more difficult "impossibilities" and were sufficiently encouraged by these accomplishments to take succeeding steps. I do not mean to imply that our work was without frustration. There were many blind alleys, but our attitude was that of the bumble bee. We simply did not know that we could never fly, so we worked a little harder after every set-back until, lo and behold, the darned thing began to work.

I can only say that I sympathized then with the gentlemen who made those comments and I understood their reasons, but I submit that a change of viewpoint has been indicated for some time. Nothing is greater proof of the validity of our original, but carefully conservative, claims than the Chrysler Corporation gas turbine passenger cars in the hands of private users today.

When we originally faced these problems we divided them into several classifications. First, those which looked impossible and which would require early solution before we could concede even to ourselves that we had a possibility of making an automotive gas turbine passenger car powerplant. Second, those which appeared difficult, but possible, and which we expected to solve during the normal course of research and development. Third, those which we considered normal engineering problems which could be solved in our initial design phase.

Let no one think that we went into this work with our eyes closed. Industrial research can only be done with careful, thoughtful, and intelligent planning beforehand. This planning must include not only the assessment of technical success but also the economic implications of success as well. In the case of the gas turbine we had to add the possibility of a technical, manufacturing, and economic revolution in a well-planned and well-operated industry.

This paper will outline some of the background of our present engine, our reasons for following our present course and the results as far as the vehicle is concerned. The second paper will be delivered by Mr. William I. Chapman who will discuss the engine design and our approach and execution of that design. Dr. Amedee Roy will tell about the material requirements of our present engine and the unique and proprietary means used to meet these requirements. Finally, Mr. Gerald DeClaire will deliver a paper concerned with laboratory techniques of both component and engine development.

BACKGROUND OF CHRYSLER POWERPLANT RESEARCH

Reciprocating Engines

Automotive powerplant research at Chrysler has had a long and fruitful career. The genesis of the Chrysler car was to a great extent initiated because three Chrysler engineers, Fred Zeder, Owen Skelton, and Carl Breer had the vision and courage to conceive and develop a reciprocating engine which in its time was a giant step forward. They were not, however, satisfied that this was the end of the line for the automotive powerplant and, from the time of the original founding of the Chrysler Corporation, powerplant research has never stopped.

On a carefully planned basis, various engine cycles were tested and many different engine arrangements were designed and tried. The effects of higher compression ratios were explored. Novel combustion chambers were investigated. Supercharging was extensively tested.

The engineering objectives of research activity of this type are to increase specific output from the standpoint of both displacement and weight, to increase thermal efficiency, to decrease mechanical losses, and to reduce cost. The commercial reason for this effort is, of course, to give the automotive user -- the customer -- more value for his dollar, and from this work flows a steady stream of economy and performance advancements which are passed on to the customer as rapidly as we can be assured that they also improve the reliability and life of the engines.

To a great extent, as a result of this work, Chrysler Corporation was approached by the Army Air Corps at the beginning of World War II to design and develop an aircraft engine which would have an extremely small cross sectional area, higher output than any engine then available, and better installed power-to-weight ratio than contemporary aircraft engines. Although this was a reciprocating engine, it had a profound influence on our later gas turbine work. Two different means were chosen for the supercharging of this engine: a gear-driven two-stage radial compressor and a multi-stage axial flow compressor. During the later phases of the project, work was also done on an exhaust-gas turbine geared to the output shaft of the engine.

Both supercharging systems were successful, although the engine was flown only with the gear-driven two-stage radial unit. This compressor work, together with the geared turbine studies, provided us with data and a working background for gas turbine powerplant design and development.

Early Gas Turbine Studies

At Chrysler Corporation, the earliest work on gas turbine engines dates back to before World War II, when an exploratory engineering survey was conducted. These studies showed that, although the gas turbine engine had strong possibilities of being an ideal automobile engine, neither materials nor techniques had advanced to the point where the cost and time of intensive research would be warranted.

At the close of World War II, studies of completely new concepts in gas turbine design were started and layouts were made of automotive gas turbines utilizing exhaust heat recovery devices. As a result of this fundamental work Chrysler was awarded, in the fall of 1945, a research and development contract by the Bureau of Aeronautics of the U.S. Navy to create a recuperative turboprop engine.

The specifications for the Navy engine were unique, calling not only for light weight but for an economy approaching that of reciprocating aircraft powerplants under cruising conditions. This was a rather startling requirement, since aircraft gas turbines which had been built so far showed their best fuel economy at full power and deteriorated rapidly from there on down. Yet, the engine was designed, built, and operated. The recuperator was a success from the beginning, and the objective of obtaining 1000 horsepower with a brake fuel consumption of 0.52 at 70% power was achieved and, in fact, exceeded.

This program -- although terminated in 1949 -- resulted in the development of a turboprop engine which achieved fuel economy approaching that of aircraft piston engines.

CHRYSLER AUTOMOTIVE GAS TURBINES

Initial Planning and Passenger Car Selection

From the Navy experience we learned enough to realize that the automotive turbine problem was much more difficult than the aircraft problem. After all, an aircraft engine can cruise successfully at 70% power and can have fairly good economy with only 70% heat recovery, but an automobile spends most of its life under 25% of its power potential, and getting enough exhaust heat recovery for fuel economy at that load factor, or below, is an extremely difficult job. However, there was no reason to be discouraged, and we resumed the calculations interrupted by the Navy interlude.

Finally, in October, 1949, a project was initiated to determine the potentialities of the gas turbine powerplant for automotive use. A very small group of men were assigned to this work and a number of studies were made. These studies showed that it would be possible to build a gas turbine engine of such size that it could be placed in a production automobile and have fuel economy as good as current reciprocating engines, provided certain requirements could be met.

These requirements were that component efficiencies equal to those being obtained in large engines be achieved in the small sizes required for automotive use, and that a very high effectiveness heat exchanger with low pressure drop be built in small enough size to allow engine installation under a passenger car hood. Other requirements included flexibility of operation, low noise level, adequate engine braking, and reasonable gas generator acceleration time.

In addition, readily available and non-strategic high temperature materials had to be developed, exhaust gas temperatures had to be low, and development work had to meet the requirements of building an engine which would be light, compact, reliable, easy to maintain and, from the cost aspect, competitive with conventional automobile engines.

In our development work a considerable, but not exclusive, emphasis has been placed on the application of the turbine powerplant to passenger cars. This was done not only because successful passenger car application solved most of the special requirements of other surface vehicles, but also because the passenger car provides the volume for a mass production base in the automotive industry.

Trucks, buses, and off-highway equipment are readily suited for quick adaptation to the gas turbine since they operate at higher load factors and do not require the ultimate refinements of the passenger car. Such vehicles will, of course, benefit from the turbine to as great an extent as the passenger car, and some turbine characteristics such as the ability to accept sudden over-load without stalling would be particularly valuable. But low cost powerplants for a wide variety of uses can best be obtained by having a basic unit which can be applied to a volume market.

In spite of these difficult requirements, Chrysler research engineers were convinced that the potentialities of the automotive gas turbine engine were more than sufficient to warrant intensive research and a full-scale design and development program.

First Turbine Engine

The design of our first engine, shown on Figure 1, was started in December, 1952. Its design rating was slightly over 100 horsepower. A large number of arrangements were investigated before this one was decided upon, and

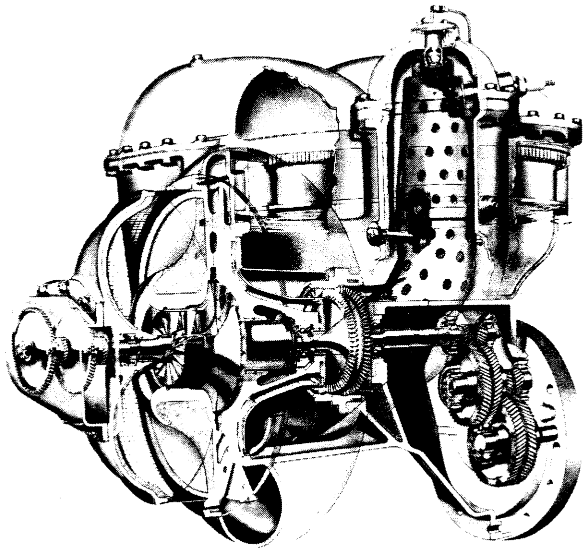


Fig. 1 - First Chrysler Gas Turbine

many considerations were involved in this decision. First, it was decided that the engine would have to be installed in a production automobile with the minimum of interference with the steering, frame, and body. Since this engine was completely exploratory, it was desirable that it should be easy to disassemble for inspection, and allow for easy component modification.

Compressor efficiency postulated for this first engine was 74.5% at maximum operating speed. Everything then thought possible was done to achieve high component efficiency from the very beginning, with the idea that it would be later simplified. For example, a two-stage axial inducer was used to insure that no flow separation would occur before the radial portion of the impeller was reached. The impeller was completely shrouded, as it was believed this would also aid in obtaining high efficiency.

The compressor was one of the first components tested, and we were very happy when the test results showed up quite well, even though the parts themselves were not all that could be desired from the standpoint of fabrication.

The heat exchanger was of the rotating type. The matrix was fabricated by winding together a flat strip and a corrugated strip .004 inch thick by 3 inches wide of straight chromium stainless steel under controlled tension conditions. The strips were spaced .012 inch apart by the corrugations and the whole unit was copper-brazed together. Approximately 50 pounds of steel strip were used in the unit.

The burner consisted of an outer housing and a liner made from aluminized low-carbon steel.

Turbine wheels were fabricated from unit-cast stellite blade rings welded to low-alloy forged disks.

The main engine housing was made from nodular iron, and it was decided to use a casting for the first engine to allow instrumentation holes any place.

The accessories, consisting of a combined starter-generator, fuel pump, and oil pump, were driven from the front of the compressor shaft through a series of reduction gears.

The first engine was designed primarily as a laboratory tool to check component performance and matching, and to determine if a small gas turbine engine based on the regenerative principle could be practical when installed in a passenger car.

This engine was first operated in a standard Plymouth sedan (Figure 2) in December, 1953, and later demonstrated at the Chrysler Proving Grounds in March, 1954 at which time a public announcement was made.

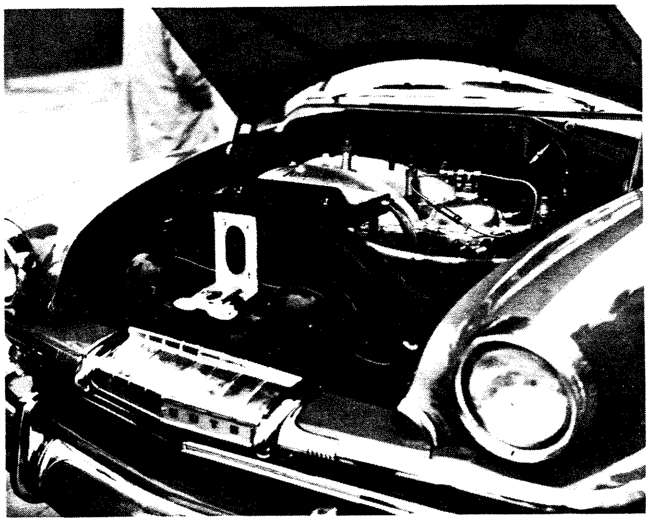


Fig. 2 - First Turbine - Car Installation

Fig. 3 - 1956 Plymouth Turbine Car

The first engine served many useful purposes. It was the first gas turbine engine in the world to power a production automobile, and to achieve reasonable performance and controllability, and it proved the practicality of the regenerative principle. It also powered the Plymouth car which, in 1956, made the New York - Los Angeles trip (Figure 3) -- a trip which even then offered visible proof of the practicality of the gas turbine-powered passenger car.

This engine was used to check almost continuous component development work, and was an invaluable laboratory tool in approaching the final integrated gas turbine powerplant that would eventually evolve for automotive use.

Second Turbine Engine

In August, 1955, the design of a second gas turbine powerplant was started. The first engine, in the period during which it was worked upon, had never had sufficient temperature gradient available for acceleration to determine what sort of car activity could be expected from a gas turbine engine under traffic requirements. The size chosen for the second engine was such that it would develop 140 H. P., on an 85°F day, with component performance equal to that which had been actually obtained in the original engine, and 190 H.P. with the improvement in component performance which we felt could be achieved during the engine development period. At the same time the design of this engine was started, a stepped-up component development program was also initiated.

Fig. 4 - Second Turbine - Car Installation

This engine was first operated in July, 1956 and the performance was very close to that which had been predicted.

In December, 1958, one of these engines, fitted with adjustable nozzle vanes, was installed in a standard production 1959 Plymouth four-door hardtop (Figure 4), and finally tested on round trip run between Detroit and New York. The results showed that variable nozzles could be used to give significant improvements in fuel economy.

Component Development Program

From the time that the first engine was conceived and throughout our experience with automotive gas turbine engines, it had been apparent that a satisfactory engine could be obtained only through a thorough and time-consuming component development program. To obtain worthwhile results, it was necessary to develop our own test fixtures, instrumentation, and techniques, since work on components of that size had never before been done in the detail we had found to be necessary.

The original compressor, as designed, had very good aerodynamic performance even though we were never able to obtain experimentally a diffuser that corresponded to the design. This compressor was, however, too long, too complicated, and had too much inertia. Through a development program which consisted of both experimental work and advanced theoretical analysis we were able to correct the deficiencies of the first compressor and at the same time obtain improved performance.

We have had to pioneer in the field of heat exchangers and develop our own matrix shapes and methods of sealing the high-pressure gas from the low-pressure gas. At the start of the program, information on heat exchangers of the effectiveness required was non-existent. This problem was approached both from a theoretical as well as empirical standpoint. We tested in small sample size approximately 275 configurations and obtained sufficient data to establish relationships between passage shape, passage size, and metal thickness that allowed us to make designs with confidence.

Our work on turbine wheels and nozzles has consisted in the determination of overall performance as well as detailed surveys of temperature, pressure, and angle conditions, both entering and leaving the various blade rows. This work allowed us to pin-point any deficiencies that were present and the reason for their occurrence.

In general, our laboratory work on the turbine portion of the engine has shown that our early designs performed quite satisfactorily, with efficiencies equal or better than those obtained in larger units. We found that the proper matching was of extreme importance and that the angle at which the gas leaves the various stages had to be controlled within ±0. 5°, which appeared, however, to be well within the tolerances that could be met in the fabrication process we were using.

Design investigations of possible turbine wheel configurations were then carried out successfully to determine the feasibility of obtaining lower inertias with an idea of reducing the gas generator acceleration time.

Design studies were also initiated to determine a reliable variable nozzle operating system and laboratory tests were run on its various components.

A large amount of other component work was also carried out on burners, passage shapes and controls. Endurance work, both on the test stand and in the automobile, further increased our understanding of the problems and pointed to means of improving our next proposed engine design.

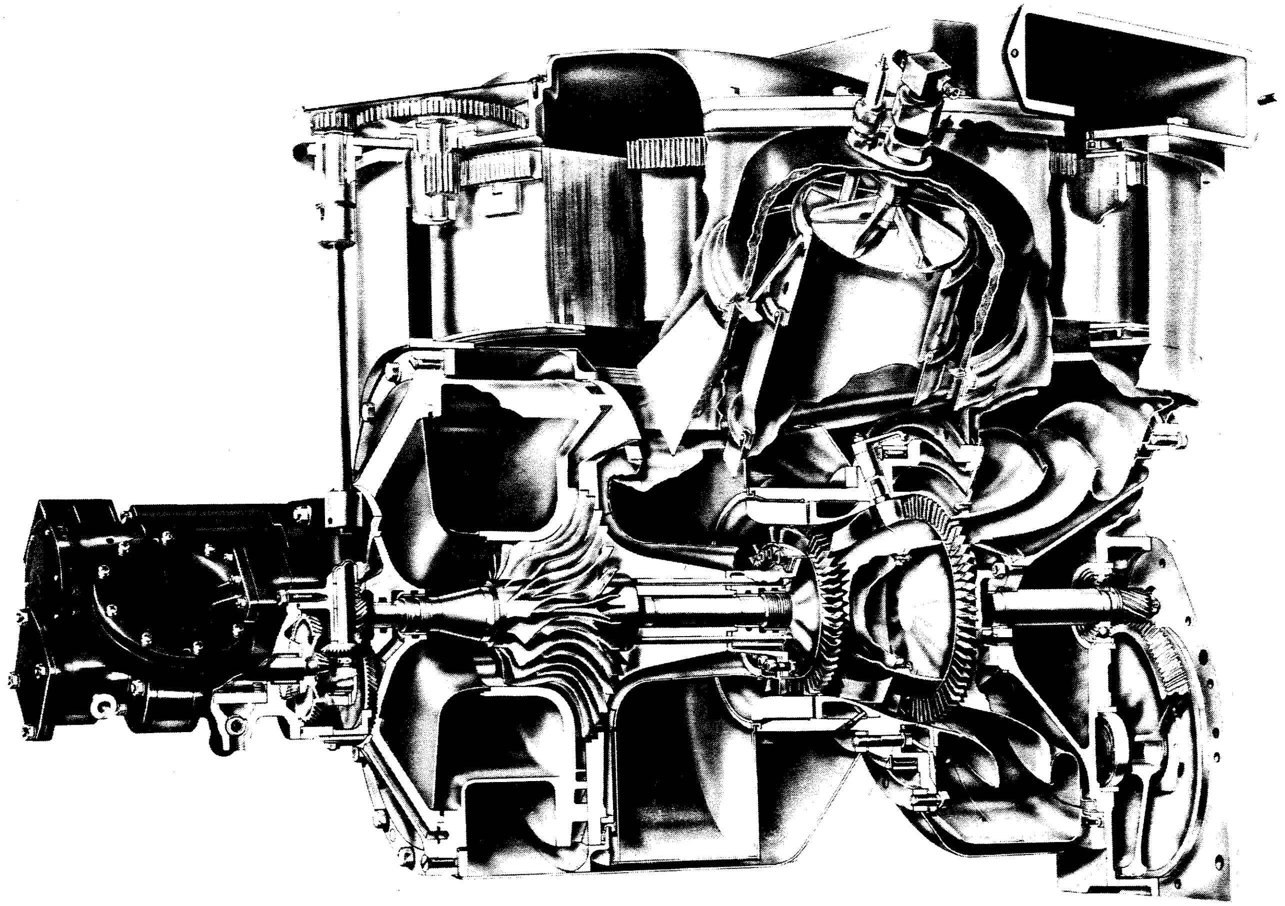


Fig. 5 - Third Chrysler Gas Turbine (CR2A)

Third Turbine Engine

All of this component work had been directed toward the design of a third turbine engine which would be much more practical than its predecessors from a standpoint of vehicle application. The design output selected was a sensible 140 H. P. and the weight was drastically reduced to 450 lbs. The overall dimensions were perfectly suitable for incorporation in the engine compartment of a standard-size automobile.

As shown on Figure 5, the basic structure of the engine consists of a fabricated steel housing which supports the major component assemblies and provides the connected flow passages. The housing is heat-insulated internally. This insulation also acts as sound insulation, while the regenerator core serves as an effective muffler for the exhaust gases. An intake filter silencer is provided in front of the compressor to prevent dirt accumulation in that component and to reduce the noise generated at the compressor inlet.

The gas generator assembly is installed in the front part of the housing and consists of a radial flow compressor and a first-stage axial flow turbine which drives the compressor impeller and the accessories. This rotor assembly operates at a maximum speed of 44,610 rpm with a turbine inlet temperature of 1700°F at rated power on an 85°F day.

The second-stage axial flow power turbine, preceded by variable nozzles and installed in the rear section of the housing, is co-axial with the gas generator turbine but is not connected mechanically to it. Its rated output is 140 hp at 39,000 rpm with a maximum speed of 45,730 rpm. The turbine speed is reduced by a single-stage helical reduction gear of 8.53:1 ratio, resulting in a rated output speed of 4570 rpm and a maximum speed of 5360 rpm.

The disk type rotary regenerator is mounted in a cylindrical chamber in the top of the housing. The regenerator core and seals are assembled into the housing and are enclosed by the regenerator cover. The seals divide the regenerator core into two flow passages, the front half at (high) compressor outlet pressure and the rear half at (low) turbine exhaust pressure.

The single can-type burner, easily accessible, is located at an angle to the side of the housing and is provided with a fuel nozzle and a single spark plug.

The accessories are mounted on the front of the gas generator and driven from the rotor by a simple gear train. A vertical shaft connected to a gear box in the regenerator cover rotates the regenerator core through a pinion and large ring gear, with the required overall reduction ratio of 2,800 to 1.

The fuel system incorporates a gas generator speed governor and a fuel scheduling control for acceleration, which are integrated with a gear-type fuel pump in one housing to minimize plumbing. This assembly, as well as the fuel nozzle air pump and the lubrication pump, are driven from one accessory drive pad.

The starter-generator is geared directly to the gas generator rotor and operates at a maximum speed of 20,000 rpm. For automobile application a 12-volt system is used, and burner ignition is provided by a high-voltage buzzer coil and spark gap igniter plug.

CURRENT CHRYSLER GAS TURBINE

The current gas turbine activities of our corporation are concentrated on the development and operation of what might be termed a fourth generation powerplant. This new engine has essentially the same aerodynamic design as our third engine, the arrangement being changed to allow the use of two regenerators. This rearrangement, together with a new accessory drive, has allowed a substantial decrease in powerplant bulk and weight, and made its use more practical in vehicles of the more compact size which are the vogue today.

A detail description of this engine will be given in the next paper (777B) to be presented today. My own discussion will therefore be limited to a review of the factors considered in the selection of our engine cycle, and also to various considerations and results pertaining to powerplant and vehicle performance.

The reliability and minimum service requirements which have always been a part of gas turbine usage are, of course, also present in automotive applications. But there are imposed an additional set of conditions which are quite foreign to most gas turbine history and experience --

(1) an extremely wide load variation, with stringent requirements on operating efficiency over the range, (2) an engine idle condition which is a large portion of the duty cycle, (3) a fantastic dynamic response requirement, (4) a strict noise level limitation, and (5) cost and production situations which are without precedent.

Cycle Considerations

In approaching the general problem of gas turbine design with a completely open mind, a number of possibilities present themselves. Singly, or in a combination, a partial list might read as follows:

- Simple cycle
- Regenerative cycle
- Single shaft
- Free turbine
- Reheat
- Intercooling
- Supercharged cycle

And so on. Obviously, the intended application is the strongest factor in making the final selections, but nevertheless all reasonable arrangements must be studied.

In the case of an automotive passenger car engine, cost, simplicity and ease of manufacture are the predominant influences; so predominant that they form, in our judgement, a sufficient basis for eliminating from serious consideration the supercharged cycle, as well as other more exotic arrangements. It also seems clear that reheat and intercooling must be eliminated from consideration for the same reasons. This is not to deny the substantial gains in efficiency that can result from these devices; it is, in fact, quite possible that further study and experience will show one or more of these features to be practical on a cost and manufacturing basis. But at this point in the development of the automotive turbine for passenger cars, this does not seem to be the case.

The regenerative cycle, on the other hand, offers advantages peculiar to this application that do seem to be worth the penalty in cost and complexity that accompanies it. As mentioned before, the passenger car engine must operate over an extremely wide load range, and in fact spend the major portion of its life in the low end of that range. Although the high-pressure ratio, simple cycle machine can achieve good efficiency at high output, its fuel consumption increases prohibitively at light loads. Even the addition of intercooling and/or reheat is of questionable value here, since these features depend upon cycle pressure ratio for their maximum effect. The regenerative cycle, on the other hand, exhibits the most pronounced advantage at light loads. The lower the pressure ratio, the larger is the proportion of energy available for regeneration. Here, then, is a device that seems most suited to passenger car application, and in our judgment one that is indeed worth the trouble.

The question of a single or multiple rotor arrangement is also decided on the basis of load variation. A single shaft gas turbine coupled to the drive line through a manual transmission would require excessive driver skill and dexterity. The useful speed range of the gas turbine is about 2-1/2 to 1 compared to about 10 to 1 for the reciprocating engine, and the torque change through the speed range is abrupt. The automotive application of the single-shaft turbine would require the long sought infinitely-variable ratio transmission, not yet commercially available. A free turbine, i.e., a gas producing compressor-turbine unit, combined with an independent power turbine geared to the drive line, on the other hand, provides much the same characteristics as a reciprocating engine with torque converter, because the two gas-coupled turbines behave in essentially the same way as the elements of a torque converter. The only limitation on engine response to load changes is then the rate at which the gas generator unit can change speed.

Limiting Parameters

Having chosen the basic arrangement discussed above, i.e., a regenerative, free turbine cycle, the selection of the limiting values of cycle parameters is, to a great extent, determined by metallurgical considerations. This is the subject of another paper in this group (777C); suffice it to say here that the turbine inlet and outlet temperatures are the two factors most strongly affected. The inlet temperature is limited in part by the relatively unstressed ducting and stator vanes of the first-stage turbine, and in a more pronounced way by the first-stage turbine wheel blade and disk strength. On the basis of the factors discussed in Paper 777C, a working range for turbine inlet temperature is defined by the selection of turbine materials. (In our terminology, this point is identified as T_5.) The exit temperature from the last turbine stage is an important limiting parameter because it is also the maximum regenerator inlet temperature, which we call T_8, and is determined by the materials available for the heat exchanger matrix and attendant equipment. Now these two factors essentially establish an approximate value for turbine temperature ratio (T_5/T_8) since neither temperature can exceed its limit for long periods of time for given material selections.

The cycle pressure ratio, on the other hand, is primarily influenced by three factors:

(a) Cycle optimization: There is an optimum ratio for best cycle efficiency with a regenerative engine (Figure 6). This value is usually exceeded, however, to favor part load operation.

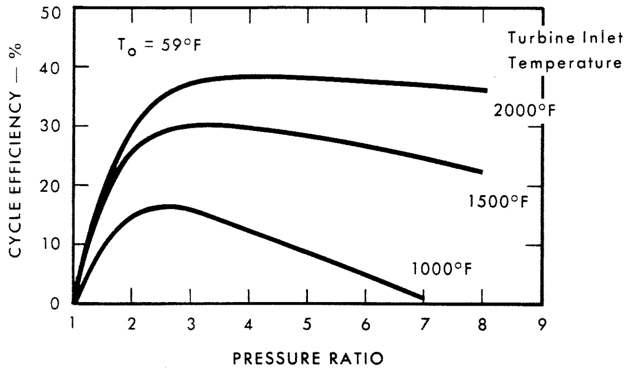


Fig. 6 - Cycle Efficiency

(b) Component complexity and cost: The single-stage radial compressor, at this time, seems to be the simplest, sturdiest, most economical type and lends itself rather well to regenerative engine arrangements. With such a unit it is difficult to maintain high component efficiencies above approximately 4:1 pressure ratio. Fortunately, two simple turbine stages adequately fulfill the cycle expansion requirements for this pressure ratio. Appreciably higher expansion ratio would require multistage turbines.

(c) Rotor inertia: This all-important factor is heavily dependent on impeller and turbine wheel diameter, and places another limit on cycle pressure ratio for an automotive engine.

The above considerations, then, are major influences in selecting the prime cycle variables.

Part-Load Considerations

It has already been mentioned that an automotive engine spends a great percentage of its life at loads which are but a fraction of its design capacity. This has conclusively influenced our design selections.

The first clue to an efficient gas turbine is offered by the effect of maximum gas temperatures on cycle efficiency and specific fuel consumption at any operating load factor. It will be noted in Figure 7 that maintaining a constant turbine inlet temperature (T_5) at all loads gives an attractive increase in efficiency for a regenerative engine over the more conventional characteristic in which T_5 decreases at reduced output. One way in which this can be accomplished is to allow one of the key restriction points in the engine to be varied as a function of load. We have chosen to do this with the power turbine nozzles. By means of a hydraulic scheduling actuator, the blades are gradually closed from the "design point" setting as load is reduced,

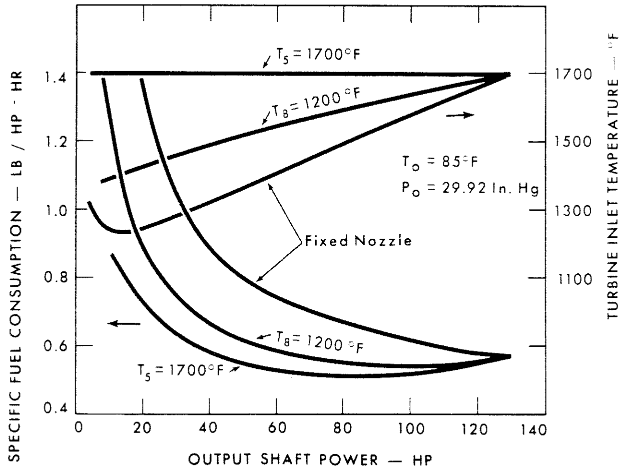


Fig. 7 - SFC Characteristics

thus reducing that share of the overall pressure ratio which is allotted to the compressor turbine stage, and preventing T_5 from decreasing as rapidly as it would if all of the turbine geometry were fixed.

With a regenerative free turbine powerplant, and the material limitations mentioned above, it is impractical to maintain constant T_5 for all operation. As engine load and gas generator speed are reduced, the total turbine work decreases markedly and, of course, so does turbine temperature drop. With a constant T_5, the low pressure regenerator inlet temperature, T_8, would rise quickly above its permissible maximum. The nozzle schedule is therefore established in such a way that one of these temperatures is always at its limit for any road load condition. The resulting effect on T_5 and sfc is shown in Figure 7.

There are other advantages with variable power turbine nozzles. These are:

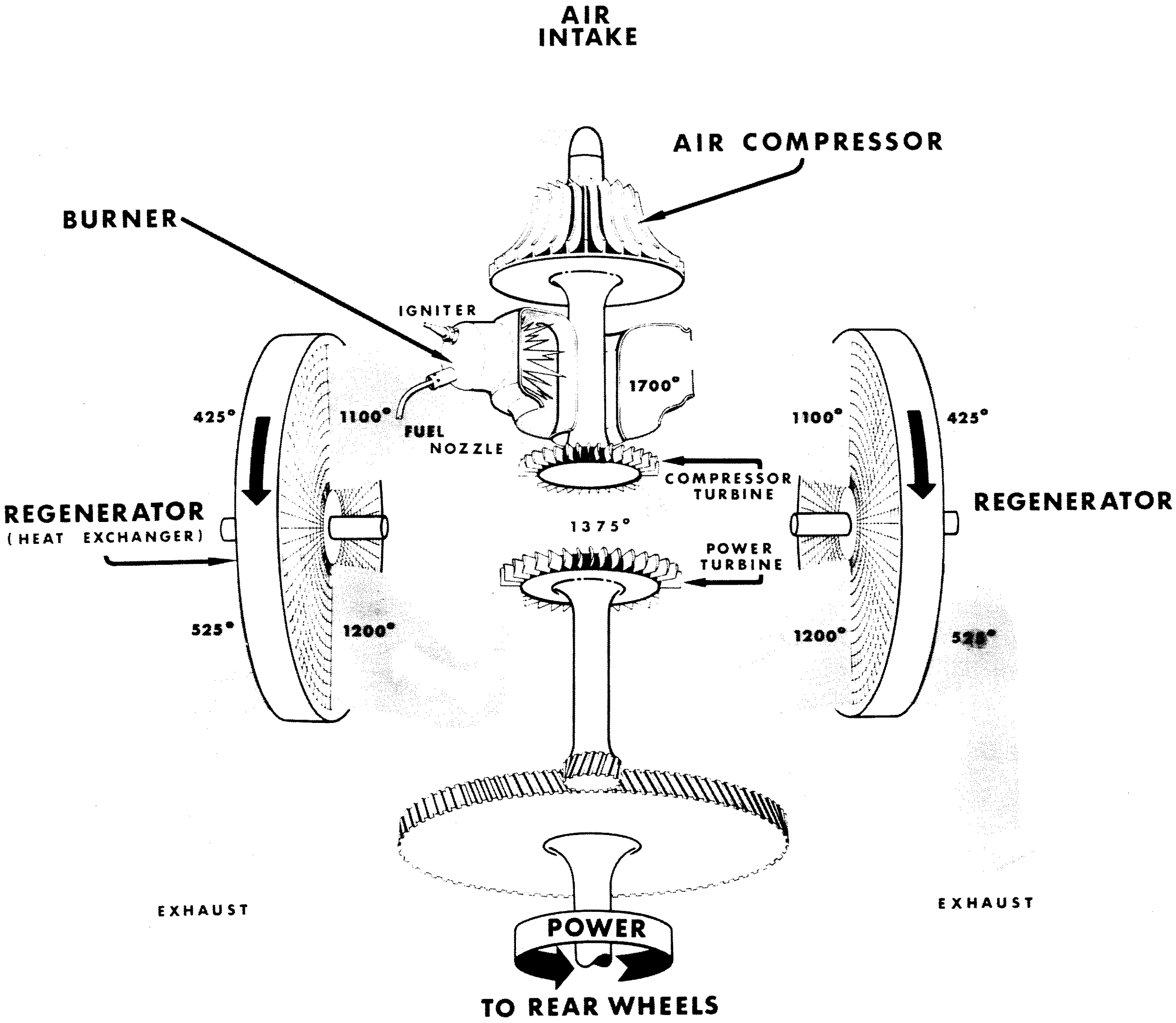


Fig. 8 - Schematic Flow Diagram

(a) The provision of engine braking by opening the blades to the point where power turbine torque is reversed.

(b) The facility to make minor adjustments in flow area and obtain the same engine "match" temperatures from engine to engine, regardless of small manufacturing variations.

(c) Control of cycle temperature and creep torque at idle.

We would be less than realistic, however, if we did not also recognize the disadvantages of this arrangement. Briefly, they are:

(a) Added cost and complexity, though not as great as one might at first anticipate.

(b) Some compromises on flow path, since spherical surfaces are required for the blade shrouds.

(c) Clearance at both root and tip of the nozzle blades.

All things considered, however, our experience and results indicate that the advantages of the variable power turbine nozzles far outweigh their disadvantages.

Design Point Selection

Based on the above reasoning, and the experience that fifteen years of design and development activity have provided, the design point selection for the Chrysler automotive gas turbine has been made, as shown schematically in Figure 8, where the thermodynamic values are also given at various points in the cycle.

Powerplant Performance

Power and Torque

Figures 9 and 10 represent the power and torque maps for various gas generator speeds as functions of output shaft speed. Also shown are the vehicle power-required curves for two values of rear axle ratios.

The gas generator speeds are given as per cent of the mechanical design speed, 44,610 rpm. The aerodynamic design speed is 97.5% of this, or 43,500 rpm.

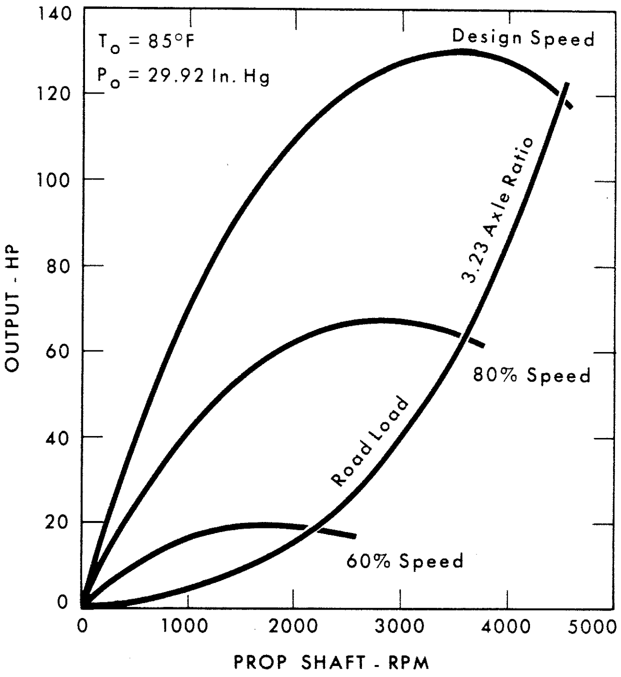


Fig. 9 - Performance Characteristics - Power

The overall gear ratio from power turbine to rear wheels determines maximum vehicle speed as well as the speed at which maximum power occurs. It also exerts some influence on the vehicle acceleration rate and fuel consumption characteristics. This overall ratio is the product of the engine reduction gear and the rear axle ratios, and the latitude afforded the designer in its selection is limited by two major considerations: (a) conventional transmission and drive shaft requirements, (b) power turbine wheel maximum stress limits.

Some degree of power turbine overspeed (i.e., ratio of maximum speed to speed at aerodynamic design output) is desirable for most vehicle applications, but any excess will result in a fuel consumption penalty.

It may be noted in Figure 10 that the ratio of stall to design point torque is about 2.3 to 1.

Fuel Consumption

Figure 7 presents minimum specific fuel consumption characteristics. The use of a fixed surface recuperator would have eliminated a 3% leakage penalty on sfc, but the reduced effectiveness of this type of heat exchanger of comparable size has an adverse effect.

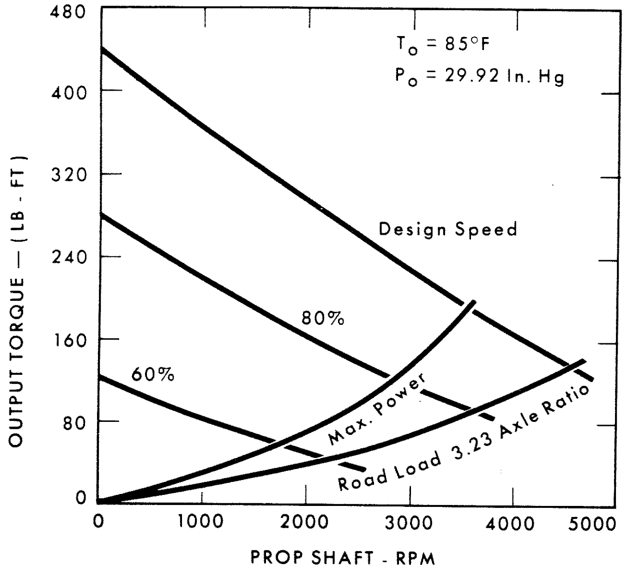


Fig. 10 - Performance Characteristics - Torque

Vehicle Performance

The term "vehicle performance" as far as the engine is concerned generally means two things:

(a) The way a car "feels", that is, the manner in which it responds to the driver's commands, and (b) its overall fuel economy, or tank mileage under all driving conditions.

The first item is concerned primarily with acceleration potential and engine braking capacity.

Acceleration

If the gas generator is brought up to full speed with the car stopped (brakes applied), the vehicle acceleration is readily predictable from the engine performance curves (Figures 9 or 10) and nominal loss allowances for the drive train. Such a curve is given in Figure 11. This is known as a "jump start".

Although this method of accelerating the car has no detrimental effects on the engine, it is hardly the most convenient way to maneuver in normal traffic and it is not likely to give optimum fuel economy. The more prudent driver will usually accelerate from the operational engine idle setting which is 50% of full speed.

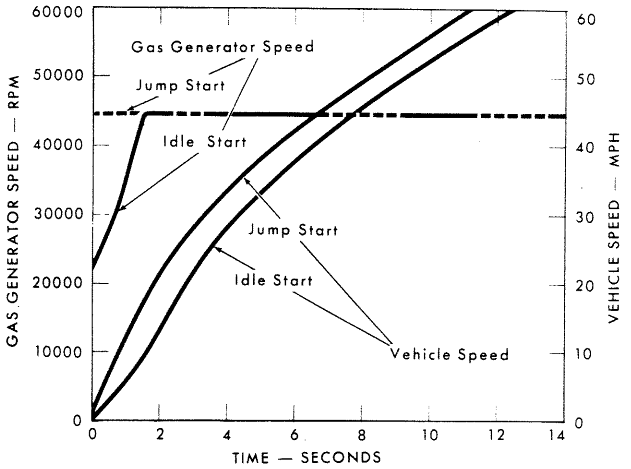


Fig. 11 - Dynamic Response Characteristics

A modern reciprocating engine with a torque converter will deliver a noticeable "kick" within about 0.3 second from the time the throttle is opened. This is about the time required to take up any slop in the linkage, deliver the slug of enriched mixture to the cylinders, and ignite it. Of course, the rather large vacuum that lurks downstream of the throttle blade just prior to opening is of considerable help in this process. The gas turbine, on the other hand, responds to this pedal action by injecting an increase in fuel to the burner, so that T_5 rises to a predetermined maximum. This produces an excess torque at the compressor turbine, which then accelerates the gas generator in accordance with a very old and trusted law:

$$M = I\alpha$$

Note that both excess torque (M) and rotor inertia (I) have linear, though opposite, effects on angular acceleration (α). It is equally important, then, that each be emphasized. The acceleration torque is maximized by: (a) allowing T_5 to increase to its greatest allowable limit, considering that this is a short duration, intermittent condition, (b) being attentive to compressor and turbine efficiencies under conditions of speed change, and (c) minimizing parasitic losses in the gas generator and in the accessory section.

Gas generator rotor inertia is minimized to the utmost. The most important factors are impeller and turbine wheel diameters. Polar moment of inertia varies with the fourth power of diameter, for constant axial width, and this fact explains a great deal of what we have done in the design of gas generator equipment. The impeller diameter is closely tied to the desired cycle pressure ratio, so there is not much latitude here. The compressor turbine wheel, on the other hand, can be selected for low inertia by using a large change in tangential velocity, thus minimizing peripheral blade speed (and wheel diameter) to obtain the required work output. Optimum use of lightweight materials in both impeller and turbine wheel also contributes significantly to minimum inertia.

The end result of all these efforts is shown in Figure 11; acceleration from idle to full speed is currently being accomplished with our engines in about 1.5 seconds.

This is not all lost time as far as car motion is concerned, however. With power turbine nozzles in the optimum position, the vehicle begins to move immediately, and acceleration time from idle to 60 mph is only 1.1 seconds more for an idle start than for a jump start.

One factor that is of considerable importance to vehicle acceleration is the power turbine rotor inertia. Its effect in terms of equivalent car weight is dependent on the square of the reduction gear and drive train ratios, and must therefore be considered in selecting optimum transmission shift points. In order to be conservative on power turbine disk and blade life, we found it necessary to choose a design which is heavier than we would have liked, equal to about 140 lb. equivalent car weight in direct drive. As more vehicle experience with this engine is acquired, and the vibrational sources which affect life are more accurately identified, it may be possible to reduce this figure.

Our experience has proven that good vehicle response from idle, despite certain widely publicized statements to the contrary, is not only a possibility – but a reality. It requires nothing more mysterious than the application of engineering principles and careful attention to the important details discussed above.

Engine Braking

The other feature that makes a car responsive to the driver's commands is engine braking on deceleration. The driver is accustomed to it and counts on it, not only at high speeds but in all driving situations, and especially when maneuvering in heavy traffic.

This braking effort is natural to a reciprocating engine because friction and pumping work for idle throttle setting are appreciable. With a gas turbine, however, friction is negligible, and a turbine with nozzles fixed in the power position cannot absorb work. In the Chrysler engine when the foot pedal is released, these nozzles open to a point where the change in tangential velocity through the wheel is negative. This turbine then acts as a compressor (though not a very efficient one) and absorbs energy from the vehicle, thus reducing its speed.

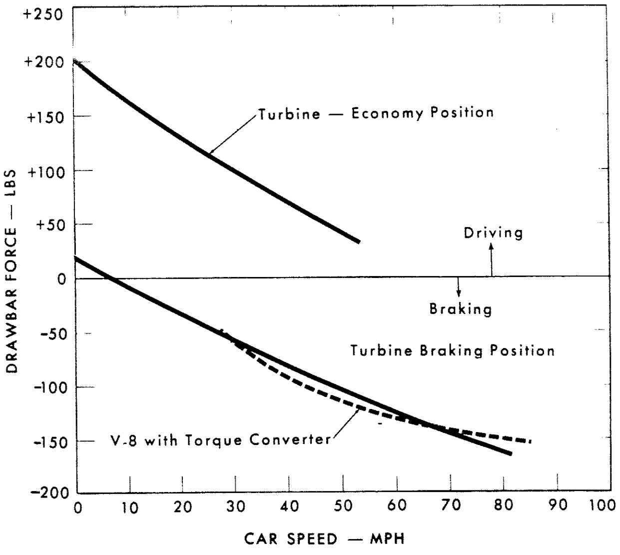


Fig. 12 - Engine Braking Characteristics

This characteristic is shown in Figure 12 in comparison with a standard Plymouth V-8 and TorqueFlite transmission. Data for both engines are given for the direct-drive ratio, with the engines at idle speed throttle setting.

For the turbine, this "compressor" action has two side effects: (a) the power turbine flow restriction increases, reducing the compressor-turbine expansion ratio and raising the temperature (T_5) required to run, and (b) work is being put back into the gas stream at the power turbine.

Both of these effects drive T_8 upward, and this, then, becomes the limit on nozzle angle setting and the degree of braking attainable.

Within these limits, however, the designer can still optimize the system. For maximum braking effort, the nozzle discharge flow should remain "attached" to the blades, whereas the wheel discharge should be separated from the suction side since this results in the largest negative torque. These requirements are not easily reconciled with those of the power output conditions, especially in the nozzles which may be opened by as much as 100 degrees. A blade leading edge which is tolerant of a wide inlet flow angle range is obviously desirable. The necessary design compromises, however, are best evolved experimentally, since there is as yet no reliable method for analyzing generally separated flow situations.

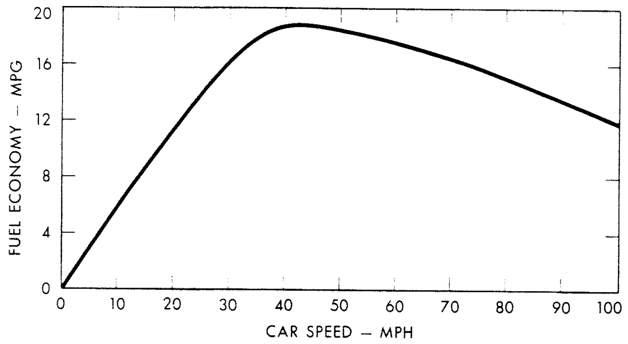


Fig. 13 - Road Load Fuel Economy

Fuel Economy

Figure 13 is a conventional miles per gallon estimate made from engine sfc data and vehicle road load power requirements. But cars built to be driven do not run on such a curve, except perhaps in carefully controlled proving ground tests. Acceleration, hills, starting, and idling all take their toll of extra fuel. So the engine that would produce good tank mileage must provide these extras with minimum consumption of fuel. The first two are conditions of net power output, so that the high cycle temperatures that give good efficiency are most important. Starting and idling, however, are strictly parasitic functions that produce no useful power. In these cases we want the absolute minimum fuel flow, and that is attained by keeping cycle temperatures and pressure ratio as low as possible. This minimizes both the required turbine work and the penalty of regenerator ineffectiveness $(1 - \eta)$; these are the two factors that determine fuel flow for parasitic functions.

Once again, variable power turbine nozzles come to the rescue. They are scheduled to a point of minimum restriction (actually, minimum T_5) for starting and idling. Any depression of the foot pedal after idle has been reached, then moves the blades to the optimum position for vehicle acceleration, as discussed earlier.

This control of cycle temperature is, we feel, an important feature of an automotive gas turbine, and contributes significantly to the tank mileage in the 15 to 18 mpg range which is attained by the Chrysler engine.

GAS TURBINE VEHICLE INSTALLATIONS AND DEMONSTRATIONS

Encouraged by the substantial progress achieved on the third and fourth generation powerplants, Chrysler Corporation decided to intensify its car installation and demonstration program. For example, our engineers installed the third powerplant in three different vehicles and proceeded with an initial showing to newsmen on February 28, 1961. The vehicles were displayed publicly in Washington, D.C., March 5-9, 1961, in conjunction with the Turbine Power Conference of the American Society of Mechanical Engineers, co-sponsored by the Department of Defense.

The first of these gas turbine vehicles (Figure 14) was an experimental sports car called the "Turboflite". In addition to the engine, other advanced ideas of the car were the retractable headlights, a deceleration air-flap suspended between the two stability struts, and an automatic canopied roof. This "idea" car received wide public interest and was shown at auto shows

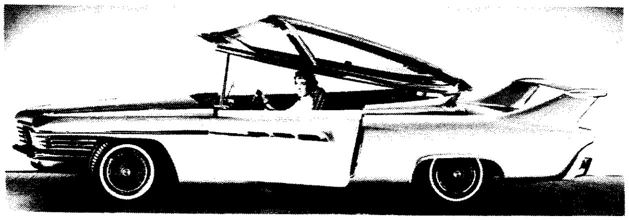


Fig. 14 - TurboFlite Car

in New York City, Chicago, London, Paris, Turin, and other cities.

The second of the vehicles (Figure 15) was a 1960 Plymouth which was standard in every respect except for the engine and minor exterior styling modifications.

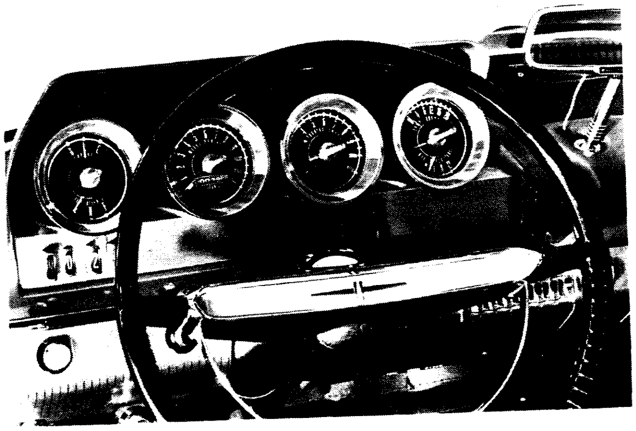


Fig. 15 - 1960 Plymouth Turbine Car

The final member of this trio (Figure 16) was a one-and-a-half-ton Dodge truck which was a standard production vehicle -- except for its gas turbine engine. This application demonstrated the turbine's versatility and adaptability because the engine in this truck was basically the same as those in the passenger cars.

Fig. 16 - Third Turbine - Truck Installation

After months of test and development work, the third Chrysler gas turbine engine was installed in a modified 1962 Dodge (Figure 17). The car left New York City on December 27, 1961, to begin a coast-to-coast engineering evaluation. After traveling 3,100 miles through snowstorms, freezing rain, sub-zero temperatures and 25 to 40 mile per hour head winds, it arrived in Los Angeles on December 31.

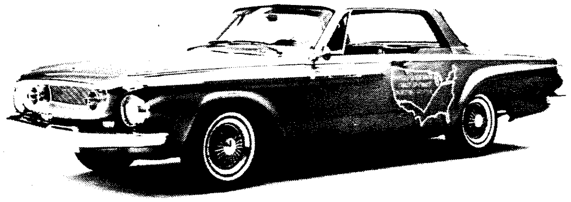


Fig. 17 - 1962 Dodge Turbine Car

The turbine had not only lived up to all expectations, but had exceeded them! An inspection showed every part of the engine in excellent condition. Fuel economy was consistently better than that of a conventional car which traveled with the turbine car and was exposed to the same conditions.

Another experimental turbine-powered car – the Plymouth Turbo Fury – joined the Dodge Turbo Dart, and the two turbine-powered cars began extensive consumer reaction tours at dealerships throughout the country in cities such as Los Angeles, San Francisco, Kansas City, St. Louis, Cleveland, Detroit, Chicago, etc. (Figure 18). Two other turbine cars, a

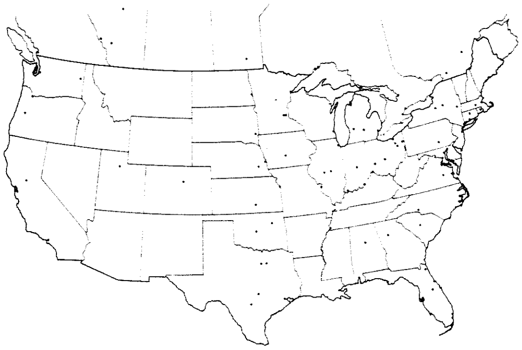


Fig. 18 - Consumer Reaction Tour

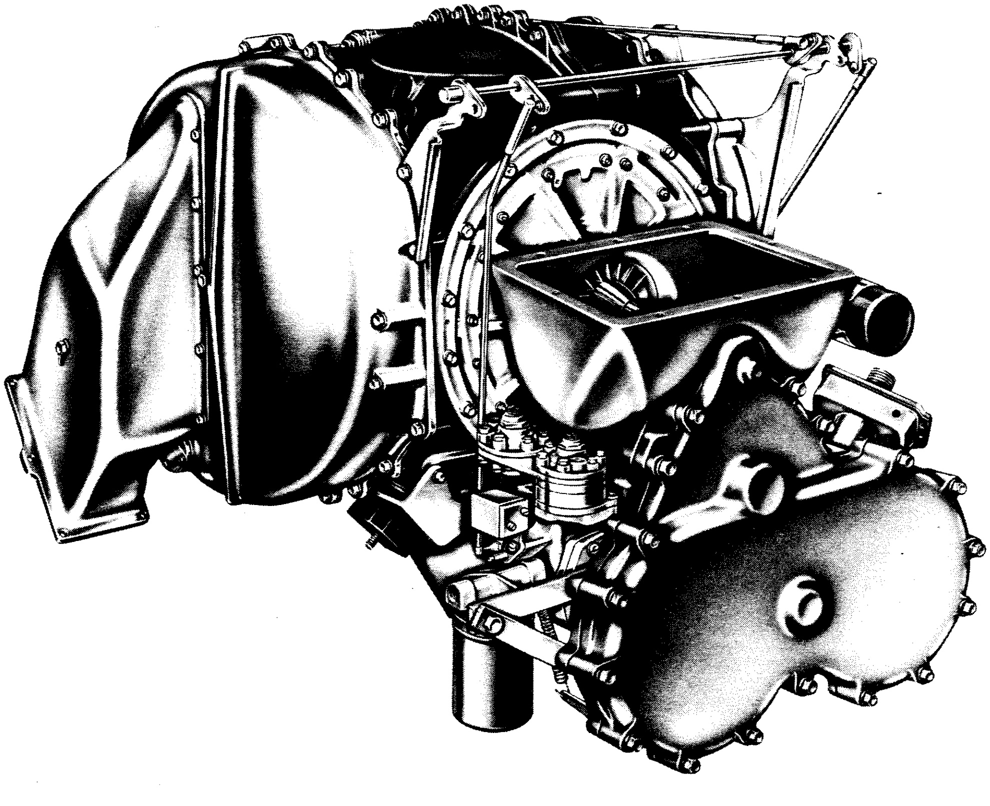
second Dodge and a second Plymouth, were added during the month of April in order to expand coverage of the tours. All four cars were powered by versions of the same turbine engine.

The tour schedule was similar in each area. When the cars arrived in a given city they were first displayed to members of the local press. The press events involved explaining the turbine and answering questions, giving each newsman a ride in one of the cars, and, in some cases, staging special tests. After members of the press had viewed the cars, they were then displayed at various dealerships.

The key reason for these tours and exhibits was to elicit and evaluate consumer reactions to the turbine. The cars were shown at Plymouth and Dodge dealerships in approximately 90 major cities in the United States and Canada.

During this time, millions of people came to see and hear the turbine vehicles in which nearly fourteen thousand people had a ride. Public interest was intense and serious. When asked, "if this car were offered for sale to the motoring public, do you think you would buy one?" Thirty per cent of the turbine viewers said "yes", they would definitely buy one, and 54 per cent answered they would think seriously of buying one.

As a result, on February 14, 1962, Chrysler Corporation announced that it would build 50 turbine-powered passenger cars which would be made available to selected users by the end of 1963, for an opportunity to evaluate turbine cars under a variety of driving conditions. All these vehicles were to be powered by our newest powerplant, which will be described in detail in all the other Chrysler papers presented today.



Chrysler Gas Turbine Engine

CHRYSLER CORPORATION TURBINE CAR

A complete description of the Chrysler Corporation turbine car would be difficult in the time allowed today. It is primarily a conventional automobile so that only those things which are markedly different will be described.

The car is a front engine, rear drive, four seat, two-door hardtop, of the "sports" type. (Figure 19). It was styled completely in Chrysler Styling Studios. The body engineering was done completely by the Chrysler Body Design and Engineering Group. Body design is conventional with the exception that front and rear bumpers

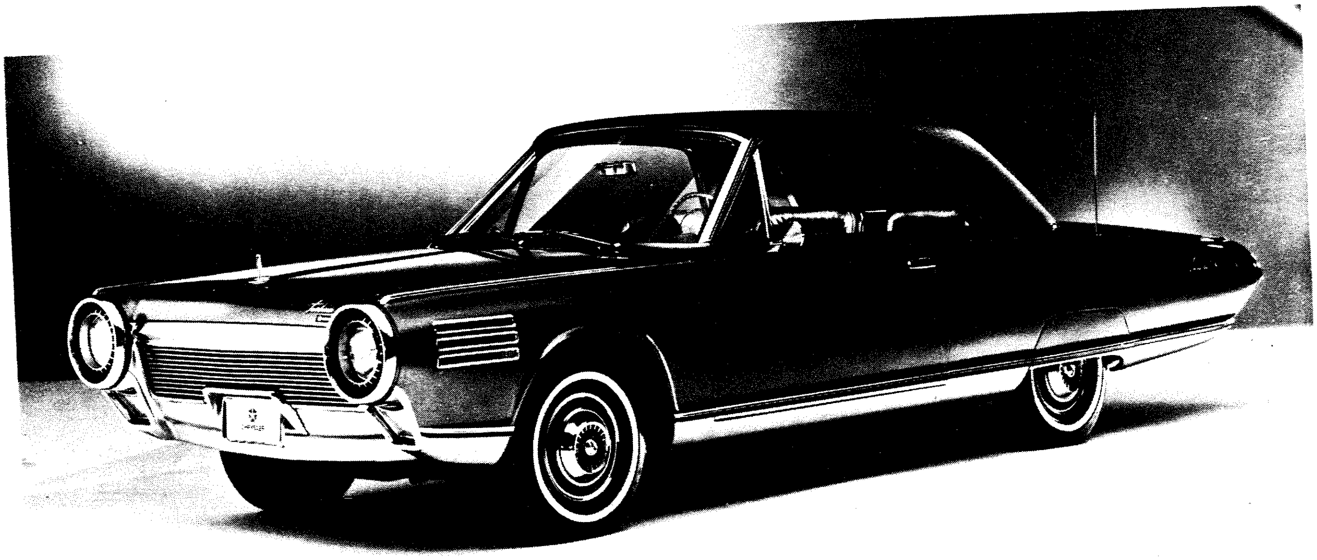


Fig. 19 - The Chrysler Corporation Turbine Car

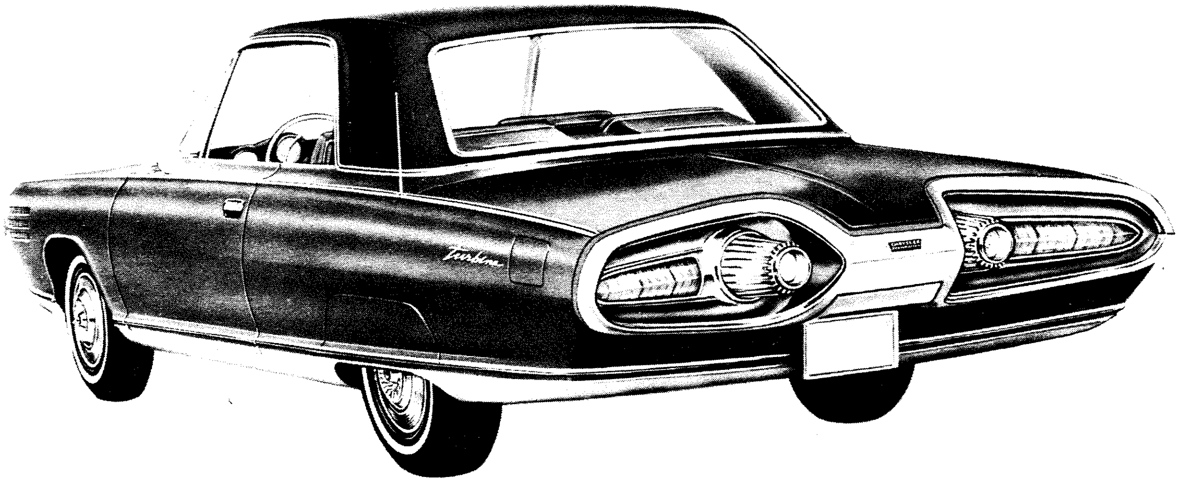


Fig. 20 - Turbine Car Rear View

as separate elements have been eliminated, and in their place, the sheet metal below the inlet grille in the front has been covered with chrome plated bumper stock, and two ornamental and functional bumper stock rings have been placed around and slightly forward of the two fender-mounted headlights. In place of the rear bumper (Figure 20), the body is extended to form a shape suggestive of the sweepback of a delta wing aircraft in which the trailing edges are formed of bumper stock surrounding two tail lamp assemblies.

Extending longitudinally from the dash, completely to the back of the passenger compartment, is a control console (Figure 21) which contains within it the operating controls of the vehicle. These include the transmission selector lever and indicator, headlamp, windshield wiper, heater, rear window defroster, and interior light controls. Instruments are placed in a triple cluster behind the steering wheel and within the driver's field of vision. Windows are all electrically operated.

The cars are painted externally, using a special high metallic content paint called Turbine Bronze. The roof is covered with black vinyl. The turbine bronze color scheme is carried out in the interior of the car, not only on the instrument panel, but in the leather interior trim and in the deep pile carpet on the floor.

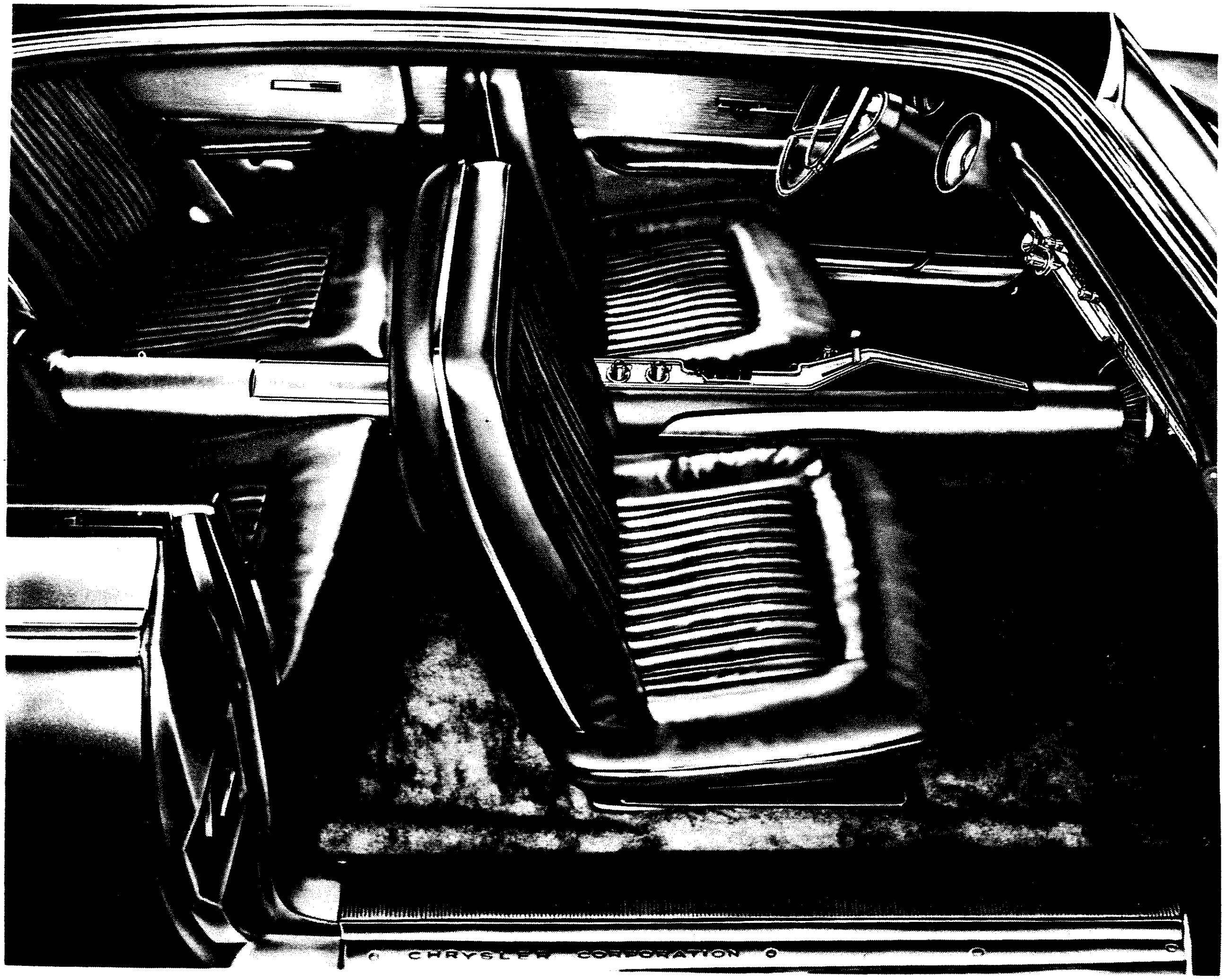


Fig. 21 - Turbine Car Interior

Although individual test varies, the overall impression produced by the body styling and engineering is that of elegance without ostentation, and the effect has been to give a suggestion of jet-powered modern design without creating a Buck Rogerish or a "way out" atmosphere.

Chassis design for the car was executed by the Chrysler Engineering Chassis Design Section. Wheel brakes are drum-type-servo brakes, 10" in diameter by 2.5" lining width. The hand brake on the rear wheels is operated by a lever on the driver's side of the control console. The master cylinder is boosted by compressed air furnished by an electrically driven compressor placed on the left front fender shield (Figure 22). Brake pedal travel is only 2.5 inches, which adds greatly to driving convenience and comfort.

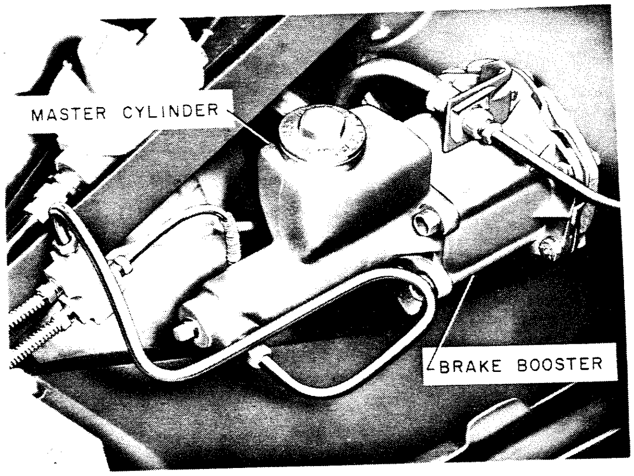


Fig. 22 - Power Brake System

The front end structure is unconventional in that the front longitudinals extend upward from the attaching points on the dash and forward over the engine curving down to the normal front cross member location. This has been done to allow installation of a rubber isolated front suspension system (Figure 23) which is mounted on a free cross member, to which the engine itself is rubber mounted. This was deemed necessary to prevent transmission of road shocks through the suspension system into the car structure, since the turbine engine is so smooth its operation does not mask the road shocks transmitted by normal suspension, as does the reciprocating engine. The engine is assembled into the car by first being mounted on the suspension cross member. This assembly is then mounted to the front longitudinals by means of four (4) rubber isolators and stabilized by a rubber isolator at the end of the transmission.

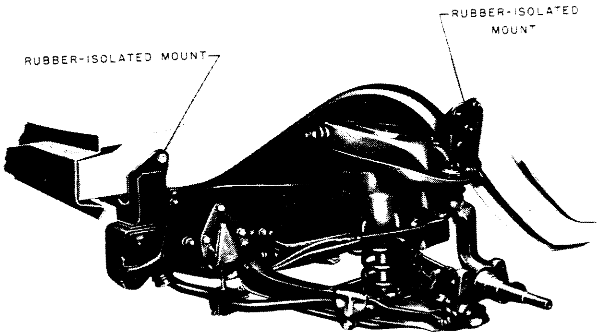


Fig. 23 - Front Suspension

Rear suspension consists of two asymmetrical leaf springs, a conventional axle and differential. To obtain the necessary drive line smoothness to match the smoothness of the turbine engine, a tuned dynamic absorber is mounted on the transmission extension.

The electrical system consists of a gear-driven starter generator unit which is continuously engaged to the accessory reduction system. The ignition is supplied by a conventional ignition coil and gear-driven breaker to a single spark plug mounted in the can-type burner.

All hydraulic functions of the powerplant and vehicle are supplied by a single oil pump which supplies lubricating oil to the engine, reduction gear and transmission and high pressure oil to the conventional Chrysler power steering unit, the variable nozzle actuator, and the modified Torqueflite transmission. Modifications to the transmission include not only those necessary for attachment to the turbine powerplant but the elimination of the torque converter, elimination of both front and rear oil pumps, and changes in servo actuators and control system to be able to produce smooth shifting with the higher torque but substantially reduced inertia of the power turbine wheel.

Perhaps a brief description of the driver's control operations would be of interest. The transmission selector lever, which is mounted on the control console in a convenient position under the driver's right hand, is placed in a "park-start" position. The key is then inserted in the ignition lock and turned past the ignition point to the crank position, held momentarily, and then released. This act has armed the starter relay, energizing the starter, opening the fuel solenoid, and turning on the ignition. Light-off occurs in one to one-and-one-half seconds and the gas generator accelerates rapidly to idle speed, which is 40% of governed speed. A normal warm start takes approximately six to six-and-one-half seconds and a hot start a second or more less than this. Starting at -10°F takes approximately twelve to thirteen seconds. Before the idle speed is reached, between 15,000 and 16,000 rpm, the starter relay drops out due to the reduction in starter current demand and the generator field is then energized.

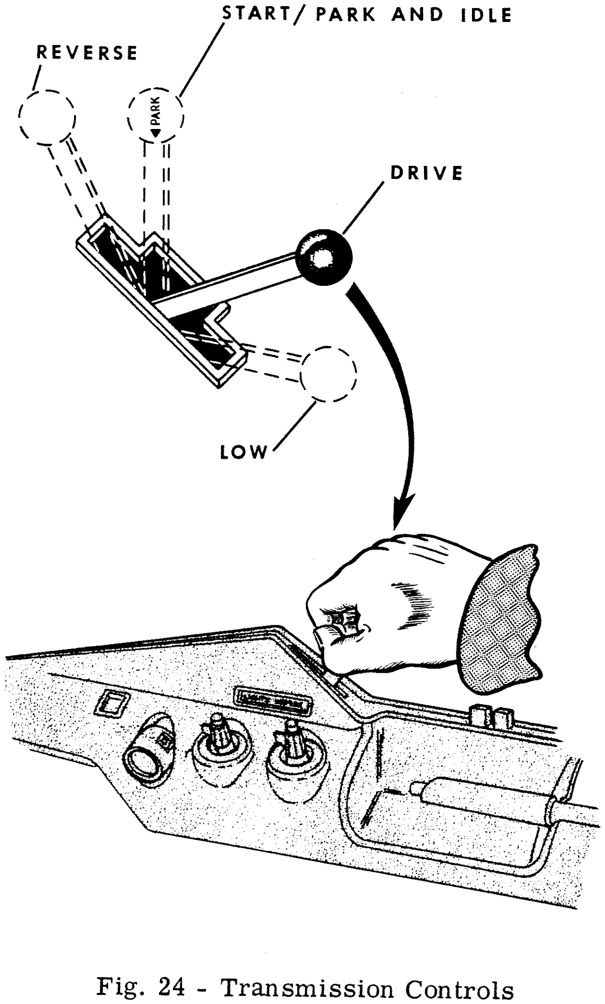


Fig. 24 - Transmission Controls

On reaching idle speed the driver lifts the transmission selector knob straight up from its "start-park" position (Figure 24). This raises the idle speed to fifty per cent. Moving it forward he can then engage reverse or back to drive. A finger control lock is provided on the selector lever to prevent inadvertently shifting the lever into the park position, since the transmission sprag is also engaged with the selector lever in either the start-park or the raised park-idle position. There is no neutral position, of course, since the power turbine wheel must be coupled to the rear wheels at all times. Not only is the transmission parking sprag engaged in both part positions, but forward and reverse are also simultaneously engaged.

Some change in driving technique is desirable. The car is driven much as one would drive a sports car. That is, by decelerating into a turn and then driving through and out of the turn with power on. It is interesting to watch how quickly drivers acquaint themselves with this method of operation even though they have been totally unacquainted with it before driving a turbine car. As you know, what they are doing is allowing for the slight gas generator acceleration lag. After twenty to thirty minutes, almost all drivers with which the writer is acquainted were doing this easily and without premeditation.

The sensation of driving a turbine car can be described, but is largely meaningless unless actually experienced. One can compare it to the difference in the sensation of a piston-powered aircraft take-off and the take-off of a jet. It is an impression of superb smoothness, of sleekness. Although there is no direct mechanical connection between the gas generator and the power turbine, the driver has the feeling of positive control. When the accelerator pedal comes back, engine braking is fast and positive. Conversely, acceleration under passing conditions is quick and safe.

No transmission kick-down is provided in these vehicles. Torque available for acceleration is high, but, if desired, the driver can shift the transmission selector lever into the low range which will provide him with the next lower transmission ratio for acceleration. To protect the power turbine wheel during maneuvers of this type, the transmission up-shifts again at its maximum-governed speed.

Although not necessary for ordinary driving use, the turbine is provided with a tachometer which indicates gas generator revolutions per minute and a pyrometer which indicates first-stage turbine nozzle inlet temperature. In addition, an oil pressure gauge and low oil pressure warning light are supplied, and in the same cluster, there is an ammeter to indicate generator performance.

As we have indicated during this entire program, the selected users of these vehicles have been supplied with a car which forms a pleasing and non-radical background against which they may judge performance of turbine engines. We have attempted to make the car attractive and exciting, but do this in such a way that it would not intrude into the primary purpose of this whole activity. That primary purpose is to arrive at a normal consumer evaluation of turbine-powered passenger cars.

Users have been and are being selected from people who have written to Chrysler Corporation indicating interest in driving these cars. They are chosen by an independent firm of auditors in order to obtain complete objectivity in the choice of typical drivers. Six (6) units have been delivered so far. The first delivery was made at the end of October, 1963 and the sixth one just last week. Reaction of all of the users has been very enthusiastic. The drivers like the car, they like the turbine powerplant, and they like the whole idea of being allowed to evaluate an entirely new idea.

Present indications, both from extensive road test work at our Proving Grounds and numerous cross-country test trips and from the users themselves, indicate that they will receive reliable, rewarding and exciting service from these cars.

What the final conclusion of these tests will be, we certainly cannot foresee. Admittedly, the automotive gas turbine powerplant is in its infancy, but we can be assured that future development over a relatively short term period will make it far superior to the present powerplant in specific output, size, weight, and in fuel consumption. In the meantime, we have submitted our case to a jury of customers and we await with great interest, and also with great confidence, their verdict.

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