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Test Program to Provide Confidence in Liquid Oxygen Cooling of Hydrocarbon Fueled Rocket Thrust Chambers

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TEST PROGRAM TO PROVIDE CONFIDENCE IN LIQUID OXYGEN COOLING OF HYDROCARBON FUELED ROCKET THRUST CHAMBERS

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ABSTRACT

An experimental program has been planned at the NASA Lewis Research Center to build confidence in the feasibility of liquid oxygen cooling for hydrocarbon fueled rocket engines. Although liquid oxygen cooling has previously been incorporated in test hardware, more runtime is necessary to gain confidence in this concept. In the previous tests, small oxygen leaks developed at the throat of the thrust chamber and film cooled the hot-gas side of the chamber wall without resulting in catastrophic failure. However, more testing is necessary to demonstrate that a catastrophic failure would not occur if cracks developed further upstream between the injector and the throat, where the boundary layer has not been established. Since under normal conditions cracks are expected to form in the throat region of the thrust chamber, cracks must be initiated artificially in order to control their location. Several methods of crack initiation are discussed in this report.

As a minimum, it is recommended that four thrust chambers, three with cracks and one without, be tested. The axial location of the cracks should be varied parametrically. Each chamber should have sufficient instrumentation to determine the effects of the cracks, as well as the overall performance and durability of the chambers. Comments are solicited from the engineering community to insure that the test program will provide confidence in liquid oxygen (LOX) cooling.

INTRODUCTION

The concept of LOX/hydrocarbon rocket engines is being given serious consideration for future launch vehicle propulsion in vehicles, such as the mixed-mode single-stage-to-orbit (SSTO) and the heavy lift launch vehicle (HLLV).[1-4] These vehicles could provide an economical means of accomplishing many of the space missions envisioned for the 1995 and beyond time period. Liquid oxygen is being considered as the coolant in several of the advanced engine concepts proposed for these vehicles, but more research is necessary before liquid oxygen cooling can be considered a viable alternative to hydrogen or hydrocarbon cooling.

Typically, the fuel in a rocket engine is used to cool the combustion chamber. But hydrocarbon cooling at the high chamber pressures being considered for advanced engines would accumulate carbon deposits in the coolant passages resulting in decreased heat transfer to the coolant. To maintain the required heat transfer may necessitate the use of oxygen as the regenerative coolant. Analysis in Ref. 4 using a heat transfer correlation like that developed in Ref. 5 has indicated that oxygen is capable of cooling such engines to chamber pressures in excess of 27.6 MN/m^2 (4000 psia) with reasonable pressure drop allowances. Testing with hydrogen and liquid oxygen[6] and RP-1 and liquid oxygen[7] has demonstrated the feasibility of using liquid oxygen as a coolant at 4.1 MN/m^2 (600 psia) and 8.3 MN/m^2 (1200 psia) chamber pressure. However, runtime with LOX cooling is needed to build the required data base before the confidence level and reliability of this concept is sufficient to consider this alternative cooling technique.

For both hydrogen and RP-1 tested at 4.1 MN/m^2 (600 psia) chamber pressure with LOX, cracks developed in the throat region and the leaking coolant film cooled the hot-gas side of the chamber wall. Cracks also developed in the throat region during hydrogen and liquid oxygen testing at 8.3 MN/m^2 (1200 psia) chamber pressure with similar results. However, there is still some question as to whether cracks between the injector and the throat would affect the performance of the thrust chamber. Close to the injector, the boundary layer has not been fully established. The boundary layer partially protects the metal wall from the turbulent combustion gases. Without this boundary layer, the wall may oxidize when leaking oxygen is introduced. Therefore, the chamber wall may not be as protected near the injector as in the throat region. With RP-1 as the fuel, carbon deposits would develop along the combustion chamber wall decreasing the amount of heat transfer to the chamber wall and increasing the temperature of the soot layer. Because the wall temperature will be closer to its ignition temperature using RP-1 than using hydrogen as the fuel, the tests should be run with LOX and RP-1 to validate the system's reliability.

To insure that the program would provide confidence in LOX cooling, comments and suggestions are encouraged from the engineering community. If it is thought that the test program should be conducted in a different manner, any constructive comments on altering the test plan would be welcomed.

TEST HARDWARE

An experimental program using LOX cooling for hydrocarbon fueled thrust chambers should be conducted with scale model hardware. The proposed thrust chambers consist of a combustion chamber, an acoustic resonator, and an injector, similar to those shown in Fig. 1. RP-1 is the suggested fuel and tests should be conducted at chamber pressures of 8.3 MN/m^2 (1200 psia) and 13.8 MN/m^2 (2000 psia).

COMBUSTION CHAMBER

Dimensions of the contoured combustion chambers can be seen in Fig. 2. The chamber liner which is manufactured from copper is electrodeposited onto a steel mandrel. One hundred axial coolant passages are then milled into the copper. After the milling, electrodischarged machining (EDM) is used to cut thin slits into four coolant passages as initiation sites for later crack formation (Fig. 3). The slits would be 90° apart at each axial location. The coolant passages are then filled with wax before the closeout of electroformed nickel. After testing the chambers, additional slits would be machined completely through the thrust chamber wall in the ribbed section as an alternative, more controlled method of leaking oxygen into the combustion chamber (Fig. 4). A small tube would inject oxygen from the outside of the chamber through these slits into the combustion area.

INJECTOR

The design for the injector faceplate, similar to the one shown in Fig. 1, is a 61 element oxidizer-fuel-oxidizer triplet injector, designed especially for use with hydrocarbon fuel as described in Ref. 8. The outer ring of the injector consists of 24 fuel holes with 24 inner liquid oxygen holes acting as showerheads. For the 8.3 MN/m^2 (1200 psia) chamber pressure, the oxygen to fuel (O/F) ratio is 1.03 on the outer ring and 2.32 in the core for an overall O/F ratio of 2. For the 13.8 MN/m^2 (2000 psia) chamber pressure the O/F ratio is 1.18 on the outer ring and 2.35 in the core for an overall O/F ratio of 2.

RESONATOR

An acoustic resonator should be incorporated to provide stable combustion in the thrust chamber similar to that shown in Fig. 1. It consists of 16 cavities, evenly arranged around the inside surface of the resonator. The cavities are arranged so that they dampen the expected frequency of combustion oscillations causing instability.

IGNITER

The hydrogen/oxygen spark torch igniter is inserted through the resonator wall just downstream of the cavities (Fig. 2). The igniter supplies the energy needed to begin LOX/RP-1 combustion. Once the LOX/RP-1 combustion begins, the torch flow is replaced by a small inert purge gas flow. This prevents hot combustion gases from flowing back into the igniter.

TEST FACILITY

The tests could be conducted at the Lewis Research Center rocket engine test facility. The facility uses pressurized propellant storage tanks to supply the liquid oxygen and ambient temperature RP-1 to the combustion chamber. Separate piping systems would be used for the coolant oxygen and the injector oxygen. The liquid oxygen flowing through the coolant passages would be at pressures up to 34.5 MN/m^2 (5000 psia) allowing chamber pressures up to 13.8 MN/m^2 (2000 psia) when using liquid oxygen and RP-1. More details about the rocket engine test facility can be found in Ref. 9.

TEST PLAN AND OPERATING PROCEDURE

Four thrust chambers would be tested at both 8.3 MN/m^2 (1200 psia) and 13.8 MN/m^2 (2000 psia) as shown in Table I. A baseline case with no cracks, Chamber 1, is tested for comparison with the data previously obtained in Ref. 7. Chambers 2, 3, and 4, can then be tested to determine the effect of cracks. These cracks should initiate at the site of the EDM slots in the coolant passages of the chamber wall described earlier. Since the slots do not allow the liquid oxygen coolant to reach the combustion area initially, the RP-1 would leave carbon deposits along the chamber wall, as occurs under normal operating conditions of a LOX/RP-1 thrust chamber. After several cycles, it is anticipated that the chamber wall would fatigue and crack where the slots are located. A small portion of the liquid oxygen coolant would then flow into the chamber through the cracks from the coolant passages. Chambers 2, 3, and 4 would be cycled at 8.3 MN/m^2 (1200 psia) until cracks develop and then the chambers would be tested at steady-state for 10 seconds.

Since previous testing has been done with cracks in the throat area of the thrust chamber with no adverse effect on the chamber performance, Chamber 2 would be tested with cracks located 7.0 cm (2.75 in.) upstream of the throat. The cracks in Chamber 3 will be located 15.5 cm (6.5 in.) upstream of the throat, and the cracks in Chamber 4 will be located 24.1 cm (9.5 in.) upstream of the throat. The cracks in Chambers 2 and 3 will be in the converging section of the combustion area and the cracks in Chamber 4 will be in the cylindrical section of the combustion area.

Chambers 2, 3, and 4 would undergo 15 cycles, at 13.8 MN/m^2 (2000 psia) chamber pressure in order to obtain more runtime at higher pressures. After analyzing the results from tests of chambers 2, 3, and 4, additional EDM slots would be machined completely through the ribs of the thrust chamber wall. A small tube would then be used to inject oxygen from the outside of the chamber wall through the slots into the combustion area. These slots would be located at 4 radial locations, 90° apart. The axial location of these slots would depend on where more data is desired after completing the original tests.

DISCUSSION

The main objective of this experimental program is to provide confidence in the concept of LOX cooling, through increased operating time and by characterizing the effect of crack formation in several areas of the thrust chamber. Prior testing has demonstrated that cracks in the throat region allowed oxygen to flow into the combustion area without catastrophic failure occurring. Instead, the oxygen seemed to film-cool the combustion chamber wall. There is some concern that cracks near the injector would be more vulnerable to damage. Close to the injector, the boundary layer has not been fully established. It is this boundary layer that protects the metal wall from reaching the temperature of the turbulent combustion gases. If oxygen is allowed to leak where there is no boundary layer, the copper wall may oxidize. Therefore, the chamber wall may not be as protected near the injector as in the throat region. Successful testing with cracks between the throat and the injector, the combustion area, would alleviate that concern. Under normal operation, cracks would propagate in the throat region, rather than in the combustion zone. Therefore, a mechanism to initiate cracks upstream of the throat must be devised.

There are three areas of consideration when initiating cracks in the thrust chambers: (1) the type of chamber to test, (2) the method of developing cracks, and (3) the control of variables. When an experiment is planned, many variables are considered for investigation. The amount of control over these variables determines whether factors can be altered in a logical and orderly manner. Also of importance is the simulation of naturally occurring cracks. Each chamber configuration will consider these points.

Two types of thrust chambers were considered for the test program. The first is the conventional contoured combustion chamber shown in Fig. 2. The second is an outer cylindrical chamber and a water-cooled centerbody shown in Fig. 5. Although the cylindrical combustion chamber does not physically resemble an actual rocket engine, it is a good research tool, because of the ease with which data can be obtained. This cylindrical chamber also has the ability of promoting natural cracks upstream of the throat by running cycles with a shortened water-cooled centerbody. When fatigue is imminent, the testing is then resumed with a normal length centerbody, placing the throat downstream of the incipient cracks. The resulting cracks would be natural cracks upstream of the throat, but there would be no control over their number, size, or radial location. The flow of oxygen would be difficult to calibrate since the size of the cracks and the number of cracks are unknown. Cracks could not be initiated within 2 in. of the injector because the gases could not combust in such a small area. Therefore, it was decided to propose the contoured thrust chamber as the best compromise between realism and control of the variables.

A number of other methods were evaluated to form cracks in the combustion chambers. One method of initiating cracks is to machine a small slit from the coolant passage to the hot gas side (Fig. 6). Such a slit would allow oxygen to flow into the combustion area from a cooling channel. However, the exit of the slit would be smooth and uniform, unlike a naturally occurring crack which has a rough surface and would form along a weakened grain boundary. The roughness of the natural crack would disrupt the boundary layer and affect the heat transfer coefficient of the chamber wall. A smooth opening from a machined slit would also disrupt the boundary layer, but to a lesser degree. Also, the oxygen flow from the coolant passages would begin before any carbon could be deposited on the chamber wall, as occurs under normal operating conditions.

To alleviate this difficulty, a slit could be machined partially through the chamber wall, resulting in a weakness at that location. A slit machined from the hot-gas side part of the way to the coolant passage (Fig. 7) would allow carbon to build up on the hot-gas side wall before the slit breaks through to the coolant passage. However, as in the previous concept, the exit of the slit would be smooth and uniform because the slit would be machined from the hot-gas side inward.

A slit machined from the coolant passage part of the way to the hot gas side (Fig. 3) would also allow carbon to build up on the hot gas side before the slit becomes a crack. Since the break would occur at the hot-gas side rather than at the coolant passage, the exit would be rough, simulating the surface of naturally occurring cracks. This concept of crack formation appears to be the closest to reproducing natural cracks and is presently proposed for implementation. The most controlled environment for cracks would be a specific number, at specific locations, with a specific amount of oxygen flowing through each. The best controlled method of crack simulation would be slits running from the outside of the chamber to the hot gas side (Fig. 4). Oxygen would be allowed to flow through a valve into the slit. The amount of flow could vary, and the number of slits would be predetermined as would their location. This method is an alternate method for implementation. Unfortunately, these slits would not have the exit roughness of real cracks, nor would all their characteristics simulate cracks from the coolant passage to the hot-gas side.

CONCLUDING REMARKS

Prior work with LOX/Hydrocarbon thrust chambers has demonstrated the feasibility of LOX cooling at 4.13 MN/m^2 (600 psia) and 8.3 MN/m^2 (1200 psia). Even after cracks developed in the throat region, the overall performance was not affected and no catastrophic failure occurred. To gain more confidence in the concept of LOX cooling, further research with hydrocarbon fuel must be performed, particularly at the high chamber pressures being considered for advanced rocket engines. Also, research into the effects of cracks in the combustion area between the throat and the injector is necessary to determine the safety of oxygen as a coolant. In the combustion area, the boundary layer is not fully formed, which would protect the chamber wall from the turbulent combustion gases. Therefore, there is a possibility that the wall would oxidize and reach its ignition temperature. The proposed research would investigate the results of small amounts of oxygen flowing into the thrust chamber along the sides, as well as increase the total experience of LOX cooling. This research would increase the data base on LOX cooling and determine the safety and reliability of using liquid oxygen for cooling thrust chambers.

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TABLE I. Proposed Test Plan

Config. no.	Chamber no.	Nominal chamber pressure, MN/m^2 (psia)	Crack location	Test condition
1	1	8.3 (1200)	No cracks	10 sec of steady state
2	1	13.8 (2000)	No cracks	10 sec of steady state
3	2	8.3 (1200)	No cracks	Cyclic testing until cracks form
4	2	8.3 (1200)	7.0 cm (2.75 in.) from the throat	10 sec of steady state
5	3	8.3 (1200)	No cracks	Cyclic testing until cracks form
6	3	8.3 (1200)	16.5 cm (6.5 in.) from the throat	10 sec of steady state
7	4	8.3 (1200)	No cracks	Cyclic testing until cracks form
8	4	8.3 (1200)	24.1 cm (8.5 in.) from the throat	10 sec of steady state
9	2	13.8 (2000)	7.0 cm (12.75 in.) from the throat	15 cycles
10	2	13.8 (2000)	7.0 cm (12.75 in.) from the throat	10 sec of steady state
11	3	13.8 (2000)	16.5 cm (6.5 in.) from the throat	15 cycles
12	3	13.8 (2000)	16.5 cm (16.5 in.) from the throat	10 sec of steady state
13	4	13.8 (2000)	24.1 cm (9.5 in.) from the throat	15 cycles
14	4	13.8 (2000)	24.1 cm (9.5 in.) from the throat	10 sec of steady state
15	1	8.3 (1200)	Based on results of acquired data	15 cycles
16	1	13.8 (2000)	Based on results of acquired data	15 cycles

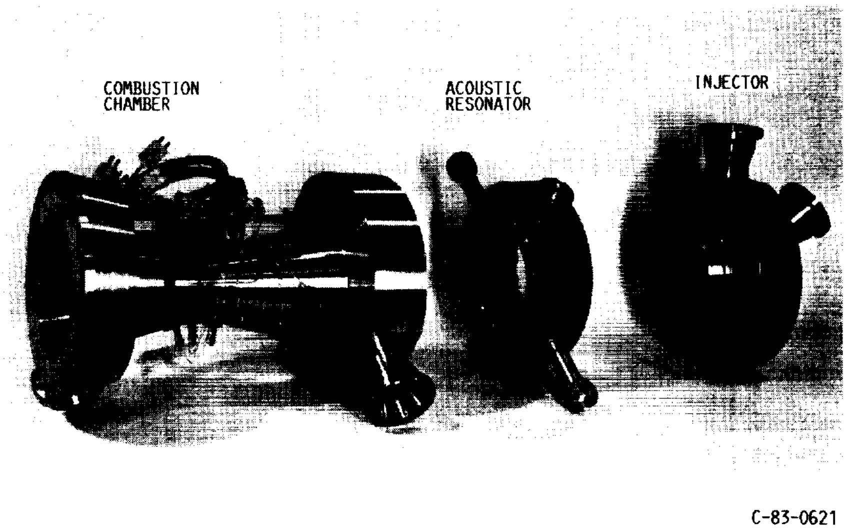

FIGURE 1. - PROPOSED THRUST CHAMBER.

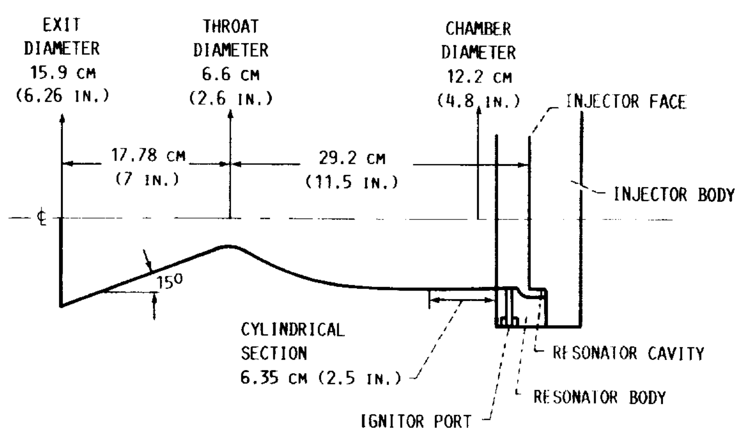

FIGURE 2. - THRUST CHAMBER DIMENSIONS.

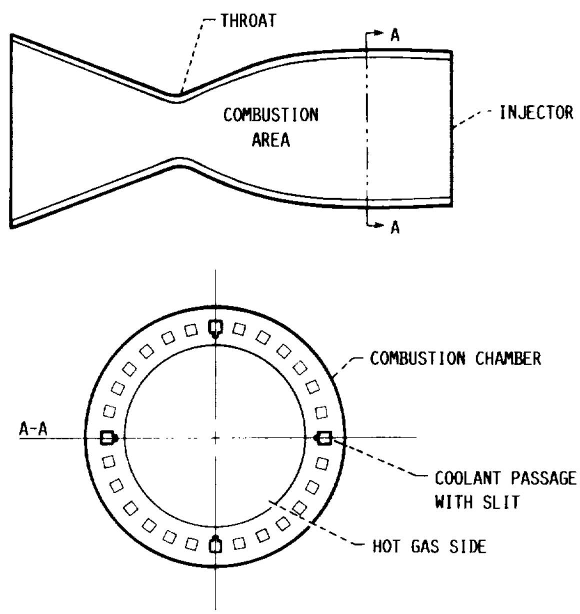

FIGURE 3. - SCHEMATIC OF SLIT PART WAY FROM COOLANT PASSAGE TO HOT GAS SIDE.

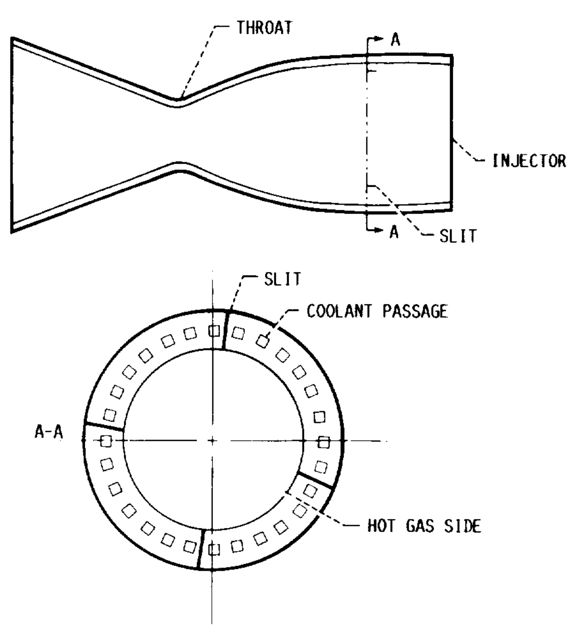

FIGURE 4. - SCHEMATIC OF SLIT FROM OUTSIDE TO INSIDE OF COMBUSTION CHAMBER.

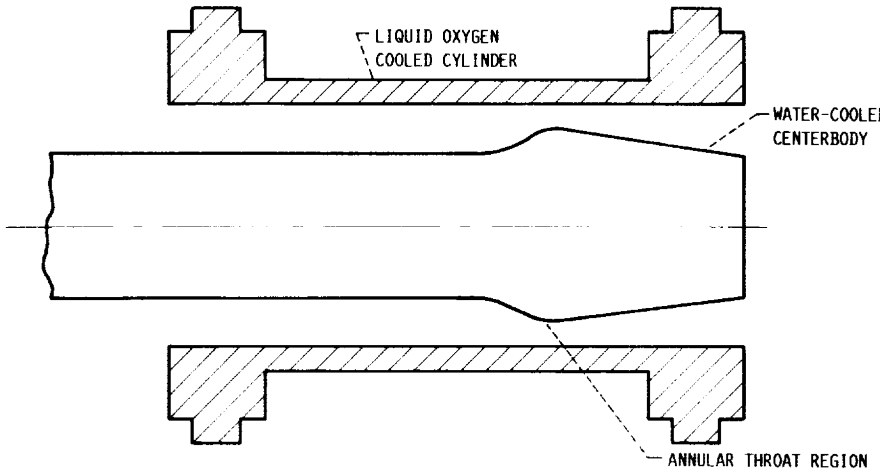

FIGURE 5. - SCHEMATIC OF CYLINDRICAL COMBUSTION CHAMBER.

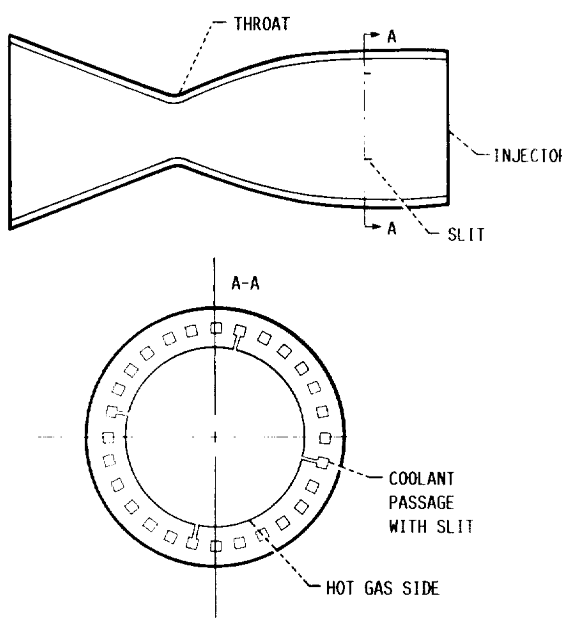

FIGURE 6. - SCHEMATIC OF SLIT FROM COOLANT PASSAGE TO HOT GAS SIDE.

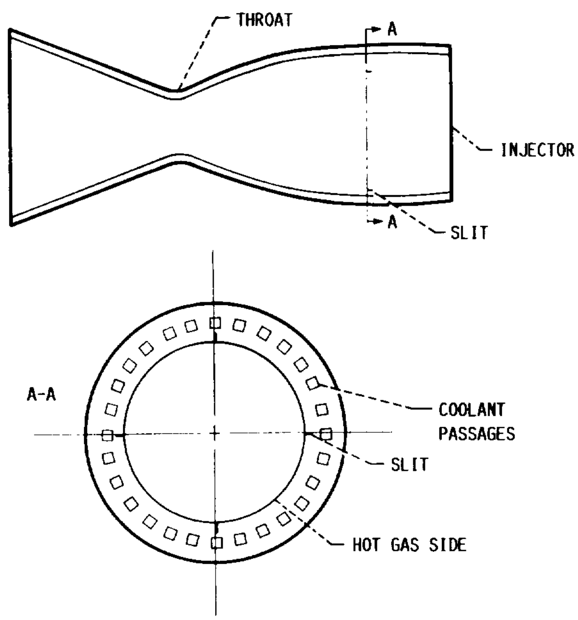

FIGURE 7. - SCHEMATIC OF SLIT PART WAY FROM HOT GAS SIDE TO COOLANT PASSAGE.

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16. Abstract

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