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FINAL REPORT

for

DESIGN AND FABRICATION OF AN ULTRA-LOW-COST TURBOPROP FOR RPV/UAV APPLICATIONS

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During the performance period, a heavy-wall ground-test turboprop engine was designed, fabricated and tested. The engine was comprised of turbine stator and rotor, exhaust duct, reduction drive, propeller, lubrication system and electronic control, all mated to the exhaust pipe of a Sundstrand TJ-90 expendable turbojet engine. Maximum horsepower attained was 118 at an inter-turbine temperature of 1536°F and output shaft speed of 2963 rpm at ambient conditions of 104°F and 29.61 in. Hg. Total weight of the complete engine was 68 lbs. The analog electronic control featured two speed governors, one each for gas-generator and drive-turbine speed, as well as a turbine inlet temperature limiting function.

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1.0 EXECUTIVE SUMMARY

An ultra-low-cost turboprop engine derived from existing expendable turbojet technology would provide heavy fuel burning capability to small missiles and other remotely-piloted vehicles (RPVs) allowing replacement of existing gasoline-fueled piston engines. Higher power density of the turboprop would provide improved vehicle performance for a given vehicle weight. For this program, M-DOT designed, fabricated and tested a turboprop module consisting of:

- Drive turbine nozzle and rotor.
- Exhaust duct.
- Gear reduction drive.
- Lubrication system.
- Fixed-pitch propeller.
- Electronic control.

The module was designed to install onto the exhaust duct of a Sundstrand TJ-90 expendable turbojet engine. The intent was to create a module that could be attached to an existing low-cost expendable turbojet engine to yield an ultra-low-cost turboprop engine for use on unmanned aircraft. Specifications of the Phase I engine are as follows:

Overall length	26 inches
Weight	68 lbs W/O accessories
Max corrected shaft power	123.4 Shp*.
SFC at max power	.939 lb fuel per hp. hour
Power turbine speed	56,480 rpm
Gas generator speed	102,000 rpm
Propeller speed	2962 rpm
Power turbine inlet temperature	1453 F*
Maximum cycle temperature	1806 F

** The original calculated design point was 101.3 corrected shaft horsepower at 1453 F power-turbine inlet temperature. During engine testing however, 118.5 shaft horsepower was achieved at a corrected power-turbine inlet temperature of 1376 F. If shaft power is recalculated at the original specified temperature of 1453 F, corrected shaft horsepower increases to 123.4. This potential value can be achieved at standard day conditions by rematching the power turbine inlet nozzle area and increasing propeller load.*

Figure 1, on the following page, is a cross section of the entire engine assembly including Sundstrand gas generator.

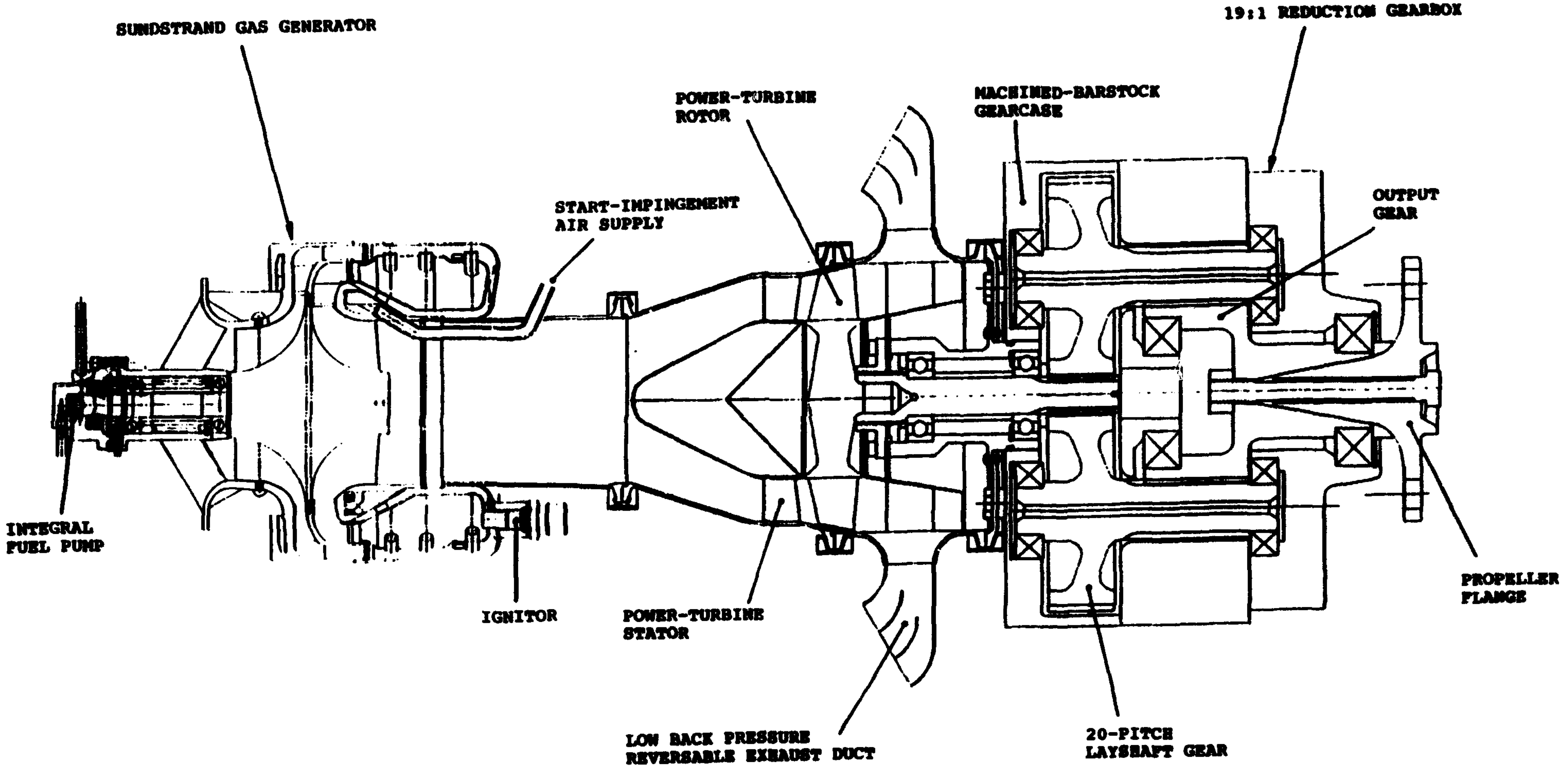


Figure 1 - Cross section of complete engine

The engine incorporated an analog-electronic fuel control. The control governed gas-generator and power-turbine spool speed, and contained a temperature limiting loop. The operator would command a desired propeller shaft speed and the control would adjust gas generator speed to maintain it. An overspeed governor provided a ceiling for gas-generator speed and a temperature limiter provided a ceiling for gas-generator turbine-exit temperature.

The control was of modular design with a single backplane with power supply and four plug-in cards.

The engine was designed for ground test only. Thus significant weight reduction is possible through redesign.

The prototype engine incorporated a symmetrical exhaust duct allowing it to be installed facing either forward or rearward. This allows simple conversion from a tractor to a pusher configuration.

The gas generator was a government-owned prototype TJ-90 turbojet manufactured by Sundstrand Power Systems of San Diego CA. Modifications were made to the engine at M-DOT to remove the existing bifurcated duct and incorporate a circular duct with V-band flange.

All hardware, except for TJ-90 gas generator and lube system oil mist units, was designed and fabricated at M-DOT.

Engine testing was conducted on an M-DOT-owned thrust stand modified to measure output torque. Instrumentation consisted of type K (chromel-alumel) thermocouples at station 5.0 (gas generator exit), static pressure at station 3.0, engine shaft speed, bearing temperature, and torque. Fuel was Jet-A aviation kerosene.

All performance objectives were met or exceeded. Hardware exhibited excellent durability. An input-shaft bearing failure occurred which was attributed to inadequate lubrication. The oil jet design has been modified to correct this problem. The engine will be repaired and retested prior to shipment to the Army.

1.1 OBJECTIVES

The overall objective of the program was to design, fabricate and demonstrate an ultra-low-cost turboprop engine suitable for use on an RPV/UAV or expendable missile.

Achievement of this overall objective resulted in the following technical accomplishments:

- Design fabrication and test of a drive turbine and exhaust system suitable for use on a TJ-90 gas generator.
- Design, fabrication and test of a two-stage 19:1 gear reduction drive.
- Design, fabrication and test of a full-authority analog engine control.

1.2 CONCLUSIONS

Based upon test results, the following conclusions can be reached:

- It is possible to convert an expendable turbojet engine into a turboprop and to realize a significant amount of useful shaft power and high power density. The Phase I prototype engine is capable of generating 124 shp at reasonable turbine inlet temperatures. Although not designed for low weight, the prototype achieved a power to weight ratio of 1.73 hp/lb.
- It is feasible to reduce engine cost by utilizing gearing machined and hobbed from Stressproof steel. Gearing on the prototype engine exhibited excellent wear characteristics.
- It is possible to achieve high turbine efficiency with simple blade geometry at low mass flow rates. The drive-turbine blade profile on the Phase I prototype consisted entirely of conic and planer surfaces yet achieved a total-to-total efficiency of 87%.

1.3 RECOMMENDATIONS

The following is recommended if future development is to be done on this engine:

- A more efficient gas generator should be developed utilizing the same low-cost design concepts found in the Sundstrand TJ-90.
- A careful market study should be conducted to determine power requirements of potential applications so that the gas generator can be sized for efficient operation in the end application. The current TJ-90 configuration is too large for currently envisioned RPV/UAV applications.
- A light-weight gearbox be developed.
- A light-weight engine-mounted starting system be designed and developed.
- Further development of the gearbox/drive turbine lubrication system should be done. The effort should include a heat rejection study to establish oil cooling requirements.

2.0 BACKGROUND

Deployment of battlefield surveillance systems that utilize remotely-piloted air vehicles is becoming practical. On a typical mission, the vehicle would be launched from a remote site, dash to the area to be monitored, remain on station at reduced power for a specified period of time transmitting data to the ground station and finally, return to the launch site for recovery. The Unmanned Air Vehicle (UAV) Joint Project Office has defined five major categories of UAVs of which two, the close range and the short range, fall within a size category that can utilize a 50 to 100 horsepower engine. The Close-Range category power requirements are generally from 18 to 50 horsepower. Short-Range requirements run from 68 to 100 horsepower. Current systems employ two- and four-cycle piston or wankel rotary engines. These engines have demonstrated power to weight ratios as high as 1.72 SHP per pound and specific fuel consumption values as low as .52 under ideal conditions. However, piston and wankel type powerplants have the following drawbacks:

High Output Shaft Speed - Reduction drives are often required adding significantly to powerplant weight and parts count.

Cooling - Piston-powered aircraft pay a significant penalty in vehicle drag due to engine cooling requirements. With fixed cooling-system geometry, a system adequate for climb is oversized for cruise.

High Vibration - The vehicle must often have provision for vibration damping to protect structure and sensitive payloads.

Maintenance - Piston engines historically have required more maintenance than turbines.

Fuel - Gasoline-fueled engines are scheduled for elimination from the U.S. military inventory.

The UAV Joint Program Office (JPO) has expressed the requirement for a heavy-fuel engine (HFE) for the Short-range UAV system (UAV-SR). They have issued a statement of work (SOW) to the contractor (TRW/IAI) which outlines requirements for the engine.

Due to their high specific power and multi-fuel capability, gas turbines represent an excellent alternative to piston or rotary engines to meet requirements for a HFE for UAVs. Additional advantages include lower maintenance and extremely low vibration. Currently, no turboprop engines exist for this application.

Sundstrand Power Systems of San Diego, CA has designed and manufactured numerous small gas-turbine power plants including an expendable turbojet engine for use in tactical missiles. This engine, designated the TJ-90, is a compact, low-cost powerplant that weighs 15 lbs and is capable of delivering 100 lbs of thrust. This engine served as the gas generator for the heavy-wall ground-test turboprop built during Phase I. Sundstrand has demonstrated through computer modeling that a modified reduced-airflow version of the TJ-90 would be capable of delivering less total power but at higher efficiency than the existing design. Due to the nature of modifications, engine cost would not be increased.

If a gas-generator section based on the Sundstrand low-flow TJ-90 were to be mated to a power turbine and gearbox, the result would be a heavy-fuel engine capable of meeting close-range and short-range surveillance mission requirements.

2.1 STATEMENT OF WORK

For Phase I, *M-DOT* proposed to design and test an ultra-low-cost turboprop module suitable for use on a Sundstrand TJ-90 expendable turbojet. The module would consist of :

- Drive turbine nozzle and rotor.
- Exhaust duct.
- Gear reduction drive.
- Lubrication system.
- Fixed-pitch propeller.
- Electronic control.

Output power goal for the Phase I program was 101.3 horsepower.

2.2 THE SUNDSTRAND POWER SYSTEMS TJ-90 ENGINE

The TJ-90 expendable turbojet engine is derived from the earlier Gemjet which, in turn, was derived from the Sundstrand Turbomach Gemini T-20G-20 auxiliary power unit. Sundstrand Turbomach received a contract in 1986 from the U.S. Army Missile Command (MICOM) to provide a turbojet engine rated at 40 lbs thrust for use on the FOG-M missile. This model configuration was grown into the TJ-90 which is rated at 107 lbf thrust at 103,000 rpm. This family of engines is characterized by the single piece "monorotor" (compressor impeller and turbine rotor in a single piece casting) and "monostator" (compressor diffuser and turbine nozzle in a single piece casting). Figure 2, on the following page, is a cross section of the TJ-90.

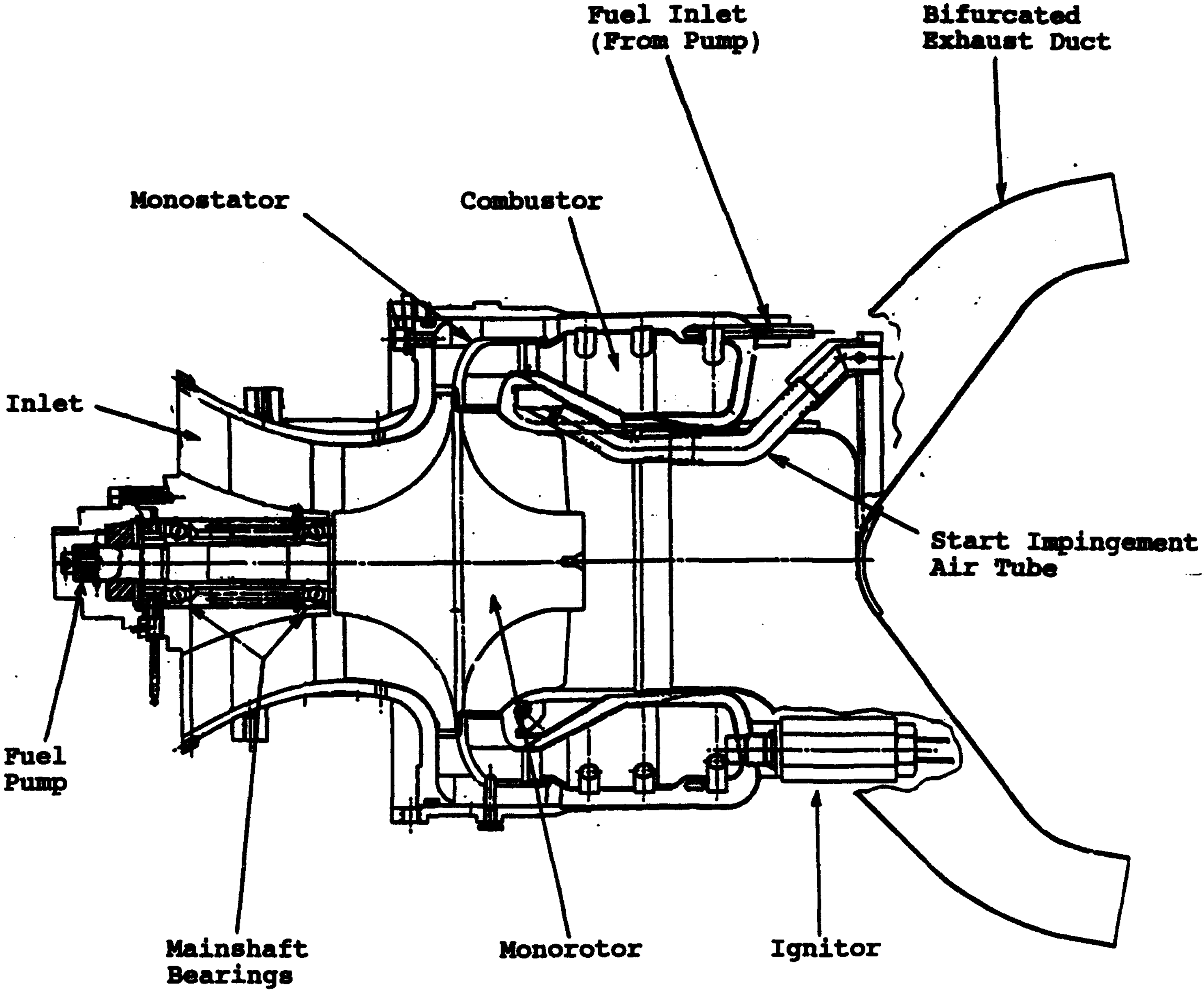


Figure 2 - Cross section of Sundstrand TJ-90

3.0 BASIC RESEARCH AND DESIGN

3.1 ENGINE CYCLE ANALYSIS

A simple cycle analysis was performed utilizing parameters provided to M-DOT by Sundstrand. Data was representative of a TJ-90 operating at a station 4.0 (turbine inlet) temperature of 1806°F. A fictitious core engine was defined which duplicated the gas flow properties provided by Sundstrand. Various loss and turbine efficiency assumptions were evaluated. Results of these studies provided the design point objective of the power turbine.

Turbine design point parameters are as follows:

Gas flow	1.558 lb. per sec.
Inlet total pressure	26.22 lb. per sq. in.
Inlet total temperature	1913 R.
Estimated efficiency	75%
Pressure ratio	1.684
Exhaust nozzle exit Mach No.	0.10
Estimated inlet duct losses	4.5%
Downstream exhaust losses	5.0%
Gearbox parasitic loss	5.0%
Calculated output power	101.3 SHP.

3.2 DRIVE TURBINE AND EXHAUST SYSTEM

3.2.1 Aero/Thermodynamic Gas-Path Design

The turbine gas path was designed for minimal total-pressure loss and minimal back pressure. The turbine transition duct, which ducts gas from the TJ-90 exit to the integral power-turbine nozzle vanes, was a compound "S" curve intended to accomplish the radius change as gently as possible. The design intent was to provide a nearly linear diffusion rate from inlet to turbine nozzle. Area ratio was 1.29.

A choice of two rotor design speeds was available, 54,000 rpm and 60,000 rpm. The 54,000 rpm speed was selected because it resulted in lower blade loadings and more reasonable annulus dimensions. A parametric study was performed evaluating tip diameter, through-flow velocity and axial velocity diffusion across the rotor. Three constraints were applied. The hub work coefficient must be ≤ 2.0; the absolute nozzle-exit flow angle must be $\leq 65°$ and rotor exit swirl must be 0°. The objective was to find an optimum flow and work coefficient combination satisfying these constraints. The final mid-span velocity diagram parameters are:

Flow Coefficient	0.70
Work Coefficient	1.41
Hub Work Coefficient	1.99
Axial Velocity Ratio	1.0

Rotor and nozzle blade geometry was designed to greatly simplify machining and fabrication. The rotor blade sections are comprised of two circular arcs and two straight sections. The pressure surface of the hub section is an arc and straight section and is constant from hub to tip. The hub suction surface is another arc and straight section and is defined to yield a passage area distribution that allows smooth acceleration of flow. The aft portion of the blade is a wedge defined by two straight sections. This wedge is constant from hub to tip. After blade thickness was defined, blade quantity was calculated to achieve a tip solidity ratio of 1.32. Number of blades is 22.

Nozzle blade sections were of constant thickness to permit fabrication from sheet metal. The forward half of the section on both suction and pressure sides is a constant cylindrical surface from root to tip. From mid-chord to the trailing edge, the section is planer on both suction and pressure sides. The vane leading edge contour was a 3-to-1 ellipse. Exit angle is 62.5°.

The exhaust geometry is very compact. The design intent was to achieve the lowest possible back pressure with a two-dimensional design. The rotor exit configuration requires an immediate turn radially outward after the turbine rotor exit. The mixing, turning, diffusion and secondary flow losses have been minimized by providing 40.5% increase in flow area at the exit of this 90° bend. After exiting the bend, the flow enters a plenum which has a constant depth of 1.0 inch. This plenum is bifurcated into two curved two-dimensional diffusing exhaust nozzles. These exit nozzles each contain three two-dimensional diffusers. Total combined exit area is 40 square inches. Exit Mach No. is calculated to be less than 0.15. Figure 3, on the following page, is a cross sectional view of the turbine section showing the exhaust duct configuration. Figure 4 is a photograph of the turbine nozzle/transition duct clamped to the exhaust duct.

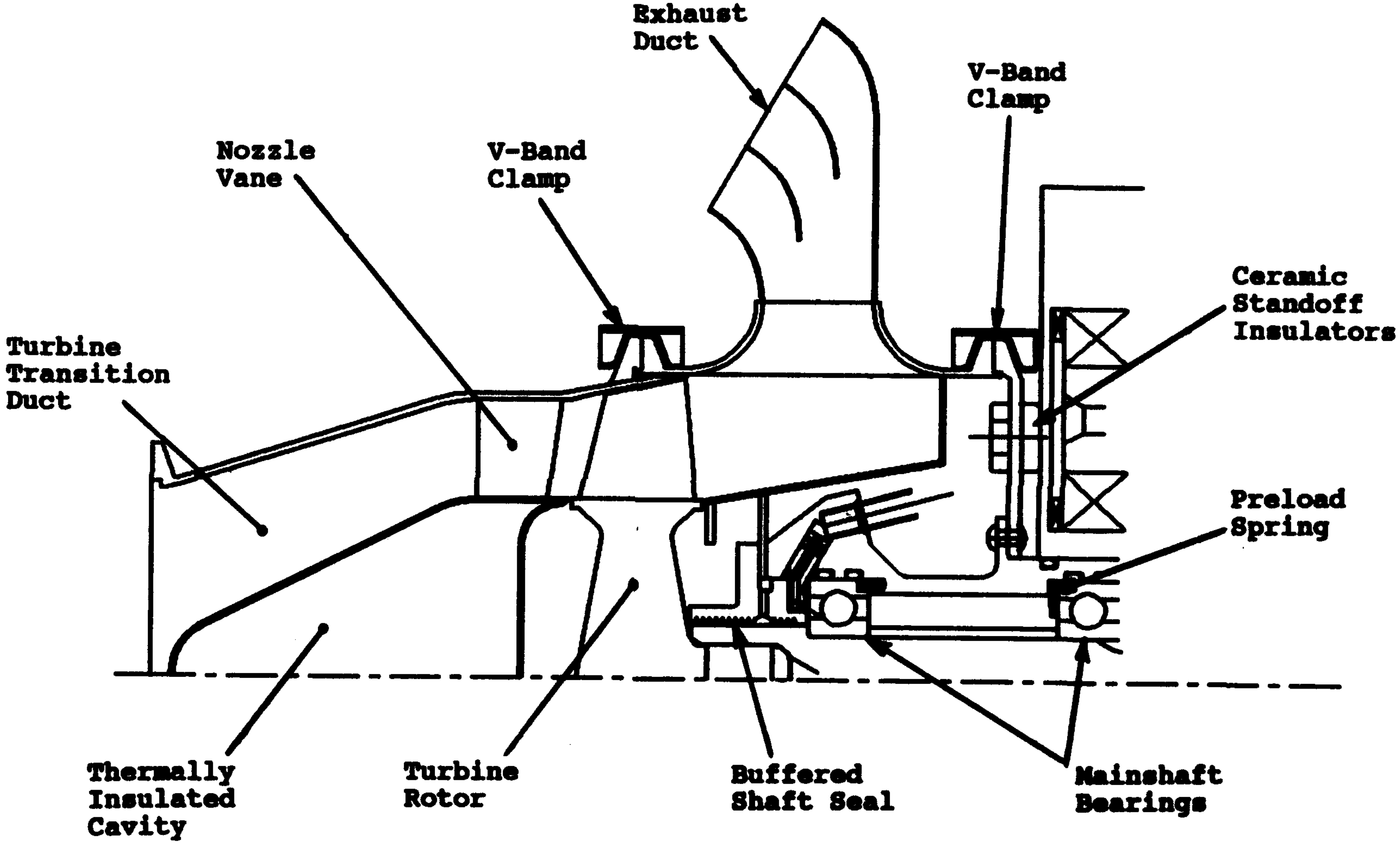


Figure 3 - Cross section of turbine section

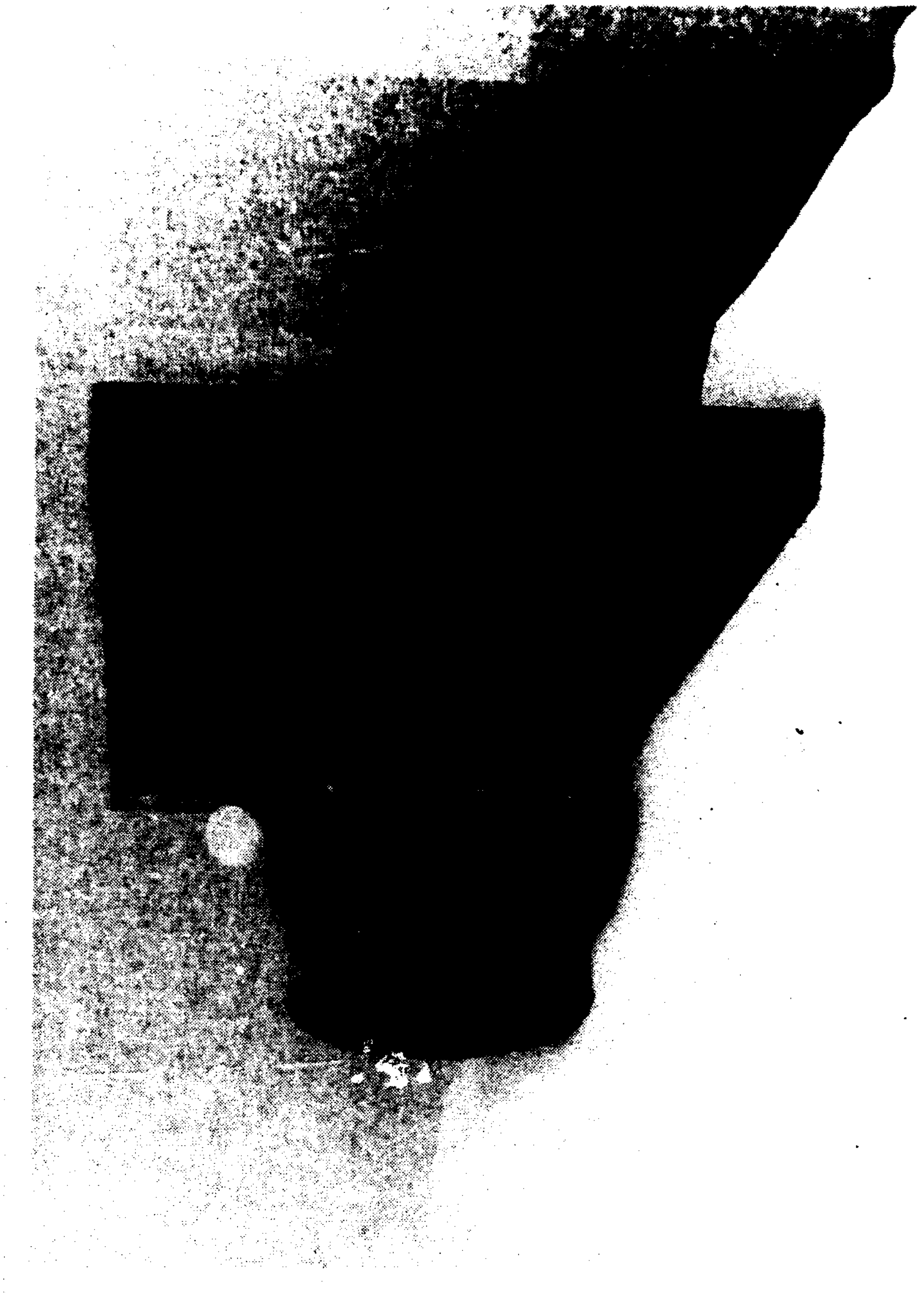


Figure 4 - Turbine transition duct and exhaust duct

3.2.2 Structural Design

The turbine drive section consisting of inlet duct/nozzle, rotor assembly and exhaust duct was designed to minimize fabrication cost and facilitate assembly/disassembly. Thus, the majority of surfaces are simple-curve and the entire assembly is held together with V-band clamps. Refer to Figure 3 for a cross-sectional view of this arrangement. Overall bending loads are transmitted through the skin of the inlet duct and then through four carry-through struts in the exhaust duct to the forward-most V-band flange. Material was Hastelloy X for the inlet duct, stator and carry-through struts and 347 CRES for the exhaust duct flanges and walls.

The turbine nozzle or stator assembly was a weldment consisting of formed sheet metal-duct, rolled sheet-metal inner dome, rolled sheet-metal vanes and machined V-band flanges at inlet and outlet. The outer duct serves as the structural member between gas generator and turbine reduction drive therefore the material thickness of 0.063 inch was chosen to meet cantilevered-load requirements. The inner dome is located only by the vanes. Wall thickness is 0.025 inch. The interior of the dome was filled with 3M Nextel 312 ceramic cloth to reduce heat flux into the turbine disk. The filled dome cavity was sealed with a sheet-metal plate welded to the forward face. Figure 5 is a photograph of the stator and inlet-duct assembly showing details of design.

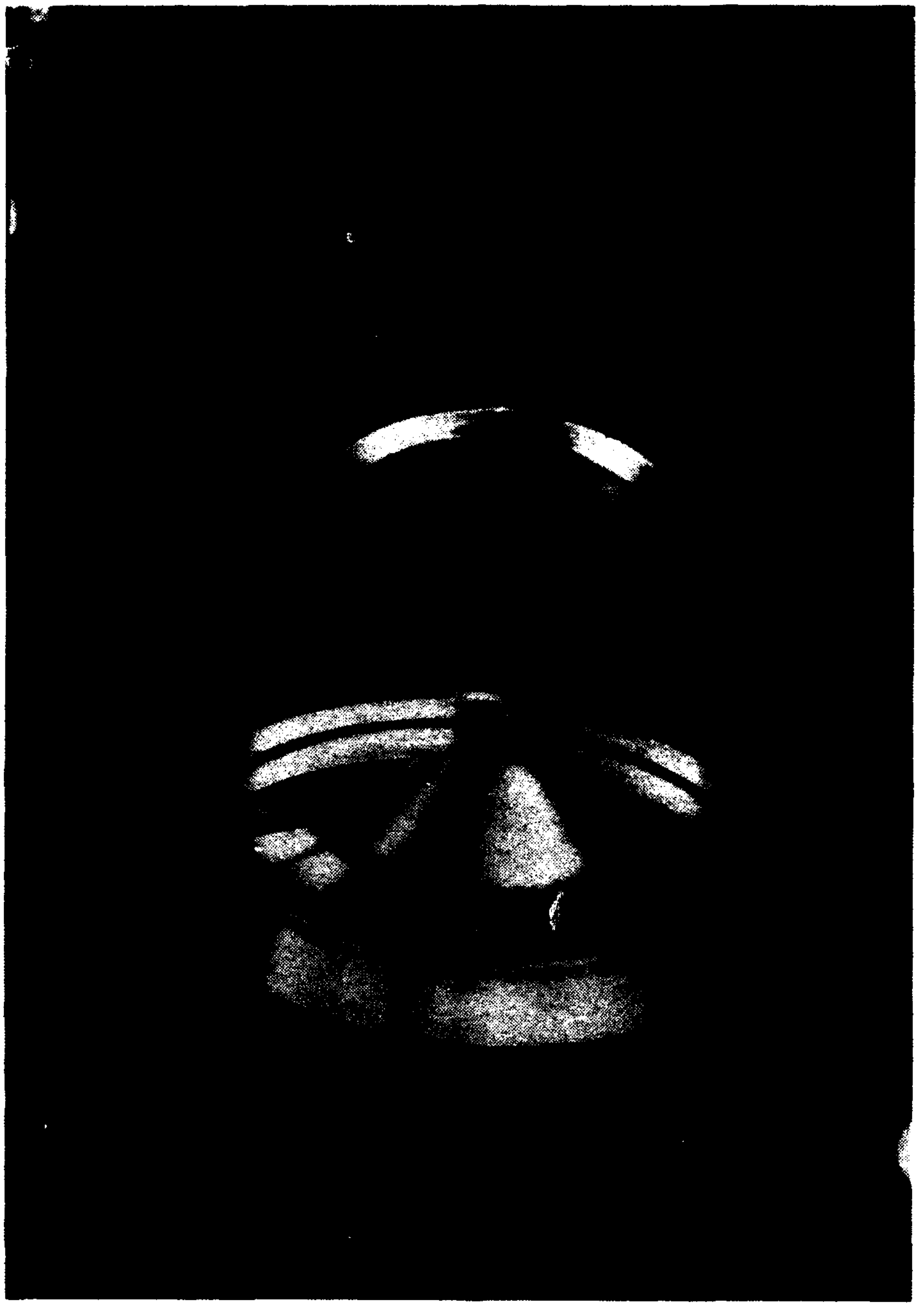


Figure 5 - Turbine stator and inlet duct assembly

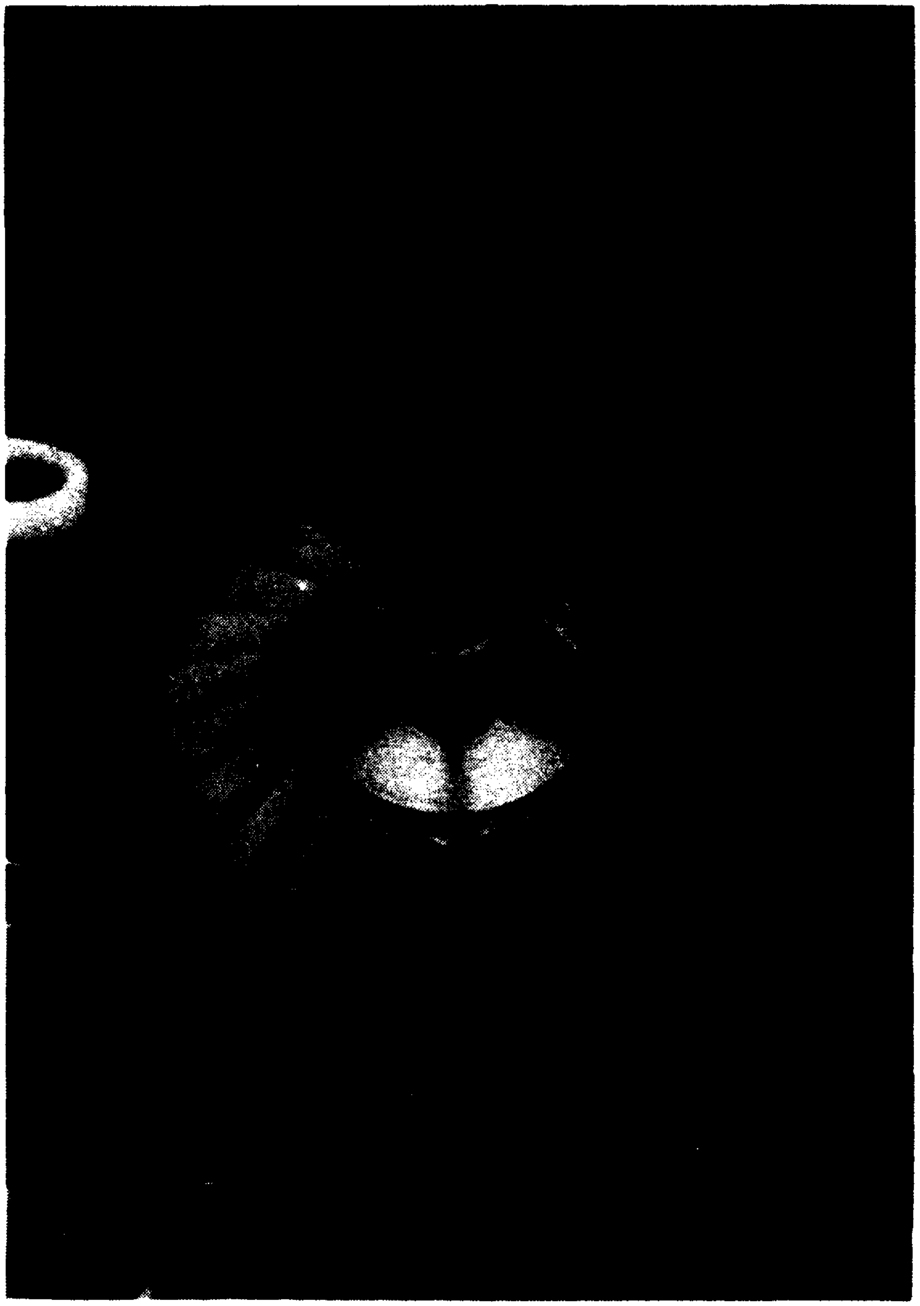


Figure 6 - Turbine rotor assembly

The turbine rotor assembly consisted of a single-piece machined bladed disk pressed into a machined 17-4PH shaft. Waspaloy was chosen for the disk and blade material because it had the best high-temperature creep properties of any of the readily available machinable alloys. Blade midspan leading-edge static temperature was calculated to be 1280°F at 100 percent power.

Concurrent with fine tuning of vector diagrams was analysis of blade stresses. The predominant forces were found to be blade-root bending stresses due to centrifugal straightening of the blades. Stacking of chord sections was accomplished by accurately laying out the shapes on paper, cutting out the sections and balancing them to establish the centroids. Centroids were then stacked radially. To verify that no dangerous blade resonant frequencies existed in the design, the completed wheel was acoustically excited at various frequencies. (See Figure 7.) Resonance was detected using salt particles. Using this method, the first bending mode frequency was measured at 4650 to 5400 Hz. From these data, an interference diagram was generated to provide guidance for engine operation. It was concluded that the design was adequate for the Phase I effort.

An interference fit was chosen to fasten the shaft to the bladed disk. Eliminating the hole in the disk center and replacing it with a stub shaft reduces hub stresses by a factor of three. Interference fit between shaft and disk was 0.001 inch. Refer to Figure 6 for a photograph of the turbine rotor assembly.

3.3 REDUCTION DRIVE DESIGN

Once power-turbine speed was fixed, a reduction ratio of 19 to 1 was selected representing the highest ratio possible using the largest diameter available stressproof steel bar stock. This yielded an output speed of 2830 rpm. To minimize frontal area, reduction was handled in two stages. To minimize side loading of the turbine shaft bearings and pinion, a twin-layshaft design was selected having the layshaft gears located 180° apart. Oil-mist lubrication was chosen to minimize cost.

3.3.1 Gearing

The intent of the gear design was to provide adequate life at the lowest possible fabrication cost. For this reason, straight-cut hobbed gearing was selected. All gears were sized using AGMA methods using best-case assumptions (i.e. torsional vibration will be minimal and tooth geometry will be perfect.), and properties of Stressproof steel from LaSalle Steel Co. The material was used in the cold-finished state. An AGMA Class-A gear hob was used to ensure that tooth profile met AGMA Quality Class 10 requirements. Gears and layshafts were internally configured to provide deflections that minimized tooth edge loading due to torsional deformation of the first pinion under load. The intent was to preclude accelerated wear of the first pinion. Weight reduction was a byproduct.

Figure 7 - Set up for turbine-blade resonance testing.

Both gear meshes were given the same tooth count to yield collinear input and output shafting. Layshaft gears were given an odd number of teeth so that they could be identical. Tooth count was chosen to provide a hunting-tooth situation where each tooth mates with every other tooth on the mating gear. This was to assure uniform wear. Gear specifications are as follows:

Tooth pitch	20 DP
Total tooth count per stage	97
First reduction contact face width	1.4 in.
Second reduction contact face width	2.3 in.
First reduction pitchline velocity	165 feet/sec.
Second reduction pitchline velocity	46 feet/sec.

Layshaft gears were mounted on low-cost off-the-shelf 6205 series deep-groove radial ball bearings. Bearings were preloaded to 30 lbs on the outer races using wave springs. Limiting B-10 life was estimated to be 400 hours.

3.3.2 Housings

The reduction gearcase housing was machined from solid 6061-T6 aluminum bar stock and hard anodized. It consisted of three pieces, input housing, midsection and output housing. The entire assembly was held together using ¼-28 SAE Grade-8 threaded rod and nuts. To reduce heat flow into the gearcase, the V-band flange that attaches the gearcase to the exhaust duct was configured as a separate steel part that was mounted to the input housing on ceramic stand offs. This arrangement can be seen in Figure 3.

3.3.3 Input Shaft

The input shaft is part of the turbine rotor assembly. It is pressed onto the disk hub at one end and has gear teeth machined into it at the other end. Material is 17-4PH CRES. The shaft was hardened to H 1075 prior to machining.

Barden M204X22 20mm-bore, deep-groove radial ball bearings were chosen for the input shaft. These are made of M-50 tool steel stabilized for operation at temperatures up to 750°F. This temperature capability was deemed critical since high soak-back temperatures can be experienced at shutdown. The bearings were preloaded using spring washers against the forward bearing outer race.

To help estimate bearing load conditions, turbine rotor thrust was calculated using estimated static pressure values against hub and blading. At full power, this value was 34 lbs forward. (In the direction of the gearcase.) Once bearing load conditions were known, the engineering department at Split Ball Bearing Inc. was consulted. They ran several trial cases through their bearing life computer model and obtained a B-10 life for this bearing/speed/load combination of 726 hours.

In the initial design, bearings were retained in the shaft by an interference fit ring made of Tinel alloy. This is a memory alloy manufactured by Ray Chem Corp. of Menlo Park, CA. The ring was machined from pre-stressed bar stock, installed onto the shaft and shrunk into place by raising the temperature to 330°F using a torch. After failure of the aft input shaft bearing occurred, the retainment design was modified. The Tinel ring was replaced with a split-threaded ring that can be easily removed thus simplifying disassembly of the input shaft rotating assembly for inspection or replacement of the bearings.

3.3.4 Output Shaft

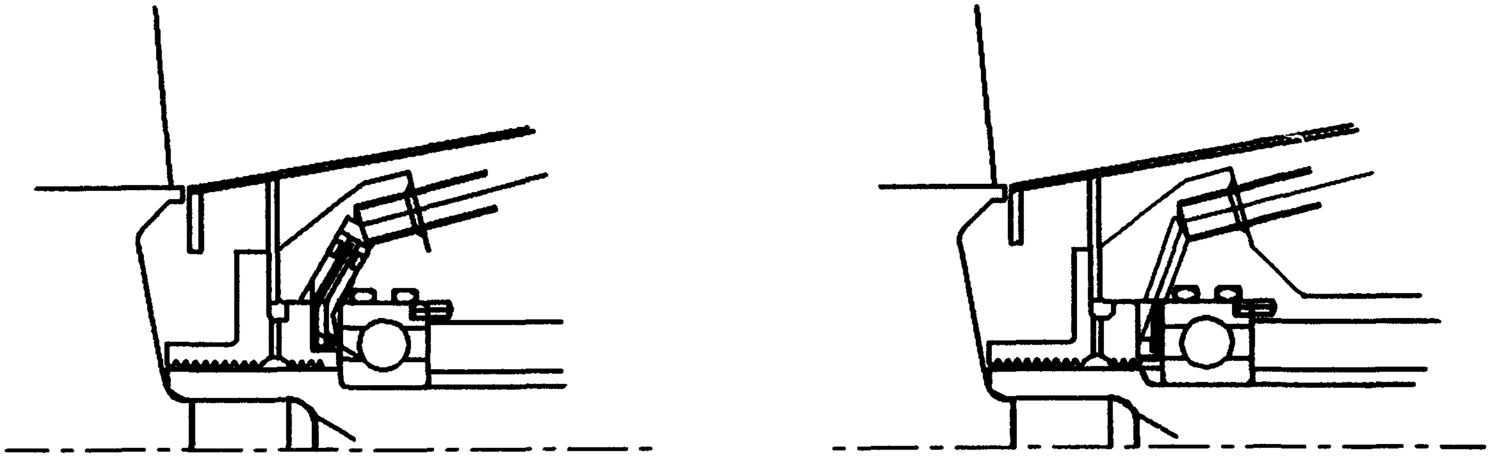
The output shaft assembly consisted of gearshaft, propeller flange, plastic bumper and tiebolt. The gearshaft was machined from Stressproof steel and incorporated the output gear. The propeller flange was anodized 6061-T6 aluminum. It incorporated a tapered shank that pressed into a matching bore on the gearshaft. A machined nylon bumper was incorporated to transfer aft thrust to the forward bearing. The output shaft was mounted on 6208 series bearings. The aft bearing was oil-mist lubricated and the forward bearing was sealed and grease packed.

The tiebolt was a standard ½-13 SAE Grade-8 bolt necked down to the thread minor diameter to reduce spring rate.

3.3.5 Lubrication System

To keep the lubrication system simple, commercially available oil mist units were purchased and adapted for use on the Sundstrand gas generator and reduction drive. Air at 20 psig. was supplied by an external compressor and synthetic turbine oil was used as the lubricant. Lubrication mist was introduced at the inner race aft input shaft bearing. The case was designed to direct this flow from the input shaft bearings through the first pinion mesh. Spent mist was routed over the out-of-mesh sides of the second reduction before being vented overboard into the engine inlet. To improve transport of lubricant contaminates within the gearcase, spiral grooves were machined into the layshaft gear bores to utilize gear-tooth windage. Magnetic chip collectors were incorporated into cavities in the center gearcase assembly.

During controls testing of the engine, the aft input-shaft bearing failed. A subsequent investigation revealed that failure was due to lack of lubrication. As a result, jetting was redesigned. Figure 8 depicts cross sections of both oil jet configurations.



Final configuration with higher flow capacity. Jet is directed at base of rolling element.

Initial configuration with oil/air mist jetting indirectly into the bearing cavity.

Figure 8 -- Mainshaft bearing oil-jet configuration.

3.4 ELECTRONIC CONTROL

An analog electronic control unit (ECU) was designed for the engine. It was designed to operate the HSC torque-motor valve supplied by Sundstrand. The ECU incorporates all analog circuitry and is comprised of two closed speed loops, closed-loop temperature, a low-wins arbitration circuit, a throttle conditioner, speed and temperature conditioners, and an output driver circuit. Inputs to the ECU are limited to the throttle and the off/run/start switch. Outputs include current to the HSC fuel metering valve and an LED to indicate when the ECU is in closed-loop control of the engine. The ECU does not include automatic engine starting.

3.4.1 Engine Matching and Theory of Operation

To ensure that the control was properly matched to the engine, a study was conducted to establish response characteristics of the engine and fuel system. Raw data included rotating assembly inertias, cycle characteristics, control valve data and sensor time constants. The controls model of the gas generator (N1) speed loop is a simple proportional/integral (PI) control typical of most speed governors. To properly set the proportional gain, gas-generator rotating group unbalanced torque must be established. The unbalanced torque is the torque produced by the turbine while not in equilibrium and indicates the amount of torque available to accelerate the rotor. This torque and the rotor inertia determine how fast the engine will respond to external perturbations as well as internal commands in the form of fuel flow changes. This data was not available for this program. Therefore a value was estimated. It is our experience that most gas turbine engines, regardless of size, demonstrate a rotor speed bandwidth of between 0.5 and 2.0 Hertz. Using 2.0 Hz. as a worst case value, and knowing rotor inertia, a rotor torque gain (RPM/ft-lb) was back calculated.

Other gas generator control factors considered were:

- The gas generator rotor turbine does not exhaust to ambient, but has an uncoupled (free turbine) behind it. As the free turbine changes speed, it's pressure ratio changes and therefore the apparent discharge pressure of the N1 turbine changes. This introduces nonlinearities and higher order effects into the speed loop to an unknown extent.
- The fuel controller is a simple servovalve without a constant delta-P valve and therefore exhibits a nonlinear current/flow relationship.

Since so little engine performance was known, control gains selected were conservative. The hope was that the control would at least be stable and gains could be adjusted to damp oscillations or improve bandwidth. Engine tests proved the N1 loop to be stable and no control gain adjustments were made.

As with the gas generator rotor, power turbine torque characteristics were unknown and an educated guess of control gains was made as described above. Actual engine testing of this speed loop showed a stable, bounded oscillation at a frequency of about 0.3 Hz. Reducing the control gains by 2.5 eliminated the oscillations.

The exhaust-gas temperature control loop utilizes a high-response type-K, open-bead thermocouple to provide the feedback signal. The time constant of this sensor was estimated to be 1.0 seconds, therefore a five-to-one lead/lag compensator was used to improve the loop bandwidth. Control gains were selected based on an estimate of the engine temperature/delta fuel flow of 40 degrees F/pph. Engine testing proved this loop to be stable and no control gain adjustments were made.

Each of the three loops described above uses engine fuel flow as the control variable. Since only one loop can be in control of the fuel flow at any given time, some sort of arbitration must be accomplished. Each control loop submits it's "request" for a fuel flow to an arbiter circuit which selects the lowest value and passes that value to the current driver for output to the fuel valve. The "winner" of the low-wins arbitration remains in control as long as no other loop requires the fuel flow to be lowered. The control loops which are not controlling the fuel flow quickly request higher and higher values due to the integrators and ultimately reach the ECU rail voltage where they will remain unless and until their respective setpoints are crossed causing them to integrate down.

The final circuit of interest is the throttle conditioner which is a simple integrator and restricts the maximum rate of change of the N2 setpoint.

3.4.2 Hardware Design

The Phase I control was designed as a bread-board unit that utilized standard off-the-shelf commercial grade components and a modular configuration. Perforated board was used for the circuit boards. Each of 5 modules was assembled on its own board. Molex edge connectors were used to connect modules to a central backplane. A Burr Brown Model 558, ± 15 VDC power supply was also bussed into the backplane. The entire control was housed in a commercial aluminum enclosure.

3.4.3 Sensors

Gas-generator speed was sensed by an integral monopole supplied by Sundstrand. Power-turbine/Propeller speed was sensed by an Electro model 3010HTB monopole reading passing frequency of the layshaft gear teeth. Inter-turbine temperature was sensed by four chromel-alumel thermocouples located upstream of the power-turbine nozzle in the transition duct. (See Figure 4.)

3.5 SUNDSTRAND GAS GENERATOR

A government-supplied Sundstrand TJ-90 expendable turbojet engine was employed as the gas generator. Modification consisted of removal of the bifurcated exhaust duct and replacement with a circular duct with V-band flange. To improve airflow in the inlet, a machined aluminum centerbody and inlet bell were designed.

3.6 LABORATORY FIXTURE DESIGN

3.6.1 M-DOT Test Facility

The facility was modified to accept the turboprop and measure output power instead of static thrust. To measure output torque reacted at the propeller hub, the engine was mounted sideways on the stand on a pivoting arm such that torque applied at the engine mounts was transmitted as an axial load to the electronic load cell. Torque was determined by multiplying force on the load cell by the distance between the thrust platform pivot (fulcrum) and the load cell centerline. This yielded a moment equal to the torque that the engine was transmitting to the propeller. See Figure 9.

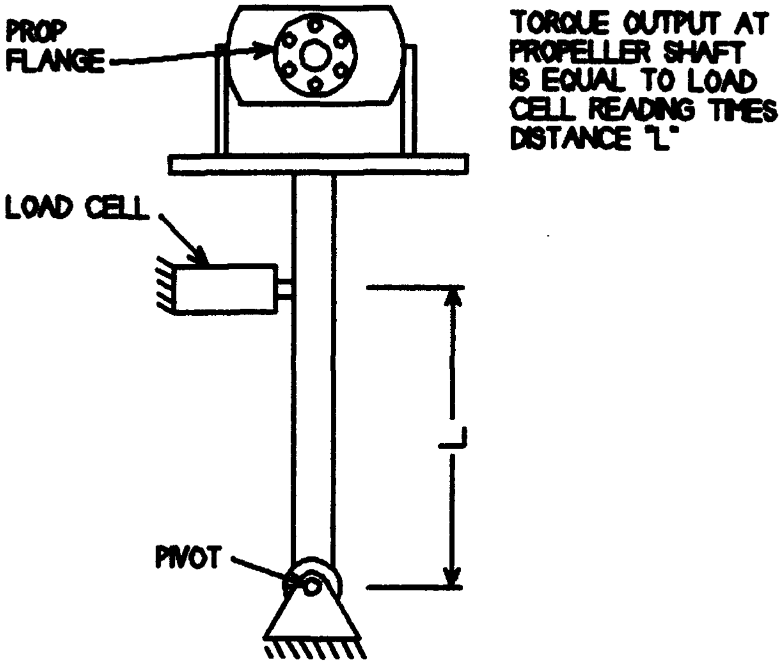


Figure 9 - Schematic layout of torque measurement system.

3.6.2 Test Stand Adapters

Adapters were designed to accommodate the turboprop test stand installation. These included a 10-inch steel "U" channel on which the engine was mounted, struts that attached the stand to the bumper of a pick-up truck, and engine mounts that attached the gearbox to the U channel. The engine mounts consisted of half-inch thick steel straps bolted directly to the sides of the gearcase and the steel channel.

To improve airflow around the centerbody and struts in the engine inlet, an aluminum fairing and bellmouth were designed. The bellmouth also served as an adapter to connect the engine inlet to the "U" shaped inlet duct. Figure 10 is a view of the basic engine assembly showing the inlet bellmouth and center body fairing.

Because the Sundstrand engine inlet faces rearward, provision had to be made to prevent re-ingestion of engine exhaust gases. This was accomplished by installing a "U" shaped sheet metal duct on the TJ-90 inlet that curves upward and forward to accept propeller blast. See Figure 11.

4.0 HARDWARE FABRICATION

4.1 POWER TURBINE ROTOR AND NOZZLE

To obtain the best possible material properties, a pancake forging was obtained from Fannsteel California Drop Forge in Los Angles, CA. Post-forge heat treating was accomplished by H&H Heat Treating, also in Los Angeles. The power turbine was machined as an integral bladed disk. The disk blank was first turned on the lathe. Fixturing was then designed to facilitate indexing and generation of the blade profile radii and the rotor was machined on a vertical mill using tapered carbide milling cutters. The shaft was turned on a lathe and then farmed out to a local gear manufacturer to have the pinion teeth cut on the input end. Assembly was accomplished by cold soaking the disk in dry ice, heating the shaft with a propane torch and quickly pressing the shaft on the rotor using a hydraulic press. The complete assembly was then dynamically balanced.

To fabricate the inlet duct and nozzle assembly, a simple cone was laid out on flat sheet, rolled and welded. The cone was then placed in a female die and hydraulically bulged into the final compound shape. The inner dome was constructed in three segments. A cone was laid out on flat sheet and rolled. To this, a cylindrical section and hydraulically-formed hemispherical cap were then welded. The complete welded assembly was then hydraulically formed in a female die to the final aerodynamic shape. Nozzle vanes were cut from sheet metal and hydraulically bent to the proper radius. The elliptical leading edge was then hand dressed with a file. V-band flanges were turned from bar stock. Outer duct, V-band flanges, inner dome and vanes were then assembled and TIG welded. The inner dome was stuffed with ceramic cloth and a forward plate welded over the opening to contain the cloth. After welding, the entire assembly was stress relieved and the turbine shroud profile turned on a lathe.

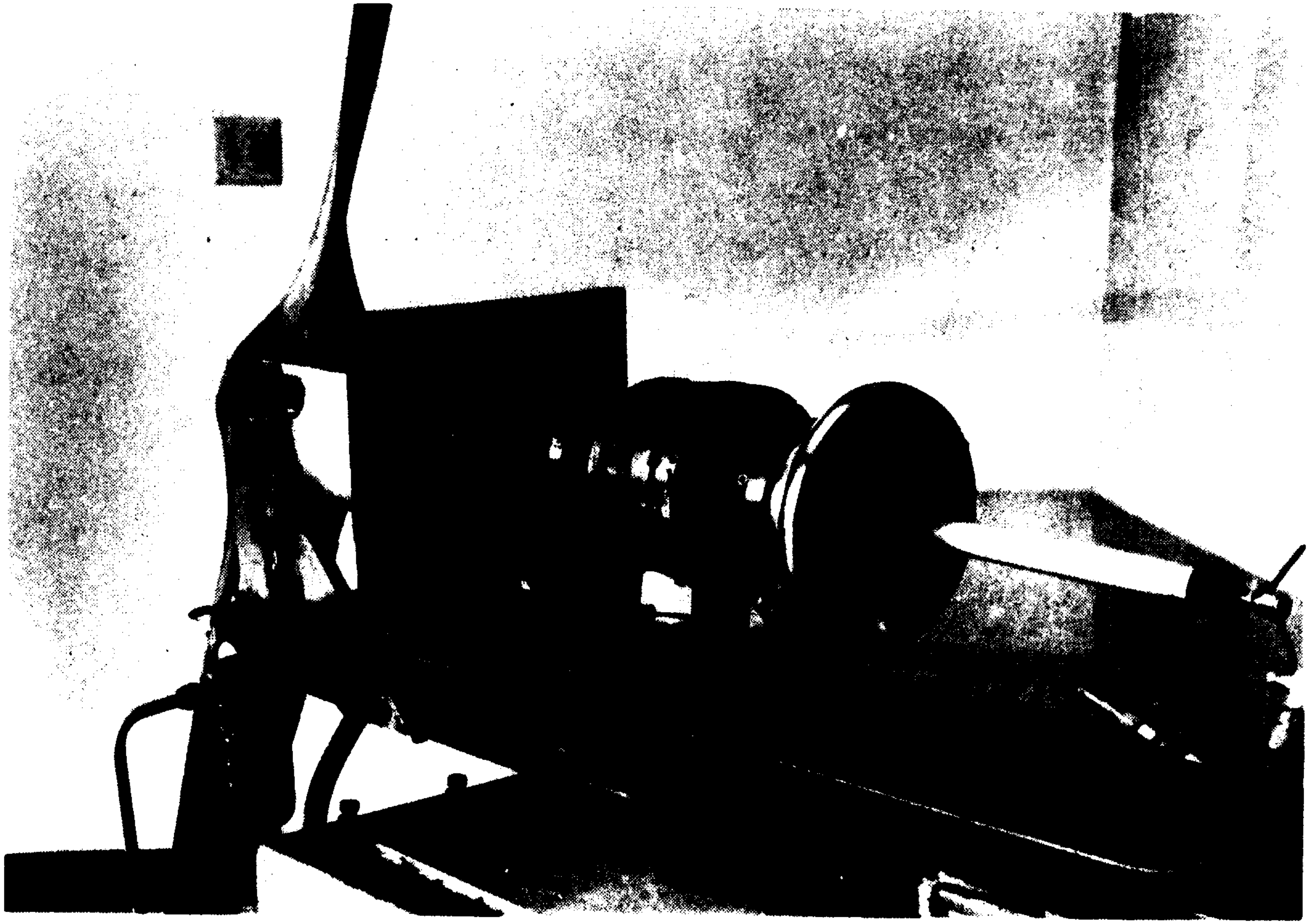


Figure 10 - Basic engine assembly showing inlet fairings

Figure 11 - Engine installed on test stand

4.2 EXHAUST SYSTEM

V-band flange blanks, axial to radial transition shrouds and carry-through struts were machined from Hastelloy-X and CRES 321 bar stock. Remaining duct walls and diffuser vanes were cut from CRES 347 sheet stock and bent to the final shape either by hand or using a hydraulic press. The entire assembly was then TIG welded and stress relieved. After stress relief, V-band flanges were finish turned to the final shape.

4.3 REDUCTION DRIVE

Gear blanks were machined from Stressproof steel bar and then farmed out to a local gear manufacturer for machining of the teeth. Layshaft gears were then statically and dynamically balanced. All gears were black oxide coated after machining.

Gearcase housings were machined from AL 6061-T6 bar stock taking care to maintain accurate placement of all bearing bores.

4.4 PROPELLER

A ground-test propeller was provided for the program from M-DOT inventory. It consisted of mahogany core with glass-epoxy laminate.

4.5 ELECTRONIC CONTROL

The electronic control was fabricated using standard circuit bread board fabrication techniques and off-the-shelf prototyping equipment and supplies.

4.6 TEST FIXTURES

All test fixtures were fabricated in the M-DOT machine shop. Steel adapters for the test stand were machined and welded from square tube stock and steel channel. Engine mounts were cut from cold rolled 1018 steel, welded and machined. The inlet adapters were machined from solid 6061-T6 aluminum bar stock.

5.0 BENCH TESTING

Bench testing of the ECU consisted of calibrating the control loops and verifying that they were functioning over the full range of inputs and outputs. Loop Bode plots were not made since all circuits were extensively analyzed using PSpice and found to function as theory predicts.

6.0 ENGINE TESTING

Engine testing was conducted outdoors approximately 25 feet from the rear facility door. This permitted use of facility air and electricity while maintaining a safe distance between the building and engine for fire protection. The operator was seated at the engine control panel approximately 25 feet from the engine. Figure 11 is a photograph of a typical test setup.

Prior to each test run, instrumentation and shut down systems were calibrated using a signal generator and thermocouple voltage source. The stand was leveled and the torque measuring system was calibrated using dead weights.

Due to the expendable nature of the gas generator design, run time was minimized to reduce probability of hardware failure. Data were recorded immediately upon reaching the desired setpoint.

6.1 M-DOT ENGINE TEST FACILITY

The test facility consists of test stand, control stand, and fuel delivery system.

The test stand uses a 500 lb. capacity strain-gage load cell to measure the force applied to a hinged platform. Accuracy is ± .1 % F.S or ± 0.5 lbf. The platform was designed so that it could be leveled independently of the frame for zeroing the thrust reading prior to test. The stand is portable to allow remote testing. To test the turboprop, output torque, rather than thrust, was measured. This was accomplished by mounting the engine sideways on the thrust platform so that propeller load was reacted directly into the load cell. Additional details of this arrangement can be found in Section 3.6.1.

Control stand instrumentation readouts consist of:

- Three factory-calibrated analog pressure gauges with an accuracy of ± 0.25 % F.S.
- Four calibrated digital temperature indicators with an accuracy ± 0.9° F.

- One digital frequency indicator with an accuracy of ± 1 least significant digit (LSD) or ± 2 ppm of input. This was used to measure engine speed and to operate the overspeed shutdown system.
- One digital torque load meter with an accuracy of ± 0.05% of reading or ± 1 count.

The test stand has four emergency engine shut-down systems: turbine overtemperature, mainshaft bearing overtemperature, engine overspeed, and low oil/air mist lubrication pressure. The stand is also equipped with a Hoke ten-turn needle valve to manually control fuel flow. Fuel flow rate was monitored using a calibrated turbine flow meter.

The fuel delivery system consisted of a 55-gal drum (with casters), 1/3 hp electric motor, 90 gph pump, relief valve, pressure gauge, and 20 micron filter. This unit was positioned 20-30 feet away from the engine and operator during testing. It provided a fuel pressure of 120 psig.

6.2 INSTRUMENTATION

In addition to the test stand thrust cell, the following performance instrumentation was used for testing:

One type K (chromel-alumel) thermocouple at station 1.0 to measure total temperature.
Four type K thermocouples at station 5.0 to measure total temperature. (See Figure 4)
One static pressure tap at the combustor plenum (station 3.0).
One static pressure tap at station 5.0.
Engine shaft speed magnetic pickup.
Total temperature at station 7.0 (power turbine exit).
Static pressure at station 7.0.
In addition to the above, type K thermocouples were installed on the aft mainshaft bearing outer race as a safety precaution to alert the operator of impending bearing failure.

A Hewlett Packard strip-chart recorder was used to record engine speed and inter-turbine temperature as required during controls testing.

6.3 ENGINE OPERATING LIMITS

The following operating limits were observed during testing:

Gas generator speed - 102,000 rpm
Drive turbine speed - 57,000 rpm
Gas generator exit temperature - 1720°F (Starting)
Gas generator exit temperature - 1550°F (Steady state)
Mainshaft bearing temperature - 150°F
Air/oil pressure - 20 psig. minimum
Output torque - 230 lb. ft maximum

6.4 ENGINE STARTING AND OPERATION

Engine starting was accomplished as follows:

- Air pressure in the compressor receiver tank was brought to 175 psig.

- Air flow to the bearing lubrication and servo cooling system was turned on and an assistant to the operator monitored the oiler to verify oil flow prior to start initiation.

- The off/run/start switch on the control is placed in the start position. In this position, the control emits a predetermined fuel flow request to the low wins arbiter. This position also disables the temperature loop preventing it from interfering with the start due to brief but high-temperature transients. Since the N1 (gas generator) and N2 (power turbine) speeds are low (and therefore are requesting high flows), the preset fuel flow request becomes the low winner and the fuel valve opens to a position which would result in a fuel flow slightly higher than idle. On a signal from the engine operator, the start assistant would turn on the ball valve at the compressor receiver and spool the engine.

- The test stand start system would then automatically turn on the master fuel solenoid when engine speed reached 5000 rpm.

- A second hand valve in series with the engine fuel valve is used to modulate the fuel while the engine spools up. As the engine approaches idle, the N2 loop begins to integrate down and finally becomes the low winner. To indicate this event, a green LED on the front of the control is illuminated. At this point, the ECU has control of the engine and the hand valve may be fully opened and the switch placed in the "run" position. In the run position, the temperature loop is enabled and the throttle may be opened to increase the N2 speed.

- O The assistant would close the ball valve slowly as the engine approached idle speed. If a deceleration or hung start occurred, the air valve was reopened until idle speed was reached.

6.5 ENGINE TESTING

Testing began 8-21-93. Seventeen brief runs were attempted, all resulting in flame out prior to recording data. Problems with the electronic control were diagnosed. It was decided to do a test run without the electronic control in order to demonstrate operation of the gearbox and collect performance data. The engine was started and accelerated to 185 lb-ft torque and data recorded. Power was then increased until a power turbine inlet temperature of 1536 F was achieved and data were recorded. During this test, ambient temperature was recorded at 104 F and barometric pressure was 28.585 in Hg.

After this test run, the gearbox was disassembled and gearing inspected.

The engine was reassembled and testing resumed on 8-29-93. Difficulties sustaining operation were traced to an overtemperature indication on the TJ-90 mainshaft bearing outer race which triggered an automatic shutdown. Initially, the problem was thought to be due to lack of lubrication. Oil/air flow to the bearing was increased and testing resumed. It was later discovered that the thermocouple had detached from the outer race and was rubbing on the rotating assembly. The thermocouple was removed.

Engine tests were conducted to evaluate operation of the electronic control. Over several test runs, control gain was adjusted and operation without the N2 (power turbine) integrator was tested. On 8-30-93, two test runs were performed. The first run was a test of N2 speed stability with the proportional gain set at 10. The control exhibited a mild oscillation until the run was ended by a safety system shutdown due to low oil-air mist supply pressure. Supply pressure was increased and another test run was made with proportional gain reduced by a factor of 2.5. On this run, control stability was evaluated and performance data were recorded at two power levels. Before data could be recorded at a third power setting, a droop in power turbine speed was noted accompanied by an unusual noise emanating from the engine. Power was immediately reduced and the engine shut down. Subsequent disassembly and inspection revealed a power turbine bearing had failed.

The gas-generator governor and turbine-temperature limiting function of the electronic control were evaluated using the TJ-90 alone as a turbojet. On the first test run, the engine was started and accelerated to idle. The gas-generator governor was set to 70K rpm and the engine accelerated by opening the fuel valve. The governor assumed control with no divergent oscillation. On the second test run, the temperature limiter was set at approximately 1150 F and the engine was started and slowly accelerated. The temperature limiter assumed control at approximately 1275 F. After stable operation was demonstrated, the temperature setting was dialed down in increments of approximately 100 F. The limiter performed as required reducing engine speed to achieve the required temperature. No sign of instability was noted during transient or steady-state operation.

Total Engine Run time during testing was 39 minutes. Total Starts were 23.

7.0 DATA REDUCTION AND TEST RESULTS

Hand calculations were done to correct performance to sea level standard day conditions.

7.1 ENGINE PERFORMANCE

Measured and corrected performance is as follows. A delta correction factor based on a field elevation of 1107 feet was used to calculate corrected horsepower. The root-theta correction was based on measured temperature at station 1.0.

TABLE I

Run	*Measured power (shp)*	*Corrected Power (shp)*	*Engine-inlet Temperature*	*TJ-90 exit Temperature*
1A	101.6	102.0	564 °R	N/R
1B	118.0	118.5	564 °R	1996°R
2A	50.7	51.2	554°R	1490°R
2B	71.9	72.7	554°R	1576°R

Figure 12, on the following page, is a plot of corrected performance of the Phase I engine.

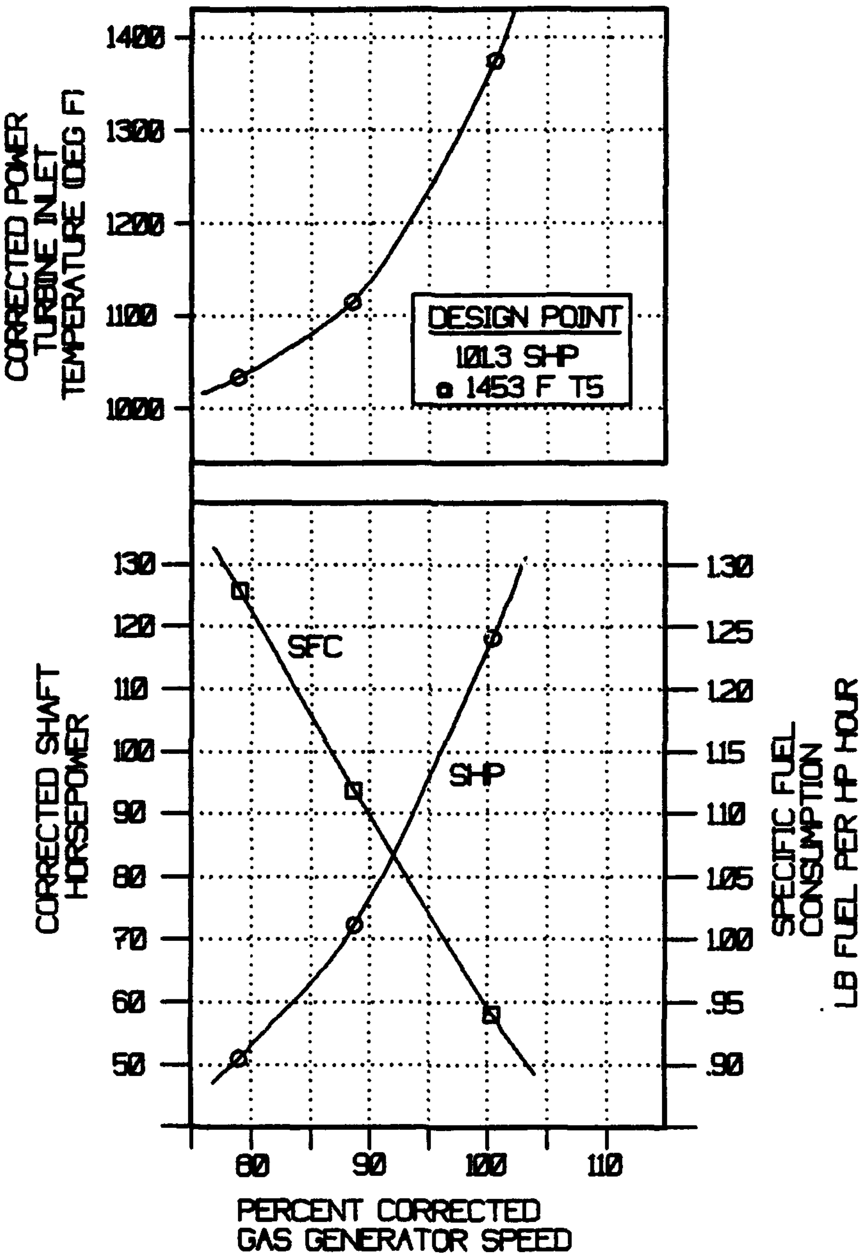


Figure 12 - Engine Performance

7.2 ELECTRONIC CONTROL PERFORMANCE

The electronic control performed well after proper gain values were set on the control loops. With a proportional gain of 10, power-turbine speed oscillated at a frequency of 0.3 Hz. The oscillation was stable at about 2% peak-to-peak amplitude. After further gain reduction by a factor of 2.5, this oscillation was low enough to be barely discernable from background noise. Transient performance of this control was not tested.

The gas-generator (N1) speed governor performed as required with no oscillation problems. When the governor assumed control, a stable oscillation of approximately 1.0 Hz and 0.5% peak-to-peak amplitude occurred. This was deemed acceptable. Transient performance was not tested.

The temperature limiter performed as designed. Demonstrated was the ability to assume control from the N1-speed governor when the temperature limit was reached. Also demonstrated, was the ability to reset temperature on the run and have the control make necessary adjustments in gas-generator speed to compensate.

7.3 HARDWARE DURABILITY

All observable engine hardware was found to be in excellent condition after the initial test run. As stated previously, failure of the aft input shaft bearing occurred during controls testing with approximately 39 minutes run time on the engine. Details on specific items follow.

7.3.1 Drive Turbine

The drive turbine rotor was in excellent condition after testing showing no signs of temperature distress, and no evidence of tip rub. (See Figure 13.) It is believed that the self piloting feature of the twin layshaft design, and the buffered labyrinth seal, prevented turbine tip damage by maintaining centering of the wheel when the bearing failed.

Debris from the aft input-shaft bearing was found in the gearcase indicating that it passed through the forward bearing. The forward bearing was damaged but did not completely fail. Both bearings were shipped to Barden for analysis. Barden engineering indicated that failure was most likely due to overheating from lack of lubrication.

The turbine nozzle was in good overall condition. However, some buckling of vanes occurred at the leading edges. (Figures 14 and 15.)

7.3.2 Reduction Drive

After the initial test run, gearing was in excellent condition exhibiting uniform wear at the pitch line indicated by removal of the black oxide. (See Figure 16.) Layshaft and output shaft bearings were in excellent condition. Input shaft bearings were not inspected because the initial design utilizing the Tinel retainer ring was not easily disassembled. After the bearing failure, gearing exhibited signs of foreign-object damage. Teeth were chipped and pocked along the entire profile. Greatest damage was experienced by the input pinion and first reduction drive.

7.3.3 Exhaust Duct

The exhaust duct (which also serves as the carry-through structure between the gas generator and reduction drive) was in excellent condition showing no signs of excessive distortion.

7.3.4 Sundstrand Gas Generator

The Sundstrand gas generator experienced no noticeable damage or degradation as a result of testing.

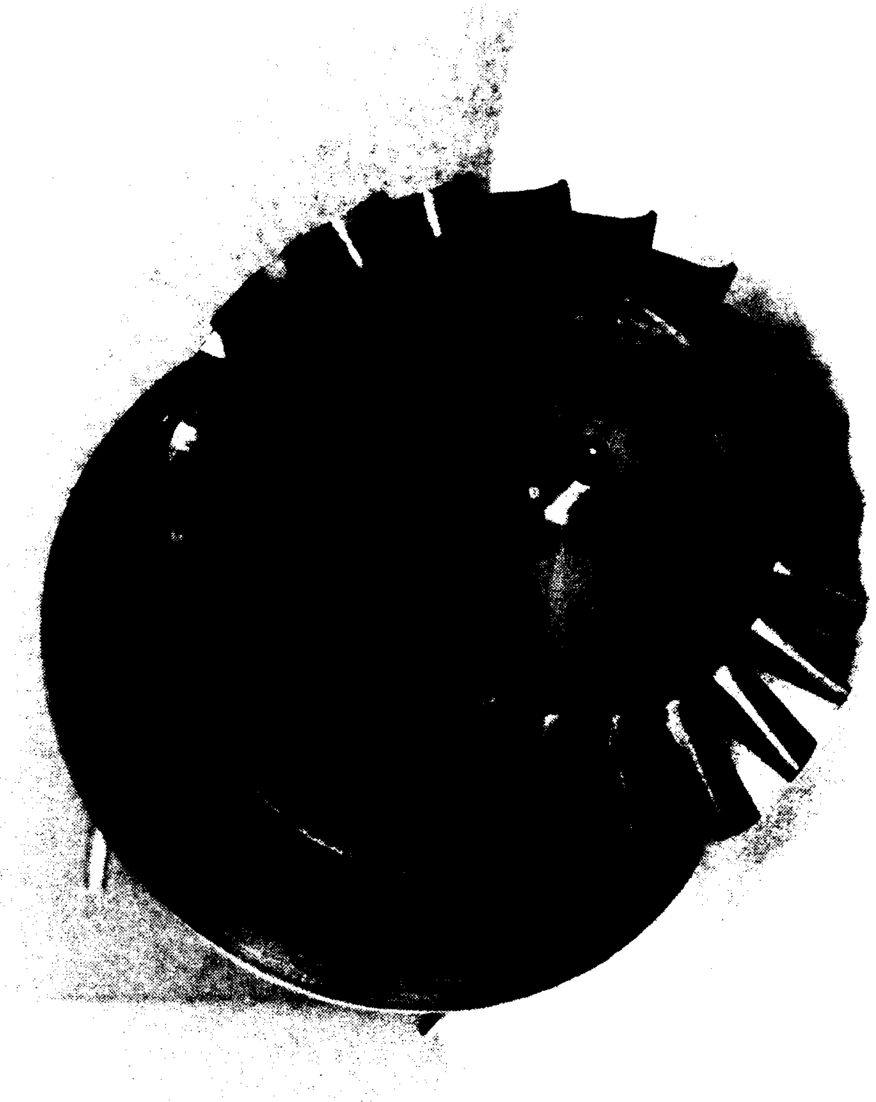


Figure 13 - Turbine rotor after testing

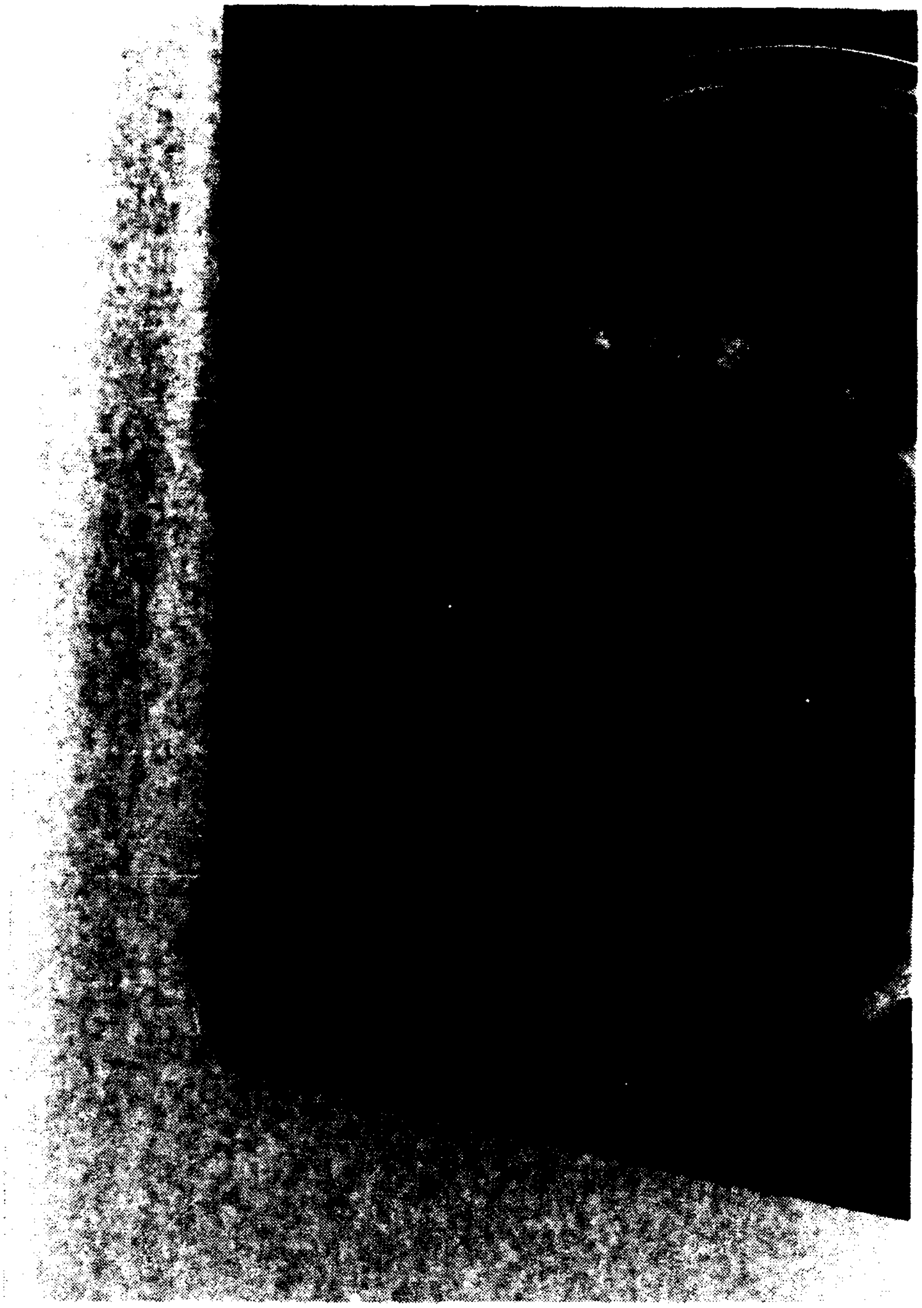


Figure 14 - Turbine nozzle inlet after testing

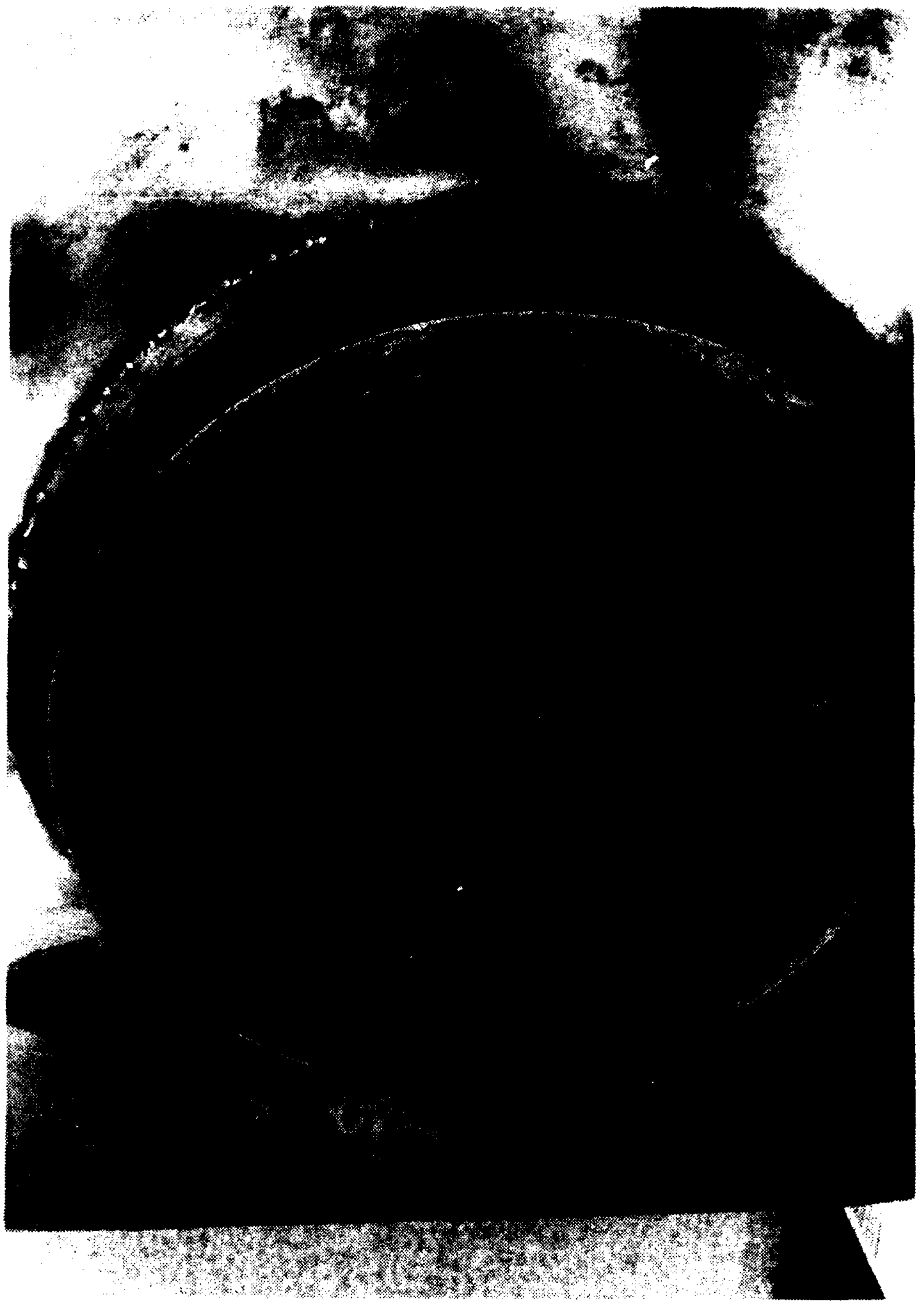


Figure 15 - Turbine nozzle exit after testing

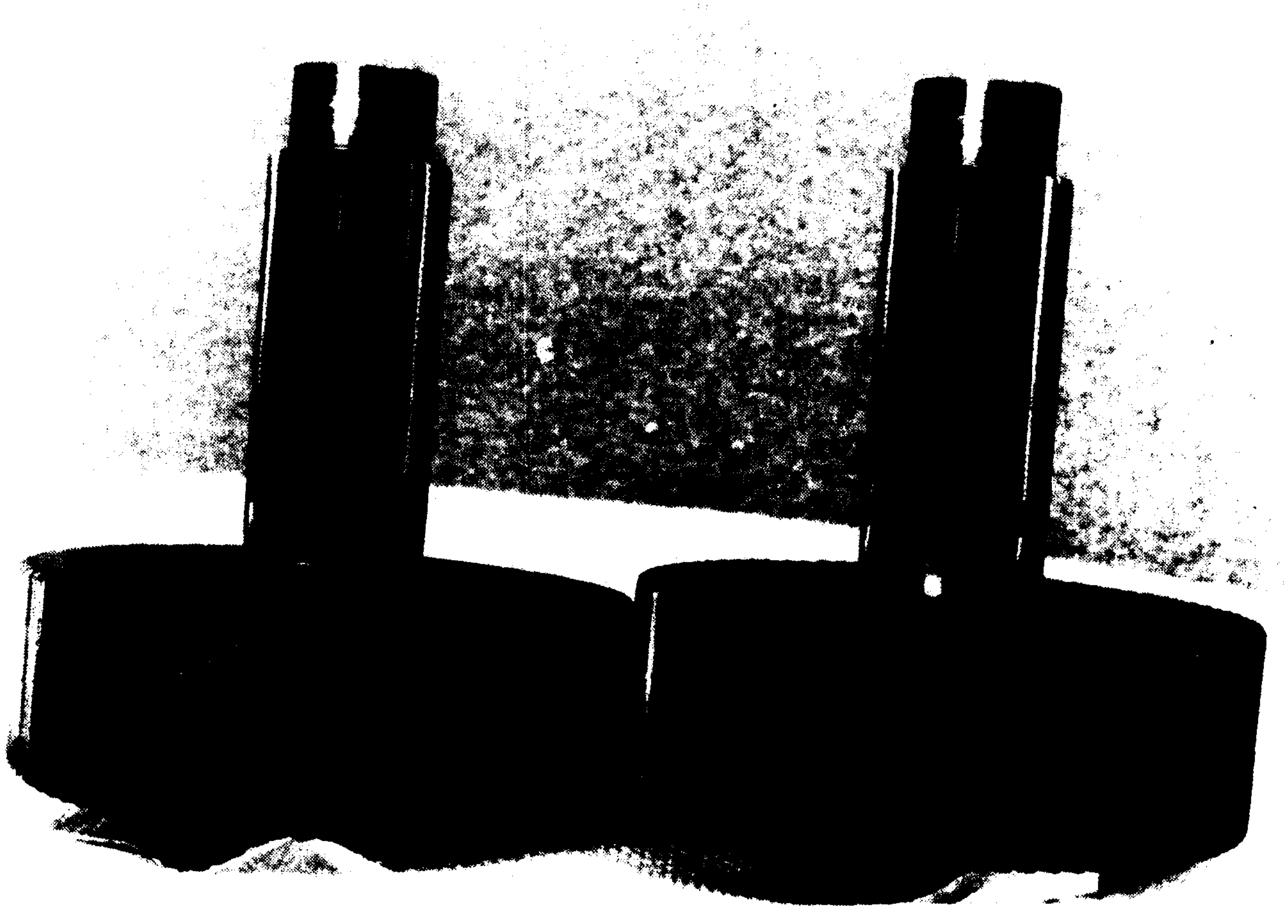


Figure 16 - Gearing after initial power run

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QUALIFICATION TEST LOG

ACCT. No. 9122.001	Date 8-21-93	Test Fac. PORT TEST STAND
Assembly No.	Model M-DOT TURBOPROP	Unit Serial No.
Engineer J. SHERBECK	Technician D. SHREINER	Supervisor
Test Type PERFORMANCE	Customer DARPA	Build No. 1

Start Time	Stop Time	Hours	Starts	REMARKS
13:01	13:02	—	—	FALSE START SHUT·DOWN TO REPAIR START AIR FIRE
13:17	13:17			" " NO IGN.
13:23	13:23			" " NO FUEL
14:10	14:11			" " NO IGN.
14:33	14:34	:01	1	ENG. STARTED AND BEGAN TO ACCEL. SAFTY SYSTEM S/D ON T_5
14:38	14:39	:01	13	13 BRIEF ACCELERATIONS ENDED BY SAFTY SYSTEM
				SHUT DOWNS
14:42	14:43	:01	1	SUCCESSFUL START AND ACCEL TO IDLE
15:09	15:11	:02	1	STARTED TO ACCEL THEN STOPPED RESIDUAL FUEL FIRE
15:26	15:27	:01	1	STARTED ACCELED TO IDLE SHUTDOWN
15:38	15:43	:05	1	STARTED WITHOUT ELECTRONIC CONTROL RAN
				UP TO 120% TORQUE 104.8% SPEED. PROPPELLOR
				WENT TRANSONIC AT 2960 RPM. COLLECTED
				PERFORMANCE DATA

SUMMARY:

Total Operating Time -0- hrs. 11 min.

Ref. Data Page

Total Manual Starts 18

Total Automatic Starts -0-

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QUALIFICATION TEST LOG

ACCT. No. 9122.001	**Date** 8/29/93	**Test Fac.**
Assembly No.	**Model** M-DOT TURBOPROP	**Unit Serial No.**
Engineer J. SHERBECK	**Technician** O. SHRIENER	**Supervisor**
Test Type CONTROLS	**Customer** DARPA	**Build No.** 2

Start Time	Stop Time	Hours	Starts	REMARKS
12:45	12:52	:07	1	started engine handed control over to
				electronic control with N_2 integrator
				disabled still exhibited instability
				aft brg temp shutdown. (230F) Reduced
				Gearbox regulator pressure to increase
				N_1 cooling.
				Start w/o electronic control to see
1:17	1:19	:02	1	if N_1 speed indicates properly
				brg temp shutdown 240F
				~~start without 180° turn on~~ JS
2:22	225	:03	1	added extension to 180° turn on inlet to
				prevent recirculation started brg
				temp S/D - T/K was rubbing
				group - removed T/K

SUMMARY:

Total Operating Time -0- **hrs.** 23 **min.**

Total Manual Starts 21

Total Automatic Starts -0-

Ref. Data Page

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QUALIFICATION TEST LOG

ACCT. No. 9122.001	**Date** 8/30/93	**Test Fac.** PORT. TEST STAND
Assembly No.	**Model** M-DOT TURBOPROP	**Unit Serial No.**
Engineer J. SHERBECK	**Technician** D. SHREINER	**Supervisor**
Test Type CONTROLS/PERFORMANCE	**Customer** DARPA	**Build No.** 2

Start Time	Stop Time	Hours	Starts	REMARKS
1:22	1:27	:05	1	N_2 loop proportional gain decreased
				by factor of 2½ - mild oscillation
				of N_2 S/D due to air comp. droop to
				75 PSI - readjust low reg setting
1:57	2:08	:11	1	RUN TO verify control stability
				and get SFC DATA engine started
				to make unusual noise manually
				shutdown.
		8/30/93		1:50PM P 29.85
				94F

SUMMARY:

Total Operating Time -0- **hrs.** 39 **min.**

Ref. Data Page ____________

Total Manual Starts 23

Total Automatic Starts -0-

ENGINEERING ____________