HYDRAZINE MONOPROPELLANT RECIPROCATING ENGINE DEVELOPMENT

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ABSTRACT

A hydrazine-fueled piston-type engine for providing 11.2 kW (15 hp) has been developed to satisfy the need for an efficient power supply in the range from 3.7 to 74.6 kW (5 to 100 hp) where existing non-air-breathing power supplies such as fuel cells or turbines are inappropriate. The engine was developed for an aircraft to fly to 21.3 km (70 000 ft) and above and cruise for extended periods. The NASA Hugh L. Dryden Flight Research Center developed a remotely piloted aircraft and the associated flight control techniques for this application. The engine is geared down internally (2:1) to accommodate a 1.8-m (6 ft) diameter propeller. An alternator is included to provide electrical power. The pusher-type engine is mounted onto the aft closure of the fuel tank, which also provides mounting for all other propulsion equipment.

About 20 hr of run time have demonstrated good efficiency and adequate life. One flight test to 6.1 km (20 000 ft) has been made using the engine with a small fixed-pitch four-bladed propeller. The test was successful in demonstrating operational characteristics and future potential.

BACKGROUND

Hydrazine (N_2H_4) is finding increasing acceptance as a non-air-breathing energy source for applications in which the complexity of using two reactants is prohibitive. Examples include many satellite rocket systems, aircraft emergency power units, undersea buoyancy systems, and as a primary energy source for the Space Shuttle flight control system. These applications have evolved because of the fundamental characteristics of high energy content and easy conversion of the liquid hydrazine, as a monopropellant, into hot gas at a temperature of approximately 1200 K (1700 deg F). However, very little work has been done on systems in the range of 7.5 to 37.3 kW (10 to 50 hp).

CONCEPT SELECTION

After the industry had been surveyed and several proposals had been considered, the "mini-sniffer" aircraft (fig. 1) was almost dropped as being beyond the scope of the available funding. The battery/motor approach for powering the mini-sniffer lacked high-energy capability and low-weight characteristics needed. The turbine machines lacked efficiency and the throttleability required. It seemed that some sort of hot-gas expander of the positive displacement type would fit the application and result in cost-effective system. Hydrazine was attractive as the fuel, because of its high energy content.

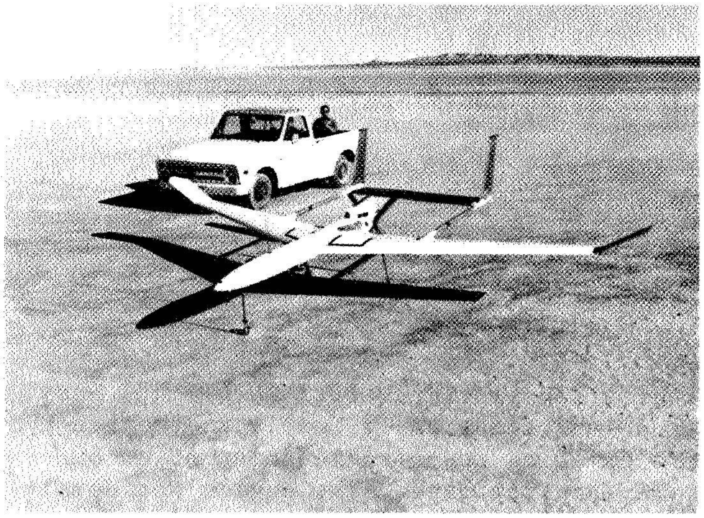

Figure 1.- The "Mini-Sniffer" aircraft.

The basic objective of the mini-sniffer aircraft is to fly an 11.3-kg (25 lbm) air sampler unit to an altitude of 21.3 km (70 000 ft) or higher and maneuver it within a 370-km (200 n. mi.) range. Preliminary studies indicated that this objective could be accomplished with a vehicle having a wingspan of approximately 5.5 m (18 ft) and a takeoff weight of less than 90.7 kg (200 lbm). The climb power required was on the order of 11.2 kW (15 hp), the cruise power was approximately 2.2 kW (3 hp), and the fuel consumption was in the range of 1.01 kg/MJ (6 lbm/hp-h). (The theoretical minimum for hydrazine is approximately 0.59 kg/MJ (3.5 lbm/hp-h).) The configuration required a pusher propeller with a diameter of approximately 1.8 m (6 ft). A variable-pitch unit enabled the choice of a constant-speed engine.

DESIGN ANALYSIS

Power Level

An iteration of power level as a function of total propellant required was the first analysis performed. A high power level (22.4 kW (30 hp)) minimized the run time to reach altitude and, thereby, minimized fuel consumption. However, the large engine more than offset the hydrazine weight saving. Conversely, a smaller engine caused increased run time, which caused additional weight of hydrazine to be carried. The choice of 11.2 kW (15 hp) provided the minimum overall weight and was operationally consistent with ordinary airplanes; i.e., no vertical flight. An energy level of 26.85 MJ (10 hp-h) was established to fly the desired air-sampling mission.

Expansion Ratio

A second analysis was performed to determine the best choice of displacement for the engine. A large-displacement engine, operating at 11.2 kW (15 hp) output, could reduce the hydrazine required by increasing the expansion energy. Conversely, a small-displacement engine could minimize engine weight but would be less efficient in converting the hydrazine decomposition gases into shaft power. A trade study indicated that an intermediate size with an expansion ratio of approximately 5.5 to 1, using a total displacement of approximately 131 cm^3 (8 in^3), was near optimum. This value provided a theoretical specific fuel consumption (SFC) of 0.73 kg/MJ (4.337 lbm/hp-h). Assuming a loss of 2% due to gas leakage, 7% due to heat leakage, 10% for mechanical loss, and 7% to run the fuel pump, the oil pump, and the alternator (72% overall efficiency), the SFC would be approximately 0.99 kg/MJ (5.85 lbm/hp-h). The total of engine and fuel weight varied about 50% between the extremes considered. However, for any normal operating pressure and efficiency, the trade was only affected by approximately 20%, or 9.1 kg (20 lbm), which made the final selection somewhat insensitive to displacement.

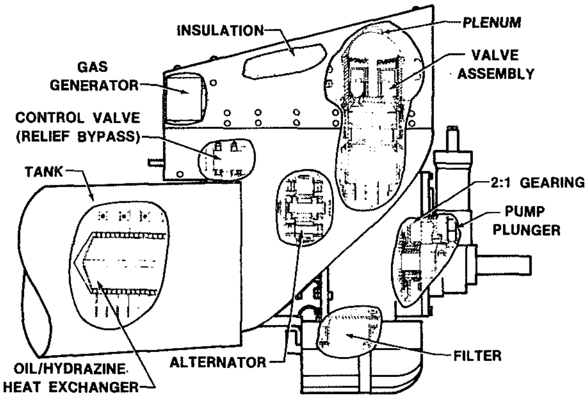

Figure 2.- Engine cross section.

SYSTEM DESCRIPTION

The description of the engine includes mechanical and electrical design, oil circuit design, and fuel circuit design.

Mechanical and Electrical Design

The mechanical arrangement is shown in its final form in figure 2. The assembly is mounted to the aft end of the aircraft fuselage by eight radial bolts and two tabs that attach the trailing edges of the wings. It weighs 17.3 kg (38.1 lbm) including the tank but excluding the propeller. The engine mechanism is conventional and uses elements typical of many small two-stroke engines of similar power output.

The alternator is mounted adjacent to the forward end of the crankshaft by a set of four fingers, which are a part of the crankcase. A clamp holds the fingers against the outside of the alternator stator to provide a friction-force retention. The magnesium crankcase also serves as a path for heat rejected from the alternator stator. Permanent magnets are used to provide the alternator flux field. Eight rare-earth magnets are mounted on the rotors on each end of the alternator and are rotated at engine speed with a coupling using dowel pins for the drive mechanism.

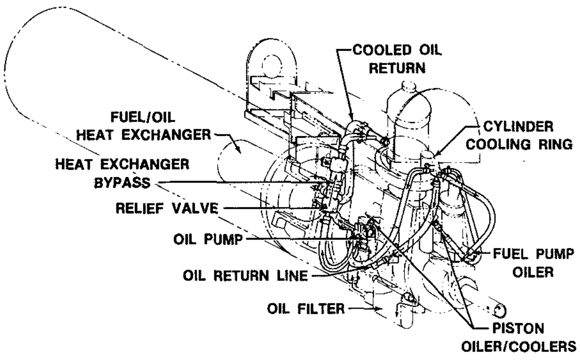

Figure 3.- Oil distribution system.

Oil Circuit Design

The oil circuit is shown isometrically in figure 3. It is designed for both lubricating and cooling and uses 5606 hydraulic fluid with a 3% by weight molybdenum disulfide additive. The system will operate satisfactorily with an oil quantity as low as 200 cm^3 or as high as 800 cm^3. The oil that is sprayed onto the underside of the piston for cooling also provides cylinder lubrication. The oil splashes through eight 0.102-cm

(0.040 in.) diameter holes in the piston wall just below the top ring. The holes are in line radially with the bridges between the exhaust ports in the cylinder. The holes in the piston also enable pressurization of the sealed crankcase and prevent cavitation of the oil pump in vacuum operation. Normal piston ring leakage goes into the crankcase during the top part of the piston travel, and oil flows out through the holes during the lower part of the piston travel. The lower ring spreads the oil on the upstroke and wipes the oil splashed on the lower cylinder back into the crankcase on the downstroke. The average crankcase pressure is approximately 13.8 kN/m^2 (2 psia) during vacuum operation.

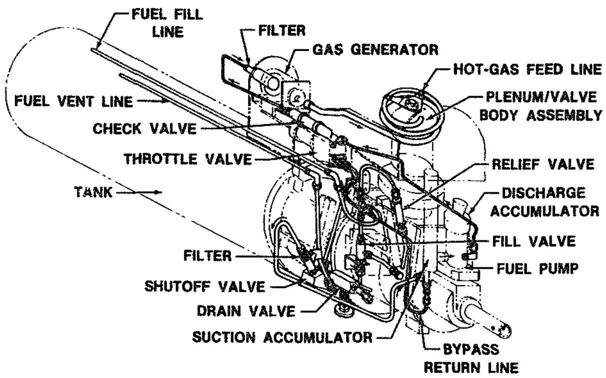

Figure 4.- Fuel piping system.

Fuel Circuit Design

The fuel circuit is shown in figure 4. The hydrazine is chemically unstable and requires special handling to avoid excessive pressure buildup due to decomposition and/or possible detonation, especially where the hydrazine is used as a heat-transfer fluid. The fuel transfers heat from the submerged lubricating oil heat exchanger to the surface of the tank.

The fuel system is fundamentally simple in that the hydrazine is pressurized with a plunger-type pump and the pressure is regulated with a controllable relief valve. The pressurized hydrazine is decomposed in a catalyst bed to generate hot gas to run the engine. However, the elements for safety, servicing, and draining add considerable complexity.

A suction accumulator supplies fuel to the pump intermittently on demand from the pump plunger; by this means, the flow from the tank is stabilized. A trap is built into the lower end of the suction accumulator to keep the gaseous bubble "spring" from passing into the pump. The proper bubble size is loaded as a part of the servicing. The system will not work with continuous negative gravity but will work with intermittent negative gravity.

The fuel pump uses a scotch yoke actuator mechanism and reed-type check valves. It pumps approximately 0.361 cm^3 (0.022 in^3) per revolution using a 0.953-cm (0.375 in.) bore. The reeds are fitted with a curved backstop to avoid overstressing. The steel plunger runs in a bronze bushing to provide proper alinement with the pumping cylinder. The plunger has a stainless steel cap which operates in a stainless steel cylinder with about 0.008-cm (0.003 in.) clearance. The bronze bushing fits close enough to the steel plunger to prevent contact between the stainless steel elements. An O-ring made of ethylene propylene rubber backed up by a tetrafluoroethylene insert acts as the plunger seal for the hydrazine. A second seal, below the stainless section, holds the oil in the pump case. A vent between the seals to the overboard relief valve prevents any leakage from either side from entering the other system.

A high-pressure accumulator is built into the pump body and connected to the discharge port. The piston-type accumulator has redundant O-ring seals and a nitrogen charge for a spring. A conventional charging-type check valve is used for charging the nitrogen, and a strain gage is mounted on the side of the accumulator for monitoring the nitrogen charge pressure.

The pressurized hydrazine flows through 0.318-cm (0.125 in.) tubing to the throttle valve, which is basically a relief valve with a controllable setting. At the idle position, the relief valve spring has enough tension to hold approximately 2068 kN/m^2 (300 psig). Any fluid in excess of the amount that will go through the engine at 2068 kN/m^2 (300 psig) is bypassed back to the suction accumulator through a 0.318-cm (0.125 in.) line. At full throttle, the throttle actuator compresses the relief valve spring by way of a push rod to hold approximately 5860 to 6205 kN/m^2 (850 to 900 psia) in the high-pressure section. To prevent oscillations in the spring/plunger mechanism of the throttle valve, a viscous damper is installed on the plunger. The damper is charged with oil (hydrazine-compatible polyalkaline glycol) with a viscosity of approximately 0.001 m^2/sec (225 Sus), providing a slow response to avoid engine speed oscillations.

A check valve is installed just downstream of the throttle valve in the liquid line to the gas generator to prevent backflow from the engine/gas generator into the fuel feed system. A 0.318-cm (0.125 in.) tube connects the feed system to the inlet of the gas generator through an inlet filter. The filter minimizes the possibility of catalyst from the gas generator entering the liquid feed system and causing decomposition and overpressures or detonations.

The gas generator is a catalyst type normally used on a small rocket engine. It was selected for its availability, not its design. The proper design for this application is a thermal-type gas generator having an almost unlimited life. The catalytic gas generator functioned satisfactorily, however, in converting the liquid hydrazine into hot gas as required.

The hot gas is piped across the engine-mounting interface through a 0.953-cm (0.375 in.) Hastelloy B (high nickel-chromium alloy) tube welded at each end. This tube circles twice around the hot-gas plenum on the engine to provide sufficient flexibility to minimize stress. The last loop of tubing is loosely restrained by a bracket joined to the plenum to minimize low-frequency, high-amplitude vibrations.

The plenum holds approximately 49 cm^3 (3 in^3) of hot gas, awaiting opening of the hot-gas valves. As the valves open, an additional 16-cm^3 (1 in^3) volume is provided in the cylinder, resulting in a rapid drop in plenum pressure to about three-fourths of the plenum charge pressure. After the valves close, the plenum repressurizes and the gas charge in the cylinder expands to push the piston to do work.

The hot-gas valves and associated hardware (fig. 5) are actuated open to approximately 0.064 cm (0.025 in.) by the piston as it reaches the top end of its stroke. To prohibit the valves from bouncing off the piston and lifting open more than they should, a cup-shaped foot seals a cavity between the valve and the piston. As the cylinder pressure rises, a clamping force develops. This pressure force holds the poppets against the piston as the piston goes

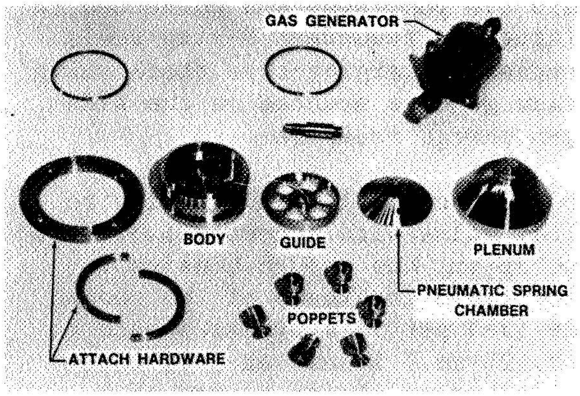

Figure 5.- Valves, plenum, and gas generator.

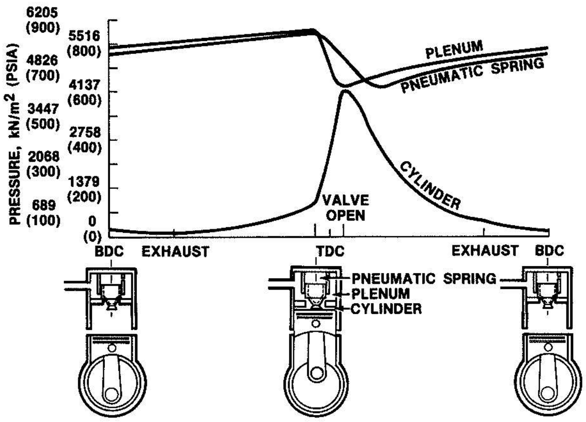

Figure 6.- Plenum pressure vs crank angle.

over top dead center (TDC). A pneumatic spring in the plenum helps hold the poppet against the piston and holds the valve closed as the piston pulls away from the poppet. The pneumatic spring is a small volume of gas trapped in a cavity behind the valve poppet and sealed by the valve guide as shown schematically in figure 6. The cavity is pressurized by the plenum and is sealed sufficiently by labyrinth-type seal glands to maintain the pneumatic spring pressure above plenum (and cylinder) pressure during the cylinder filling time, the closing part of the poppet motion, and for a period afterward. This pressure difference keeps the poppet from bouncing open after it seats. The piston velocity at the time of initial contact and during closing of the valve is low enough to avoid impact damage. The operation of the valves and the associated pressures are shown in figure 6.

Finally, the expended hot gas is vented to the atmosphere through eight exhaust ports at the lower end of the cylinder and ducted through a pair of short exhaust stacks - one out each side of the cowling. The fuel system also includes a tank drain valve, a fill tube, a vent tube, and an overboard relief valve.

TESTING

The testing is discussed in three parts: (1) component evaluation tests (pumps, valves), (2) engine evaluation, and (3) flight test.

Component Evaluation

The early tests were directed at establishing acceptable component performance and component configuration so that the integrated system design could proceed.

Fuel pump. Testing of the fuel pump resulted in several refinements. Early tests were performed with water. The results demonstrated the need for the accumulators and a controlled flexure of the reed valve. The pump will produce a discharge pressure of 6895 kN/m^2 (1000 psi) at the flow required for 11.2 kW (15 hp) output with a 13.8-kN/m^2 (2 psia) inlet pressure and operation at 314.2 rad/sec (3000 rpm). The output pressure is steady within approximately 414 kN/m^2 (60 psi) using an orifice for flow control (simulation of the gas generator). In the approximately 20 hr of testing accumulated on the pump, the only problem was with particulate contamination under the reed valve. This contamination resulted in the addition of the filter at the outlet of the tank shutoff valve just upstream of the pump inlet. Momentary operation at pressures near 34 474 kN/m^2 (5000 psi) were observed without damage to the pump.

Hot-gas valving. Early tests of the hot-gas valves were done using a modified two-cycle engine. The results were very disappointing and indicated the existence of a very severe environment. Hammering was immediately evident even in tests using cold gas as a working fluid. It was apparent that the piston could potentially cause damage to the poppets during opening but not to the seat during closing, and the seats sustained the most damage. The valve was apparently being closed by the flowing gas, and the first design change was to reduce the opening lift to maintain enough pressure drop across the valves to force valve contact with the piston at all times. This modification severely reduced the power of the engine and increased the required feed pressure. At slow speeds, the pressure equalized anyway, still allowing the "float" situation and an uncontrolled gas-flow-induced closure of the valves.

The next modification was to make a suction cup on the stem of the valves such that, as the cylinder was pressurized, the pressure differential across the cup or valve "foot" would hold the valve onto the piston as outlined previously. This change gave tremendously improved life and performance, but the data relating gas pressure and output torque were still inconsistent and unpredictable. At this point, it was decided to instrument the cylinder pressure to see exactly what was happening. It became apparent that the valve poppet - once released from the hold of the suction cup - was bouncing off the seat very momentarily, admitting additional working fluid. The amount of extra fluid admitted was a function of speed and throttle setting.

Because the bouncing effect was not causing significant damage, there was a great temptation not to worry about it. The power could be adjusted with the throttle in any event. However, the bouncing could be expected to result in a somewhat reduced efficiency because the gas admitted late would not expand as much as planned. Because efficiency is very important for the application involved, a design change was considered.

Various concepts of antibounce mechanisms were evaluated analytically. Mechanical spring arangements considered lacked sufficient response to track the motion and could not apply an appropriate valve-closing force. Finally, the idea of a "pneumatic" spring evolved as outlined in the preceding design discussion. The pneumatic spring cavity "consumed" some of the plenum volume in an early version requiring extra feed pressure but produced repeatably good results. In the flight version, plenum volume was increased sufficiently to house the pneumatic spring and to feed the working chamber without excessive pressure drop.

The high efficiency achieved in tests of the flight engine evidences very little valve leakage. The most common problem with the valves was contamination of the seal area with particles from the gas generator. In runs using a new gas generator, which produced few particles, the performance was near the theoretically expected levels.

Other tests. The alternator was tested extensively on the workbench. Several sets of stator windings were tested in an effort to achieve the rated 4-A current at as wide a speed range as possible. The only significant problem was with the pin drive, and the diameter of the pins was increased from 0.318 to 0.635 cm (0.125 to 0.25 in.).

The throttle valve was tested extensively in both water and methyl alcohol before it was committed to use with hydrazine. The throttle valve is probably the only part that functioned entirely satisfactorily as designed and fabricated the first time. It required only the appropriate shimming and adjustment. An improved version might be built with a steeper angle on the poppet seat or a longer spring to reduce the effect of flow variations on the pressure setting.

The oil pump tests were uneventful. However, the pump, a gear-type unit in an aluminum case, is prone to generation of particulate contamination and could be improved in that respect. Pump flow is 3.8 liters/min (1 gal/min) at 209.4 rad/sec (2000 rpm). It is about 85% efficient at 517-kN/m^2 (75 psi) discharge pressure. About 10% losses are due to leakage and about 5% to drag effects.

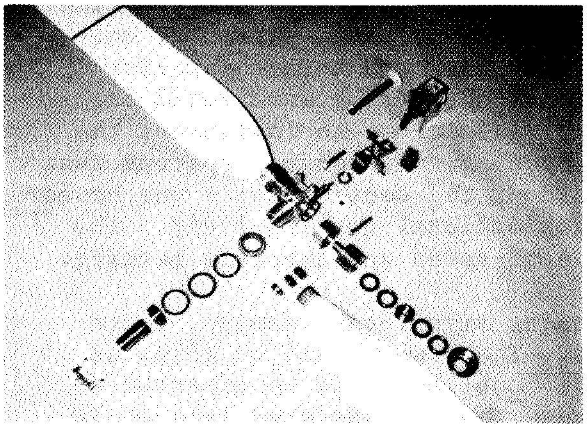

Figure 7.- Propeller assembly.

Performance testing of propellers and propellers in general was a problem in the program. The large, low-speed units required for this application require an extra degree of precision in manufacture to provide the same effective lift on both blades to avoid excessive vibration. The propeller being developed at the NASA Hugh L. Dryden Flight Research Center (DFRC) for ultimate use on the mini-sniffer is shown in figure 7. It is ground controllable in the same way as the throttle setting. Testing of this unit had not begun at the time of this writing.

Engine Assembly Tests

All the flight engine assembly testing was done on the stand arrangement shown in figure 8. Various loads were simulated by using different propellers. Most testing was done at sea level, with some high-altitude testing. Measurements were primarily of the slow-response type using the meters shown, except for the high-speed measurements of cylinder pressure and pump discharge pressure mentioned previously. The data were recorded on film in the form of meter readings.

The testing was done at the NASA Lyndon B. Johnson Space Center thermochemical test facility primarily by support contractor personnel. The

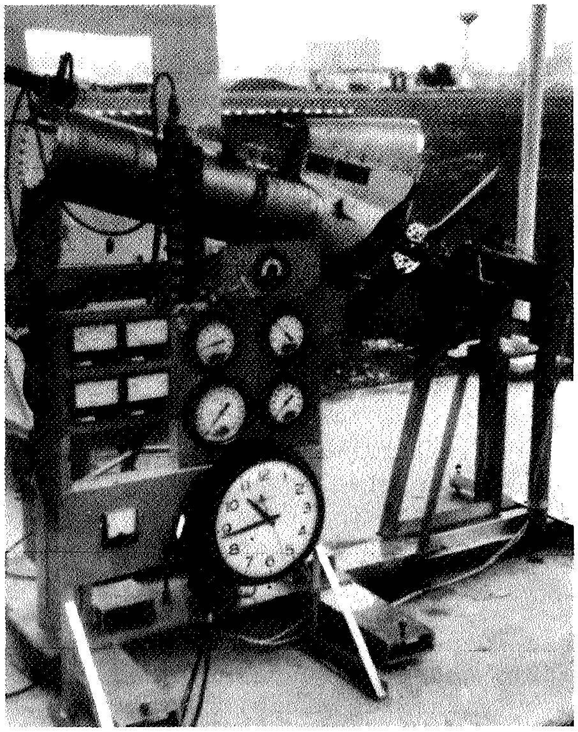

Figure 8.- Flight engine test stand.

secondary-priority nature of the work, behind Space Shuttle and other ongoing programs, and continuous redesign activities extended the testing over about 2 yr. The test stand was designed primarily to minimize interface with the facility data and control systems such that tests could be run on short notice whenever a schedule opening occurred. This configuration provided a very appropriate environment for experimental testing in which intermittent activity is caused by modifications and rework.

Only two controls were used: (1) the electric-motor-operated throttle and (2) a supplemental vent valve that positively vented the fuel pump discharge pressure back to the tank and simultaneously vented the fuel tank pressure.

The data for engine speed, feed pressure, and fuel level are shown in figure 9 for a 17-min, 638.79 ± 10.47-rad/sec (6100 ± 100 rpm) run (11.19 kW (15 hp)). It should be noted that the engine required approximately 1 min to heat the gas generator and the plenum. At about 60 sec, the throttle was

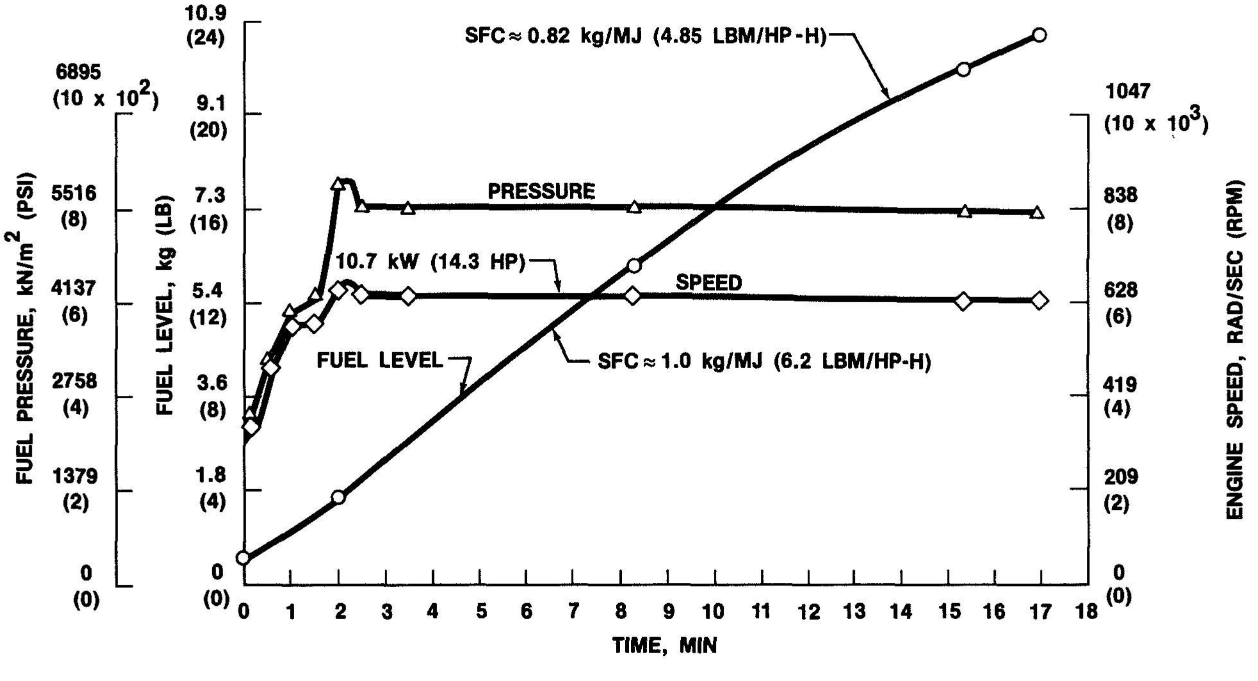

Figure 9.- Speed, pressure, and fuel level vs time for 17-min run at 628.32 rad/sec (6000 rpm) with small four-blade propeller.

advanced to full power, which resulted in slightly more than desired pressure at the 2-min point. The throttle was reduced slightly, and the power level stabilized approximately 150 sec into the run. The run was essentially steady for the duration and was terminated because of oil depletion. One significant aspect of this run, the improvement in efficiency as the run progressed, is apparently the result of steadily decreasing windage as the oil is lost and/or stabilization of the temperature of the hot-gas section occurs. The flight configuration was modified to include an oil baffle in the crankcase to reduce windage.

The heat leak through the Inconel piston cap is apparently minimal. No evidence of oil coking in the piston ring groove or on the bottom of the piston dome was observed, an indication that the operating temperature of the unit was less than 422 K (300 deg F). The stainless steel piston cap generally produced a straw color on the back side indicative of a temperature of approximately 589 to 700 K (600 to 800 deg F). The steel exhaust manifold showed no evidence of excessive heating, indicating that the flow of cooling air maintained a temperature below 533 K (500 deg F). It did get hot enough to coke oil, however.

Several interesting data points were taken in unusual circumstances, especially when the oil was lost and piston seizure caused a sudden stop. (Most oil losses were by way of broken lines caused by excessive propeller vibration.) Under this condition, liquid hydrazine is trapped between the check valve and the hot-gas generator. Typically, the shutdown would occur with the pressure at 5515.8 kN/m^2 (800 psi). In these cases, the pressure would slowly decrease to about 2758 kN/m^2 (400 psi) over a 30-min period. During this time, the only escape of gas is past the hot-gas valves and the piston rings. It is this condition that should provide the environment necessary to produce overpressurization of feed system hydrazine; however, it never occurred.

Apparently, the slow leakage past the valves and the piston was enough to vent the decomposition products as they were being generated by heat soak from the gas generator back into the feed tube. The feed tube into the gas generator is a comparatively heavy piece of aluminum into which the inlet filter is fastened. This element can apparently reject heat as rapidly as it soaks out of the gas generator to maintain a safe hydrazine temperature. The highest temperature measured at the gas generator inlet under these circumstances was about 366 K (200 deg F).

Another interesting occurrence documented some safety margin in the system. Excessive valve leakage caused ignition of the exhaust gases at a temperature of about 866 K (1100 deg F). Subsequently, several of the cloth and rubber oil lines just under the exhaust manifold ignited. The engine was shut down, but the fire continued and resulted in considerable heating of the hydrazine pump. Essentially all the combustible material in the engine cowl burned, but the hydrazine was not heated sufficiently to cause overpressurization. New oil lines were installed, the hot-gas valves were repaired, and the testing was continued.

On several occasions, hydrazine leaks occurred; however, no ignition resulted, even though the liquid and vapor were sprayed through the exhaust. This leakage also occurred in flight without incident. Of course, leaking hot-gas valves (which dump 1200-K (1700 deg F) unexpanded gas out the exhaust) combined with a hydrazine leak would probably result in a fire, but that combination of problems never occurred.

One of the major problems in verifying the flight configuration was establishing the proper size holes in the piston to provide sufficient cylinder oiling without excessive loss of oil through the exhaust. The decision to fly a "demonstration" test using a fixed-pitch propeller complicated the situation because it demanded operation from about 419 rad/sec (4000 rpm) to 628 rad/sec (6000 rpm) during the climb. Holes that lubricated sufficiently at 419 rad/sec (4000 rpm) were insufficient at 628 rad/sec (6000 rpm). Conversely, holes that oiled sufficiently at 628 rad/sec (6000 rpm) passed oil excessively at 419 rad/sec (4000 rpm). A compromise could probably have been worked out; but, as the flight time approached, the only test catalyst bed available was shedding many particles, causing valve leakage, producing excessive heating, and shadowing the results. As a temporary solution for the one test flight, a special oiler was added having four separate injectors powered by a small electric motor. This system injected upper cylinder lubricant into the engine just downstream of the valves through small (0.033-cm (0.013 in.) i.d.) steel tubes. A final test run verified good performance, and the test injector was installed on the aircraft for lack of a new unit.

Flight Test

The new engine for the test flight passed all the checkout criteria with a good margin. Although a static test of the new engine before flight would have been desirable, the fact that the gas generator was seriously life limited together with the schedule and man-hour limitations prohibited a static test run.

The vehicle was checked out and serviced at DFRC the night before the flight. It was carried about 8 km (5 s. mi.) across the dry lake the morning of November 23, 1976. A final communication link checkout was made, the tank was pressurized to 413.69 kN/m^2 (60 psia), and the upper cylinder oiler was turned on. At about 9:30 a.m., the engine was started and the flight was begun. The same basic engine parameters were monitored in the ground telemetry van as were monitored in the development tests. Engine pressure and speed increased normally as the aircraft taxied for takeoff. The aircraft lifted off much the same as it had many times before using a chain-saw engine. About 20 sec into the climbout, however, the fuel feed pressure dropped suddenly and the power sagged; then, almost as suddenly, the power increased again. The first thought was that a bubble passed through the hydrazine pump.

The climbout continued, and a right turn was performed as planned. Within about 5 min into the flight, it became apparent from the climb rate that the power was a little less than expected but within the estimated tolerance. However, within 8 to 10 min, it appeared that the power level was out of tolerance on the low side.

About 25 min into the flight, the throttle was advanced in an effort to obtain more power, but this setting caused the power to decrease still further, even though the pressure increased properly. Since the pressure was then dangerously high (near 6550 kN/m^2 (950 psi), the upper maximum allowable), the throttle was decreased slightly. The power increased appreciably. When the power increased, the climb began again but still at a less than desirable rate. At about 30 min into the flight, the fuel tank pressure was indicating near depletion of the fuel.

The slow climb proceeded to near 6.1 km (20 000 ft) at 34 min, when fuel feed pressure became slightly intermittent; the pressure dropped, the engine speed dropped, and the run was finished. The pilot, located in the base tower about 8 km (5 s. mi.) away, nosed the plane over, set the throttle to "cff," and began the long glide down. About 30 min later, the vehicle landed on the dry lake near the takeoff point. The tank still had the same low pressure (about 13.8 kN/m^2 (2 psia)). The engine windmilled at about 189 to 209 rad/sec (1800 to 2000 rpm) all the way down because of the fixed-pitch propeller. The gas generator and all other components were at ambient temperature on landing.

The retrieval crew noticed almost immediately that the finish was removed from the propeller blades in an area about 15 cm (6 in.) from the hub. It was apparent that a strong solvent had rinsed the finish off. Approximately in line with the area, the hydrazine pump discharge fitting was found to be loose. There were no other indications of any problem with the engine at that time.

The craft was carried back to the checkout/servicing area and flushed with methanol; the loose fitting was verified as the source of a leak. The engine was disassembled to evaluate the condition of the hardware and to determine the cause of the low power and the inverted throttle response. No external leaks were found in the high-pressure hot-gas section, but one of the small oiler tubes was broken where it connected to the engine. Also, the valves and seats were somewhat brinelled. The piston and rings appeared normal and had no measurable dimensional change.

The liquid hydrazine leak could not account for the power reduction because it was small enough to be automatically correctable by the throttle valve. The momentary power sag during the takeoff had the characteristic timing of the throttle valve response. Also, because the pressure increased and was maintained during the flight, this leak was not the cause of the power sag. The valve damage observed (brinelling) was apparently the result of windmilling the engine with hot valves during the glide down (without the pneumatic springs operating). This problem will be eliminated with the new controllable-pitch propeller, stopping the engine after the run by going slightly past the feather point. The leak resulting from the fracture of the upper cylinder oiler tube (0.033 cm (0.013 in.) i.d.) was insufficiently large to be significant and very likely occurred on the way down since there was no evidence of any hot-gas leakage. There simply was no immediate explanation of the power reduction during the flight, or of the inverted throttle response.

The two possible explanations of the flight anomalies are fuel feed blockage and/or mechanical reduction of valve lift. The fuel system was verified to be open in the process of system flushing after flight. However, the new engine could possibly have readjusted itself mechanically during its first run to effectively reduce the valve lift. Actually, this self-adjustment was expected, because it occurred to some extent on the test engine but not to the degree that apparently occurred during flight. The lift was set at 0.069 cm (0.027 in.) during assembly, 0.005 cm (0.002 in.) more than normal in the development engine. This adjustment was made to allow for "set" in the new three-piece crankshaft, run-in of the new bearings, and any other deflections which might affect the lift adversely. However, behavior of the flight engine in the final minutes of operation was similar to that of the development engine with low-valve-lift setting. With the valve lift near 0.030 cm (0.012 in.), higher pressure causes structural flexure and additional reduction in lift, which reduces both the flow area opened by the valves and the time for flow. Conversely, reduced pressure reduces structural deflection and thereby increases the area-time integral, which increases flow and power. The valves were deformed just enough by windmilling during descent to prohibit a good indication of whether valve-lift reduction actually happened, but it seems reasonable.

The flight test demonstrated the operational characteristics of a hydrazine-fueled non-air-breathing aircraft engine. The flight produced no complications or other unforeseen problems. With appropriate precautions, the system can be handled with little more time and effort than any other power system. Although the fluid is toxic, it requires a cumulative exposure to be seriously dangerous, barring excessive exposure. The most dramatic hazard is of course a fire, but the fluid - having relatively low vapor pressure - is not easily ignited. The possibility of detonation of the hydrazine is practically eliminated by proper design to keep the fuel cool (below about 366 K (200 deg F).

CONCLUSIONS

The valving concept has been demonstrated and is being patented, but the work required to optimize the performance of the valving concept for any specific application still must be done. The design for the best choice of seal perimeter, lift height, poppet length (for elastic deformation on contact with the piston), seal width, pneumatic spring volume, guide clearance and tolerances, and material choice for guide, seat, and poppet can only be established through analysis and considerable testing.

Any vapor or hot-gas expander-cycle machine can utilize the valving concept. A steam engine is a good example. The low-weight, simple, positive mechanism involved can make it a candidate for mobile applications. However, the valving concept may be limited to applications in which the engine always drives the load. In that case, the pneumatic springs are always pressurized and the valves will not float as they did during the downward glide in the flight test. However, if valve floating occurs at a sufficiently low speed and/or temperature, it may cause no problem. Also, depending upon the temperature and speed involved, a mechanical spring might be added to supplement the pneumatic spring for eliminating the floating operation. The most significant improvement for the concept might be the use of a thermal-type gas generator (one that does not shed particles into the engine). The technology is available, but the design details must be resolved and the hardware developed. A gas generator that mounts on the valve plenum, eliminating the hot-gas delivery tube, would also be a significant improvement. An appropriate thermal-type gas generator could withstand the vibration environment of the engine, and its volume and weight could be combined with that of the plenum.

It appears that the most promising direction for optimizing the concept is to strive for higher pressure ratios across the engine (plenum to ambient); by this means, the theoretical work produced by the engine is maximized and the size required in the plenum and valving is minimized. The only offsetting effects are the leakage across the valves during the closed portion of the cycle and extra mechanical loading during opening. The results to date indicate, however, that these problems should not be serious, and pressures as high as 20 684 kN/m^2 (3000 psi) might be used.

Also, the use of very large bore to stroke ratios (2.0 or greater) should prove attractive because very large valves can be used and correspondingly smaller lifts. This technique enables an increase in engine speed with corresponding decrease in size and weight. It also enables building a stiffer engine mechanism so that higher pressures can be used. If the engine weight is reduced, the optimization of displacement and expansion ratio outlined in the design discussion is driven toward larger expansion ratios, which result in a more efficient overall design.

A mathematical model constructed to encompass all aspects of the engine operation and design will enable quick, easy optimization for any particular application. Testing of various designs as they evolve will refine the model. Hot-gas and vapor-cycle expanders using low-grade heat are finding increased applications because of the continued changes in the basic energy supply. This engine concept offers one additional design alternative for power system selection; its mechanical simplicity provides good economic viability.