TWENTY-THIRD COMBINED QUARTERLY PROGRESS REPORT

BASELINE GAS TURBINE DEVELOPMENT PROGRAM

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ABSTRACT

Progress is reported for a program whose goals are to demonstrate an experimental Upgraded gas turbine-powered automobile which meets the 1978 Federal Emissions Standards, has significantly improved fuel economy, and is competitive in performance, reliability, and potential manufacturing cost with the conventional piston engine-powered, compact-size American automobile. This is the concluding progress report for this program; it covers the period from May 1, 1978 to January 31, 1979. The next formal report will be the final report, which is currently in process.

Activity during this reporting period has continued to emphasize development towards correcting a power deficiency in the Upgraded Engine. Efforts are also being directed towards reducing fuel usage through improved heat recovery and towards improving the mechanical reliability and control of the engine.

The final engine performance with all retro-fitted components showed a nominal value of 90 HP at design speed in contrast to the design value of 104 HP. The design-speed SFC was 0.55 versus the goal 0.44. During the program, the original goals were revised as a result of a re-assessment of the component efficiencies to values that were thought to be more likely in turbomachinery of this size. This resulted in revised design-point goals of 95.6 HP at an SFC of 0.49. Detailed examination of final engine data indicated that even the revised turbine efficiency goals could not be met in this size. Full evaluation will take place on component rig tests at NASA-Lewis. Part-load fuel consumption is still about 20% too high. Most of this is due to excessive bulkhead-cooling heat loss.

Vehicular fuel consumption tests for both cold '75, hot '74, and FEC were conducted on chassis rolls for an inertia weight of 3500 pounds. Fuel consumed (gasoline) was weighed directly. Various schemes tested did not significantly change the fuel economy. The best combined cycle fuel economy was 15 MPG without engine braking.

Heat Recovery

Tests to reduce bulkhead-cooling heat loss continued.

Control Development

Development testing continued on the ECU and power turbine nozzle actuator.

Ceramic Burner Liners

To date, only one acceptable silicon nitride prevaporized burner liner has been received. Testing has been deferred, due to other program priorities. The order for silicon carbide samples has been cancelled, since the vendors cannot furnish defect-free parts.

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INTRODUCTION

This is the concluding progress report for this program. The next formal report will be the final report, which is currently in process.

This Baseline Gas Turbine Development Program is being sponsored by the Heat Engine Systems Branch, Division of Transportation Energy Conservation (TEC) of the Department of Energy (DOE). One of the major components of the Department of Energy, when formed October 1, 1977, was the former Energy Research and Development Administration (ERDA). ERDA in turn had been established in January, 1975, as a result of the 1974 Energy Reorganization. Prior to this reorganization, TEC had been the Advanced Automotive Power Systems Division (AAPSD) of the Environmental Protection Agency (EPA).

The overall mission of AAPSD, which resulted in the generation of this particular program, had been to evaluate, develop, and demonstrate power plant concepts potentially superior, in the area of emissions control and fuel economy, to the standard spark ignition reciprocating engine. A principal area of activity has been the automotive gas turbine. Programs were first initiated in this area early in 1971 when several contracts were let for the development of low emissions combustion, and for studies related to cycle optimization, engine arrangement, and cost to manufacture. Additionally, EPA enlisted NASA for technical support to these programs through an inter-agency agreement.

This Baseline Engine program was implemented on November 22, 1972, with the signing of a contract between EPA and Chrysler Corporation. Specific goals of this program were to demonstrate in 1976 an experimental gas turbine-powered automobile which would meet the 1978 Federal Emissions Standards, have significantly improved fuel economy and be competitive in performance, reliability, and potential manufacturing cost with the conventional piston engine-powered, standard-size American automobile.

Structurally, this program was made up of three parts: (1) documentation of the existing automotive gas turbine state-of-the-art, (2) conduction of an extensive component improvement program, and (3) utilization of the improvements in the design and building of an Upgraded Engine capable of demonstrating program goals.

Chrysler Corporation's Sixth Generation Gas Turbine Engine, having been selected as representative of the state-of-the-art at the beginning of this program, was used as the Baseline Engine. This was a 4:1 pressure ratio regenerative engine with variable power turbine nozzles which meets the .41 HC, 3.4 CO, 3.0 NOx grams/mile original 1975 emissions standards. The Baseline vehicles were intermediate-size, 4-door sedans

INTRODUCTION - (CONT'D)

modified to accept the turbine engines.

Efforts still to be completed include building and testing Upgraded Engines and vehicles, Tasks 7 and 8.

With respect to Tasks 7 and 8, initial running of the Upgraded Engine took place on July 13, 1976. This engine, though mechanically sound, started out about 43% deficient in power. The principal problem has been low efficiencies of the aerodynamic subsystems resulting from compromises made to satisfy packaging/interface and other design constraints. Changes in the compressor and compressor-turbine along with some reductions in leakage and pressure drop reduced the power deficiency to about 25%. To fully eliminate these deficiencies, major turbomachinery redesigns, made possible by reconsideration and relaxation of stress and overspeed constraints were carried out.

The final engine performance with all retro-fitted components showed a nominal value of 90 HP at design speed in contrast to the design value of 104 HP. The design-speed SFC was 0.55 versus the goal of 0.44. During the program, the original goals were revised as a result of a re-assessment of the component efficiencies to values that were thought to be more likely in turbomachinery of this size. This resulted in revised design-point goals of 95.6 HP at an SFC of 0.49. Detailed examination of final engine data indicated that even the revised turbine efficiency goals could not be met in this size. Full evaluation will take place on component rig tests at NASA-Lewis. Cycle analysis shows that at low speeds, 60% of the deficit due to lack of heat recovery is due to the bulkhead-cooling heat loss.

Vehicular fuel consumption tests for both cold '75, hot '74, and FEC were conducted on chassis rolls for an inertia weight of 3500 pounds. Fuel consumed (gasoline) was weighed directly. Various schemes tested did not significantly change the fuel economy. The best combined cycle fuel economy was 15 MPG without engine braking.

Chrysler Corporation efforts on this program are being managed and coordinated by the Research section of the Engineering Office. Those who have contributed directly in writing this report include A. Billington, B. Chapman, T. Golec, J. Gross, E. Kohl, R. Pampreen, N. Sparks, and E. Trieskey.

PROGRESS SUMMARY

Support To Government

Upgraded Vehicles U-2 and U-3 participated in both Spring and Fall DOE Contractor Coordination Meetings.

Engine Testing

Upgraded Engines R1 and R2 underwent various corrective development tests with modified and redesigned turbine stages for performance improvement and with other engine modifications directed toward improved fuel economy, mechanical reliability and engine control.

The final engine performance with all retro-fitted components showed a nominal value of 90 HP at design speed in contrast to the design value of 104 HP. The design-speed SFC was 0.55 versus the goal of 0.44. During the program, the original goals were revised as a result of a re-assessment of the component efficiencies to values that were thought to be more likely in turbomachinery of this size. This resulted in revised design-point goals of 95.6 HP at an SFC of 0.49. Detailed examination of final engine data indicated that even the revised turbine efficiency goals could not be met in this size. Full evaluation will take place on component rig tests at NASA-Lewis. Part-load fuel consumption is still about 20% too high. Most of this is due to excessive bulkhead-cooling heat loss.

Tests to reduce bulkhead-cooling heat loss continued.

Control Development

Development testing continued on the ECU and power turbine nozzle actuator.

Ceramic Burner Liners

To date, only one acceptable silicon nitride pre-vaporized burner liner has been received. Testing has been deferred, due to other program priorities. The order for silicon carbide samples has been cancelled, since the vendors cannot furnish defect-free parts.

Vehicle Testing

Vehicular fuel consumption tests for both cold '75, hot '74, and FEC were conducted on chassis rolls for an inertia weight of 3500 pounds. Fuel consumed (gasoline) was weighed directly. Various schemes tested did not significantly change the fuel economy. The best combined cycle fuel economy was 15 MPG without engine braking.

DETAILED PROGRESS STATEMENT BY TASK

TASK 3a - SUPPORT TO D.O.E. - (DEPARTMENT OF ENERGY)

Baseline vehicles B-2 and B-3 have continued to be used during this reporting period for ride/drive demonstration at D.O.E. Headquarters in Washington, D.C. For most of the time, however, only one vehicle has been driveable.

This reporting period began with vehicle B-2 in Detroit for replacement of a leaky gas-generator oil seal. Oil had contaminated the compressor and air pump, which caused both low power and hard starting. This vehicle was returned to Washington in late June. After six weeks of service, it had to be deactivated when an oil plug blew out of the power turbine nozzle-actuator; this caused oil starvation, a failed gas-generator bearing, and an impeller-to-shroud rub. Since then, it has been used as a spare-parts supply for vehicle B-3.

Service for vehicle B-3 throughout this reporting period included:

- Replacement of the main hydraulic control system actuator.
- An attempt to correct erratic start-safety-box behavior during the summer months by addition of a heat shield.
- Replacement of heater control and heater core.

Upgraded vehicles U-2 and U-3 were demonstrated at the Contractors' Coordination Meeting at the Hyatt Regency Hotel in Dearborn, Michigan during the period of October 17-20, 1978.

TASK 3b - SUPPORT TO NASA

Controls

A service call was made to assist shakedown of Engine 4 (PP 5-4), which was recently installed in the transient test facility. The engine idled at 60% speed, and hot restarts resulted in overtemperature shutdowns. The control system breakout module wiring was checked and corrected. An additional PROM card was generated with a lower fuel schedule. These changes allowed normal start and running. NASA requested and received the following parts during this period for transient engine testing:

- Two packets of control system schematics, program, and PAC manual
- Test cell electrical connectors and sketch
- Operator's test cell, diagnostic modules

A customized, 12-volt D.C., reluctance-type speed-sensing system for use with all-aluminum impellers has been ordered, and delivery is expected late in 1979. If successful, this system will also be procured for Upgraded Vehicle use. The present system uses a magnetic pick-up and, therefore, can only be used on engines equipped with steel-inducer impellers.

The following additional components have been ordered for NASA-Lewis transient cell facility:

- PAC 500 ECU
- Keyboard programmer
- Printer option
- Metering valve assembly
- Spare PROM board

Purchase of Pro-Log PROM programmer has been delayed until early 1979.

TASK 7.2 - PROCUREMENT OF RETROFIT PARTS

All retrofit Upgraded Engine hardware has been received. Airfoil inspection of the Howmet-cast Mod 1 turbine nozzle and rotor, are described below.

Mod 3 Compressor-Turbine Nozzle

Inspection of a nominal-angle nozzle casting revealed the vane shape and angle to be to print. See Figure 1B. Airflow data shows the -1° nozzle to be approximately 4% larger in flow rate than the nominal nozzle. However, because this flow size was required for engine test and since dimensional inspection required removal of the outer shroud, hardware availability precluded detailed inspection.

Mod 3 Compressor-Turbine Rotor

The inspection result is shown on Figure 2B. The airfoil contour is to blueprint specifications, but the blade stagger angle is 1° (closed) out of print specification for all sections. No computations were made to estimate the effect on performance.

Mod 1 Power-Turbine Nozzle

Two typical machined vanes - one each 'A' and 'B' - are defined in Figure 3B. The airfoils follow the required contour but are almost uniformly thick by about 5% of the maximum thickness. The largest effect on aerodynamic performance would come from the trailing edge, where the thickness is about 20% larger than print specification. This was judged to yield less than one point in efficiency deficit.

Mod 1 Power-Turbine Rotor

Due to the blade shape, it was necessary to cut a rotor to inspect the blades at each section to permit shadowgraph inspection by a backlighting technique. Figure 4 shows the results of this inspection. The blades are fairly close to print. It was not possible to evaluate the local deviations in camber and thickness without detailed analysis. It was judged that the best and most timely evaluation would come from test results. The deviation on the root suction-surface was attributed to the proximity of the fillet.

TASK 7.5 - CORRECTIVE DEVELOPMENT

Principal efforts under this task continued to be directed towards development of the aerodynamic components to bring the engine up to design power. However, efforts are also being directed towards improved fuel economy through improved heat recovery and towards improved mechanical reliability and control of the engine.

Summary Of Results

Engine Performance Improvement

Significant improvement in engine performance was achieved during this reporting period. Testing with the Mod 3 compressor-turbine resulted in a 12% increase in power over that obtained with use of the Mod 1 compressor-turbine. Twisting the blade tips of the original power turbine closed by 10° resulted in a 5% increase in power.

The final engine performance with all retro-fitted components is shown on Figs. 5 and 6. Fig 5 shows a nominal performance of 90 HP at design speed with an SFC of 0.55. Fig. 6 shows that this is 15% below the target power, 20% above the target SFC, and about 10% from the corrective development goals. The latter are revisions to the original goals as a result of a re-evaluation of the component efficiencies that are more likely to be expected in turbomachinery of this size. Detailed examination of engine data indicates that even the revised turbine efficiency goals could not be met in this size. Full evaluation will take place on rig tests at NASA-Lewis. Part-load fuel consumption is still about 20% too high. Most of this is due to excessive bulkhead-cooling heat loss.

As the comparisons show, there was little difference in engine performance with either the modified version of the original power turbine design (twisted blades) or with the Mod 1 configuration of Noel Penny Turbines Limited.

Heat Recovery

Progress has been made in correcting overcooling of the Bulkhead (Figure 7). This has been of some benefit in reduced fuel flow by reducing the amount of heat the compressor discharge air picks up before passing through the regenerator. However, because fuel flow is still over goal, optimization of the flow using gas temperature grids, together with additional efforts at uniforming regenerator flow is warranted. This will be undertaken in conjunction with final fuel economy documentation efforts.

Control Development

Development testing continued on the ECU and power turbine nozzle actuator. The keyboard programmer and printer were received and integrated into the developmental program.

Several ECU anomalies were noted, e.g. multiplexer circuit board cross-talk, failure to achieve 100% speed, speed/temperature instability et cetera. Corrections and/or improvements were implemented as required.

Two redesigned power turbine nozzle actuators were assembled and bench tested. The design of the variable inlet guide vane actuator was modified as a two-position, improved response device.

Ceramic Burner Liners

To date, only one acceptable silicon nitride, pre-vaporized burner liner has been received. Testing has been deferred, due to other program priorities. The order for silicon carbide samples has been cancelled, since the vendors cannot furnish defect-free parts.

Detailed Test Results

Engine 1 (R1 - Power Plant 3-13)

This power plant, the first complete retrofit Upgraded Engine, was initially tested on May 30, 1978. The engine housing had been updated, since its previous build (PP 3-9Z), to include the Mod 3 compressor-turbine and Mod 2 power-turbine components. The gas generator, together with the burner and regenerator systems were transferred unchanged from PP 10-12F. Subsequent builds evaluated the effects of reduced power-turbine nozzle and rotor clearances, reduced compressor-turbine nozzle flow size, and removal of the air pump. An extensive engine mapping program was then begun, to study the engine's performance over a range of prop-shaft speeds, VIGV settings, and cycle temperatures.

Following an overtemperature failure (Build G), the engine was completely rebuilt with the best available corrective development parts, including compressor-turbine nozzle with 1° vane opening (-1°) and a cutback 18-18 impeller. Cold leakage was brought down to 4.8%. 90.30 HP was produced at 100% speed, with 60° T₅ (turbine inlet temperature) overtemp power of 95.55 HP demonstrated without surge.

Additional test items for this power plant included:

- Evaluation of modifications to reduce impeller backface parasitic losses
- Comparison of exhaust emissions for both burner types
- Verification of oil system pressure losses

In addition to the overtemp failure noted above, the engine also sustained two air bearing failures, a power turbine bearing failure, and a complete separation of the drive gear from the regenerator. To date, 124.8 hours and 250 lines of data have been logged. Highlights are as follows:

Build A - Runs 1-16

Initial power plant checkout through 80% speed, matched on T_5 , and at varying prop shaft speeds. Maximum T_5 power was 37.05 at 80% speed. Green dye was injected into the cavity surrounding the combustor at 80% speed to view flow and leakage paths, but no photographs were taken. Inspection showed no aerodynamic problems with the Mod 3 compressor-turbine or the Mod 1 power-turbine, other than leakage paths around the power-turbine nozzle vanes.

Build B - Runs 17-29

Power-turbine nozzle vane clearance and rotor blade tip clearance were reduced through plasma spraying of the shrouds. The exhaust diffuser inner insulation biscuit was resized to match the rotor. Power increased to 39.27 HP at 80% speed. In spite of a new baseplate, which had reduced cold leakage, indicated hot leakage was up two percentage points. Teardown revealed a broken regenerator seal. A slight rotor tip rub was polished out.

Build C - Runs 30-34

No changes other than a new rear rim seal. Running with air injection showed the following power improvements:

<u>Added Air, PPH</u>	<u>Horsepower @ 80% Speed</u>
0	39.19
150	43.13
300	47.65

The engine was kept below the surge point to minimize the risk to the limited-service compressor-turbine rotor. Following the build, the regenerator leakage was again checked and found to be excessive at 9%, although no seals were broken. The baseplates were reworked to reduce leakage to 6.5%.

Build D - Runs 35-45

Gas generator No. 2 installed in place of No. 6. Changes included a new compressor-turbine nozzle with a 3% reduction in flow size and a new rotor with improved blade chord length and no 80% speed limitation. To provide a better comparison with previous power plants which used the premixer-type burner (for which the engine had been characterized), the air pump was removed, and shop air was supplied to the burner. It was found that 7 PPH of added air (0.2% of engine air flow at 80% speed) gave good burner performance, although emissions were not checked. A new regenerator drive pinion shaft seal was installed, reducing blow-by

35 to 40%. Power increased 10%, with 43.80 HP demonstrated. Augmentation to -12° VIGV setting produced 44.50 HP. A fuel system limitation prevented running above 98.8% speed. As a check on possible parasitic losses, this build was also fitted with an oil pressure tap at the discharge of the oil pump, upstream of the pressure regulating valve. No excessive pressure drop across the regulator was noted - at maximum tested conditions (3,100 prop shaft rpm), the pump element discharge pressure was 68 psi and the power-turbine oil feed pressure (following regulator, cooler, filter, and line losses) was 56 psi. On teardown, a 1/8" gap was found around the split line of the two-piece vortex, which explained the low burner pressure drop and high T₅ spread noted earlier in the build. The vortex chamber was properly secured for the next build.

Build E - Runs 46-49

Rebuilt following burner inspection with no major changes. Power was down 5%, with indication of excessive seal leakage.

Build F - Runs 50-62

Minor burner modifications to cool hot spots, and a new inner baseplate was installed. Cold leakage was not checked. A value of 84.92 HP was demonstrated at 98.8% speed with -12° VIGV augmentation.

Build G - Runs 63-105

To permit running to 100% speed, fuel system and ECU changes were made. The engine performed well at 100% speed, but attempts to increase output power by augmenting beyond -12° were not successful. Following a set of peak power surveys on T₅ match and a power run on T_{7.5} (power turbine outlet) + 100°, an attempt was made to run T₅ + 100°. On setting the 80% speed-point (T_{7.5} actual: 1,440°F), binding in the power-turbine nozzle assembly led to an overtemperature operation, followed by repeated surges. The blades of the compressor-turbine rotor were burned off over half their length, with minor secondary damage to downstream components. Teardown also revealed heavy erosion of the insulation biscuit forming the outer wall of the exhaust diffuser, which may have contributed to gradual power losses noted earlier.

An extensive leak check program was then run to isolate items contributing to overall leakage and to reduce them where possible. Expressed in percent of total engine air flow at 80% speed, the following leakages were found:

- 0.2% Engine housing, including:
 - external and internal gaskets and bolt threads
 - external and internal casting porosity (if any)
 - PTN actuating and readout systems
- 4.2% Regenerator system, including:
 - seal leakage
 - matrix porosity
- 0.4% Power turbine shaft seals
- 1.8% Power turbine nozzle assembly
- 6.6% T O T A L

The high leakage in the power-turbine nozzle assembly appeared to be associated with poorly-sealed instrumentation holes. The instrumentation was removed; and the holes were sealed, dropping the leakage to 1.3%. Then, by heavy application of anti-seize compound (Fel-Pro C-100) to the vane stems and strut pilots, the nozzle leakage dropped to 0.5%. Assuming that the sealant is not lost during running, these changes should reduce total leakage to 5.3%. Further reductions in the regenerator seal leakage will be attempted, when priorities permit.

Build H - Runs 106-110

The engine was then rebuilt with the following:

- VIGV
- Cutback 18-18 impeller
- 40% increased exit area diffuser
- Mod 3 compressor-turbine with -1' nozzle
- Mod 1 power-turbine
- Housing with blocked cooling, flow baffles top and bottom, and crossarm baffle (but no deflector in cover).

At assembly, power-turbine rotor shroud runouts were found to be unacceptable. Investigation showed the engine housing to be distorted, causing the nozzle and rotor pilots to be eccentric by 0.010". Correction of this misalignment required extensive machining and shimming of the nozzle support pilot surfaces.

While the exact cause of the housing distortion is unknown, it is assumed that uneven cooling in the bulkhead area is a contributing factor. Previous bulkhead temperature studies have shown excessive cooling of the bulkhead flanges and insufficient cooling of the crossarm, particularly at the centerbolt area. To reduce thermal gradients in these areas, this engine was fitted with a cooling baffle for the crossarm. Power was 42.18 HP at 80% speed and 65.62 at 90% speed. However, on setting the 95% speed point, the regenerator mounting system failed, terminating the test. Teardown revealed massive failure of the maxtrix/edge coating interface, with extensive engine contamination from matrix debris. A possible cause was previous water contamination during extensive cold flow testing in the power turbine rig in Room 7. Another possible cause would be high torque loads imposed by the zirconia crossarm seal. Ford has experienced similar failures with the thin wall matrix.

Build I - Runs 111-132

Engine rebuilt with new regenerator. Extensive running included three runs at 100% speed, $T_{7.5/\theta} = 1,450^{\circ}\text{F}$ from 50 to 100% speeds, and surge margin at 80 and 90% speeds. Unfortunately, the air injection system for surge margin reintroduced matrix debris from the previous failure, damaging the matrix cold face and outer "D" graphite. A final check run showed a 5% loss in power as a result (84.60 HP at 100% speed).

Build J - Runs 133-143

Engine rebuilt with seals repaired and graphite hand-worked to remove grooves, but no new regenerator was available. Power checked with only slight improvement (86.16 HP at 100% speed). On teardown, full engine cold leakage was checked and found to be 6.3%. With the regenerator and seals removed and blocked, leakage dropped to 1.2%, which compares well with the 1.0% prior to Build H. In effect, all but 0.2% of the leakage increase since Build H (4.8% to 6.3%) was caused by regenerator and seal deterioration.

Build K - Runs 144-164

Engine was essentially unchanged from Build J, except for seal modifications to reduce high leakage. Selective leak checks showed a final leakage of 6.0%, with 1.2% charged to nonregenerator areas (power turbine nozzles stems and shaft seals) and 0.3% to grooves in the regenerator surface. Power was 41.77HP at 80% speed and 75.94 HP at 95% speed. Speed fluctuations prevented running 100% speed. Low power peak prop shaft speed points (50 to 80% speeds) were then run, with results shown on Figures 8 to 11. Finally, emissions were recorded at 50 to 90% speeds, as shown on Figure 12.

Build L - Runs 165-174

During the previous build, it was found that pressure pulsations from the high-pressure fuel pump were exciting mechanical vibrations in the fuel lines. These vibrations were transferred to the fuel metering valve, resulting in speed fluctuations. It was demonstrated that lightly touching the fuel line would noticeably affect both speed and stability. For this build, the lines were more securely fastened, and a new pump installed as a precaution. Speed stability was greatly improved, and peak power points at 90 and 95% speeds were run. At 100% speed, however, a gradual speed drift was encountered. While attempting to diagnose this apparent control problem, the power-turbine rotor bearings seized, terminating the test. No secondary damage was found.

Build M - Runs 175-219

The gas generator (No. 2) was rebuilt with a new air bearing, since the previous part was found with a shifted foil on teardown. The support was modified to increase impeller backface clearance. The frontface of the front bearing carrier was also cut back to increase the clearance. Power was 85.30 HP at 100% speed. Performance was then evaluated at 50% speed over a VIGV setting range of +60° to -18° and a prop shaft speed range of 600 to 1200 rpm (see Figure 13). Augmentation at 80% speed, over a range of 0° to -24° VIGV, was also evaluated. Testing was terminated by an air bearing seizure.

Build N

Speed stability problems at idle - unable to record valid emissions data.

Build O - Runs 220-226

Following an ECU change, a power run to 100% speed was made. Performance was good (86.56 HP at 100% speed), but low-speed emissions were higher than recorded on Build K.

Build P - Runs 227-233

Following unsatisfactory emissions results of the previous build, a number of fuel system plumbing changes were made; and the entire system was bench checked. Excessive bypass fuel flow was traced to an improperly fabricated bleed orifice. Burner performance was improved, but instability at low speeds was still evident, and emissions data were still not as good as those for Build K. Performance was otherwise good, with 40.84 HP at 80% speed and 87.55 HP at 100% speed.

Build O - Runs 234-237

The burner was then converted to a premixed, prevaporized combustor, with no other changes. This was the first test of this combustor type in a retrofit Upgraded Engine. Limited testing showed high indicated fuel consumption and excessive hydrocarbon levels in the background (test cell) air. Both problems were traced to fuel vapors venting from the cell float chamber, due to excessive engine heat rejection to the recirculating fuel.

Build R - Runs 238-245

A fuel cooler was installed in the fuel return loop, and the torch air line modified to improve torch combustion. At the same time, the housing baffles were modified to the latest configuration. The power/SFC curve showed a 5 to 8% improvement over Build Q, and was virtually identical to Build P. Burner performance and emissions parameters are shown on Figure 14. Testing was terminated by an air bearing failure while re-checking a data point at 80% speed.

Engine 6 (R2 - Power Plant 10-12)

This engine was first run on May 4, 1978, and provided initial checkout for the Mod 3 compressor-turbine. Additional corrective development parts included engine housing baffles, modified regenerator cover, bent power-turbine rotor (Mod 2 turbine), and recontoured exhaust diffuser. Also evaluated for the first time were an aluminum silicate regenerator and a cadmium-oxide-coated air bearing. Power output was the best to date, with several runs demonstrating over 38.5 HP at 80% speed. Using the 24-point T₃-grid thermocouples and 21 bulkhead thermocouples available on this housing, several tests were run to evaluate modifications to bulkhead cooling airflow. The engine was removed on May 24, 1978, to permit installation of the first full retrofit Upgraded Engine, PP 3-13. A total of six builds were tested with 45 data lines recorded and 23.7 hours logged. Test highlights are as follows:

Build A - Runs 1-9

As initially built, this engine had the majority of corrective development hardware previously tested successfully in PP 3-9Y:

- . Plastic VIGV set locked at zero degrees
- . Double-divergent 40% increased exit area diffuser
- . Flow deflectors in the compressor collector
- . Modified regenerator cover with 24-point T₃ grid
- . Power-turbine rotor blading closed down 11°
- . Recontoured exhaust diffuser

Major hardware changes for this build included:

- Mod 3 compressor turbine
- 24-blade all-aluminum compressor
- Aluminum silicate regenerator
- Cadmium-oxide/graphite coating on air bearing foil
- Baseline-type diffusion-flame burner
- New engine housing with 21 bulkhead and crossarm thermocouples
- Extensive static and total pressure instrumentation at stations 6.3, 6.5, 7.0, and 7.5.

Initial mechanical checkout of this power plant was successful, although the new tie-bolted compressor-turbine rotor limited operation to 80% speed. Power at 80% speed was 38.52 HP, in spite of compressor efficiency being down due to high clearances. It is assumed that the added power was the result of reduced clearances in the variable power-turbine nozzle vanes.

Build B - Runs 10-17

After inspection of the gas generator, several modifications were made to improve compressor performance:

- The impeller was changed to an 18-18 splitter type
- Impeller radial and axial clearances were reduced
- Tapered vaneless diffuser modification made to the gas generator support

These changes resulted in one point increases in airflow, pressure ratio, and efficiency with power increasing to 38.94 HP. A run with 300 PPH added cycle air (well below the surge limit) demonstrated 47.24 HP at 80% speed, which compares well with the 48.6 HP desired at this speed.

Build C - Runs 18-25

A standard (LAS) regenerator was installed in place of the AS material part. Previous build test data suggested a higher than normal regenerator pressure drop, which had not been expected, based on cold flow checks. Power was down slightly as a result of increased leakage (due to surface damage on this high-time LAS regenerator), and regenerator pressure drop was down only four percentage points. Pressure drop was still 13 percentage points above the previous runs with this core (in PP 3-9), but it is now believed that the difference is due to static port differences and/or leaking instrumentation lines.

Build D - Runs 26-29

The AS regenerator was reinstalled, and the flow deflectors removed to determine the effect of the deflectors on performance, T₂₋₃ rise, and bulkhead temperatures. Performance was down three percentage points from Build B with indications of higher leakage being partially responsible.

Build E - Runs 30-33

In an attempt to force a counterflow of cooling air from the top to the bottom of the bulkhead, the lower deflector was reinstalled; and the bulkhead cooling elbow blocked 95%. A continued degradation of engine performance was noted, but BSFC improved by five percentage points. A preliminary check of the housing temperatures showed the desired increase of 50 to 100°F in the areas previously noted as being overcooled, but the hottest point only increased 15°F. Because of the urgency to make the cell available for PP 3-13, further bulkhead cooling work was postponed until a later date.

Build F - Runs 34-45

Following a minor burner change to cool a hot spot on the transition piece, a series of runs were made to document performance at varying output shaft speeds at each point. The engine was then pulled to make way for the first retrofit Upgraded Engine, PP 3-13.

Engine 6 (R2 - Power Plant 10-14)

Initial checkout of this power plant was made on July 14, 1978. This engine had previously been run as power plant 10-12 A-F, discussed above. For this installation, the engine was fitted with the latest Mod 3 compressor-turbine hardware, an 18-18 impeller with cut back leading edges and a cast compressor-turbine nozzle with reduced flow area. Several nozzle and impeller combinations were evaluated to obtain the best compromise between power and surge margin. A major rebuild was then made to install several additional modifications, including increased power-turbine bearing oil feed, crossarm baffle, and damped reduction gears. The engine was transferred to Vehicle U-2 on September 29, 1978. Following rebuild necessitated by a possible overtemp start in the vehicle, the engine was returned to the test cell October 2, 1978, for final checkout. It was returned to Vehicle U-2 on October 3, 1978. The test program was hampered by two air bearing failures and a persistent speed stability problem, but 60.5 hours and 56 data runs were still logged. Test highlights are as follows:

Build A - Runs 1 and 2

The engine performed well at 50% and 60% speeds, with power levels of 6.09 HP and 13.70 HP demonstrated - the best to date. However, at 70% speed, the air bearing seized, causing no secondary damage but terminating the test.

Build B - Runs 3-6

No changes except an alternator was installed, and an air pump was removed. Clearances were slightly higher. Power at 80% speed was 40.4 HP.

Build C and D - Runs 7-11

Changes continued to be made in fuel and control systems. At 80% speed, 40.22 HP was demonstrated.

Build E

Investigation of speed instability continued. After two erratic starts, the rotor was found tight. Air bearing shim found moved forward - no secondary damage.

Build F - Runs 12-15

Gas generator No. 6 was installed with the following components:

- 3-strut inlet
- 24-blade original release impeller
- 40%-increased-exit-area diffuser
- Mod 3 compressor-turbine with 0.943 flow-size nozzle

Compressor performance was down substantially, with power reduced to 35.80 HP at 80% speed. Air bearing housing metal temperatures were recorded. See Figure 15.

Builds G - I

Fuel delivery system parts changes continued, with no improvement in the instability problem. The engine was finally run on manual fuel control, but the problem remained. Since the ECU and FMV were then eliminated as contributing factors, the burner was reexamined. Two problems were found:

1. The mixer did not fit firmly against the insulation, thus reducing the amount of swirl in the primary air.
2. The fuel nozzle was found partially plugged with carbon.

Build J - Runs 16-24

Gas generator No. 2 was reinstalled and fitted with a -1° Mod 3 nozzle. The burner problems were corrected. There was no further evidence of instability. Power was back to Build B level (40.76 HP at 80% speed), but surge margin was minimal, with surging encountered at 30° below T_{7.5} match at 100% speed.

Build K - Runs 25-30

Gas generator No. 6 was installed, essentially unchanged from Build F except with a 3-strut inlet in place of the VIGV. Power showed some improvement compared to Build F (37.44 HP vs. 35.80 HP), but T₅-match running above 80% speed was impossible, due to surge.

Build L - Runs 31-37

Between 8-18 and 9-8, the engine was given a major teardown and rebuilt in preparation for car installation. Changes included:

- o Crossarm cooling baffle installed
- o Power-turbine nozzle assembly was cleaned and rebuilt with vane stems sealed with C-100.
- o New bent-blade power-turbine rotor replaced previous part with tip damage from previous runs.
- o Updated power-turbine thrust bearings with increased oil feed
- o Damped reduction gears
- o New crossarm seal - cold leakage 4.4%.

Test results showed 38.09 HP at 80% speed, but at 95% to 100% speeds, power fell off to 65 HP.

Build M - Runs 38-48

Cast -1° compressor-turbine nozzle was installed (0.964 flow size) to replace 1.012 flow size nozzle. A steel-inducer impeller was installed for car application. Power increased substantially, with 41.20 HP at 80% speed and 88.57 HP at 100% speed.

Build N

Final checkout for car installation, with functional air pump and hydraulic power-turbine nozzle actuator. The engine was transferred to Vehicle U-2 on September 20, 1978.

Builds P and Q - Runs 49-56

The engine was reinstalled in Room 4S for a brief checkout on October 2, 1978, following an internal fire, due to an over-fueled condition in Vehicle U-2. The engine was rebuilt with minor bearing and seal changes, but no aerodynamic parts changes were required. The unburned fuel had attacked the silicone rubber regenerator mounting pads, necessitating regenerator replacement. Cold leakage was 5.1%. Indicated performance was down slightly compared to the previous calibration (37.80 HP at 80% speed), due apparently to a speed readout error. Unfortunately, the minimum instrumentation on this vehicle engine prevented further verification. The engine was transferred back to Vehicle U-2 on October 3, 1978.

Engine 7 (R3 - Power Plant 9-11)

This initial power plant build is being checked out and performance calibrated prior to shipment to NASA-Lewis, where it will be exchanged for power plant 2-3. The new engine will be shipped as a full Upgraded Engine retrofit, with 18-18 splitter impeller, latest housing baffles, and diffusion-flame burner. Testing has been uneventful to date, with good performance demonstrated; and no major mechanical problems noted. During 11.3 hours of operation, 11 lines of data have been recorded. Test highlights are as follows:

Build A - Runs 1-5

To expedite testing, this first build was with a car spare gas generator, Gas Generator No. 1. This gas generator has limited instrumentation and the 24-blade steel-inducer impeller for vehicle use. Some instability was noted during starting, but no other problems were found. Power levels of 37.46 HP at 80% speed and 60.01 HP at 90% speed were demonstrated - higher points were not attempted, due to the limited-service impeller. On teardown, the mixer, burner tube, and adapter all showed scaling from excessive temperature; and it was discovered that the dilution holes had been inadvertently omitted from the adapter during fabrication and assembly. The lack of P_5 instrumentation had prevented detection of the high burner pressure drop.

Build B - Runs 6-11

The designated NASA gas generator (No. 6) was installed, with the 18-18 impeller and standard Mod 3 compressor-turbine instrumentation. The burner parts were cleaned, and the correct dilution holes were added. As expected, performance improved substantially, with 41.51 HP at 80% speed, 63.92 HP at 90% speed, and 77.59 HP at 95% speed. Due to burner or control instability and excessive

flow of blow-by air from the oil sump, 100% speed was not attempted. The high blow-by (0.3% of engine air flow above normal) was noted with both gas generators, indicating the source to be either power-turbine seal pressurizing air or P₃ leakage past the regenerator drive pinion shaft seal. Once the problem is isolated and corrected, the instability above 90% speed will be addressed.

Engine 2 (R4 - Power 4-15) - Builds A and B

This engine was retrofitted with all final-development hardware, following 220.4 hours as PP 4-2 A-AF in Vehicle U-2. This adaptation consists of the Mod 3 gas generator turbine and the Mod 2 power turbine (standard wheel with blades bent closed 11°). A standard 24-blade steel-inducer impeller was used (in place of the 18-18 splitter type) for car use. Upper and lower flow baffles, crossarm baffle, and regenerator cover baffle were included. Cold leakage was 4.5%. Minimum instrumentation was installed. A functional air pump was included for the diffusion-flame burner, but no alternator. Performance was good, with 39.27 HP at 80% speed and 75.67 HP at 95% speed. Following checkout with the car actuator, the engine was transferred to Vehicle U-1 on October 12, 1978. Total test cell time was 6.3 hours, with 6 lines of data recorded.

Engine 3 (Power Plant 2-3)

During this period, the engine was utilized briefly for actuator development, after which it was fully rebuilt with corrective development components, check run, and delivered to NASA-Lewis Research Center on July 6, 1978. Prior to shipment, 11.1 hours and 8 sets of data were logged, with highlights as follows:

Build BI

Several hours of checkout running were made with power-turbine nozzle actuator No. 2. No formal data was recorded.

Build BJ - Runs 489-492

Following a major teardown and inspection, the engine was rebuilt with a number of corrective development items for checkout prior to delivery to NASA-Lewis. These items included:

- Plastic VIGV support and vane set
- 40% increased exit area diffuser
- Machined Mod 2 compressor-turbine nozzle
- Cast Mod 1 compressor-turbine rotor (0.8 scale of Baseline Engine rotor)
- Mod 2 power turbine

A standard steel-inducer impeller was used to simplify speed sensing at NASA. Minimum instrumentation was included. Power was only marginally acceptable at 32.56 HP at 80% speed, due primarily to high impeller clearances and 5% oversize compressor-turbine nozzle.

Build BK - Runs 493-496

The NASA ECU was then installed, and final runs up to 100% speed were made without incident. The engine was shipped to NASA-Lewis on July 6, 1978, for checkout of their transient test facility. It will remain on test there until the next retrofit engine (R3 - Power Plant 9-11) is available for shipment, after which PP 2-3 will be returned to Chrysler.

Control System

All ECU units have been updated to current field mod status.

Multiplexer circuit-board cross-talk resulted in failure to engage the starter relay in Test Cell 4S. Subsequent bench testing revealed this behavior on a different ECU. The exact cause is unknown, but a temporary programmed 'fix' has been implemented.

Failure to achieve 100% gas generator speed in both test cell and vehicle operation stems from 1% to 3% speed reference depreciation through multiple 'greatest of' store operations in the pedal schedule. A bench test does not duplicate this deficiency, which may require an engine control program to duplicate the problem. The gain-controlled amplifier board from Unit SN2 was particularly deficient. It computed speed 7% high, as well as demonstrating intermittent starter engagement failures. It has been returned to Ultra with a replacement board on loan.

The keyboard programmer has been checked out and has been used for direct control in both test cell and vehicle. The printer accessory has been received and is in use for program checkout and record keeping.

Several precautions are required in using the keyboard programmer. The unit is susceptible to circuit opens and shorts and is more sensitive to stray, low-level signals when transferring PROM data than the PRO-LOG programmer. This has contributed to an engine failure. In a separate incident on Vehicle U-2, a PROM chip verified on the PRO-LOG to the keyboard RAM failed to switch from start to run modes. Several PROM IC's and sockets have been replaced or repaired. Two RAM IC's have been replaced. Procedures for retaining RAM memory in standby and on modes have been established and must be strictly observed.

An ECU deficiency was noted during cold soak vehicle starting. The fuel metering analog output exhibited significantly higher valve current than normal, resulting in an overtemperature abort during the start. This single occurrence followed a 30°F, high humidity, overnight soak. Ultra has experienced similar problems at other installations and is seeking a solution. By leaving the unit on for several hours at room conditions, the distorted valve current vanished.

Program modifications in service this period include power-turbine nozzle actuator null current adjustment and idle closed limit. Alternate control tests have shown superior T_g transient response of a scheduled routine, albeit, at the expense of steady-state accuracy. A hybrid schedule-plus-trim routine has been programmed for test at a later date. The program input-output listing has been updated (Figure 16).

A functional diagram of the fuel/air system for the droplet-diffusion combustor is shown in Figure 17.

Power Turbine Nozzle Actuator

Redesign of the power-turbine nozzle actuator, discussed conceptually in the Twenty-First Quarterly Report - Pages 22 and 23 - was completed, using the Design Services of Chrysler Canada. The original modular configuration successfully applied to the current vehicles was redesigned to integrate the components into a "low cost" unit. It also incorporates a feature which hydraulically reverses the null valve logic of the trimmer piston such that increasing the linear solenoid voltage will increase engine cycle temperature in both power and braking modes. Reversing of logic within the ECU would require an external switching and fail-safe system which could not be provided for without a great deal of complexity. Two units were procured, and the actuators were assembled and bench tested. Its function was also satisfactorily demonstrated in a cold chamber. One unit is scheduled for application to the NASA transient test engine, the second unit will ultimately be programmed for vehicle use. Figures 18 and 19 illustrate schematically the piston assemblies in the power mode (retracted) and braking mode (extended). Note the simplified attachment to the power-turbine-nozzle mechanism. An adjustable stop on the transmission-governor pressure-controlled valve can be calibrated to vary the slew rate and reduce actuator response when shifting from the power mode to braking mode. This procedure will reduce the excessive engine braking feel experienced with the prototype units. Figure 20 shows the assembled actuator ready for engine installation.

Inlet Guide Vane Actuator

Development effort to improve actuator response resulted in limited success. Constraints imposed by the die casting, porting size, and oil-pressure control-valve size restricted modification of existing hardware. Internal and external casting leakage mentioned in the Twenty-First Quarterly Report - Page 23 and 24 - was corrected by the application of a Loctite 290 sealant. An acceptable response time actuator was compromised by:

- Eliminating the modulating feature off idle and augmentation beyond 95% speed
- Use of a solenoid to shift the oil pressure control valve
- Increasing all porting size to maximum

All current vehicles (3) are operating with two-position, slow-response actuators but will be updated as time permits.

An additional control requirement which became apparent with the increased-power engines is that of engine run-away during shut-down. This condition is particularly objectionable after high-speed vehicle operation. Control can be implemented by throttling airflow at the air inlet or at the variable power-turbine nozzles. The fast-response, two-position actuator is configured such that the VIGV move to the throttling mode (+60°) after engine shutdown, thus minimizing engine run-away (Figure 21). The simplicity of the control logic dictates that the VIGV be used to perform this function.

Gas Bearing Development

These bearings have been used in engine development for over two years, and individual bearings have been operated up to 140 hours. However, air bearing failures have continued to adversely affect the engine development program, despite attempts to resolve the problems in fabrication procedures noted. A meeting was held in August with representatives of the bearing vendor, Mechanical Technology, Inc. (MTI), NASA, and Chrysler to establish a program which should provide more reliable air bearings for Upgraded Turbine Engine operations. The modes of failure (smooth foil cracking and/or weld failure plus rapid coating wear) were reviewed and related to the probable causes, such as inadequate material fatigue, welding control, coatings, and foil distortion. Fabrication and inspection procedures were also discussed.

Work on a short-term project to improve bearing reliability is underway. The tasks include: a review of possible improved foil mounting arrangements, particularly at the welded joint; a

search for new and improved materials; testing of new mounting concepts and improved materials; fabrication of new manufacturing tooling; establishing better fabrication and quality control procedures for bearing manufacture; and examination of modified bearings following engine operation.

Several proposed foil-mounting concepts have been evaluated for stress, endurance limit, and anticipated ease of manufacturing. These were compared both to the original as-released concept utilizing conventional spot welds and to this concept incorporating improved spot welds made with improved fixtures. The mechanical mounting concepts with slots cut in the cartridge had the highest endurance limits but will require careful control of slot location and foil forming to assure good quality bearings. Development and tooling costs for this concept will be estimated to determine if they can be covered under this contract. Work on an electron beam (EB) welded joint is progressing to determine the best weld spacing and length for optimum strength and minimum distortion. It has been determined that a continuous EB weld results in excessive distortion. Brazing is also being investigated as an alternative.

Bearings have been received which were made using the improved tooling for controlling foil fabrication, location, and installation (spot-welding). These bearings will be installed as needed in program engines.

Fine-grain Inconel X750, 17-7 PH, and Rene 41 are being considered as alternate materials.

Foil fatigue and coating life tests have been started.

The possibility that rotors may have developed unacceptably large orbits which could put excessive loading on the bearing surface was considered. However, it was felt that investigation of this would be beyond the scope of this program and require additional funding.

TASK 8.3 - UPGRADED VEHICLE EVALUATION

Vehicle U-1

All engine-related vehicle systems have been completed. This includes oil cooling, control, braking systems, transmissions and sheet metal work patterned after Vehicle U-2, released inlet and exhaust systems, and wiring assemblies patterned after Vehicle U-3. The heater/air-conditioning system is installed; the heater is operational; the air-conditioning system awaits charging.

Vehicle shakedown was delayed by various control problems. The engine was unable to start, due to an anomaly in the fuel metering valve characteristic. Incorporating a dual starting fuel schedule for cold/hot soaks has greatly improved starting capability.

Power-turbine nozzle control is still deficient. Sluggish actuator response has been due to debris and a burr on the null valve and a galled output shaft adaptor. With the actuator working well, the engine still would not run match temperatures, requiring a shift in the programmed position calibration. The car still runs 200°F cold in braking even with full actuator force, indicating a hot power-turbine nozzle mechanism seizing problem.

The power-turbine reduction gear set noise is more objectionable than Vehicle U-2.

TASK 8.4 - UPGRADED VEHICLE DEVELOPMENT

Vehicle U-2, Tests With Engine 2 (Non-Retrofit)

The vehicle experienced an air bearing failure while in transit to the Spring coordination meeting. The spare gas generator was installed, and the vehicle participated in a Ride and Drive demonstration, losing only one day. The failed air bearing foil had seized on the wheel sleeve journal, destroying the foil/shims and galling the journal.

The vehicle was run on a general endurance cycle to:

- Establish air bearing life parameters
- Determine life expectancy of the increased-capacity power-turbine flat-thrust-bearing design.

This general endurance cycle was carried out in concert with transmission shift-quality and power-turbine nozzle-actuator response tests.

The cycle included both expressway and city traffic conditions and is tabulated below:

Number of Starts:	10
Distance:	74 miles
Driving Time:	140 minutes
Total Time:	200 minutes
Average Speed:	32 M.P.H.

Transmission-shift quality is now commercially acceptable. However, the high horsepower at idle/neutral-park results in excessive power-turbine speeds. This condition was corrected by using a two-position VIGV actuator. The creep torque is reduced by throttling the compressor inlet at +60 VIGV's with the VIGV's set at 0 for speeds above 50%. Use of a low-stall torque converter enhanced overall vehicle feel but had objectionable hydraulic noise and is suspected of contributing to minor driveline disturbances.

Three power-turbine nozzle control routines were evaluated in the vehicle, using the new keyboard programmer. Scheduled nozzle position gave the best overall feel, this routine will be developed as time permits. During the interim, closed loop T_g with nozzle blipping remains.

Vehicle performance tests were conducted at the Chrysler Proving Grounds to establish the engine power as installed and to gather base information for future studies. The data showed the installed power to be 60 to 65 horsepower, which has the state-of-the-program development at the time of installation.

Rotor acceleration times are 2.0 to 2.5 seconds, which is one second over design specification.

The power plant was replaced with retrofitted Engine 6 (R2). This engine produced an output of 88 horsepower in test-cell check-out.

Inspection of the original engine showed the following items:

Burner:

(Droplet Diffusion) - no obvious problem.

Regenerator Assembly:

Good overall condition - excellent crossarm polish; there is some lack of contact at both rim areas. The inner rear graphite had cracked and had run this way for some time. The cracked graphite and possible cross-arm rim leakage could have contributed to the hot starting problems experienced.

Engine Housing:

The power-turbine nozzle assembly is very free; no blade rubs. The insulation is in good condition except for the outer exhaust diffuser, which is cracked in several locations.

Gas Generator:

There were no rubs of any type; no dirt contamination of the compressor section. The rotor bearing has a new, not-run appearance. The air bearing spacer foil moved forward, touching the middle seal. The smooth foil exhibited uniform contact (wear), and the air bearing journal is very smooth. There was no indication of the spacer foil problem while running.

Reduction Gear Assembly:

The large flat eight-pad thrust and antithrust bearings exhibit a new, not-run condition. Both journal bearings are in excellent condition, showing no wear.

The condition of the power turbine is significant, since these bearings were subjected to heavy loads associated with wide-open-throttle and braking functions for both high- and low-stall torque converter operation.

Statistics for the engine are listed below:

	Gas Generator		Reduction Gear		Engine Housing	
	Air Bearing		Thrust Bearings			
	<u>Endur.</u>	<u>Overall</u>	<u>Endur.</u>	<u>Overall</u>	<u>Endur.</u>	<u>Overall</u>
Miles	1038.3	1874.1	1038.3	2697.5	1038.3	3306.6
Hours	32.4	80.8	32.4	138.3	32.4	220.4
Starts	177	663	177	1322	177	2102

Vehicle U-2 Tests with Retrofitted Engine 6 (R2)

The retrofit-engine power-turbine assembly utilizes a higher-capacity spherical-seat thrust-bearing system with increased oil feed. A total of 304 miles of ride/drive demonstration were accumulated when the thrust/antithrust bearing system failed, and the rear pinion journal seized. No apparent cause for failure can be ascertained at this time. The rear pinion journal did exhibit lead sweating during a previous failure. However, no dimensional changes were present. The replacement power-turbine utilizes an identical bearing system and has accumulated 791 miles of general driving conditions without incident.

The cold light-off capabilities down to 30°F have been improved, using a dual fuel schedule (lean schedule for hot engine $T_8 > 700^\circ\text{F}$, rich schedule for cold engine). This technique has been successfully run at room temperature for the premixed burner on this vehicle (later date) and a droplet-diffusion combustor on Vehicle U-1. Cold starting tests are scheduled to improve the vehicle reliability.

The original-released nozzle actuator (modular construction) required rework to eliminate mechanical lockup, due to the differential contraction of the steel/aluminum pieces. Trouble-free operation down to 32°F was verified in a cold chamber. This actuator accumulated 226 hours and 4078 miles of trouble-free operation, prior to this mechanical interference problem.

Fuel consumption characteristic tests for both cold '75, hot '74, and FEC were conducted on chassis rolls for an inertia weight of 3500 lb. Fuel consumed (gasoline) was weighed directly. In addition, emissions were monitored (droplet-diffusion combustion) during these tests. Various schemes tested did not significantly change the fuel economy.

The best combined economy was 15 mpg with gasoline. The test results of November 9, 1978 (without engine braking) were used for this calculation. See Fig. 22B.

Steady-state fuel economies (chassis rolls) for Vehicle U-2 yielded the following results:

<u>Speed</u>	<u>Economy</u>
	<u>MPG</u> <u>Gasoline (3900 A)</u>
20	19.12
30	21.80
40	23.67
50	20.73

Details are shown on Figures 22A to 22C. Steady-state emission tests for both the droplet-diffusion and premixed, prevaporized combustions are tabulated on Figure 23.

F.D.C. emissions tests with the low-emission combustor are scheduled for early in 1979.

FUTURE ACTIVITIES

In the next quarter, it is expected that the following will be completed:

- final retrofitting of engines and vehicles
- emission testing
- bearing durability tests and,
- writing of the final report

APPENDIX A

TWENTY-THIRD QUARTERLY REPORT

DECEMBER 31, 1978

FIGURES

A926-1 COMPRESSOR TURBINE NOZZLE MOD III

A926-1 COMPRESSOR TURBINE WHEEL MOD III

STACKING LINE

Figure 2A

A926-1 COMPRESSOR TURBINE WHEEL - MOD III
4096390 - NOMINAL - HOWMET

VANE - - - - -

SPECIFIED ON DWG. + + + + +

Figure 2B

A926-1 POWER TURBINE NOZZLE VANE MOD I

STACKING LINE

A926-1 POWER TURBINE NOZZLE VANE - MOD I

4096602 - NOEL PENNY

'A' VANE ⊖
'B' VANE —

SPECIFIED ON DWG. $\begin{array}{c} \text{---} + \text{---} \\ \text{---} + \text{---} \end{array}$ } TOLERANCE BAND

A926-1 POWER TURBINE ROTOR MOD I

DIMENSIONS SHOWN = MM (IN.)

A926-1 POWER TURBINE ROTOR-MOD I
P/N 4096623-NOEL PENNY

BLADE CONTOUR -----
 SPECIFIED ON DWG: TOLERANCE BAND

Figure 4B

UPGRADED ENGINE

FINAL COMPRESSOR CONFIGURATION; MOD 3 COMPRESSOR TURBINE POWER & BSFC CHARACTERISTICS

Figure 5

UPGRADED ENGINE

FINAL COMPRESSOR CONFIGURATION; MOD 3 COMPRESSOR TURBINE

POWER & BSFC CHARACTERISTICS

	PP 10-14 M	3-13 I	3-13 K,L
	▽—▽	x—x	○—○
POWER TURBINE	MOD 2 (BENT BLADE ORIG.DES.)	MOD 1 NPTL	MOD 1 NPTL
MOD REGEN COVER	YES	NO	YES
COLLECTOR BAFFLES	YES	YES	YES

Figure 6

UPGRADED ENGINE BULKHEAD
BULKHEAD COOLING DEVELOPMENT

COOLING DUCTS CONDITION

	<u>Duct</u>			<u>W_f</u> <u>50%</u> <u>Power</u>
	<u>A</u>	<u>B</u>	<u>C</u>	
1. Original Test	Open	Open	Open	6.7
2. Restricted	Baffle	Baffle	Blocked	6.1
3. Restricted with Crossarm Baffle	Baffle	Baffle	Blocked	6.0

Figure 7

Figure 8

Figure 9

Figure 10

UPGRADED ENGINE
EXHAUST EMISSIONS

PP 3-13 K 09-19-78

sample upstream of blowby

Figure 13

A-926-1 UPGRADED ENGINE

PRE-MIXED/PRE-VAPORIZED COMBUSTOR PERFORMANCE

EXHAUST EMISSIONS

Figure 14

A-926 AIR BEARING HOUSING TEMPERATURES

STEADY STATE AND SOAK-BACK CONDITIONS

PP 10-14 F room 4 S

runs 12-15 08-01-78

Figure 15

ECU PROGRAM INPUT-OUTPUT CHANNEL LISTING

2-30-76

230±20PPH=1000Hz=10V INJECTOR FUEL FLOW
0PPH=0Hz=0V

0	RO	0	
1	R1	1	
2	GO	2	
3	MULT	D3	3 w diagnostic
4	1V	ANOP2	4 v-y IGV ACTUATOR neutral/idle 0V=0mA=0° F8 must be +ve 10V=750mA=+60°
E-F	5 Wf	ANOP3	5 u PTN ACTUATOR null valve 0V=0mA=extend 10V=1000mA=retract
(K)		ANOP4	6 t FUEL METERING VALVE 0V=0mA 10V=500MA (300mA side PPH)

Key

3814546 ECU
PROGRAM INPUT-OUTPUT CHANNELS
Coll:IP characteristic
2:IP description
3:terminal location,PL1 unless specified,
return via PL1 NN unless specified,
() indicates dedicated diagnostic,
TC= thermocouple block,
RV= PCB7 variable resistor
4:IP address
5:IP mnemonic
6:IP & OP mnemonic
7:OP mnemonic
8:OP address
9:terminal location
10:OP description
11:OP characteristic

8	WS1	8	
9	WS2	9	
10	WS3	10	
11	WS4	11	
12	11	12	
13	12	13	
14	13	14	
15	14	15	
16	WS5	16	
17	WS6	17	
18	WS7	18	
19	WS8	19	
20	15	20	
21	16	21	
22	17	22	
23	18	23	
24	F1	24	
25	F2	25 h	1amp-FLAG 2
26	F3	26	
27	F4	27	
28	F5	28	
29	F6	29	
30	F7 & SW1	30 x	FUEL BLEED SOLENOID VALVE +ve=off=bleed open 1amp-ACCEL SOL -ve=on =bleed closed
31	F8 & SW2	31 y-v	IGV ACTUATOR max power +ve=on ANOP2 =preswirl -ve=on =-30° =counters

0%= ORPM= OHZ= 0V ANCILLARY SHAFT SPEED
100%=5138RPM=5138Hz=10V
0degC=604a= 0V AMBIENT TEMPERATURE
50degC=752a= 5V
40%= 0V Ngg idle reference adjust
55%=10V
= 0V spare
=10V
0%= ORPM= OHZ= 0V GAS GENERATOR SPEED
100%=5850RPM=23400Hz=10V
0degC= 0mV=10V TURBINE INLET TEMPERATURE
1000degC=43mV= 0V
" TURBINE OUTLET TEMPERATURE
" TURBINE OUTLET TEMPERATURE
10%= 0V Na underspeed reference adjust
17%=10V
a3.450±a1.27mm=a1V PTNA TRIM POSITION

U-V	32 Na	MTR1	32 W	T8 meter
(j)				
R-S	33 T1	MTR2	33 X	Ngg meter
a-P	34 TRIM2	D	34 c	diagnostic
RV5				
LL-P	35 TRIM3	D	35 d	diagnostic
RV6				
T-V	36 Ngg	D	36 e	diagnostic
(k)				
TC3	37 T5	D	37 l	diagnostic
TC2	38 T8B	D	38 M	diagnostic
TC1	39 T8A	D	39 L	diagnostic
(p)				
MM-P40	TRIM5	D	40	
RV8				
f	41 /3			

0V=0mA= 800degF
10V=1mA=1800degF
0V=0mA= 0%
10V=1mA=100%

undefined AMBIENT PRESSURE

N 42 P1

normally>2V ABORT TIMER 30sec ±RV7 adjust 43 TIMER
after OP SW8+ve<1V requires12V on PL1b

J-P 45 <

CT= 00=10V ACCELERATOR PEDAL POSITION

WOT=90°= 0V

1250degF= 0V T8 reference adjust

1450degF=10V

= 0V spare

=10V

normally=-ve Ngg OPEN CIRCUIT SAFETY

open circuit=+ve

≤ 28MPH=open circuit=+ve TRANSMISSION GOVERNOR SWITCH D

2 28MPH= ground=-ve

P-N= ground=-ve TRANSMISSION NEUTRAL/PARK SWITCH C

R-D-2-1=open circuit=+ve

normally=-ve Na OPEN CIRCUIT SAFETY

open circuit=+ve

ground=-ve spare

+12V or open circuit=+ve

off,acc,run=open cir=-ve

start= +12V=+ve

(key) B 61 SW1

KK 60 SW6

59 SW5

58 SW2

57 SW3

56 SW4

47 TRIM6

46 TRIM1

RV4

SW10

SW7

SW8

SW9

SW6

SW5

SW4

SW3

SW2

SW1

48 JJ PTNA GOVERNOR VALVE

1amp-NOZ BRAKING

49 EE 1amp-0/C TEMP

50 FF 1amp-NO START

51 HH STARTER RELAY

1amp-START

52 DD WATER INJECTION VALVE

1amp-WI

53 CC 1amp-0' TEMP

54 BB 1amp-0/C SPEED

55 AA 1amp-0/C SENSOR

+ve=off=power mode

-ve= on=braking mode

-ve=off

+ve= on

-ve=off

+ve= on

-ve=off

+ve= on

-ve=off

+ve= on

-ve=off

+ve= on

-ve=off

+ve= on

Figure 16

FUEL/AIR SYSTEM SCHEMATIC,
DIFFUSION FLAME BURNER,
UPGRADED ENGINE

POWER POSITION

BRAKING POSITION

BRAKING POSITION CONTROL DIAGRAM
FOR POWER TURBINE NOZZLE ACTUATOR

POWER TURBINE NOZZLE
ACTUATOR, INTEGRATED DESIGN

Figure 20

INLET GUIDE VANE ACTUATOR
(2 POSITION)

SUMMARY - FUEL ECONOMY
 VEHICLE U-2 TEST INERTIA - 3500 LBS.
11.2 HP (NO AIR CONDITIONING) - FUEL: GASOLINE

<u>DATE</u>	<u>TEST SCHEDULE</u>	<u>TEST CYCLE</u>	<u>COMP. INLET T.</u>	<u>FUEL LBS. (3900A)</u>	<u>CYCLE MPG.</u>
10/27/78	Heated Disconncted Tires F78 X 14 Bias Belted (G.Y.)	Hot 74 (1371 Sec.)	87	3.95	11.80
10/27/78	Heated Disconncted Tires F78 X 14 Bias Belted (G.Y.)	FEC	87	3.15	20.32
10/31/78	VIGV Reprogrammed to Pedal Position (+60° Closed Throttle)	Hot 74	86	3.60	12.95
10/31/78	VIGV Reprogrammed to Pedal Position (+60° Closed Throttle)	Hot 74	89	3.75	12.43
10/31/78	Same as Above - Change Driver	Hot 74	89	3.70	12.61
11/01/78	By-Pass Blow-By to Atmosphere	Cold 75 At 505 Sec. At 1371 Sec. At 505 Sec. Hot	67 79 89 84	Initially 2.45 4.70 1.65	 9.13 9.92 12.43
11/01/78	By-Pass Blow-By to Atmosphere	FEC	84 85 85	3.10 2.90 3.05	20.53 21.97 21.95
11/02/78	By-Pass Blow-By to Atmosphere	Cold 75 At 505 Sec. At 137 Sec. At 505 Sec. Hot	64 78 77 79	 2.4 4.6 1.6	 9.32 10.13 13.56
11/02/78	Increase T _g Ref. for Part Throttle Operation	Hot 74 At 505 Sec. At 1371 Sec.	89 84 84	Initially 1.55 3.55	 14.43 13.13

Summary Fuel Economy
Page 2

<u>DATE</u>	<u>TEST SCHEDULE</u>	<u>TEST CYCLE</u>	<u>COMP. INLET T.</u>	<u>FUEL LBS. (3900A)</u>	<u>CYCLE MPG.</u>
11/02/78	Reset T ₈ Ref. Back to Original Setting	Hot 74 At 505 Sec. At 1371 Sec.	88 Initially 89 88	 1.55 3.60	 14.33 12.95
11/08/78	Increased Braking Stroke	Hot 74 At 505 Sec. At 1371 Sec. At 505 Sec. At 1371 Sec.	 78 80 80 80	 1.7 3.55 1.37 3.40	 12.80 13.13 15.88 13.71
11/08/78	Change Tires-FR 78/14	Hot 74 At 505 Sec. At 1371 Sec.	 80 84	 1.59 3.71	 13.68 12.56
		FEC	83	3.07	20.73
		Hot 74 At 1371 Sec.	 83	 3.60	 12.95
11/09/78	Re-install Original Tires F78/14	Hot 74 At 505 Sec. At 1371 Sec.	 79 92	 1.55 3.60	 14.03 12.95
		FEC	91	3.00	21.21
-	Eliminate Braking	This data used to compute combined fuel economy	Hot 74 At 505 Sec. At 1371 Sec.	 1.45 3.55	 15.00 13.13
		FEC	83	2.95	21.57
		Hot 74 At 505 Sec. At 1371 Sec.	 83 --	 1.50 3.60	 14.50 12.95

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Summary Fuel Economy
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<u>DATE</u>	<u>TEST SCHEDULE</u>	<u>TEST CYCLE</u>	<u>COMP. INLET T.</u>	<u>FUEL LBS. (3900A)</u>	<u>CYCLE MPG.</u>
11/10/78	Active Braking Back In VIGV's lock at 0°	Hot 74 At 505 Sec. At 1371 Sec.	79 83	1.60 3.65	13.60 12.77
		FEC	84	3.05	20.87
11/10/78	VIGV's Active-Reshimmed For-10° Above Closed Throttle +50° at 0 Throttle	Hot 74 At 505 Sec. At 1371 Sec.	91 --	1.60 3.63	13.60 12.84
	By-Pass Filters Remove Covers	Hot 74 At 505 Sec. At 1371 Sec.	97 --	1.55 3.65	14.03 12.77
		FEC	92	3.00	21.21

NOTE: Rear Axle Ratio 2.94
Hi-stall Lock-Up Converter

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STEADY STATE CHASSIS ROLLS EMISSION
VEHICLE U-2 - FUEL/GASOLINE

<u>T_{ol}</u> <u>OF</u>	PRE-MIX/PRE-VAPORIZED COMBUSTOR						DROPLET-DIFFUSION COMBUSTOR					<u>T_{ol}</u> <u>OF</u>
	<u>T_{ol}</u> <u>OF</u>	<u>%</u> <u>SPEED</u>	<u>HC</u> <u>PPM</u>	<u>NOX</u> <u>PPM</u>	<u>CO</u> <u>PPM</u>	<u>CAR</u> <u>SPEED</u>	<u>CO</u> <u>PPM</u>	<u>NOX</u> <u>PPM</u>	<u>HC</u> <u>PPM</u>	<u>%</u> <u>SPEED</u>	<u>T_{ol}</u> <u>OF</u>	
76	----	45	2.5	2.0	166	Idle Park	--	--	---	--	----	---
76	----	50	4.5	1.0	170	Idle Drive	32	13	4.5	50	1288	86
78	1350	54.8	16.0	Indi- cation	283	20	20	14	4.5	54	1361	84
77	1348	58	3.0	0.4	51	30	15	15.5	4.5	58	1366	85
77	1369	63.5	2.0	0.4	22	40	13	20	4.5	65	1378	85
76	1386	70	2.5	0.8	22	50	7	35	4.5	70	1388	86

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