FIBER OPTIC RAMAN THERMOMETER FOR SPACE SHUTTLE MAIN ENGINE PREBURNER PROFILING*

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Abstract

The feasibility of combustion gas temperature measurements in the SSME fuel preburner using non-intrusive optical diagnostics is being investigated. Temperature profiles are desired in the high pressure, hydrogen-rich preburner stream to evaluate designs to alleviate thermal stressing of the fuel pump turbine blades. Considering the preburner operating conditions and optical access restrictions, a spontaneous Raman backscattering system, implemented with optical fibers to couple to the combustion device, was selected as the most practical for gas temperature probing. A system is described which employs a remotely-located argon-ion laser to excite the molecular hydrogen Raman spectrum. The laser radiation is conveyed to the combustor through an optical fiber and focused through a window into the chamber by an optical head attached to the combustor. Backscattered Raman radiation from a localized region is collected by the head and transmitted through fiber optics to remotely-located spectrographic instrumentation for analysis. The gas temperature is determined from the distribution of rotational populations represented in the Raman spectrum.

Introduction

SSME Optical Temperature Diagnostics

Temperature nonuniformity is one hypothesis advanced to explain the cracking encountered in the

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SSME fuel pump turbine blades. The development of modifications leading to more uniform temperature profiles would be greatly facilitated by a diagnostic capable of spatially-precise gas temperature measurements in the combustor. A non-intrusive technique is desired to prevent flow and measurement disturbances and to insure survival of the apparatus. These considerations suggest the use of optical methods for remote diagnostics.

Since the advent of high power and tunable lasers a number of optical diagnostic techniques have been developed[1-4]. Typically, each of the techniques possesses advantages and disadvantages with respect to a particular application. The objective of the study reported herein is the development of an optical system for temperature profiling measurements in the SSME preburner and similar rocket combustors[5]. This report details interim progress that has been made on the construction and testing of breadboard hardware.

Environment Considerations

A large fraction of the hydrogen flow reacts with a smaller fraction of the oxygen flow in the preburner to provide a hot gas stream to drive the propellant turbopumps. The gas temperature in the preburners is approximately 970 K (1750 R) at the nominal power level. Equilibrium calculations indicate that molecular hydrogen represents 89.4 percent of the burnt gases and water vapor 10.6 percent. Atomic hydrogen and hydroxyl radical concentrations are calculated to be less than 1 ppb.

A cross sectional view of the fuel preburner, presented in Fig. 1, shows the limited optical access available. Fuel and oxidizer are injected into the combustion chamber through the face plate. Located within the chamber are three baffles, and a liner, both of which are cooled by a supply of hydrogen. Two transducer ports in the chamber walls afford optical access to the combustion medium. These ports are located in a plane at the end of the baffles, and are positioned at 165 and 360 degrees with respect to the fuel inlet flange. Therefore optical access does not exist diametrically across the combustor. These restraints clearly favor single port optical techniques.

Other problems associated with measurements on a full scale operating rocket engine challenge the diagnostics designer. The engine may move in the test stand due to gimbaling and thrust loads. Prior to and during operation, a condensation cloud surrounds the engine and ice may form on engine parts near cryogenic propellant lines. Finally very high vibration and noise levels are experienced by any equipment near the engine.

As a final caveat, it should be pointed out that little is known about the optical properties of the flow in the combustor. Nonuniformities in the refractive index resulting from incomplete combustion and possible two-phase flow may be problematic. The magnitude of gas-phase density gradients due to turbulence or compressibility effects also are unknown.

Technique Selection

Several laser-optical techniques are available for remote pointwise temperature measurements[1-4] in combustion systems. Raman, fluorescence, and nonlinear optical techniques such as coherent anti-Stokes Raman spectroscopy (CARS) and stimulated Raman gain (SRG) have received the greatest attention, recently.

CARS and SRG[4] are are very powerful techniques when used with high power lasers because a coherent, beam-like radiation is produced which can be captured with high efficiency. However these techniques require line-of-sight optical access, limiting their use when such is not available.

Fluorescence[1,3,4] is the emission of light from an atom or molecule promoted to an excited state. In laser-induced fluorescence, emission takes place following the absorption of a laser photon. The hydroxyl radical is the only species in the preburner which is amenable to probing by existing laser sources. However its concentration is too low for practical measurements.

Raman scattering[6,7] is an inelastic scattering process in which an incident photon loses or gains a quantum of energy from the scatterer. Often Raman scattering is weak and easily overwhelmed by background luminosity or laser induced interferences in combustion systems because of the small scattering cross section ($\sim 10^{-31}$ cm^2/sR). Flame luminosity is small in O_2/H_2 combustion and particulates are absent. The high gas density offsets the small cross section. The technique can be used with a single access port and furthermore, as will be shown, appears to be feasible with relatively low laser power so that optical fibers may be used to transport the probe radiation to the preburner.

Raman System Performance

The diagnostic capabilities of a system employing Raman scattering can be estimated based on the flow conditions in the preburner and known Raman properties of molecular hydrogen. The determination of the temperature from Raman scattering proceeds from an analysis of the spectral distribution, i.e. the Raman intensity variation with wavelength.

Signal level

The Raman scattered power of a particular rotational component with quantum number J is related to the incident optical power P_L by

$$P_R = \left(\frac{2\pi\nu_J}{c}\right)^4 \frac{N_{vJ}}{2J+1} C_b S(J) f(J) P_L \qquad (1)$$

where ν_J is the Raman scattered frequency, N_{vJ} is the population of the sub-level, C_b is a factor which depends on the rigid rotator polarizability[8], S(J) is the rotational line strength and f(J) is a correction for the centrifugal distortion caused by vibrational-rotational interaction[9]. These factors are all known for hydrogen and are summarized in Ref. 5.

Temperature Measurements

The gas temperature is deduced from the distribution of intensity of the rotational sub-levels. The sensitivity of these rotational transitions to temperature is depicted in Fig. 2, which shows the intensity of transitions calculated for SSME preburner conditions. Two types of transitions or branches are shown as a function of Raman frequency shift. The lines grouped near zero frequency belong to pure rotational transitions, in which the rotational quantum number changes by 2 in the scattering process (+2 for the S-branch and -2 for the O-branch). Vibrational transitions representing the Q-branch ($\Delta v = 1, \Delta J = 0$) are shown shifted by about 4160 cm^{-1}. Temperatures would be determined by comparing measured spectra to theoretical distributions. Any of the branches shown could be used, but the rotational S-branch is the strongest. The frequencies in hydrogen are well separated enough (except possibly in the Q-branch band head) to make analysis by spectral integration across the line straightforward.

Ortho-Para Modifications

Molecular hydrogen exists in two modifications depending on the orientation of the nuclear spins of the two atoms[10]. At room temperature and higher hydrogen is 75 percent ortho, in which the two spins are aligned anti-parallel, but at the normal boiling point (20.4 Kelvin) hydrogen is 99.79 percent para, in which the spins are both in the same direction. The conversion to the high temperature composition is slow[11] and may not be complete in preburner combustion. In practice this means that the even J transitions, which are para will be more intense than the odd transitions, depending on the amount of spin conversion. In the analysis of the spectral data, the even and odd manifolds will need to be analysed separately, but should yield the same temperature.

Backscattering System Performance Estimate

The performance of diagnostics based on a Raman scattering system can be determined with respect to criteria established for a useful system. These specify a measurement with 1 cm spatial resolution, 10 millisecond temporal resolution, and a 6 Kelvin temperature accuracy. The existing optical access in the preburner determines the collection efficiency of the envisioned backscattering system in which the exciting laser and the collection of the Raman scattered radiation take place through the same window.

The results of calculations for the Raman spectral irradiance for realistic input conditions is shown in Fig. 3 for one of the lowest populated rotational levels. The laser intensity has been chosen to be typical of values which can be attained with current technology optical fibers. The Raman system is constrained to satisfy system spatial (0.5 - 1 cm) and temporal (10 millisecond) resolution design goals. Shown for comparison is a calculation of the thermal radiation from a solid with emissivity, ϵ. This may represent a hot wall or particles in the flow. Note that an an emissivity of 0.3 would typify a particle loading of 25 micrograms per cubic centimeter[12], a high level. Therefore Raman signals should exceed the background by large margins.

Raman System Design

The diagnostic system is conceived to consist of a high power laser, optical head mounted directly on the preburner, and a spectrograph/optical multichannel detector combination. The laser and the spectrograph/OMD would be located remotely, and would be joined to the head by optical fiber links. Figure 4 shows a schematic diagram of the apparatus. The design of the components is considered in this section. Currently these are being evaluated experimentally in a breadboard investigation.

Optical Fiber Link

The use of optical fibers is growing in a wide variety of applications. The use of optical fibers in the present application affords location of the more delicate instrumentation away from the high noise rocket environment, while at the same time the integrity of the optical beam is insured. The low power requirements of Raman scattering for this high pressure application permit this benefit.

Naturally the fiber must be capable of transmitting the laser without serious attenuation. Optical fibers possess excellent transmission characteristics in the near infrared region of the spectrum, having attenuations as low as 0.5 dB/km. Raman scattering is stronger for short wavelengths however, so that operation is desired away from the best transmission windows for the fiber. Attenuation in the fiber generally follows an inverse fourth power relation with wavelength because the dominant loss mechanism is Rayleigh scattering. Applying this scaling, good fiber attenuation factors, in the operating range of argon ion lasers being considered for this application, would be on the order of 20 dB/km.

The transmission of several commercially available multimode fibers has been measured. The results for fibers with core diameters of 100 microns are presented in Fig. 5. Measurements have been made on smaller fibers as well. The lowest attenuation observed is 32 dB/km for the 488 nanometer line of an argon-ion laser. The required length of the fiber is about 40 meters so that the transmission is expected to be on the order of 45 percent including Fresnel reflection losses at the ends of the fiber.

The failure of several fibers has been experienced. Melting at either end of the fiber has been observed, although typically the failure occurs by melting at the output end of the fiber. One fiber exhibited nonlinear transmission characteristics, perhaps due to stimulated Brillouin scattering.[13]

Optical Head

The function of the optical head is twofold. First is to take light from the laser and focus it at the measurement point in the preburner. Second is to collect Raman backscattered light and focus it into a fiber for transmission to the spectrometer/detector. The design of the optical head will define the measurement volume.

The design of the optical head is shown in Fig. 6. The beam from the laser is collimated and directed along the main optical axis of the head by a small prism. An intermediate lens brings the beam to a real focus and, finally, the focusing lens projects it into the measurement volume. The focusing lens collects the Raman backscattered light and focuses ultimately on an optical fiber. An absorptive glass filter can be used to block unshifted, scattered laser light. By moving either the intermediate lens or the focusing lens along the axis, the focal point of the laser can be changed so that this design can be used to probe points across the diameter of the combustor.

The optical head is forced by constraints of the preburner to operate at large f-numbers when viewing across the combustor. This increases the extent of the measurement volume along the axis, which determines the spatial resolution. It is desired to keep the resolution small, 0.5 to 1.0 cm. In a high f-number system, the on-axis rays contribute greatly to the sampling length. If the central rays are blocked the resolution can be improved.[14] The obscuration disk, shown in the figure, serves this purpose.

Measurements of the spatial resolution of an initial version of the head have been made by simulating Raman scattering in the measurement volume by a cell containing a dye that fluoresces in the incident laser light. The cell is thin (2 mm) in the direction of the axis and is translated along the axis to map out the spatial extent of the optical response. The results of these tests are in accord with the simple relation derived in Ref. 14:

$$\Delta \ell = 2(A + B) f / D_o \qquad (2)$$

Here A is the collecting aperture (the fiber core diameter), B is the diameter of the laser focal volume, f is the distance of the focal point from the focusing lens, and D_o is the diameter of the obscuration disk. Restricting the focusing lens to operate at an f-number of 25, corresponding to viewing completely across the preburner through a 1 cm clear aperture window, it can be shown that the spatial resolution is given by 19 Af/D_o. In order for the spatial resolution in this system to be less than 1 cm and the obscuration diameter no greater than 0.75 cm, the focal distance must be restricted to less than 4 cm. Although this may be acceptable for some measurements, other configurations using off-axis illumination and affording better resolution with less restriction will be sought.

Spectrograph

The spectrograph used to disperse the Raman signal for analysis must couple efficiently to the optical fiber. This requires fast (large aperture) optics in the instrument. Recently fast holographic gratings have been developed to couple to a fiber (f/3) dispersing the radiation onto a flat-field required by an optical multichannel detector. The spectrograph is designed with a dispersion of 2.5 nm/mm, so that the entire rotational branch will be spread over the central portion of the optical multichannel detector. Figure 7 shows a schematic of the spectrograph.

High Pressure Simulation Tests

The diagnostic capabilities of the Raman backscattering system will be evaluated by testing with a high pressure hydrogen cell simulating conditions in the preburner. The electrically heated cell, shown in Fig. 8, can be heated to 1000 K and may be pressurized to 6000 psia. The 1 cm diameter by 25 cm length duplicates the optical access of the preburner combustor. A metallic plug can be inserted into the cell to simulate the preburner liner.

Summary

The feasibility of remote optical diagnostics in the SSME fuel preburner has been investigated.[5] The use of the laser Raman technique in a back-scattering configuration appears to have the best chance of meeting program objectives. The system would have radiation from a nominal 10 Watt argon ion laser, propagate through an optical fiber to an optical head attached to the combustor. The optical head will collect Raman scattered light and couple it into another fiber for transmission to analysis equipment. The optical head will require additional refinement to achieve 1 cm spatial resolution over distances greater than 5 cm.

It appears feasible to focus 4 to 5 Watts of optical power from the exit of the first fiber, and make temperature measurements in about 10 milli-seconds. Additional development of the head optics will better determine any trade-offs which may be required in the program goals.

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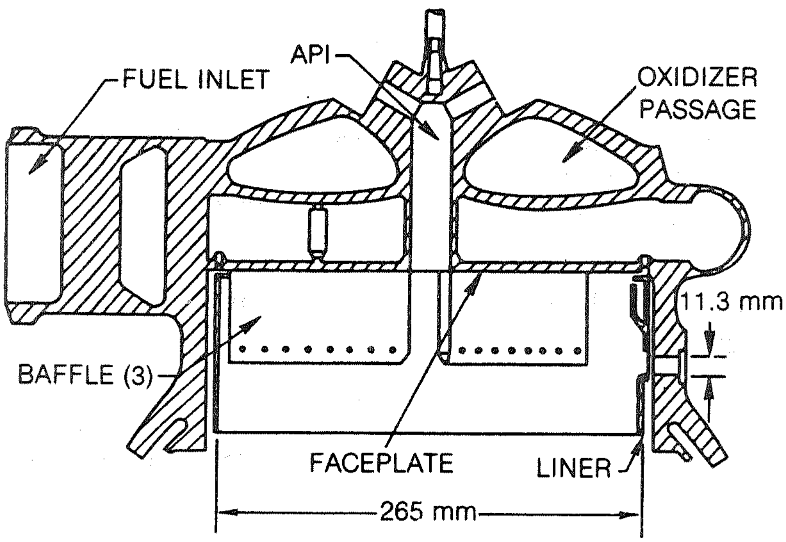

Figure 1 - Cross section view of SSME fuel preburner. The transducer are ports at 165° and 300°.

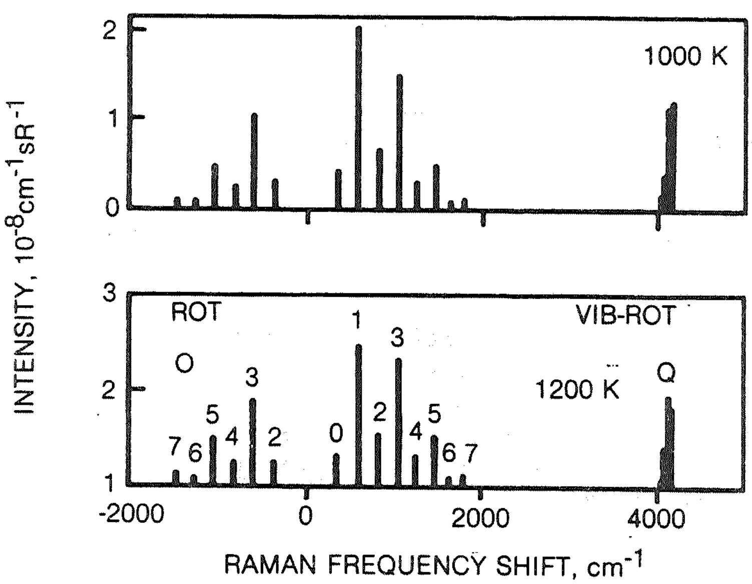

Figure 2 - Temperature dependence of calculated Raman spectra. Pressure = 5500 psia.

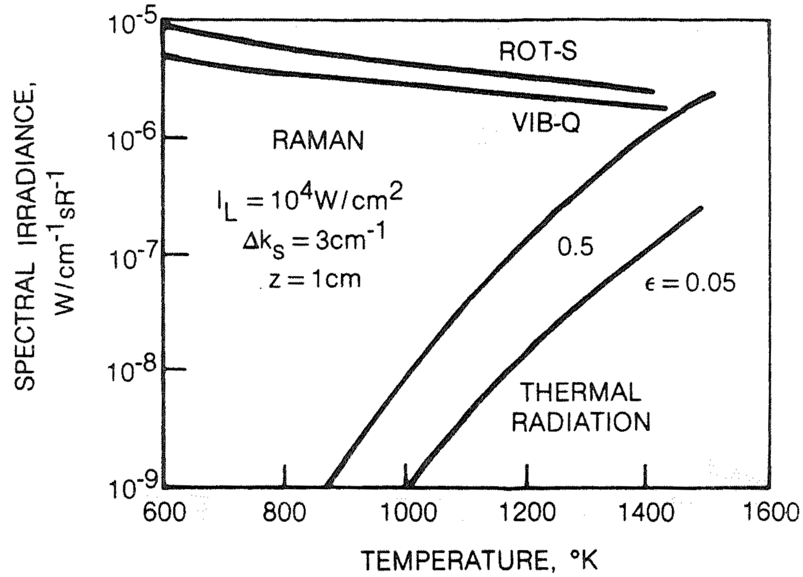

Figure 3 - Comparison of predicted Raman and thermal radiation irradiances.

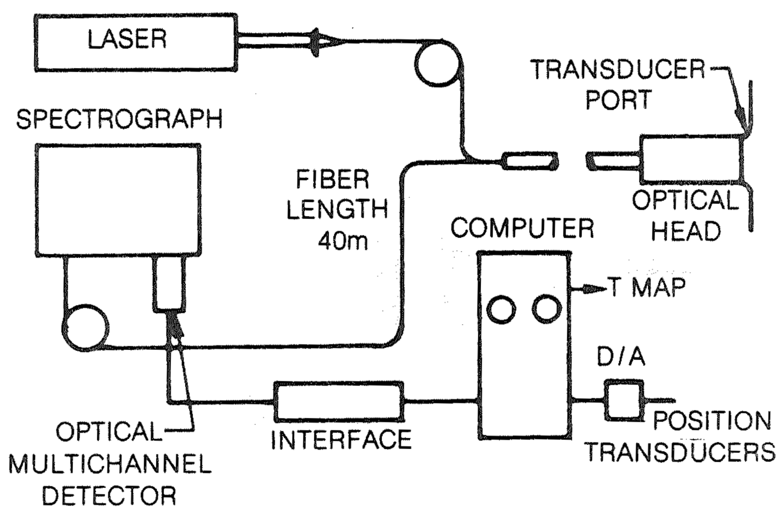

Figure 4 - Schematic diagram of the Raman back-scattering diagnostics system.

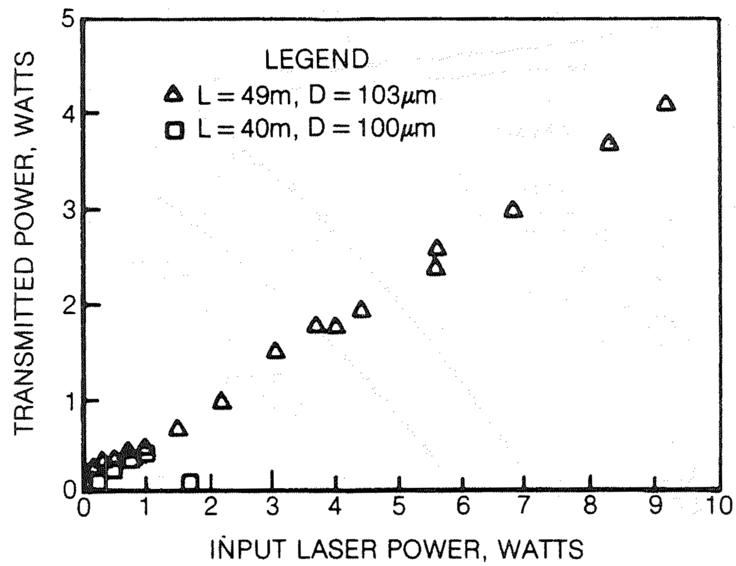

Figure 5 - Optical fiber transmission test results. Laser wavelength 488 nm line of Ar^+.

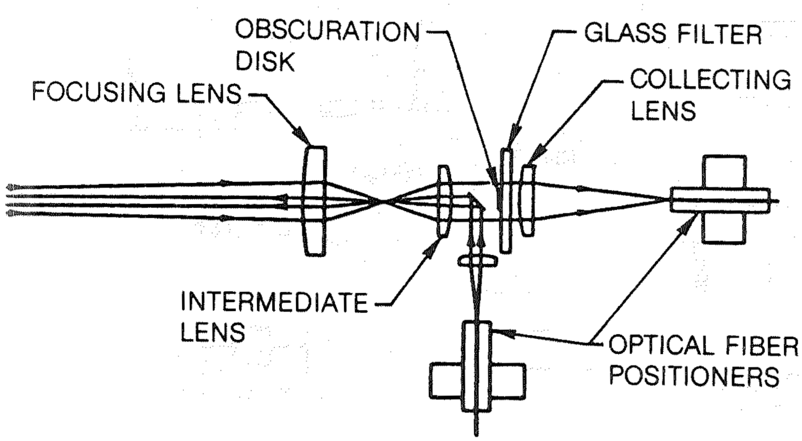

Figure 6 - Optical head design.

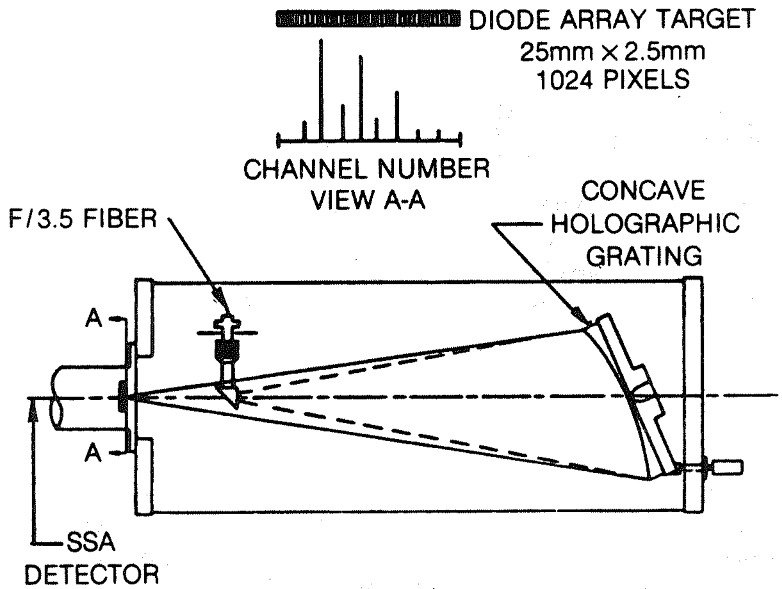

Figure 7 - Raman spectrograph designed for use with optical fiber.

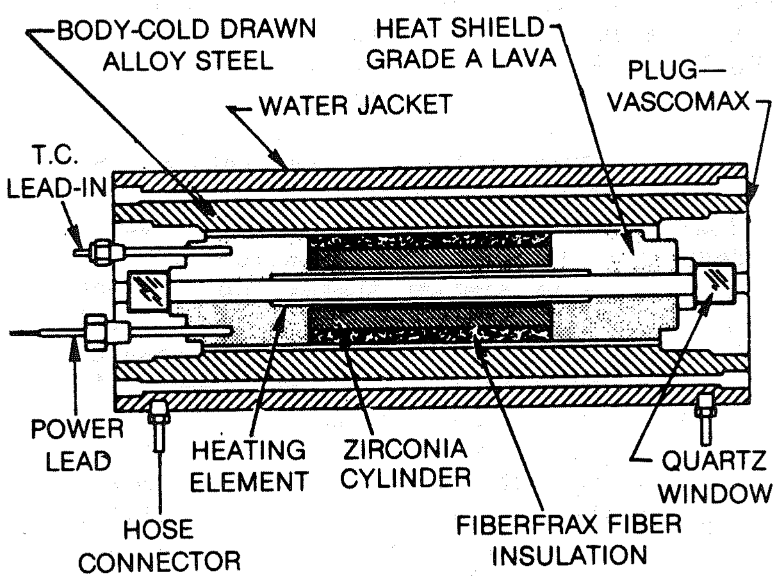

Figure 8 - Internally heated high presure cell for Raman diagnostics testing. Operating conditions: 1300 K, 6000 psia.