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STATE OF TECHNOLOGY ON HYDROGEN FUELED GAS TURBINE ENGINES

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ABSTRACT

A series of investigations was conducted episodically from the 1950's to the early 1970's to investigate the feasibility and potential problem areas in the use of hydrogen fuel for gas turbine engines. This report provides a brief summary and bibliography of the research that has been conducted by NASA, its predecessor NACA, and by industry under U. S. Air Force sponsorship. Although development efforts would be required to provide hydrogen fueled gas turbine engines for aircraft, past research has shown that hydrogen fueled engines are feasible and except for flight weight liquid hydrogen pumps there are no problem areas relating to engines requiring significant research.

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SUMMARY

A series of investigations was conducted episodically from the 1950's to the early 1970's to investigate the feasibility and potential problem areas in the use of hydrogen fuel for gas turbine engines. This report provides a brief summary and bibliography of the research that has been conducted by NASA, its predecessor NACA, and by industry under U. S. Air Force sponsorship. Although development efforts would be required to provide hydrogen fueled gas turbine engines for aircraft, past research has shown that hydrogen fueled engines are feasible and except for flight weight liquid hydrogen pumps there are no problem areas relating to engines requiring significant research.

INTRODUCTION

This report presents a survey of research that has been conducted by NACA, NASA and industry on evaluating the feasibility of using hydrogen as a fuel in gas turbine engines for aircraft. The first research that considered use of hydrogen as a possible fuel for gas turbine engines began in 1954 on combustors using gaseous hydrogen, ref. 1. In the following year a mission analysis report, ref. 2, indicated that some long range military subsonic and supersonic missions could be accomplished with hydrogen fueled vehicles that would not be possible with conventional kerosene fueled vehicles. Following the report of ref. 2, a series of NACA and NASA investigations was conducted on combustion, fuel pumps, controls, and engine demonstrations in both ground tests and in flight using liquid hydrogen as a fuel, refs. 3 to 25. During 1956 an experimental hydrogen fueled engine with an air-cooled turbine utilized heat exchangers to refrigerate the cooling air and at the same time vaporize the hydrogen fuel. This engine was operated at turbine inlet temperatures up to 1640 K (2935°R), ref. 16. At about that same time, Pratt & Whitney Aircraft was given an Air Force contract to convert a J57 engine to operate on liquid hydrogen, and satisfactory engine operation was obtained, ref. 26. In 1963, the General Electric Company operated a modified YJ85-5 engine with liquid hydrogen as a fuel, ref. 27.

During the 1960's a large amount of experience was gained in the handling and pumping of liquid hydrogen for space launch vehicles, and in the early 1970's consideration was given to providing hydrogen fueled gas turbine engines in the space shuttle to provide additional cross-range and ferrying capability. To provide verification of the feasibility of this approach, a NASA contract was let to General Electric Company in 1971 to modify a J85-13 to provide the most complete liquid hydrogen fuel system yet investigated. This engine had all of the components that would be required in flight operation. The results of this investigation are presented in ref. 28.

The purpose of the present report is to summarize and evaluate the results obtained in all of the above listed references (ref. 1 through 28), and to discuss the research or development required to provide hydrogen fueled gas turbine engines for flight applications. There are many other factors that must be evaluated when considering the use of liquid hydrogen in aircraft, such as hydrogen cost and availability, logistics of the fuel supply, safety, method of loading cryogenic fuel in aircraft, fuel storage within the aircraft, and the effects of large cryogenic fuel volumes on aircraft design and aerodynamics. The discussion in the present report will be limited to the effects of hydrogen fuel on the aircraft engine, and it will not discuss the other factors listed above.

HYDROGEN COMBUSTION

Experimental investigations on the combustion of hydrogen in gas turbine combustors are reported in refs. 1 and 3 through 13. Hydrogen is extremely easy to burn. It has low ignition energy, a heating value approximately 2 1/2 times that of kerosene fuels, and a wider range of flammable limits (from 13 to 250 percent of stoichiometric) than other fuels that have been used in aircraft engines. As a result there are no significant combustion problems. To capitalize on the burning properties of hydrogen, the combustors can be designed with shorter and leaner burning zones than for kerosene fuels.

The pollutants that are emitted from hydrogen combustors are significantly less than for combustors burning kerosene-type fuels. The idle emissions of carbon monoxide and unburned hydrocarbons normally experienced are completely eliminated by using hydrogen. Smoke is also eliminated. References 11 and 12 present results on the oxides of nitrogen that are generated. It was found that NO_x emission levels obtained with hydrogen and hydrocarbon fuels are similar on a volumetric basis for an equivalent enthalpy rise of combustion gases. Because lean combustion is possible with hydrogen, flame temperatures in future combustors can be reduced to approximately the combustor outlet temperature. As a result, further reduction in NO_x seems probable, but it is not clear that the NO_x emissions will be lower than for advanced low emission hydrocarbon fueled combustors.

To summarize: Combustion problems with hydrogen are minimal. New combustor designs could be developed to capitalize on the lean burning characteristics of hydrogen to reduce NO_x formation. All other pollutants are eliminated by using hydrogen as a fuel.

TURBINE COOLING

Hydrogen provides an ideal heat sink for cooling engine components. Liquid hydrogen should be vaporized prior to injecting it into the combustor. Hydrogen temperatures up to at least 811 K (1000°F) at the combustor fuel manifold are acceptable and desirable. This large heat sink for vaporization and heating is at least an order of magnitude greater than for liquid hydrocarbon fuels and it can be used profitably for refrigerating the cooling air used for turbine cooling. There will still be a large heat sink remaining for other cooling requirements, such as oil cooling, cabin air conditioning, etc. Refrigerated turbine cooling air can reduce the required amount of compressor bleed air by more than 50 percent in some cases as discussed in ref. 29. An illustration of just how effective reducing cooling air temperature can be, when carried to an extreme, is reported in refs. 15 and 16. In those tests the first air-cooled turbine engine was run with hydrogen as a fuel. The cooled turbine blades were of a nonstrategic steel alloy with a maximum temperature capability of approximately 920 K (1660°R). The cooling configuration was a crude, hand-built convection design. It was possible, however, to operate that engine at turbine inlet temperatures up to 1630 K (2935°R) by refrigerating the turbine blade cooling air to 217 K (390°R) at the blade base.

To summarize: Using part of the heat sink capacity of liquid hydrogen to reduce the temperature of turbine cooling air bled from the compressor could substantially reduce the coolant flow requirements with a resultant improvement in engine performance. This advantage must be balanced against the added complexity, and probably a reduction in reliability, of the fuel system containing hydrogen-to-air heat exchangers.

HEAT EXCHANGERS

Heat exchangers would be used in a hydrogen fueled engine to both vaporize the liquid hydrogen prior to injecting it into the combustors and to remove heat from engine oil and from the air used for cabin conditioning and/or turbine cooling. Because of the extremely low temperature of liquid hydrogen, special heat exchanger designs are required to insure that oil doesn't congeal or moisture from the air freeze within the heat exchangers. A novel and effective heat exchanger approach is reported in ref. 28. The heat resistance between the hydrogen and the air (or oil) is increased enough so that the outside (air or oil side) of the heat exchanger tubes is always in excess of 273 K (32°F). This high heat resistance is obtained by use of heat exchanger fuel tube assemblies consisting of two concentric tubes containing a stagnant layer of gaseous hydrogen in the annulus between the tubes. Such an arrangement was tested in ref. 28 on the air-to-hydrogen heat exchanger and it worked completely satisfactorily. The heat exchangers were light weight, compact, and in a configuration that could be wrapped around the engine. A similar type of concentric tube heat exchanger design has not been tested for cooling oil.

For temperatures above about 238 K (0°F) hydrogen embrittlement of the fuel system may be of concern. Some materials are much more susceptible to embrittlement than others. Among the materials least susceptible are the stable austenitic stainless steels. These materials would surely be satisfactory for reasonably short-time operation (hundreds of hours). Data are lacking, however on long time hydrogen embrittlement effects (in excess of 10,000 hours).

Other factors that must be considered with hydrogen fueled engines are the safety and reliability of hydrogen heat exchangers. There are many brazed joints, and in military engines, there will be a larger vulnerable area subject to battle damage. Hydrogen leaks could, in many cases, be disasterous.

To summarize: Technology is presently available for satisfactory thermal design of heat exchangers required for hydrogen fuel systems. Additional research is probably required on the long time effects of hydrogen embrittlement.

HIGH PRESSURE FUEL PUMPS

Suitable cryogenic fuel pumps have not, as yet, been developed for gas turbine engines. There is some evidence in references 23 through 26 that satisfactory engine operation can be obtained at fuel pressures less than the supercritical pressure of hydrogen (1.296×10^6 N/M^2 or 188.1 pounds per square inch absolute). In the investigation of reference 28, however, a supercritical pressure fuel system was utilized in order to avoid any possibilities of pressure oscillations in the fuel system resulting from two-phase flow in the heat exchangers. A pump was required that would supply supercritical pressure over a range of flows of at least a ratio of 20 to 1 between the highest and lowest flow. In a liquid hydrogen fuel system it is not possible to recirculate the fuel by means of a by-pass arrangement. The pump work adds heat and causes the recirculated fuel to become partially vaporized at the pump inlet pressures. Significant vapor at the liquid hydrogen pump inlet cannot be tolerated. The supercritical pressure and large turn-down ratio for the investigation of ref. 28 required the use of a positive displacement pump having either variable displacement or variable speed. Different pump configurations may be possible for other applications, particularly if the turn-down ratios are smaller or if subcritical pressures can be tolerated. In such cases a centrifugal pump may be satisfactory. Some considerations have also been given to a dual fuel pumping system that would utilize both a centrifugal pump and a positive displacement pump in parallel to obtain low flow rates with the positive displacement pump and high flow rates with the centrifugal pump. Experimental research has not been conducted to evaluate the suitability of systems containing centrifugal pumps for hydrogen fueled gas turbine engines with the requirement of a high turn-down ratio.

References 18 and 19 report on early research on a piston-type pump for liquid hydrogen for gas turbines. The mechanically driven pump was a "Gatling gun" type with 5 barrels or cylinders. The bore and stroke were 7.62 and 3.81 cm (3 and 1.5 inches). The pistons were driven from a mechanically driven wobble plate. The maximum speed was 240 rpm at a discharge pressure of 8.96×10^5 N/M^2 (130 pounds per square inch). Pump operation was considered satisfactory at these conditions. Some piston scuffing and ball joint problems were encountered. A successful flight test of this pump is reported in reference 25.

In the investigation of reference 28 an attempt was made to obtain a flight-weight liquid hydrogen pump with a discharge pressure of 2.76×10^6 N/M^2 (400 pounds per square inch) and a turn-down ratio of 20:1. The first pump to be investigated was a close-clearance vane pump driven by a variable speed hydraulic motor. Because of internal leakage, head rise and volumetric efficiency were inadequate to meet the pumping requirements. The pump that was utilized in the engine tests of reference 28 was an hydraulically driven, five piston "Gatling gun" pump. The bore and stroke were 2.54 and 2.82 cm (1.0 and 1.1 inches). Each piston was a long rod extending to a cylinder on each end. One end of the rod was the piston for the hydraulic drive (hydraulic motor) and the other end was the piston for the hydrogen pump. The five rods were attached to a nutating plate that synchronized the pistons and controlled the sequential oil flow to drive each piston. The maximum speed of the apparatus was equivalent to 1600 rpm. Such a pump probably cannot be considered to be a flight-type pump. For the J85 engine, the pump weighed approximately 14 kilograms and was approximately 1/3 meter in diameter and 2/3 meter long.

In the investigation of reference 28, engine tests were terminated at 85 percent speed because of inadequate pump performance, presumably from piston seal ring leakage, and eventual pump failure. Additional pump research and development will be required for aircraft use. A vane pump would be desirable if one can be developed with adequate volumetric efficiency for all required turn-down ratios.

To summarize: A satisfactory liquid hydrogen pump has not been developed that is suitable for aircraft gas turbine use. Positive displacement pumps capable of a large turn-down ratio are believed required, but there is some indication that centrifugal pumps could also be utilized.

HYDROGEN FUEL CONTROL SYSTEM

Experimental hydrogen fuel control systems are described in references 17, 24, 25, 27 and 28. The most sophisticated and complete fuel control system is reported in reference 28 and is illustrated in figure 1. In this system hydrogen was pumped in the liquid state; the hydrogen was vaporized as it passed through a heat exchanger that simulated one that could be used to refrigerate turbine cooling air; the hydrogen vapor then passed through a pressure regulator and into a vapor control valve that controlled the amount of hydrogen necessary for proper combustion. A three-way valve (shut-off, pass-through and dump) was placed between the control valve and the combustors to provide positive shut-off, system chill down, and hydrogen dump after engine shut-down or for emergency shut-down from over-speed or over-temperature.

The fuel pump was operated at a speed that resulted in a constant hydrogen pressure at the pump discharge. Integral with the pump was a variable speed motor as described in the previous section. Motor speed was determined by oil flow rate, which was obtained from an engine driven oil pump and metered by the engine controller. The pressure regulator downstream of the heat exchanger maintained a constant discharge pressure above the supercritical pressure. The temperature at the pressure regulator discharge was sensed (to determine hydrogen density) and fed into the engine controller. This input, along with throttle angle, engine speed, and turbine discharge temperature was used by the controller to set the vapor control valve area to provide the proper fuel flow to the engine.

Experience obtained with the fuel control system described above and in reference 28 showed that the gaseous metering used can be made acceptably stable and responsive for operation of a turbojet engine using liquid hydrogen fuel.

To summarize: The technology needed for a liquid hydrogen fuel control system has been demonstrated.

FULL SCALE ENGINE EXPERIENCE WITH HYDROGEN FUEL

Experimental engines have been tested with hydrogen as the fuel in sea level static stands, altitude test chambers, and in flight. Results of these tests are reported in references 7, 14, 15, 16 and 20 through 28. Tests were conducted on J47, J57, J65, J71 and J85 engine modified to operate with hydrogen fuel. The sea level static and altitude chamber tests of these engines (refs. 14 to 16, 20 to 23, and 26 to 28) showed that there were no significant problems with the engine operation or the fuel systems, and it was shown that there was a significant increase in the high altitude operational capability of hydrogen fueled engines. Reference 22, for example, showed satisfactory operation with JP-4 fuel at altitudes to 65,000 feet and operation with marginal combustion to 80,000 feet. With hydrogen fuel, the facility limit of approximately 89,000 feet was reached and the engine was still operating satisfactorily.

Flight tests were conducted at approximately 50,000 feet (refs. 7, 24 and 25). In all cases the J65 engines were modified for dual fuel systems to permit take-off and climb on JP-4 fuel and a short run at altitude on hydrogen fuel. This type of operation was necessary because of the limited fuel storage capacity for hydrogen in the aircraft. Initial tests were made with a pressure fed hydrogen system but later tests (ref. 25) were made with a pump fed system using the pump reported in reference 19. All flight tests were satisfactory and demonstrated the feasibility of an airborne hydrogen fuel system for gas turbine engines.

To summarize: All engine tests, whether in test stands or in flight, demonstrated the feasibility of hydrogen fueled gas turbine engines.

CONCLUDING REMARKS

From the results of component tests and full-scale hydrogen fueled engine tests conducted episodically over the last 20 years the following conclusions can be made:

1. The burning properties of hydrogen can provide improvements in gas turbine engine performance by providing stable combustion at higher altitudes and with easier relight than with hydrocarbon fuels. Hydrogen fuel eliminates all exhaust pollutants except for oxides of nitrogen.

2. The heat sink capacity of hydrogen can be readily utilized for oil cooling, turbine cooling air refrigeration, and cabin air conditioning. Oil or air-to-liquid hydrogen heat exchanger technology that eliminates congealing or frost formation is available. The use of these heat exchangers to vaporize and heat the hydrogen prior to combustion do not cause unresolved problems in the fuel control system.

3. It has been demonstrated that hydrogen fuel control systems can be made acceptably stable and responsive for the operation of gas turbine engines.

4. Tests have been conducted in test stands and in flight on engines originally designed for kerosene fuels but modified to burn hydrogen. These tests demonstrated that the design of hydrogen fueled gas turbine engines for aircraft is feasible.

5. Liquid hydrogen has been pumped to suitable pressure levels and with suitable turndown ratios for gas turbine engines using positive displacement piston pumps; however, a completely satisfactory, long life, flight weight pump has not been demonstrated.

6. The main area where additional research is warranted for hydrogen fueled gas turbine aircraft engines is on flight-weight liquid hydrogen pumps that provide the requirements necessary for aircraft gas turbine use. Research on long time (>10,000 hrs.) hydrogen embrittlement of stable austenitic stainless steels is also warranted.

7. Although research conducted on gas turbine engines has indicated hydrogen fueled engines are feasible, similar research is lacking on other potential problem areas relating to the application of hydrogen fuel to aircraft. Some of the more significant areas where adequate research has not been conducted are (1) liquid hydrogen fuel handling, and accommodation of large amount of boiloff during fuel loading in aircraft in crowded airport areas; and (2) fuel storage within the aircraft including problems in long life, light weight insulation; structural problems from extreme temperature gradients within the aircraft structure; and the effects of large fuel storage volumes on aircraft aerodynamics.

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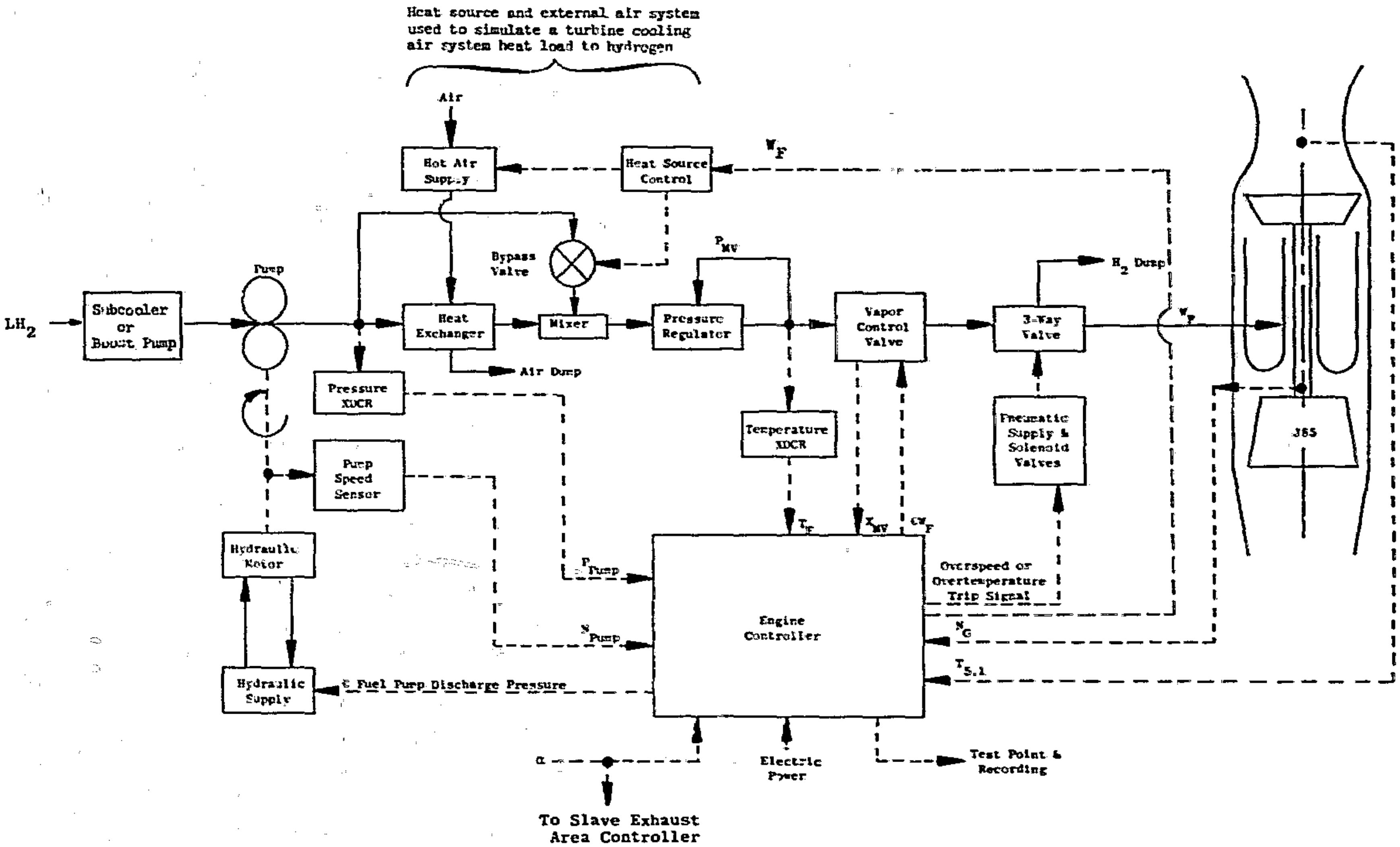

Figure 1. Schematic Diagram of Hydrogen Fuel System.