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SMALL ROCKET FLOWFIELD DIAGNOSTIC CHAMBERS

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SUMMARY

Instrumented and optically-accessible rocket chambers are being developed to be used for diagnostics of small rocket (< 440 N thrust level) flowfields. These chambers are being tested to gather local fluid dynamic and thermodynamic flowfield data over a range of test conditions. This flowfield database is being used to better understand mixing and heat transfer phenomena in small rockets, influence the numerical modeling of small rocket flowfields, and characterize small rocket components. The diagnostic chamber designs include: 1) a chamber design for gathering wall temperature profiles to be used as boundary conditions in a finite element heat flux model; 2) a chamber design for gathering inner wall temperature and static pressure profiles; and 3) optically-accessible chamber designs, to be used with a suite of laser-based diagnostics for gathering local species concentration, temperature, density, and velocity profiles. These chambers were run with gaseous hydrogen/gaseous oxygen (GH2/GO2) propellants, while subsequent versions will be run on liquid oxygen/hydrocarbon (LOX/HC) propellants. This presentation summarizes the purpose, design, and initial test results of these small rocket flowfield diagnostic chambers.

HEAT FLUX DIAGNOSTIC CHAMBER

A chamber was designed and fabricated to determine steady-state heat flux to the inner wall to be used as a diagnostic of the flowfield behavior.[1] The heat flux chamber design is an instrumented, water-cooled chamber used to gather steady-state wall temperature profiles from measured and interpolated thermocouple data. These temperature profiles are used as boundary conditions in a finite element analysis program, MSC/NASTRAN, to calculate the local radial and axial heat fluxes in the chamber. Normal heat flux down the length of the chamber is then calculated as the dot product of the total heat flux and normal vectors. It is important to emphasize that heat flux is used here as a flowfield diagnostic - the objective is not to find absolute heat flux values (which would change for differing wall conditions), but rather to use heat flux as an indicator of fundamental characteristics of the flowfield over a range of conditons.

A schematic of a heat flux chamber used with a GH2/GO2 injector is shown in figure 1. The chamber was fabricated from Oxygen-Free, High-Conductivity (OFHC) copper, with a 1.27 cm thick wall. An OFHC copper housing was welded onto the chamber to provide an annulus for water cooling along the outer wall. Chromel-alumel, grounded-junction thermocouples were embedded in the inner wall, nominally 0.159 cm from the inner wall and attached to the outer wall and exit face. It was found that boundary condition definition was critical to the accuracy and resolution of the heat flux profiles generated by the finite element program. Details of the chamber fabrication and the heat flux methodology are given in reference 1.

This heat flux chamber was used to gather temperature data over a range of mixture ratios at 61 percent fuel film cooling (FFC) and 414 kPa chamber pressure. The normal heat flux profiles (as a function of axial position) generated from the temperature data is shown in figure 2. The heat flux profiles showed a significant increase in shear layer mixing in the barrel section of the chamber for mixture ratios above five, indicated by the sharp heat flux peaks there. This increase was felt not to be a result of the flow transitioning to turbulent, since Reynolds numbers were well within the laminar regime, but rather due to increased chemical reactions in the shear layer between the hydrogen film cooling and oxidizer-rich core flows. It was uncertain what the trigger mechanism was for this increased shear layer mixing at higher mixture ratios. This heat flux methodology will be used further for investigation of flowfield behavior and characterization of LOX/HC small rocket injector configurations.

TEMPERATURE/PRESSURE DIAGNOSTIC CHAMBER

A chamber was designed to investigate small rocket flowfields via inner wall temperature and static pressure measurements,[2] as shown in figure 3. The chamber liner was fabricated from OFHC copper, with milled channels on the back side to provide water cooling. An OFHC copper outer housing was split into two parts axially along its length and slid over the chamber liner in a clam-shell fashion. The housing was joined to the liner at the inlet and outlet water manifolds, and sealed along the two axial housing seams. The chamber contained 4 axial rows of thermocouple ports which spanned from the combustion chamber to the nozzle section. The chromel-alumel thermocouples were located 0.076 cm from the hot gas side wall. The chamber also contained one row of static pressure ports. Because the backside of the chamber was not sealed to the outer housing, instrumentation seals were developed to accommodate the chamber cooling system.

The diagnostic chamber was hot fired using two platelet stack injectors of two, slightly different designs, designated SN 02 and SN 03. The chamber was operated at 262 kPa, 379 kPa, and 517 kPa chamber pressures and 60% and 75% FFC, for mixture ratios between 4.0 and 8.0. At 75% FFC, both chambers exhibited the same performance and thermal trends. However, at 60% FFC the data trends differed between the two injectors. Figure 4 show the axial inner wall temperature profiles for both injectors at 60% FFC. The inner wall temperatures for the SN02 injector displayed a greater sensitivity to mixture ratio than for the SN03 injector. Furthermore, the inner wall temperature generally increased with increasing mixture ratio for the SN02 injector, while the opposite trend was observed for the SN03 injector. The results of this testing indicated that small rocket flowfield behavior may be very sensitive to minor changes in operating conditons and injector design. Further discussion of tests results and the details of the chamber design and fabrication are found in Reference 2.

This diagnostic chamber design will be used further for investigation of flowfield behavior (in particular, an unsteady flowfield phenomenon suspected to be associated with the GH2/GO2 injectors used previously), characterization of LOX/HC small rocket injector configurations, and investigation of low Reynolds number nozzle design issues. Furthermore, the pressure ports of this chamber could be utilize for gas sampling and for the insertion of fiber optics for laser-based diagnostics.

OPTICALLY-ACCESSIBLE CHAMBERS FOR LASER-BASED DIAGNOSTICS

Optical access to the combustion chamber allows the use of non-intrusive, laser based diagnostics to gather local fluid dyamic and thermodynamic data. These diagnostics include Raman spectroscopy to measure species concentrations, gas temperatures, and flow velocity profiles near the injector and Laser-Induced Fluorescence (LIF) used to visualize the shear layer mixing process and to measure minor species concentrations.[3] Schlieren and shadowgraph techniques could also be used with optically accessible chambers to visualize the flowfield. A square rocket chamber was designed, fabricated, and hot fired to provide optical access to the combustion chamber from the sides. The square (2D), optically-accessible chamber was seen as an intermediate step toward an axisymmetric (3D), optically-accessible chamber and was therefore designed to be robust.

The 2D chamber is shown in figure 5. The chamber was machined out of OFHC copper with water cooling channels drilled in the wall above and below the combustion chamber and nozzle. On the left and right side of the chamber there were slots for the placement of 13.3 cm by 6.35 cm by 1.27 cm windows. High optical quality, fused silica was selected as the window material. Fused silica has a maximum operating temperature of only 980 °C, but has a relatively low coefficient of thermal expansion compared to sapphire. Furthermore fused silica can be machined with better surface qualities compared to sapphire, reducing the amount of diffuse scattering of laser light within the chamber. Gaseous nitrogen was injected against the windows for cooling.

The 2D chamber provides optical access down the entire length of the rocket. Because the windows are cooled independently, the interaction of fuel film cooling flow with the oxidizer-rich core flow in the shear layer (a critical phenomenon in small rocket flows) can be studied without the threat of a film cooling layer breakdown melting the windows. The main drawback, however, is that the measurements - and any conclusions drawn from them - are restricted to a two-dimensional flowfield. It will be important to distinguish between effects that are representative of the flowfield behavior and effects that result from the two dimensionality of the chamber. Also the nitrogen flow, though directed against the windows, will slowly penetrate into the hydrogen/oxygen flow.

The 2D chamber was checked out using copper slabs instrumented with thermocouples in place of the windows. The nitrogen flow was sufficient to keep the inner wall temperature below 93 °C, with no more than a 27 °C temperature variation across the slab. The chamber was then run with the windows in a series of 15-second duration tests at a chamber pressure of 296 kPa and a total mass flowrate of 0.033 kg/s. At an overall mixture ratio 6 and 55% FFC, the core mixture ratio was 13.3. After a total of 232 tests with the same set of windows, there was no evidence of cracking or degradation of the windows. Laser Raman spectroscopy was used to measure the gas temperature and oxygen concentration at the exit of the chamber sleeve insert used with the injector. The measured temperature and oxygen concentration profiles were found to be significantly different from the profiles that are usually assumed in numerical calculations. Detailed discussion of the Raman measurements with this chamber can be found in reference 4.

The next step from the 2D chamber will be an axisymmetric, optically-accessible rocket chamber. The preliminary design of a 3D chamber to be used with GH2/GO2 propellants is shown in figure 6. A modular design is envisioned with a flush-mounted injector, a cylindrical, fused silica window for the barrel section, and a water-cooled converging/diverging nozzle, all clamped together. A concern with this design are the thermal stresses that could be induced by temperature differences between the window mating surfaces. Fuel film cooling from the injector and water cooling of the nozzle section should keep the mating surfaces at a fairly uniform temperature. Water cooling of the nozzle section should also minimize thermal soakback into the window, although a low thermal conductivity interface could be used between the window and nozzle if water cooling is not sufficient.

As with the 2D chamber, the 3D chamber will allow the used of Raman spectroscopy, LIF, Schlieren, and shadowgraph diagnostics, but optical access will only be provided in the head end, relatively low temperature region of the barrel section. It is thought that much of the shear layer reactions probably occurs in this region, however. Cooling of the window will be by the hydrogen film cooling layer only, so care must be taken that the window section does not extend too far into the chamber or that the chamber is not run at conditions where the film layer will breakdown quickly. Results from the 2D chamber should provide guidance in this design issue. Later versions of the 3D chamber could include a fused silica nozzle extension to study low Reynolds number flow in the nozzle and window slots in the throat region.

REFERENCES

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3. Schneider, S.J., "Low Thrust Chemical Rocket Technology", IAF Paper 92-0669, NASA TM-105927, August 1992.

4. DeGroot, W.A., "Gaseous Hydrogen/Oxygen Injector Performance Characterization", AIAA Paper 94-0220, to be presented at 1994 AIAA Aerospace Sciences Meeting.

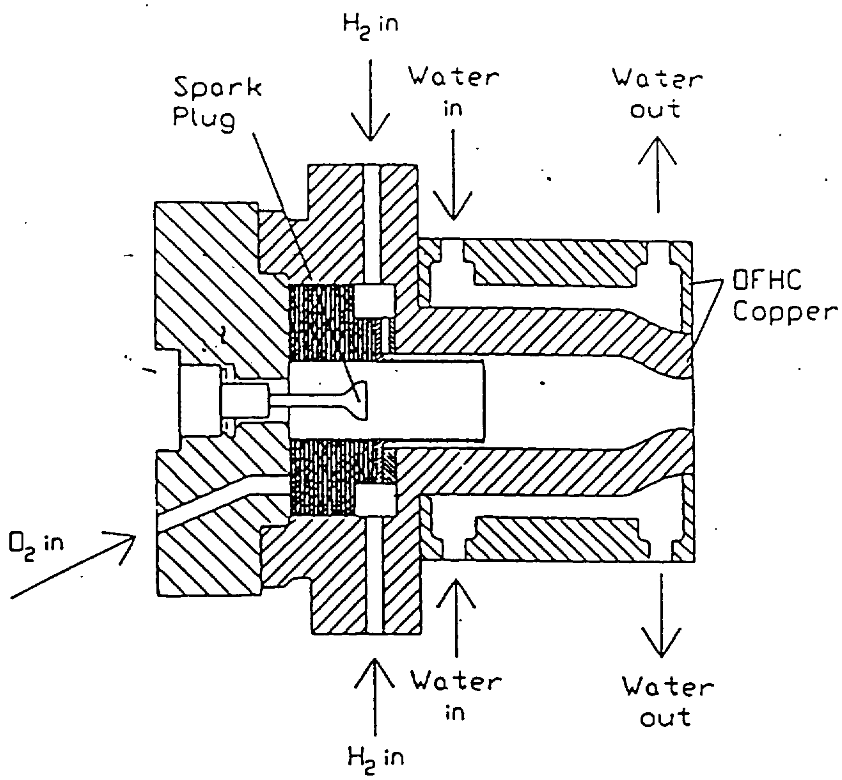

Figure 1: Schematic of Heat Flux Chamber

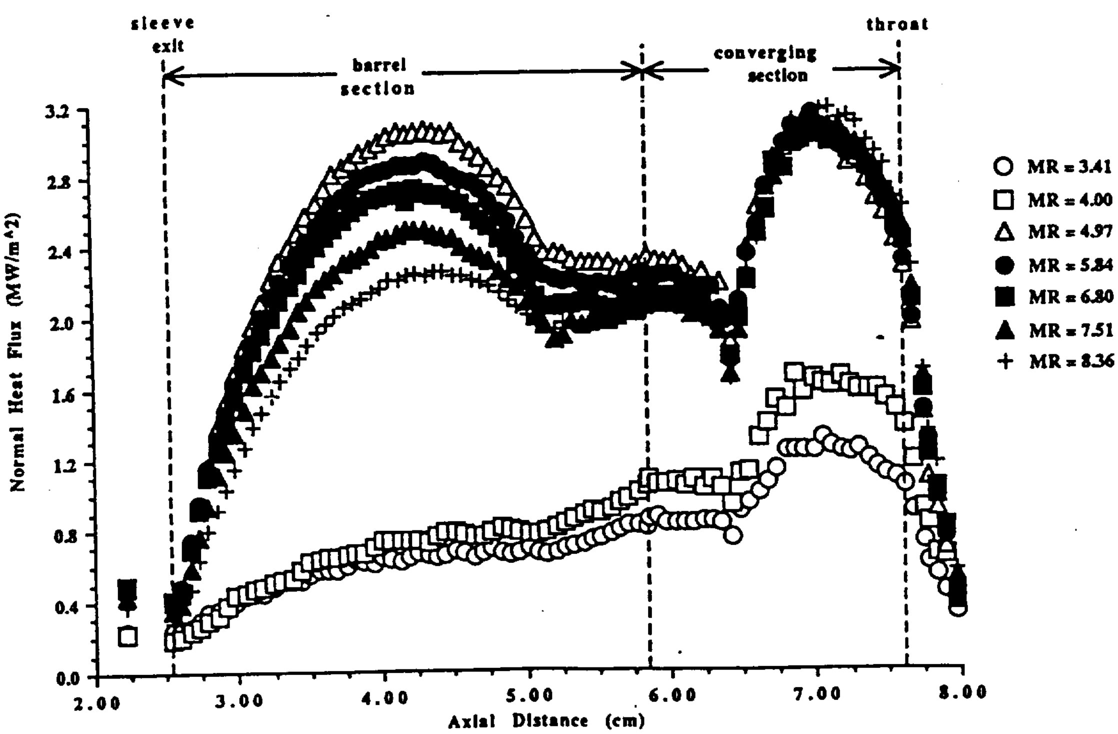

Figure 2: Inner Wall, Normal Heat Flux vs. Axial Distance

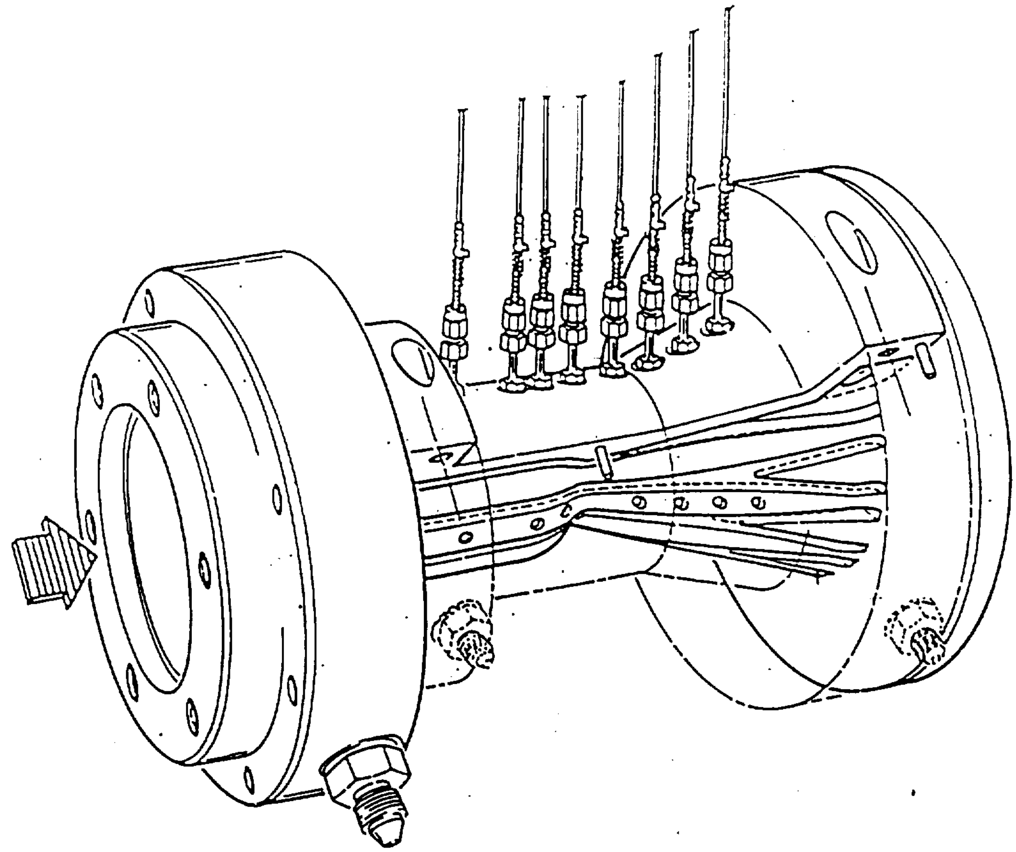

Figure 3: Temperature/Pressure Diagnostic Chamber

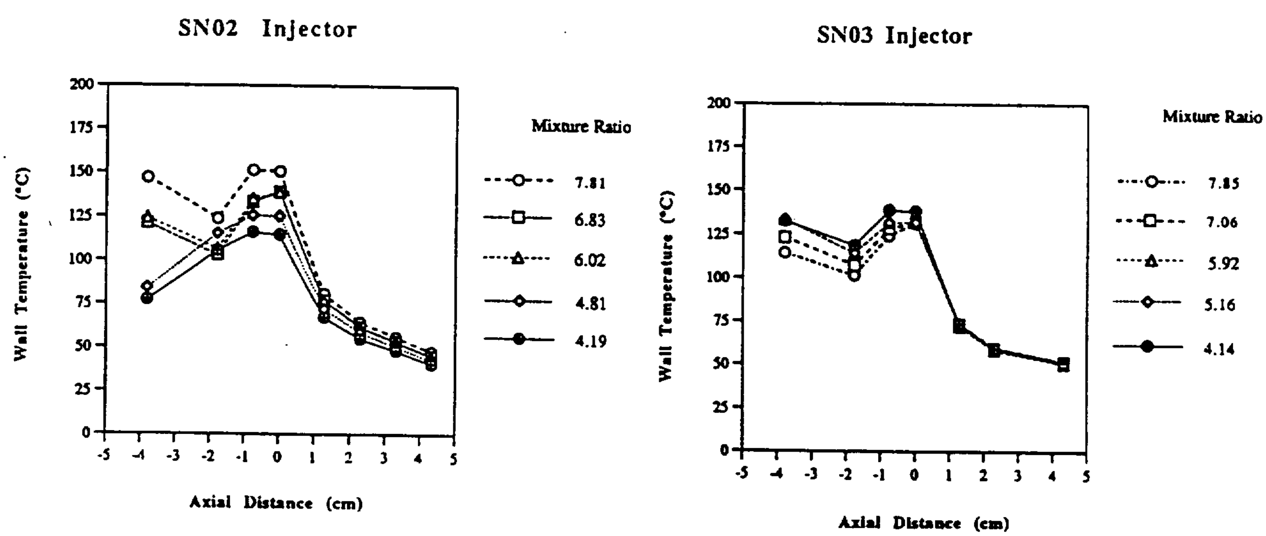

Figure 4: Axial Inner Wall Temperature Profiles
60% FFC, Chamber Pressure = 490 to 516 kPa

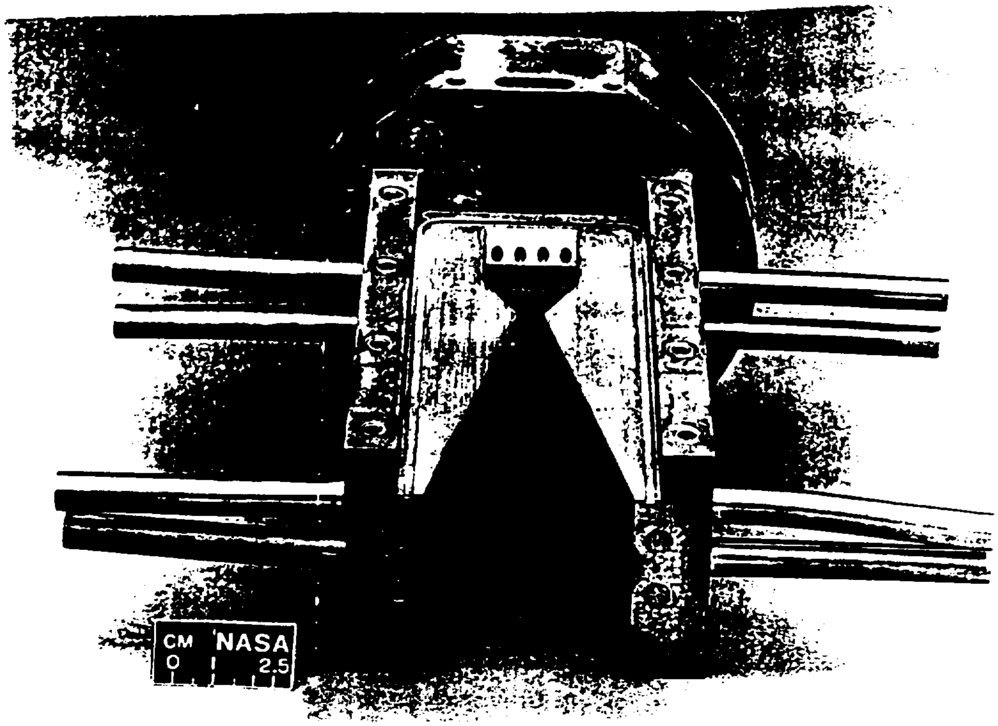

Figure 5: 2D, Optically-Accessible Chamber

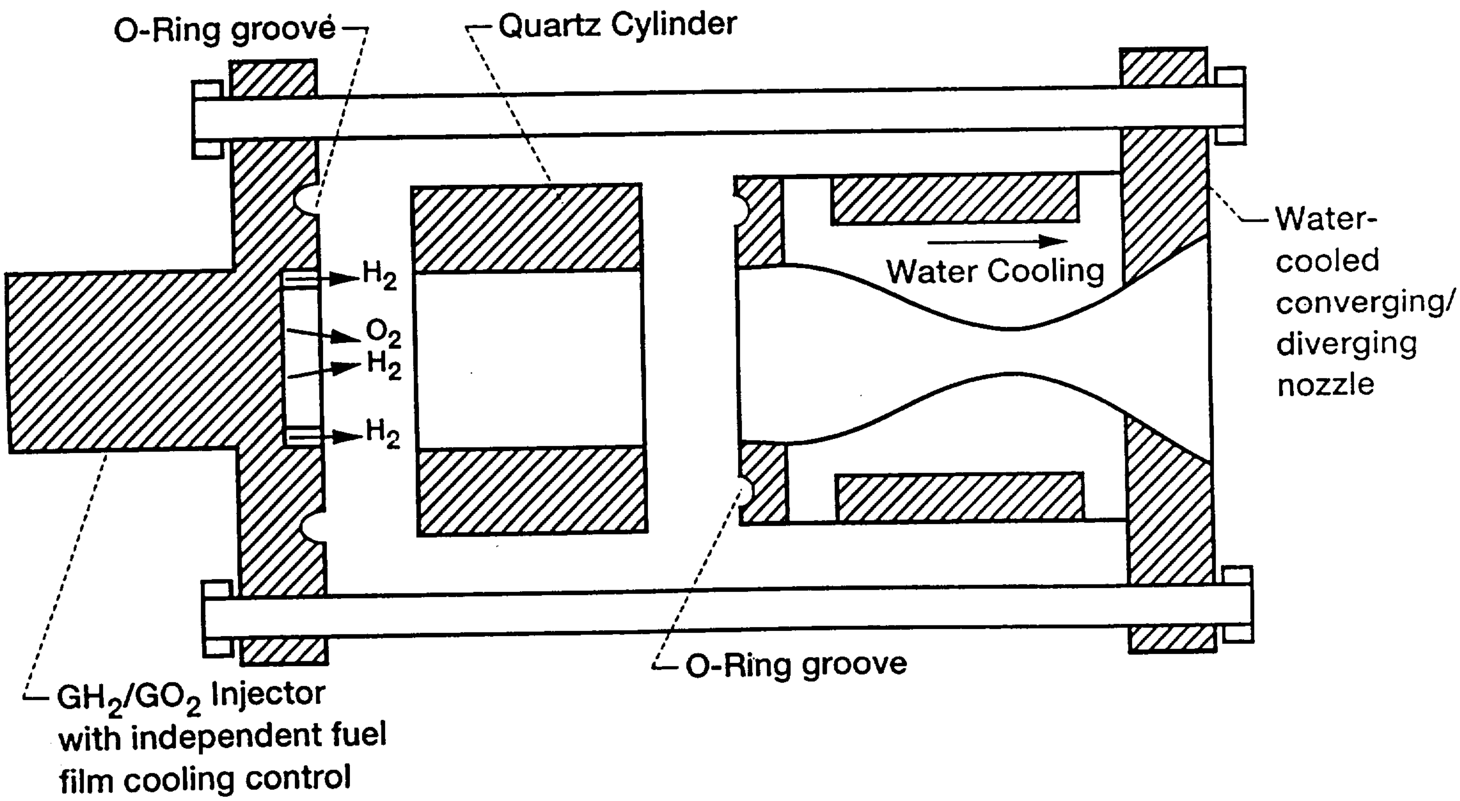

Figure 6: Schematic of 3D, Optically-Accessible Chamber