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L-910905-13

Investigation of Gaseous Nuclear Rocket
Technology --- Summary Technical Report

NASA Contract No. SNPC-70

U
A
UNITED AIRCRAFT CORPORATION

United Aircraft Research Laboratories

EAST HARTFORD, CONNECTICUT

United Aircraft Research Laboratories



EAST HARTFORD, CONNECTICUT 06108

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DATE September 1972

NO. OF PAGES 113

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FOREWORD

An exploratory experimental and theoretical investigation of gaseous nuclear rocket technology was conducted by the United Aircraft Research Laboratories under Contract SNPC-70 with the joint AEC-NASA Space Nuclear Systems Office. The Technical Supervisors of the Contract for NASA were Captain C. E. Franklin (USAF) of SNSO for the initial portion of the Contract performance period, and Dr. Karlheinz Thom of SNSO and Mr. Herbert J. Heppler of the NASA Lewis Research Center for the final portions. The following nine reports (including the present report) comprise the required Final Technical Report under the Contract:

1. Roman, W. C. and J. F. Jaminet: Development of RF Plasma Simulations of In-Reactor Tests of Small Models of the Nuclear Light Bulb Fuel Region. United Aircraft Research Laboratories Report L-910900-12, September 1972.
2. Klein, J. F.: Nuclear Light Bulb Propellant Heating Simulation Using a Tungsten-Particle/Argon Aerosol and Radiation from a DC Arc Surrounded by a Segmented Mirror Cavity. United Aircraft Research Laboratories Report L-910900-13, September 1972.
3. Jaminet, J. F.: Development of a Model and Test Equipment for Cold-Flow Tests at 500 Atm of Small Nuclear Light Bulb Configurations. United Aircraft Research Laboratories Report L-910900-14, September 1972.
4. Kendall, J. S. and R. C. Stoeffler: Conceptual Design Studies and Experiments Related to Cavity Exhaust Systems for Nuclear Light Bulb Configurations. United Aircraft Research Laboratories Report L-910900-15, September 1972.
5. Rodgers, R. J. and T. S. Latham: Analytical Design and Performance Studies of the Nuclear Light Bulb Engine. United Aircraft Research Laboratories Report L-910900-16, September 1972.
6. Latham, T. S. and R. J. Rodgers: Analytical Design and Performance Studies of Nuclear Furnace Tests of Small Nuclear Light Bulb Models. United Aircraft Research Laboratories Report L-910900-17, September 1972.
7. Krascella, N. L.: Spectral Absorption Coefficients of Argon and Silicon and Spectral Reflectivity of Aluminum. United Aircraft Research Laboratories Report L-910904-3, September 1972.

8. Palma, G. E.: Measurements of the UV and VUV Transmission of Optical Materials During High-Energy Electron Irradiation. United Aircraft Research Laboratories Report L-990929-3, September 1972.
9. Kendall, J. S.: Investigation of Gaseous Nuclear Rocket Technology -- Summary Technical Report. United Aircraft Research Laboratories Report L-910905-13, September 1972. (Present Report)

Report L-910905-13

Investigation of Gaseous Nuclear Rocket Technology ---
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Investigation of Gaseous Nuclear Rocket Technology ---
Summary Technical Report

SUMMARY

The nuclear light bulb engine concept is based on the transfer of energy by thermal radiation from gaseous nuclear fuel contained within a neon vortex, through an internally-cooled transparent wall, to hydrogen propellant seeded with tungsten to increase its opacity. Such an engine offers the possibility of specific impulses between 1500 and 3000 sec, thrust-to-engine-weight ratios greater than one, and containment of the gaseous nuclear fuel without loss of fuel and fission products in the exhaust from the engine.

The experimental and theoretical investigations conducted under Contract SNPC-70 during the period from September 1969 through September 1972 were directed toward obtaining information necessary to determine the feasibility of the full-scale nuclear light bulb engine, and of small-scale nuclear tests involving fissioning uranium plasmas in a unit cell installed in a driver reactor, such as the Nuclear Furnace. A large portion of the research employed the UARL 1.2-MW rf induction heater and dc arc heater in tests designed to simulate many of the problems which are inherent in a full-scale engine. Emphasis was also placed on development of rf simulations of conditions expected in nuclear tests in the Nuclear Furnace. The work under the contract has included investigations of the following: (1) the fluid mechanics and containment characteristics of one-component and two-component vortex flows, both unheated and rf-induction heated; (2) heating of particle-seeded streams by thermal radiation from a dc arc to simulate propellant heating; (3) condensation and separation phenomena for metal-vapor/heated-gas mixtures to provide information for conceptual designs of components of fuel exhaust and recycle systems; (4) the characteristics of the radiant energy spectrum emitted from the fuel region, with emphasis on definition of fuel and buffer-gas region seed systems to reduce the ultraviolet radiation emitted from the nuclear fuel; and (5) the effects of nuclear radiation on the optical transmission characteristics of transparent materials. In addition, analytical studies were conducted to interpret the results of these investigations in terms of the requirements for full-scale engines and in-reactor tests.

Work under this contract has resulted in the issuance of twenty-three technical reports. The present report summarizes key results discussed in these reports and provides information which permits cross-referencing between reports.

INTRODUCTION

A number of different gaseous nuclear rocket concepts have been proposed over the past fifteen years, and many investigations have been conducted to provide the basic technological information required to evaluate these concepts. Most work on gaseous nuclear rocket technology is now directed toward two concepts: the coaxial-flow engine and the nuclear light bulb engine. The primary problems associated with both types of engines are concerned with containment of gaseous nuclear fuel in a cavity and with the transfer of heat by thermal radiation from the fuel to the propellant working fluid. Containment and heat transfer must be accomplished in a manner such that conventional materials and cooling techniques may be used in the containment vessel and exhaust nozzle.

The present prime application for the nuclear light bulb is in the field of advanced propulsion for space. However, attractive possibilities may exist for other applications of reactors of this type. Those being considered include use in MHD electrical power generation, use as large high-temperature gas heaters for applications requiring temperatures higher than those achievable by combustion, use in photo-chemical processing, and use as a photon source for optically pumped lasers. Preliminary analyses of the potential use of a nuclear light bulb reactor as a breeder are also encouraging.

Research on the characteristics of gaseous nuclear rockets has been carried out at a number of Government laboratories (notably at the NASA Lewis Research Center, the Jet Propulsion Laboratory, Aerospace Corporation, the AEC Oak Ridge National Laboratory, and the Los Alamos Scientific Laboratory) and at several industrial research laboratories. The largest current research effort in a Government laboratory is at the NASA Lewis Research Center; this organization has concentrated on investigations related to the coaxial-flow reactor concept. The largest research effort in an industrial laboratory is at the United Aircraft Research Laboratories; since 1967, this organization has concentrated primarily on investigations related to the nuclear light bulb concept. In the nuclear light bulb concept, the fuel is contained in a neon vortex and there is an internally-cooled transparent wall between the fuel region and the propellant region. Because of this physical barrier between the fuel and propellant, the nuclear light bulb offers the unique possibility of perfect containment of fuel and fission products.

The research under Contract SNPC-70 was directed primarily toward investigations to simulate problems inherent in the full-scale engine. Major emphasis was placed on development of intense rf plasma radiant energy sources having fluxes which approximate that of a full-scale engine, maintaining internally-cooled transparent walls as close as possible to the radiant energy source, and demonstrating that

seeded simulated propellant can be heated to very high temperatures by thermal radiation passing through a transparent wall. These activities were carried on throughout the entire Contract period. In the latter part of the Contract period increasing emphasis, especially in the fuel region research portion of the program, was placed on development of rf plasma simulations of test conditions expected in small-scale Nuclear Furnace in-reactor tests. The program also included analytical studies of radiant heat transfer, engine kinetics, engine start-up and shut-down, and in-reactor tests in the Nuclear Furnace.

The technical results obtained under Contract SNPC-70 are reported in Refs. 1 through 23. The SUMMARY sections of these reports are reproduced in the Appendix of the present report. In addition, Table I indicates the category of technical information contained in each of these reports. Publications in technical journals and presentations at technical meetings which have resulted from work conducted under Contract SNPC-70 are given in Refs. 24 through 40.

Work on gaseous nuclear rocket technology at the United Aircraft Research Laboratories has been conducted under seven contracts other than Contract SNPC-70. These contracts were: Contracts NASw-768 and NASw-847 with the joint AEC-NASA Space Nuclear Propulsion Office; Contracts NAS3-13446, NAS3-13459, and NAS3-3382 with the NASA Lewis Research Center; and Contracts AF 04(611)7448 and AF 04(611)8189 with the U. S. Air Force Rocket Propulsion Laboratory at Edwards Air Force Base. Results obtained under these contracts are described in Refs. 41 through 109. Key technical areas covered in these reports are also indicated in Table I. In addition, research on gaseous nuclear rockets and their applications has been conducted under United Aircraft's Corporate-sponsored program. Reference 110 is the most recent report issued under this program.

The following sections of the present report describe some of the key results obtained during the course of work under Contract SNPC-70.

DESIGN, PERFORMANCE AND OPERATING CHARACTERISTICS
OF NUCLEAR LIGHT BULB ENGINE

A small fraction of the total effort under Contract SNPC-70 has been devoted to a continuation of studies of the design and performance characteristics of full-scale nuclear light bulb engine configurations. A reference engine configuration was developed as part of work performed previously under Contract NASw-847 (see Ref. 61). The present studies were conducted to provide additional information on design and performance characteristics of this reference engine.

Principle of Operation

Sketches illustrating the principle of operation of the nuclear light bulb engine are shown in Fig. 1. The overall engine is composed of seven unit cavities. Each cavity (Fig. 1(b)) contains a region of hot gaseous nuclear fuel and a region of hydrogen propellant seeded with tungsten particles; the two regions are separated by the internally-cooled transparent wall. Thermal radiation from the fuel region raises the propellant to a bulk exit temperature of about 6660°K . The fuel is isolated from the transparent wall by neon buffer gas injected from the wall to drive the vortex. A hot gaseous mixture of buffer gas, fuel and fission products exhausts through a thru-flow port located at the center of one end wall; the mixture then enters a fuel recycle system. In the thru-flow exhaust duct, the gaseous uranium entrained in the neon is condensed to liquid form by the addition of cold neon, is centrifugally separated from the neon, and is pumped back into the fuel region.

Design, Performance and Operating Characteristics

A detailed layout of the reference nuclear light bulb engine design is presented in Fig. 2. Each of the seven unit cavities has a length of 1.8 m. The total volume of all seven cavities is 4.8 m^3 , equal to that of a single cylinder having a diameter of 1.8 m and a length of 1.8 m. The total amount of fuel contained within the seven cavities is approximately 14 kg and the power is 4600 MW. The critical mass of 14 kg is less than that for a single cavity reactor because of the beneficial effects of the moderating walls between the unit cavities (see Fig. 1(a)). The total pressure in the cavity of the reference engine is 500 atm. The propellant flow (including seed and nozzle transpiration coolant flow) of 22.4 kg/sec is heated to a temperature of 6660°K , which will provide a specific impulse of 1870 sec. The resulting engine thrust is 409,000 N. The total weight, exclusive of shielding, is estimated to be 37,250 kg and is made up of the following component weights: moderator (graphite and beryllium oxide), 12,250 kg; pressure vessel, 13,600 kg; space radiator, 5500 kg; turbopumps, 1350 kg; and miscellaneous components, including fuel recycle system, 4550 kg.

A schematic diagram of the flow circuits of the reference nuclear light bulb engine is shown in Fig. 3. The primary hydrogen propellant, prior to being heated by thermal radiation from the fuel region, is used to cool the neon and fuel circuit flow and part of the secondary hydrogen circuit flow. The neon discharging from the cavity, along with entrained fuel and fission products, is cooled in the fuel exhaust duct by mixing with low-temperature neon, thus causing condensation of the nuclear fuel to liquid form. The liquid fuel is centrifugally separated from the neon and pumped back to the vortex region through the fuel injection circuit. The neon is further cooled by rejecting heat to the primary hydrogen propellant and is then pumped back into the vortex. A space radiator (also used for afterheat removal) is used to reject a portion of the heat from the secondary hydrogen circuit. The secondary hydrogen circuit is used to cool the pressure vessel, exhaust nozzle, cavity components such as the flow divider and liner tubes, and the transparent wall. The space radiator loop has a total flow rate of hydrogen of 19.3 kg/sec and rejects approximately 2.5 percent of the total engine power. The total neon flow rate required for the engine is 98.7 kg/sec, and the total fuel flow rate is 3.5 kg/sec.

The specific impulse of the nuclear light bulb engine is greater than those of chemical rockets and solid-core nuclear rockets because of the higher propellant exit temperature. This increased propellant exit temperature is attributable to the high radiant heat flux from the fuel --- equivalent to that from a black body radiating at 8330°K.

One limitation on the specific impulse which can be obtained from the nuclear light bulb engine arises because not all of the energy deposited in the propellant is transferred by thermal radiation. Instead, some is transferred by conduction and convection, due to several mechanisms of heat loss from the fuel region. The effects on specific impulse of changes in the propellant inlet temperature and in the fraction of the energy transferred to the propellant by thermal radiation are shown in Fig. 4. The values of specific impulse shown in Fig. 4 are 84 percent of the ideal specific impulse corresponding to the hydrogen propellant exit temperature. The 16 percent reduction from the ideal specific impulse results from allowances made for effects of (1) finite exhaust nozzle area ratio, (2) transpiration coolant flow in the exhaust nozzle, (3) propellant seeds (on propellant density), and (4) friction and recombination losses in the exhaust nozzle. For the reference engine configuration, the propellant inlet temperature is 2264°K and approximately 85 percent of the total energy deposited in the propellant would be transferred to the propellant by thermal radiation.

If the propellant inlet temperature were raised to 3000°K (near the upper limit for the material walls of the moderator portion of the engine) and the percent energy transferred by radiation remained at 85 percent, the specific impulse would be raised from 1870 sec to about 2200 sec. One technique by which specific impulse

could be increased is by the use of space radiators to reject a greater portion of the waste heat from the engine. However, the use of a space radiator results in a weight penalty which must be considered in the overall coolant circuit design. As shown in Fig. 3, a space radiator is included in the present reference engine design for rejection of approximately 118 MW deposited in the secondary hydrogen circuit and for rejection of afterheat following engine shutdown.

To supplement the design and performance studies, engine dynamics studies were also conducted. These considered the characteristics of the engine during start-up, full-power operation, and shutdown; the dynamic behavior at nominal full-power operating conditions; and conceptual designs of systems to control the reactor during the various phases of operation. A UNIVAC 1108 digital computer simulation program was used to determine the dynamic response of the engine to perturbations during steady-state operation and to investigate the responses of the engine with different control concepts. Detailed discussions of the results are presented in Refs. 5, 12, and 20. Discussions of the start-up characteristics of the engine and conceptual control system designs are included in Ref. 20. Shutdown characteristics and additional work on control system concepts are described in Ref. 12.

The primary conclusion from these engine dynamics studies is that satisfactory control of the engine can be achieved by varying the fuel injection control valve area (hence, fuel injection rate) using feedback from detectors sensing the difference between the desired steady-state neutron flux level in the reactor and the instantaneous neutron flux level. Typical responses of the controlled reference engine to step changes in fuel injection control valve area are shown in Fig. 5. Responses to perturbations in reactivity, exhaust nozzle area, turbopump wheel speed and fuel cloud radius were also investigated. The calculated response of the controlled engine to these perturbations are in the form of small oscillations in engine power which rapidly damp and converge to a new steady-state value, or which oscillate with a long period within prescribed control limits.

DESIGN, PERFORMANCE AND OPERATING CHARACTERISTICS
OF MODEL FOR NUCLEAR FURNACE TESTS

The next major step in determining nuclear light bulb concept feasibility is a series of demonstration tests in which the rf and dc arc plasmas used as radiant energy sources in the simulation tests described herein would be replaced by a fissioning uranium plasma as the energy source for thermal radiation. In such tests, a small-scale nuclear light bulb model would be placed within the core of a driver reactor. The neutron flux from the driver reactor would be used to create fission energy within the fuel region of the test model. Results of studies described in Refs. 6 and 13 indicate that the Nuclear Furnace, the solid-core fuel element test reactor designed and fabricated at Los Alamos Scientific Laboratories and operated at the Nuclear Reactor Development Station, is well suited for such tests.

Figure 6 is a sketch of the Nuclear Furnace reactor assembly and associated test equipment. The assembled reactor is shown mounted on a test car which is used to transport the reactor from the assembly area to the test cell. A removable bell-type shield surrounds the reactor pressure vessel during tests. The Nuclear Furnace is a hydrogen-cooled reactor and all test effluent is handled in a specially constructed scrubber system. The design power level of the present Nuclear Furnace assembly is 44 MW. It should be possible to increase the reactor power level by about 50 percent, up to its original design power level, with core modifications and additional coolant flow. For in-reactor tests of a small nuclear light bulb model, it would be desirable to have at least some of this increase available (see Ref. 6).

To form the test region, the four central fuel elements would be removed from the Nuclear Furnace core. An 8.4-cm-i.d. aluminum casing would be installed along the core centerline to form the test region.

Three model designs have evolved, representing three levels of complexity: (1) a unit cell with a reflecting peripheral wall; (2) the same cell with a segment of fused silica transparent wall over part of the peripheral wall; and (3) a cell with a transparent wall and a simulated propellant heating duct. Figure 7 is a preliminary layout of a test cell geometry of the first type, which is the configuration recommended for initial in-reactor tests. Argon buffer gas is introduced into the 6.6-cm-i.d. by 17.8-cm-long cylindrical cavity region through four buffer-gas injector tubes to drive the vortex. Fuel is injected on the centerline at the centers of both end walls. The fuel used in initial in-reactor tests would probably be uranium hexafluoride. It is possible that in later tests, solid uranium particles or other solid uranium compounds might also be used. The mixture of argon buffer gas, uranium fuel and fission products exits the cavity through exhaust ports located at the centers of the end walls. The peripheral walls of the cavity region will be highly reflective to thermal radiation from the fuel region. It is desirable to

reflect as much of the thermal radiation emitted from the fissioning plasma as possible so that the edge temperature of the plasma is greater than the condensation temperature corresponding to the uranium partial pressure in the edge-of-fuel region. This will insure that the uranium remains in vapor form at the boundary of the fissioning plasma.

The total power level in these initial tests will be a function of the cavity pressure, the amount of fuel contained, and the specific fission power of the driver reactor. Calculated in-reactor test performance (from Ref. 6) is shown in Fig. 8. Results are shown for test region pressures of 50, 200, and 500 atm for a range of specific fission powers from 0 up to 500 kW/g of U_{235} . This range encompasses levels that might be obtained in several different test reactors. The range achievable in the Nuclear Furnace reactor is between 25 and 40 kW/g. For a test region pressure of 500 atm and a specific fission power of 30 kW/g, the equivalent black-body radiating temperature of the plasma would be 3330°K ; approximately 190 kW of fission power would be generated in the plasma, and the edge temperature of the plasma would be approximately 5130°K . For the performance indicated in Fig. 8, a liner (test region peripheral wall) reflectivity of 0.91 was assumed and it was further assumed that the containment density ratio, ρ_F/ρ_{B6} (equal to the volume-averaged density of fuel within the test region divided by the density of the argon buffer gas at the edge of the fuel region), was equal to 0.6. Results of isothermal containment experiments indicate it should be possible to operate the plasma with a value of this containment ratio approaching one.

Of the reactors indicated in Fig. 8, only the Nuclear Furnace is likely to be available in late 1975 when these tests could be conducted. The Fissioning Uranium Plasma Facility (FUPF), which is presently in the conceptual design stage at the NASA Lewis Research Center, is not expected to be available until 1978-1980. The High-Flux Isotope Reactor (HFIR) at Oak Ridge is not suitable operationally for this type of test as presently configured; a new reactor of this design, with suitable modifications, is not considered a practical alternative. The Kinetic Intense Neutron Generator (KING) at Los Alamos is presently in the design stage and its future availability is uncertain.

FLUID MECHANICS RESEARCH

Fluid mechanics investigations conducted under Contract SNPC-70 have been concerned with: (1) containment of simulated fuel in vortices, as in the fuel region in a nuclear light bulb engine; (2) development of rf plasma radiant energy sources that provide high steady-state radiant energy fluxes, similar to those expected for full-scale engines and small-scale Nuclear Furnace tests; (3) development and cold-flow testing at 500 atm of a model of a Nuclear Furnace test cell for use in future rf plasma tests at high pressures; (4) development of techniques for fabrication of internally-cooled transparent-wall models, and tests of these models adjacent to the rf plasma radiant energy source; and (6) exploratory tests and conceptual designs of components for handling of effluent exhaust from the nuclear light bulb engine configuration and from the Nuclear Furnace in-reactor test model.

Isothermal Vortex Tests

The objective of these tests was to investigate the fluid dynamic containment characteristics of isothermal, two-component vortex flows. Primary emphasis was placed on establishing flows similar to those expected in the full-scale reference engine. All but a few of the tests were conducted using the high Reynolds number test facility described in Ref. 17. The test configuration consisted of a 25-cm-i.d. by 76-cm-long vortex chamber. Air (simulated buffer gas) was injected through the peripheral wall to establish a radial-inflow vortex. A mixture of nitrogen and iodine (simulated fuel) was injected axially through the end walls of the vortex chamber. The iodine was used as a trace gas to allow the concentration distribution of simulated fuel within the vortex to be measured by a light absorption technique.

Figure 9 shows a partial pressure distribution with a large amount of simulated fuel stored --- an amount which exceeds the level assumed in reference engine design analyses (shown by the dashed line). For the data shown in Fig. 9, the average value of simulated-fuel partial pressure divided by the peripheral wall static pressure is 0.52, compared with 0.25 used in the reference engine design. The results of these tests confirmed that high simulated-fuel partial pressures can be obtained with steep concentration gradients in the edge-of-fuel region.

Isothermal vortex tests were discontinued after it was demonstrated that a value of volume-averaged simulated-fuel partial pressure in excess of that desired for the reference engine could be achieved. Emphasis in the program was then placed on development of capability for rf simulation of nuclear fissioning plasmas similar to those expected in the nuclear light bulb engine and in-reactor tests.

RF-Heated Vortex Tests

Large-scale nuclear tests of gaseous nuclear rocket concepts will be undertaken only after a definitive series of small-scale tests have been completed at temperatures and heat fluxes similar to those expected in a full-scale engine. For the nuclear light bulb, the integrity of key components, such as the thin, internally-cooled transparent walls, must be demonstrated in the presence of a high radiant heat flux. The rf-induction-heated plasma is a good analog to the fissioning plasma; as in the fissioning plasma, energy is added directly to the central portion of the test region (unlike arcs with energy addition to boundary layers adjacent to electrodes).

High-Intensity Radiant Energy Source Tests

Major emphasis under Contract SNPC-70 was placed on conducting tests with rf-heated vortices to simulate nuclear fuel region characteristics of the nuclear light bulb engine and in-reactor test configurations. The UARL 1.2-MW rf induction heater used in these tests was developed under a Corporate-sponsored program.

Initially, tests were directed toward development of a high-intensity plasma energy source having a radiant energy flux in the range of interest for nuclear light bulb engines (corresponding to equivalent black-body radiating temperatures from 4500 to 8500°K). The test configuration used is shown in Fig. 10. The source was 5-cm long and was located between 2-cm-diam end walls which formed the axial boundaries of the test region; the plasma was generally smaller in diameter than the end walls (Fig. 10). Argon was used to drive the vortex from the end walls.

The highest power level achieved in tests with this configuration was 223 kW at a chamber pressure of 7 atm. A breakdown of the power deposition with respect to radiation and end-wall heating is also shown in Fig. 10.

Figure 11 is a summary of the radiant flux data obtained in the tests. Fluxes up to 7.6 kW/cm² (based on the plasma surface area) were achieved; the equivalent black-body radiating temperature was 6040°K. The highest radiant flux was achieved at a test region pressure of 16 atm at a total discharge power of 160 kW.

The results shown in Fig. 11 indicate that radiant energy fluxes well into the range of interest for nuclear light bulb engines were achieved. Moreover, no limitations were encountered which would prevent attaining higher fluxes with improvements in the test configuration and peripheral equipment.

In-Reactor Simulation Tests

Research was also conducted to develop configurations and techniques necessary to simulate Nuclear Furnace in-reactor test conditions. The long range objective

of this research is to conduct an rf plasma simulation test with simulated-fuel injection into the plasma at a pressure of 500 atm and a power level of approximately 200 kW (the approximate power in Nuclear Furnace tests).

The two types of test configurations shown in Fig. 12 were developed and tested. The configuration for tests with simulated-fuel injection shown in Fig. 12(a) had a 15.5-cm-long by 5.7-cm-diam test region. A transparent fused silica pressure vessel was used which allowed observations of the plasma to be made. The configuration in Fig. 12(b) was similar except that it had an opaque filament-wound pressure vessel and it did not have provisions for simulated-fuel injection.

Tests Without Simulated-Fuel Injection

As discussed in Ref. 1, tests employing the configuration in Fig. 12(a) have been conducted at pressure levels up to 42 atm and power levels up to 180 kW. Figure 13 shows representative data obtained using the configuration in Fig. 12(a). Also shown is the range of radiant energy flux levels expected in Nuclear Furnace tests. In the rf tests, radiant energy fluxes approaching 2 kW/cm^2 , or equivalent black-body radiating temperatures approaching 4300°K , were achieved. This flux is significantly higher than the flux expected in the in-reactor tests. However, because the diameter of the plasma was smaller than that expected in the in-reactor test, the total power levels achieved were in general lower than the power level expected in the small-scale nuclear tests. In tests at chamber pressures greater than approximately 20 atm, between 75 and 80 percent of the total power deposited into the plasma was radiated.

Tests With Simulated-Fuel Injection

For some tests, tungsten particles were injected as simulated fuel along the test region centerline (Ref. 1; also, Fig. 12(a)). Dilute mixtures of uranium hexafluoride were also injected in other tests. Figure 14 is a photograph taken during a test with uranium hexafluoride simulated-fuel injection. Results to date have been encouraging in that with simulated-fuel injection, the amount of wall coating due to simulated-fuel deposition on the peripheral wall has been small. Additional tests are required to investigate the factors which limit containment of larger amounts of simulated fuel. A specific objective of future tests must be to contain an amount of simulated fuel equivalent to that eventually required in the Nuclear Furnace tests; at a pressure of 500 atm, this would be 6.2 g.

Tests With Filament-Wound Pressure Vessels

The test configuration shown in Fig. 12(b) was developed to provide information for future tests at very high pressures. This configuration is self-contained and employs a filament-wound fiberglass tube as a pressure vessel. It is necessary to

use the filament-wound pressure vessel at pressures greater than 40 to 50 atm to provide adequate strength and to insure that the rf energy is coupled efficiently through the test chamber walls into the plasma region. The long range objective of tests with filament-wound pressure vessel configurations must be to operate the rf plasma at a pressure of 500 atm and provide the capability required to fully mock-up the Nuclear Furnace test conditions in rf tests.

In tests of the model shown in Fig. 12(b), the highest pressure reached was 43 atm and the highest power was 203 kW. These levels were limited by facility considerations. The radiant heat fluxes and plasma power levels that were obtained were similar to those obtained in tests with the fused silica pressure vessel configuration, Fig. 12(a). In future tests at higher pressures, the filament-wound test configuration can be used. Improved methods must be developed to make measurements and to observe the plasma characteristics because the pressure vessel is opaque. The results of these rf-heated vortex tests are encouraging and indicate, once suitable simulated-fuel containment is demonstrated, that a basic test chamber design similar to that shown in Fig. 12(b) could be adapted for use in Nuclear Furnace tests.

In preparation for future rf plasma tests at 500 atm, a model and test equipment compatible with the UARL 1.2-MW rf induction heater were developed. Cold-flow tests employing the in-reactor test configuration shown in Fig. 15 were conducted at pressures up to 510 atm. This model was designed to withstand both the 500-atm pressure environment and the 200-kW power level in future plasma tests. The test configuration details are discussed in Ref. 3. The vortex was produced within the test region by injection of argon through seven injectors located in end walls similar to those shown in Fig. 12(b). Cooling water was circulated along the thru-flow ducts, in the end walls, and in an annular region between the silicone rubber pressure vessel liner and the inner 6.6-cm-diam fused silica tube. The pressure across the fused silica tube was balanced with that of the test region by means of an accumulator. With the addition of heat exchangers and additional piping in the cooling water and gas supply lines, this model and associated equipment will be available for use with the 1.2-MW rf induction heater.

Transparent-Wall Models

The objectives of the transparent-wall model research were to develop techniques for fabrication of transparent structures similar to those which might be employed in the nuclear light bulb engine, and to test these models adjacent to the high-intensity rf radiant energy source to determine their operating limits.

Models similar to that shown in Fig. 16 have been tested in the 1.2-MW rf induction heater up to a plasma power level of 193 kW with a test chamber pressure of 35 atm (see Fig. 17 and Ref. 3). The model was operating satisfactorily at this test condition when an arc occurred in the test tank, causing plasma extinguishment and damage to some of the model tubes.

For the model shown in Fig. 16, the axial-coolant tube wall thickness was 0.125 mm. The diameter and wall thickness of these tubes are approximately equal to those employed in the reference engine configuration. The plasma characteristics obtained in tests with these models were similar to those obtained in the previously described high-intensity radiant energy source tests; that is, the plasma radiation efficiency was approximately 75 to 80 percent (based on plasma surface area) and the discharge diameter was approximately 2 cm. Values of radiant energy flux incident on the model wall up to approximately 1.4 kW/cm^2 were obtained in these tests. This radiant energy flux is less than that expected in the reference nuclear light bulb engine (about 23 kW/cm^2); however, it is greater than the level of approximately 0.4 kW/cm^2 which is expected in a small-scale nuclear test such as that described in Ref. 6.

As discussed in Ref. 5, the total energy deposition rate in the reference engine transparent walls due to the effect of absorption of thermal radiation, absorption of nuclear radiation, conduction from the buffer gas, and convection from the propellant stream is 54.5 MW. The equivalent surface heat flux (based on the total surface area of the transparent-wall tubes of $6.0 \times 10^5 \text{ cm}^2$) is 90 W/cm^2 . For the highest power transparent-wall model test (see Fig. 16), the total energy deposition rate in the transparent-wall model tubes was 64 kW. The equivalent surface heat flux (based on the total surface area of the axial coolant tubes of 283 cm^2) is 226 W/cm^2 which is 2.5 times greater than the equivalent surface heat flux in the reference engine design.

Propellant Heating Tests

In the reference engine, approximately 98 percent of the total thermal radiation incident on the propellant stream is calculated to be absorbed by the hydrogen propellant (Ref. 61). Hydrogen is essentially transparent to thermal radiation at the engine operating pressure of 500 atm and below a temperature of approximately 7780°K . Therefore, a seed material must be added to the propellant stream to provide the required opacity.

The ideal seed material would consist of nonreactive, high-melting-point, high-boiling-point, submicron-sized metal particles that exhibit good absorption characteristics in both particle and vapor forms. Submicron-sized particles, low-ionization-potential metal vapors, and various polyatomic gases have been examined theoretically and experimentally as possible seed materials for the propellant stream (Refs. 78, 82, 88, and 89). Submicron-sized solid or liquid particles exhibit essentially continuous spectral absorption characteristics as contrasted with discrete spectral absorption characteristics exhibited by low-ionization-potential metal vapors and polyatomic gases.

Theoretical studies (Ref. 88) of the absorption properties of small solid particles have been based on the Mie theory. This theory describes the spectral extinction, absorption, and scattering of radiation by spherical particles as functions of particle size, material properties, and the wavelength of the incident radiation. The results of these studies indicate that tungsten is attractive as a seed material because of its high melting point, high boiling point, and low reactivity with hydrogen. Thus, in the reference engine, nominal 0.05- μ -diam tungsten particles are used as the propellant seed material.

In each unit cavity (Fig. 1(b)), the inner wall of the propellant annulus is highly transparent. The outer wall is highly reflective to reduce the heat load to the moderator and to increase the effective path length for radiation absorption in the propellant region. A thin buffer layer of unseeded gas flows adjacent to both the inner and the outer walls of the propellant region. These buffer layers prevent degradation of the optical properties of the walls due to coating by the propellant seed. They also aid in keeping hot gases away from the walls, thus reducing heat transfer to the duct walls.

The principal objective of the propellant heating tests has been to experimentally demonstrate heating of simulated propellant to high bulk exit temperatures by the absorption of thermal radiation. The flow configuration used is similar to that of the nuclear light bulb engine in the sense that simulated propellant opacity is provided by use of micron-sized particle seeds in a flowing stream isolated from the propellant duct walls by buffer layers of unseeded gas.

Results of initial propellant heating tests are reported in Refs. 10 and 16. The test configuration used in the most recent propellant heating tests (Ref. 2) is shown in Fig. 18. As described in Ref. 2, a high-power dc arc was used as the radiant energy source. The arc was surrounded by a fused silica tube and was located within a mirrored cavity. Radiation from the arc focused on a 12.7-cm-long test section. Argon was introduced at the bottom of the test section to provide unseeded buffer layers adjacent to the test section side walls. The central seeded stream (in initial tests argon seeded with carbon particles, and in the most recent tests argon seeded with tungsten particles) was also introduced at the bottom of the test section. The three streams flowed upward, parallel to the dc arc source, and into a calorimeter. Radiation from the arc passed through a transparent fused silica tube and a second transparent fused silica plate, and was deposited into the central seeded stream.

The results of the key propellant heating tests are shown in Figs. 19 and 20. Figure 19 shows results of tests conducted during 1971 in which argon seeded with carbon was the simulated propellant. The maximum bulk exit temperature, determined calorimetrically, was 3860°K. The bulk exit temperature in these tests was limited by the amount of radiation from the arc source which was incident on the test section.

During 1972, improvements were made in the mirror configuration and the total arc power was increased. The maximum power used in 1971 tests was 480 kW; the maximum power used in 1972 tests was 780 kW. The results of tests in which argon seeded with tungsten was the simulated propellant are shown in Fig. 20. The maximum temperature achieved in these tests was 4515°K. This temperature is approximately twice the fuel-element exit temperature in a solid-core nuclear reactor.

The bulk exit temperatures obtained in 1972 were within 5 percent of the equivalent black-body radiating temperature corresponding to the radiant energy flux incident on the simulated propellant stream. In the reference engine design, it is assumed that the bulk exit temperature will be only 80 percent of the fuel radiating temperature. Thus, the 1972 results suggest that a higher exit temperature (and, hence, higher specific impulse) may be obtainable with the same reference engine operating power.

It is expected that further increases in mirror reflectivity can be obtained, increases in arc power can be obtained, and improved buffer layers can be developed. These improvements will lead to higher bulk exit temperatures in future tests. It is important that propellant heating data at higher temperatures be obtained to verify that the opacity of vaporized tungsten will be sufficient to allow the reference engine bulk exit temperature of 7780°K to be reached.

Fuel Handling Research

A mixture of buffer gas, fuel and fission fragments is exhausted from each unit cavity of the reference engine through a thru-flow port located at the center of one end wall. Continuous operation of the engine is dependent upon the ability to condense and separate the entrained fuel from this mixture so that both the fuel and the buffer gas may be recycled separately. In the Nuclear Furnace tests (described in Ref. 6), flow will be removed from the cavity through two exhaust ducts (see Fig. 7). For this application, it is necessary to develop the condensation technology (although not necessarily the separation technology) required to prevent deposition of nuclear fuel on the exhaust duct walls within the Nuclear Furnace core.

Experiments were conducted to study the heat transfer and condensation processes of metal-vapor/heated-gas mixtures flowing into inlets and long ducts. Information from these experiments was used to develop conceptual designs for exhaust system components for the nuclear light bulb reference engine and for a small Nuclear Furnace in-reactor test model. The results of these studies are reported in Refs. 4 and 11.

For the reference engine exhaust system conceptual design, the components considered were the thru-flow exhaust duct and the fuel/buffer-gas separator. A gaseous mixture of neon, uranium, fission products and silicon is exhausted from the fuel region in each of the seven unit cavities at a mixed-mean temperature of 6550°K and a pressure of 500 atm. Cold bypass neon is injected into the 2-m-long by 4.75-cm-diam exhaust duct to drop the temperature to 1500°K at the end of the duct. To reduce the potential for deposits forming on the wall, the bypass is injected with swirl (i.e., circumferentially) from ports along the entire length of the duct, and the duct wall is kept at a temperature of at least 1500°K . A vortex separator is used to centrifugally separate the liquid uranium droplets from the mixture leaving the seven exhaust ducts. The mixture is injected into the separator such that the initial radial acceleration field experienced is about 100,000 g's. Radially outward velocities that are large relative to the initial radially inward neon velocity are experienced by droplets having diameters greater than $0.5\ \mu$. The uranium is withdrawn through ports in the peripheral wall, and the neon is removed through a thru-flow port at the center of one end wall. The neon, upon leaving the separator, flows to a heat exchanger where it is cooled such that it can be re-injected into the unit cavity. The exhaust duct and separator components will be designed to operate at a temperature of 1500°K so that uranium droplets can be maintained in liquid form prior to injection into the separator.

For the Nuclear Furnace model conceptual design, two 0.5-cm-i.d. by 58.5-cm-long (length within Nuclear Furnace core) thru-flow exhaust ducts are used. These ducts are similar in concept to the ducts for the reference engine.

Tests were conducted with zinc-vapor/argon-gas mixtures flowing in short sections of simulated exhaust ducts. Several types of bypass inlet configurations were evaluated. The type of configuration with swirl injection described above successfully maintained clean walls over the length of the bypass inlet. These inlets were considerably shorter than required for the engine and Nuclear Furnace model. Further tests should be conducted using models which more closely mock-up the entire lengths of the exhaust ducts developed in the conceptual design studies. These tests should employ uranium-vapor/argon-gas mixtures for closer simulation of the properties of the mixtures in the engine and in-reactor test model.

RADIANT HEAT TRANSFER

Calculations have been performed to determine the spectral absorption coefficients of gaseous uranium, several buffer gases, and several candidate seed gases for reducing the uv radiation at the wall. The results were then used in calculations to determine the spectral distribution of energy emitted from the fuel-containment regions of the engine and in-reactor test models.

The absorption coefficient of nuclear fuel in the ultraviolet portion of the spectrum is an important parameter in determining limitations on the performance potential of nuclear light bulb engines. For the nuclear fuel, the absorption coefficient in the ultraviolet is usually much less than that in the visible portion of the spectrum. Therefore, an observer viewing the fuel region would "see further into" the nuclear fuel to higher temperatures in the ultraviolet portion of the spectrum and, hence, the output ultraviolet radiation is increased relative to the visible radiation. These results are undesirable, since they place more of the energy in the ultraviolet portion of the spectrum where the transparent walls are more opaque. Therefore, it is desirable to reduce this effect if possible.

One method by which the energy in the ultraviolet portion of the spectrum can be reduced in the engine is by the use of seed materials in the neon buffer gas to increase the absorption preferentially in the ultraviolet portion of the spectrum. One such possible seed is atomic silicon. It was determined in Ref. 5 that by introducing up to 10 atm of silicon seed into the edge-of-fuel and buffer-gas region of the reference engine, the ultraviolet content of the spectral radiant energy flux could be reduced substantially.

Results of calculations of the fractional heat flux distribution for the edge of fuel of the reference engine with silicon seed partial pressures of 0.1, 1.0, and 10 atm are shown in Fig. 21. The fractional heat flux for unseeded nuclear fuel is also presented in Fig. 21. The nominal wave number value for the transmission cutoff in fused silica is approximately $55,000 \text{ cm}^{-1}$. It can be seen from Fig. 21 that for the unseeded case, approximately 14 percent of the total radiant heat flux emitted from the fuel region would occur at wave numbers above which the fused silica transparent wall is opaque. This would result in an unacceptable transparent-wall heat load. With the addition of 10 atm of silicon with the buffer gas, this fraction was reduced from 14 percent to an acceptable value of approximately 0.2 percent of the total energy incident on the transparent wall.

As discussed in Ref. 5, a portion of this energy would be absorbed in the buffer-gas region before reaching the transparent wall. Calculations of the buffer-gas flow rates required and the amounts of energy convected away indicate that the added heat load is compatible with the reference engine cooling circuit. Thus, it appears that

use of silicon seed in the edge-of-fuel and buffer-gas region is an effective means for controlling the amount of ultraviolet radiation emitted from the fuel region of the reference engine in that portion of the spectrum where the transparent wall is opaque.

Results of calculations of the fractional heat flux incident on the aluminum reflective liner of the in-reactor test configuration (see Fig. 7) are presented in Fig. 22. The outward directed heat flux at the edge-of-fuel location for the in-reactor test condition is 4.8×10^{10} erg/cm²-sec (equal to approximately 18 percent of the radiant heat flux for the reference engine operating condition). The calculated fraction of the energy emitted at wave numbers greater than the fused silica transmission cutoff of $55,000 \text{ cm}^{-1}$ is equal to approximately 0.0007 (equal to 30 percent of that expected in the reference engine with 10 atm of silicon seed). Curves showing the fractional heat flux distribution for black-body spectra at temperatures corresponding to the effective black-body radiating temperature of 3330°K and the effective edge-of-fuel temperature of 5426°K expected in the in-reactor tests are also presented in Fig. 22. As expected, the calculated results indicate an increased amount of ultraviolet energy would be emitted relative to that emitted from a black body at the same effective radiating temperature. As discussed in Ref. 6, this increase is primarily due to the presence of the reflective aluminum liner at the periphery of the cavity region which acts as a photon-flux trap and causes a spectral shift in energy toward the uv wavelengths. Additional discussion of results of in-reactor test radiant heat transfer analyses is presented in Ref. 5.

MEASUREMENTS OF OPTICAL TRANSMISSION OF TRANSPARENT MATERIALS

Experimental programs to determine the effects of nuclear radiation on the optical transmission of transparent materials were continued under Contract SNPC-70 and are reported in Refs. 8, 15, and 22. Results of previous investigations are described in Refs. 41, 43, 54, 58, and 59. The purpose of this program was to determine the level of irradiation-induced optical absorption to be expected in the transparent wall of a full-scale nuclear light bulb engine during operation. The material studied most extensively throughout the program has been fused silica, which has good optical transmission, good thermal and structural properties, and which is relatively easy to fabricate. In addition, irradiation-induced absorption bands at visible wavelengths, which are related to impurities, do not develop appreciably in high-purity grades of fused silica such as Corning 7940. The irradiation-induced absorption bands that are observed after exposure to nuclear radiation are centered at ultraviolet wavelengths of approximately 0.215μ and 0.165μ , with additional structure sometimes observed near 0.270μ (see Ref. 15).

Experiments were conducted during which in-situ measurements of the optical transmission of fused silica and single crystal beryllium oxide were made during 1.5-MeV steady-state, and 5-to-7-MeV pulsed, electron irradiation. The experiments were conducted at the Space Radiation Effects Laboratory of the NASA Langley Research Center, Hampton, Virginia, using the Dynamitron electron accelerator as the source of 1.5-MeV electrons and the LINAC electron accelerator as the source of 5-to-7-MeV electrons.

The Dynamitron electron accelerator provided a continuous 1-cm-diam beam with an electron energy of 1.5 MeV and a maximum current density of 100 A/cm^2 at the location of the specimen. The specimens were in the shape of thin wafers approximately 0.5-cm square and 1.5-mm thick. The specimens were mounted in a furnace to maintain their temperatures as high as 1275°K in the absence of electron beam heating. The specimen temperature was monitored with a thermocouple placed in contact with the back surface of the specimen. The results of experiments with high-purity fused silica obtained during high-temperature irradiation are shown in Fig. 23. The data indicate that at a given temperature, the induced absorption decreases with increasing ionizing dose rate above a dose rate of about 0.4 Mrad/sec. This effect is attributed to an apparent increase in annealing rate with increasing ionizing dose rate.

During steady-state operation it is expected that the nuclear light bulb engine would operate at a transparent-wall temperature of approximately 1073°K . The data in Fig. 23 indicate that there would be negligible induced absorption at a wavelength of 0.215μ in the fused silica transparent wall at the expected ionizing dose rate of the full-scale nuclear light bulb engine of 5 Mrad/sec for temperatures in excess of

800°K. Even if a minimum wall temperature as low as 600°K is assumed, the expected absorption coefficient based on the data of Fig. 23 would be approximately 0.1 cm^{-1} in an absorption band approximately $0.04\text{-}\mu$ wide centered at a wavelength of 0.215μ . For an absorption coefficient equal to 0.1 cm^{-1} , the resulting power deposited in the fused silica transparent wall of the reference engine would be only approximately 1.1 MW, or about 2 percent of the total expected transparent-wall heat load from all sources (Ref. 5).

Results of additional experiments using the pulsed LINAC electron accelerator at electron energies of 5 and 7 MeV indicated that the level of absorption in fused silica does not increase with higher electron energies. This is in agreement with previous results which indicated that the growth of coloration in this material was dependent only on the ionizing dose rate. In addition, experiments with other candidate transparent materials indicated that single-crystal beryllium oxide should continue to be considered as a possible alternate wall material to fused silica. The wall operating temperature for BeO walls would possibly be several hundred degrees Kelvin higher than for fused silica walls to obtain annealing (Ref. 8).

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LIST OF SYMBOLS

A_F	Fuel injection control valve area, cm^2
A_M	Surface area of transparent-wall model inner wall, cm^2
A_S	Surface area of plasma discharge, cm^2
d	Discharge diameter measured at midplane, cm
\dot{D}	Ionizing dose rate, Mrad/sec
f	RF heater operating frequency, MHz
I_{SP}	Specific impulse, sec
K_F	Proportionality constant
P	Pressure, atm
P_C	Engine operating pressure, atm
P_D	Test chamber pressure, atm
P_I	Fuel injection pressure, atm
P_l	Pressure at periphery of test chamber or unit cavity, atm
\bar{P}_F	Volume-averaged simulated-fuel partial pressure in test chamber or unit cavity, atm
q_I	Radiated flux incident on propellant heating test section, kW/cm^2
q_o	Reference engine radiant energy flux, $\text{erg}/\text{cm}^2\text{-sec}$
Q_C	Power deposited in transparent-wall coolant, kW
Q_E	Power deposited in end-wall coolant, kW
Q_F	Specific fission power, kW/g U-235
Q_{INC}	Total radiation incident on propellant test section, kW

LIST OF SYMBOLS (Continued)

Q_J	Power deposited in vortex injector coolant, kW
Q_L	Power remaining in test chamber effluent, kW
Q_O	Steady-state engine power level, MW
Q_R	Power radiated to radiometer, kW
$Q_{R,T}$	Power radiated, kW
Q_T	Total discharge power, kW
Q_W	Power deposited in peripheral-wall coolant, kW
r	Radial distance, cm
r_1	Test chamber or unit cavity outer radius, cm
R	Reflectivity, dimensionless
t	Time, sec
T_E	Simulated propellant stream bulk exit temperature, $^{\circ}K$
T_{pe}	Propellant stream exit temperature, $^{\circ}K$
T_{pi}	Propellant stream inlet temperature, $^{\circ}K$
T_G	Temperature at edge-of-fuel location, $^{\circ}K$
T^*	Equivalent black-body radiating temperature, $^{\circ}K$
V	Volume of plasma discharge, cm^3
W_A	Argon weight flow rate, g/sec
W_C	Coolant flow rate, gal/min
W_F	Fuel weight flow rate, kg/sec
W_W	Tungsten seed weight flow rate, g/sec

LIST OF SYMBOLS (Continued)

α	Induced absorption coefficient, cm^{-1}
ΔQ	Power level change, MW
ΔT	Temperature difference, $^{\circ}\text{K}$
δA_{F_1}	Imposed change in fuel injection control valve area, cm^2
λ	Wavelength, μ
η_T	Fraction of incident radiation transmitted through simulated propellant stream, dimensionless
ρ_{B_6}	Buffer-gas density at edge-of-fuel location, g/cm^3
$\bar{\rho}_{F_6}$	Volume-averaged density of fuel in fuel region, g/cm^3
ϕ_R	Plasma discharge radiant energy flux, kW/cm^2
ω	Wave number, cm^{-1}

APPENDIX

COMPILATION OF SUMMARY PAGES FROM
TECHNICAL REPORTS ISSUED UNDER CONTRACT SNPC-70

Reference 1

Klein, J. F. and W. C. Roman: Results of Experiments to Simulate Radiant Heating of Propellant in a Nuclear Light Bulb Engine Using a D-C Arc Radiant Energy Source. UARL Report J-910900-1, September 1970.

SUMMARY

Experiments were conducted to simulate radiant heating of the propellant stream of a nuclear light bulb engine. The primary objective was to obtain high exit temperatures in the simulated propellant stream due to the absorption of large percentages of the incident thermal radiation. A high-power d-c arc was used as the radiant energy source and argon seeded with carbon particles was used to simulate the propellant. Unseeded buffer layers were used to prevent coating of the transparent duct walls. Methods were developed for introducing micron-sized carbon seeds into the central region of a three-stream flow in an annular duct to simulate the propellant stream.

The bulk temperature in the exhaust of a reference nuclear light bulb engine is expected to be 12,000 R. A long-range goal of the propellant heating experiments conducted in the laboratory is to obtain as high a value as possible of this bulk exit temperature in a configuration closely simulating that of the engine. The results of the first phase of these experiments indicate that simulated propellant bulk exit temperatures between approximately 3000 and 4000 R have been achieved. Based on thermocouple measurements at lower temperatures, it is inferred that local temperatures at points in the simulated propellant duct were substantially greater than the bulk temperatures. The maximum bulk exit temperatures achieved in the tests to date were primarily limited by the particular cooling configuration employed for the transparent wall adjacent to the radiation source and by partial vaporization of the foam material used at the propellant stream inlets.

By making modifications to the d-c arc radiant energy source and to the propellant heater configuration, it is estimated that propellant bulk exit temperatures approaching 6500 R can be achieved within the next year. This can be accomplished by integration of (1) an upgraded radiant energy source operating at higher powers for shorter run times with (2) an improved propellant duct inlet configuration employing upstream aerodynamic shear for improved deagglomeration of the carbon dispersion. No evidence has been found in tests to date of limitations which would prevent attainment of a bulk exit temperature equal to that in the reference engine after development of the required test equipment. Further development of high-temperature measurement techniques is required to accurately determine the heat content and local temperature of the hot, low velocity, seeded simulated propellant stream in future tests.

As part of this effort to obtain high exhaust temperatures, supporting research was conducted to increase the mass attenuation coefficient of the seeded stream, to determine the optical properties of particle clouds, to develop seeded stream and buffer layer injection geometries that minimize seed coating of the duct walls, and to develop high-temperature measurement techniques for use with particle-laden streams.

Jamnet, J. F. and A. E. Mensing: Experimental Investigations of Simulated-Fuel Containment in R-F Heated and Unheated Two-Component Vortexes. UARL Report J-910900-2, September 1970.

SUMMARY

Experiments were conducted to determine the containment characteristics of radial-inflow vortexes for application to the nuclear light bulb engine. In these investigations, the amount of simulated fuel contained in two-component vortexes was measured for both heated and unheated (isothermal) vortex flows.

In the vortex flows with heat addition, power was added to the flow by r-f induction heating of the gas within 1.26-in.-dia by 2.8- or 3.5-in.-long chambers. The simulated buffer gas, argon, was injected in a tangential (circumferential) direction either from the end walls or from the peripheral wall. The flow rate, plasma diameter, and power addition were such as to provide radial gradients of temperature of approximately 70,000 deg R/in. (15,000 deg K/cm) near the outer edge of the plasma. Xenon was employed as the simulated fuel and was injected into the vortex at several different locations. Spectroscopic techniques were used to determine the temperature distributions and the simulated-fuel partial pressures within the plasma.

Most of the tests conducted with unheated vortex flows employed a 10.0-in.-dia by 30.0-in.-long vortex tube. This vortex tube was much larger than, but was approximately similar to, the vortex tube used in the heated tests. Air or sulfur hexafluoride was used as the simulated buffer gas and mixtures of iodine with helium and iodine with nitrogen were used as simulated fuels. Several different simulated-fuel injection configurations were used, and the injection velocity of the simulated fuel was varied. In most of the tests, axial bypass flow was withdrawn through ports located around the periphery at each end of the vortex tube.

Additional tests were conducted with unheated vortex flows employing the same small vortex tube used in the heated tests. Argon was used as the simulated buffer gas and a mixture of argon and bromine was used as the simulated fuel. These tests were conducted using simulated-fuel injection configurations and flow conditions similar to those used in the heated tests and in the previously mentioned unheated tests in the 10-in.-dia vortex tube. In most of the tests, axial bypass flow was withdrawn through an annulus located at the peripheral wall at each end of the vortex tube. For all of the unheated tests, the volume-averaged partial pressures of the simulated fuel within the vortexes were determined, as were the radial distributions of the simulated-fuel partial pressures.

Comparisons were made of the simulated-fuel partial pressures in the heated and unheated flows. For the same geometries and the same buffer-gas weight flows, the heated vortexes had larger values of local simulated-fuel partial pressure in the central regions of the vortex, but lower values near the peripheral wall. For the same flow conditions and geometries, the volume-averaged simulated-fuel partial pressures were also greater in heated tests than in unheated tests. Measurements also indicated that radial gradients of static pressure in the high-temperature region of heated vortexes were much less than in unheated vortexes having the same flow rates.

Supporting research included isothermal tests in which the amount of simulated fuel stored in the vortex was measured during transient conditions. R-F plasma tests in which a reflecting peripheral wall was used to increase the local radiant energy flux were also conducted.

Vogt, P. G.: Development and Tests of Small Fused Silica Models of Transparent Walls for the Nuclear Light Bulb Engine. UARL Report J-910900-3, September 1970.

SUMMARY

A program was conducted to develop and test small fused silica models of transparent walls for the nuclear light bulb engine. The principal objectives were (1) to develop fabrication techniques for constructing models using thin-walled fused silica tubing, (2) to arrive at model configurations which provide satisfactory vortex flow patterns, and (3) to test these models in a thermal environment similar to that in the engine.

The transparent wall in the engine surrounds the fuel region and separates it from the annular propellant duct. A vortex, driven by a transparent buffer gas, is employed to isolate the fuel from the wall. The wall is internally cooled and has provision for circumferential injection of buffer gas to drive the vortex.

Fused silica models having axial coolant tubes (i.e., coolant tubes aligned with the axis of the vortex) were fabricated using tubes with wall thicknesses down to 0.005 in. A potting technique based on the use of silicone rubber sealant (RTV) was the most effective of three methods developed for joining the tubes to coolant manifolds at the ends of the model. These axial-coolant-tube models were tested using the UARL 1.2-megw r-f induction heater where an argon plasma was used as a source of thermal radiation (analogous to radiation from the fuel in the engine, although at lower flux levels). By using improved methods for circumferential gas injection with resultant improvements in the vortex flow, the amount of heat deposited in the transparent walls by conduction and convection was reduced to 30 percent of that in previous tests. The maximum radiation flux levels used were limited by overheating of the water-cooled copper injectors due to all three modes of heat transfer, rather than by any limitations of the transparent walls. Significant increases in radiation flux can be obtained by modifying the vortex injector configuration to increase its cooling capability. Improvement in the flow pattern within the models also can be obtained which will result in a further reduction in the levels of conduction and convection heat transfer to the model inner walls.

In related work, fused silica tubes having 0.005-in. wall thicknesses were also formed into shapes suitable for circumferential-coolant-tube models by sagging straight tubes into a mold at elevated temperatures. Optical transmission characteristics of arrays of coolant tubes were measured, and procedures for predicting heat transfer rates and stresses in the tubes were developed.

Roman, W. C.: Experimental Investigation of a High-Intensity R-F Radiant Energy Source to Simulate the Thermal Environment in a Nuclear Light Bulb Engine. UARL Report J-910900-4, September 1970.

SUMMARY

Experiments were continued to develop an intense radiant energy source capable of producing radiant energy fluxes approaching those expected in a full-scale nuclear light bulb engine. The test program was conducted using the UARL 1.2-megw radio-frequency (r-f) induction heater operating at approximately 5.5 MHz. R-F energy was deposited in an argon plasma discharge contained within a radial-inflow vortex. The 2.24-in.-ID test chamber was formed by concentric, water-cooled, fused silica tubes and a symmetric pair of copper end walls spaced 2 in. apart.

The effects of various geometric, flow and r-f parameters on the power radiated from the plasma, the power deposited in the surrounding water-cooled transparent peripheral wall, and the power convected away from the plasma were investigated. Tests were conducted at pressures up to 19.2 atm. A maximum heat deposition rate per unit volume of 0.57 megw/in.³ was achieved in the steady-state, ellipsoidal plasma. The maximum radiant energy flux achieved at the edge of the plasma was 49 kw/sq in. which corresponds to an equivalent black-body radiating temperature (based on the plasma surface area) of 10,860 R. For comparison, the edge-of-fuel radiant energy flux of the full-scale nuclear light bulb reference engine is about 178 kw/sq in.; the corresponding equivalent black-body radiating temperature is 15,000 R.

The results demonstrate the ability to deposit, in a steady-state manner, large amounts of r-f power into a very small plasma. The results also indicate that the total r-f power deposited, the chamber pressure, the argon vortex weight flow rate, and the operating frequency are interrelated in determining stable operating conditions for a given chamber geometry. The maximum levels of plasma power and chamber pressure used in these tests were limited by an instability of the confined plasma similar to instabilities encountered previously at lower powers and pressures. Based on data obtained during this program, it is believed that the instability is related to one or more of these factors: (1) a requirement for increased end-wall thru-flow port area to prevent choking of one or both ports, (2) r-f breakdown around the end walls due to heating of the argon vortex injectors and secondary flows, and (3) a requirement for operating at lower r-f frequencies to compensate for the changing electrical characteristics of the plasma as power and pressure increase.

Supporting research, including spectral emission measurements of the r-f plasma in the ultraviolet, was conducted. Filament-wound pressure vessels for use in the nuclear light bulb research program were also developed and tested.

Bauer, H. E., R. J. Rodgers and T. S. Latham: Analytical Studies of Start-Up and Dynamic Response Characteristics of the Nuclear Light Bulb Engine. UARL Report J-910900-5, September 1970.

SUMMARY

Analytical studies were conducted to evaluate systems for control of the reference nuclear light bulb engine during start-up and at nominal full-power operating conditions. Analytical models of the control systems were incorporated in the digital computer simulation programs developed previously to determine operating conditions of the reference engine during start-up and the transient response of the engine to various perturbations at the nominal full-power operating level.

Additional analyses were conducted (1) to determine the effects of off-design flow fluctuations and fabrication tolerances on the operating conditions of the reference engine, (2) to compare critical mass calculations with results of experiments on a seven-module cavity reactor, (3) to determine the design parameters such as radiator materials and operating temperatures and pressures for a space radiator to reject a portion of the moderator heat load, and (4) to investigate the design characteristics and performance of an alternate nuclear light bulb engine configuration employing unit cells of smaller diameter than those envisioned for the reference engine.

Start-up is divided into two phases. The first phase requires about 80 sec (1) to bring the turbopump up to operating speed, (2) to pressurize the engine to an initial condition required to achieve containment of a critical mass (20 atm or greater), (3) to initiate flow in all circuits, (4) to start fuel injection to obtain cold critical mass, and (5) to stabilize engine at 0.1 percent of full power. The second phase consists of a start-up ramp in power from 0.1 to 100 percent of full-power operation. In studies to date, no limitation has been found which would prevent the use of start-up times for the second phase as short as 6 sec using a linear ramp in fuel temperature. Neutron detectors are employed to sense absolute power level and the rate-of-change of power level during both phases of start-up. Control signals from the neutron sensors are used to adjust fuel injection rate such that the desired start-up power profile is produced. During the second phase of start-up, propellant, coolant, and buffer gas flow rates and exhaust nozzle flow area are also controlled by signals from the neutron detectors which measure absolute power level. The variation of the exhaust nozzle flow area is the primary means of establishing the desired pressure profile during start-up. Small pressure differentials within the engine are controlled by transfer chambers which allow rapid transfer of gases between regions of slightly different pressures.

The UNIVAC 1108 digital computer simulation program for the reference engine, which includes analytical models of the thermal and flow dynamics of the nuclear fuel, buffer gas, coolant, and propellant loops and their coupling to the neutron kinetics equations, was expanded (1) to include simulation of systems for controlling the engine during perturbations near full-power operating conditions and (2) to incorporate the simulation of transfer chambers added to the reference engine design to minimize pressure differentials across the transparent structure during power perturbations. Control of the engine was achieved by varying fuel injection control valve area (hence, fuel injection rate) based upon signals from neutron detectors which sense absolute power level and the rate-of-change of power level. It was concluded that satisfactory control of the engine can be achieved during full-power operation on the basis of calculated responses of the controlled engine to perturbations in reactivity, fuel injection rate, exhaust nozzle flow area, turbopump wheel speed, and fuel region radius. Pressure differentials across the transparent structure for the power perturbations analyzed were limited to less than 1 lb/in.² by the transfer chamber pressure equalization system.

The study also indicated the desirability of additional work in certain areas. Continued analysis of the start-up characteristics should be made to incorporate the variations in reactivity coefficients and evaluate engine stability during start-up. Further analysis should also be directed toward determining the factors which impose an absolute lower limit on the time required for both phases of start-up. The sensitivity of engine response to variations in fuel injection system acoustic lags and pressure fluctuations indicates that the design and response characteristics of the fuel injection system should be analyzed in greater detail and the results incorporated in the dynamics simulation program. In addition, engine shutdown should be investigated to determine the engine performance and control requirements during both a slow shutdown and an emergency shutdown. Analyses of shutdown procedures should be extended to include investigations of afterheat removal requirements and activity levels in the engine after shutdown. The activation analysis could be used to determine the reusability of the engine by determining the accessibility of the engine after shutdown.

Latham, T. S. and H. E. Bauer: Analytical Studies of In-Reactor Tests of a Nuclear Light Bulb Unit Cell. UARL Report J-910900-6, September 1970.

SUMMARY

Analytical studies were conducted to determine the performance and design characteristics of a small model of a nuclear light bulb unit cell suitable for testing in a nuclear reactor. Three nuclear test reactors were considered: Pewee and the Nuclear Furnace, which are solid-core nuclear rocket fuel element test reactors, and the High Flux Isotope Reactor (HFIR). These test reactors have thermal neutron flux levels in the test region which range from 2.0 to 5.0×10^{15} neutrons/cm²-sec. Demonstration tests with these thermal neutron flux environments would create thermal radiation fluxes corresponding to black-body radiating temperatures of 12,500 to 14,600 R for models having reflecting walls and operating pressures of 500 atm.

Preliminary design analyses of the test region pressure vessel, reflective liner, fuel handling system, and instrumentation were performed. Three types of tests of increasing complexity were considered: (1) a demonstration that nuclear fuel can be contained fluid dynamically while fissioning in a gaseous cloud; (2) a demonstration that internally cooled transparent walls are capable of withstanding both the nuclear radiation and thermal environments anticipated for a nuclear light bulb engine; and (3) a demonstration that seeded propellant can be heated to exhaust temperatures in excess of those presently attained in the solid-core nuclear rocket.

The results of the analytical study indicate that meaningful in-reactor demonstration tests of fuel containment, transparent-wall performance, and propellant heating could be conducted. In addition, it appears that the models could be thoroughly developed and tested using the UARL r-f induction heater and d-c arc facilities at performance levels similar to those anticipated for in-reactor demonstration tests.

Krascella, N. L.: Analytical Study of the Spectral Radiant Flux Emitted from the Fuel Region of a Nuclear Light Bulb Engine. UARL Report J-910904-1, September 1970.

SUMMARY

A theoretical investigation was conducted to determine the spectral distribution of radiative flux emitted from the fuel region of a nuclear light bulb engine and, hence, the spectral radiative flux incident upon the transparent containment walls or upon the reflective end walls of such an engine. The analysis was performed for a specified engine configuration, for a specified nuclear fuel partial pressure distribution and for a total of 47 wave numbers. A total of six cases were calculated to investigate the effect on the spectral radiative flux of changes in total radiated flux, seed gas partial pressure, and end-wall reflectivity. The total radiated flux was changed from a reference value of 24,300 to 48,600 Btu/ft²-sec. The effect of seed gases was examined by the addition of a mixture of 5 atm each of oxygen and nitric oxide. Wall reflectivity was examined by employing the spectral reflectivity of aluminum and silver in place of a zero-reflectivity wall employed in the reference case.

Palma, G. E. and R. M. Gagosz: Optical Absorption in Transparent Materials During 1.5 MeV Electron Irradiation. UARL Report J-990929-1, September 1970.

SUMMARY

A program of in situ optical experiments was conducted to determine the level of irradiation-induced optical absorption that exists in Corning Grade 7940 fused silica and single crystal aluminum oxide during steady-state 1.5 MeV electron irradiation. These experiments were conducted at the Space Radiation Effects Laboratory of NASA Langley Research Center using a Dynamitron electron accelerator as the electron source. The optical transmission of a total of 25 fused silica specimens was measured during electron irradiation over a range of ionizing dose rates (0.02-10 Mrads/sec) and specimen temperatures (40-900 C). Three of these specimens had been previously reactor irradiated to a dose of 10^{17} fast neutrons per cm^2 at the Union Carbide Research Center. In addition to measuring the transmission at the peak of the strong irradiation-induced absorption band centered at 2150 Å, spectral scans over the wavelength interval 2050-2500 Å were also made. The decay of the irradiation-induced absorption due to optical bleaching and the rate of recoloration following optical bleaching were measured in order to determine the effectiveness of optical bleaching and to obtain information relating to the damage mechanism responsible for the irradiation-induced absorption. The most surprising and important result was the low level of irradiation-induced optical absorption at dose rates equal to those expected in a nuclear light bulb engine which is believed to be due to radiation annealing.

Also included in this investigation were four aluminum oxide specimens, of which two had been reactor irradiated to a dose of 10^{17} fast neutrons per cm^2 at the Union Carbide Research Center. The optical transmission of these specimens was measured during electron irradiation primarily at 2050 Å, the peak of the strong irradiation-induced absorption band in aluminum oxide.

Roman, W. C. and J. F. Jaminet: Experimental Investigations to Simulate the Thermal Environment and Fuel Region in Nuclear Light Bulb Reactors using an R-F Radiant Energy Source. UARL Report K-910900-7, September 1971.

SUMMARY

Experiments were continued to develop test configurations and technology necessary to simulate the thermal environment and fuel region in nuclear light bulb reactors. The test program was conducted using the UARL 1.2-megw r-f induction heater which has 7.8-cm-ID work coils and operates at approximately 5.5 MHz. Several types of models were installed inside the coils to achieve different program objectives. All models were basically cylindrical vortex chambers with highly cooled fused silica peripheral walls and copper end walls. Argon was used to drive the vortexes. R-F power level, chamber pressure and argon flow rate were adjusted to provide the desired r-f plasma discharge test conditions.

One portion of the program involved r-f tests of models having configurations presently envisioned as suitable for tests in a driver reactor, particularly the Nuclear Furnace under construction at the Los Alamos Scientific Laboratory. The in-reactor tests will involve uranium plasmas with equivalent black-body radiating temperatures between 3333 and 3910 K; the chamber pressure will be 500 atm. In the r-f tests reported herein, a 2/3-scale version of a possible in-reactor unit cell configuration --- a 14-cm-long chamber with an inside diameter of 5.7 cm --- was tested with argon plasma discharges radiating at equivalent black-body temperatures up to 4670 K. In some tests, simulated fuels in the form of uranium hexafluoride, tungsten hexafluoride and tungsten particles were injected into the plasma discharge from probes located at the centers of the two end walls. The results are encouraging since very little of the injected simulated fuel was deposited on the transparent peripheral wall.

The maximum test chamber pressure attained in r-f tests with in-reactor-type model configurations was 40 atm. This pressure is twice the maximum level attained previously with smaller models having fused silica pressure vessels and was limited by existing cooling water pump capability. In these tests, a fiberglass filament-wound pressure vessel was used between the transparent peripheral wall of the chamber and the r-f coils. One of these filament-wound pressure vessels, which were developed at UARL as part of the NASA program, was hydrostatically tested to 550 atm --- greater than the 500 atm in-reactor requirement --- where the test was terminated due to leakage from the pressure vessel.

Another major portion of the program involved r-f tests of models having peripheral walls constructed from thin-walled fused silica tubes, as in the nuclear light bulb engine. The ultimate objective of this effort is to demonstrate the capability of such thin-wall, internally cooled structures to remain intact in the thermal environment of the engine. In the tests reported herein, models constructed from 0.125-mm-thick tubes were tested at r-f plasma discharge powers up to 116 kw and pressures up to 21 atm --- greater than twice the power and pressure levels of

previous tests. This increased performance was due to a greatly improved argon buffer gas injection configuration which is highly cooled yet maintains the injection turbulence level as low as possible. The highest radiant flux at the wall was 0.77 kw/cm^2 , compared with an estimated 23.4 kw/cm^2 for the reference engine and 0.40 to 0.76 kw/cm^2 for early in-reactor test configurations. Higher levels of power, pressure and radiating flux should be attainable in future tests in which the newly developed filament-wound pressure vessels can be used.

It is recommended that development of the test configurations and technology necessary for r-f tests of in-reactor models at 500 atm should be pursued with immediate emphasis in these areas: (1) development of diagnostic techniques for measuring the average partial pressure of simulated fuel inside the test chamber at elevated pressures; (2) tests with simulated-fuel injection to achieve high average partial pressure ratios in a configuration with the fuel-cloud-radius-to-cavity-radius ratio of approximately 0.6; (3) modification of the r-f induction heater test tank, heat exchangers, pump system and other equipment to permit safe operation at 500 atm; and (4) design, fabrication, cold-flow testing and hydrostatic testing of an in-reactor model which can subsequently be tested at in-reactor radiant energy flux levels and pressures in the 1.2-megw r-f induction heater.

Klein, J. F.: Experiments to Simulate Heating of the Propellant in a Nuclear Light Bulb Engine Using Thermal Radiation From a D-C Arc Radiant Energy Source. UARL Report K-910900-8, September 1971.

SUMMARY

Experiments were conducted to simulate radiant heating of the propellant stream of a nuclear light bulb engine. The primary objective was to obtain high exit temperatures in the simulated propellant stream due to the absorption of large percentages of the incident thermal radiation. A 500-kw d-c arc was used as the radiant energy source and argon seeded with carbon particles was used to simulate the propellant. Unseeded buffer layers were used to prevent coating of the transparent duct walls. Methods were developed for introducing micron-sized carbon seeds into the central region of a three-stream flow in a rectangular duct to simulate a portion of the propellant stream.

The bulk exit temperature in the exhaust of the reference nuclear light bulb engine design is 6660 K (12,000 R). A long-range goal of the propellant heating experiments conducted in the laboratory is to obtain as high a value as possible of this bulk exit temperature in a configuration closely simulating that of the engine.

In the tests reported herein, simulated propellant bulk exit temperatures up to 3860 K (6950 R) were achieved. The bulk exit temperatures were determined by a calorimetric technique developed during this program. The maximum bulk exit temperatures were limited primarily by vaporization of the carbon seeds and the amount of radiation incident on the test section.

It is estimated that substantially higher propellant bulk exit temperatures can be obtained. This can be achieved by further improvements to the d-c arc radiant energy source (in particular, improvement of the reflectivity of the mirrors used) and by the use of tungsten seeds which will remain in particle form to higher temperatures than carbon seeds.

Bauer, H. E.: Initial Experiments to Investigate Condensation of Flowing Metal-Vapor/Heated-Gas Mixtures in a Duct. UARL Report K-910900-9, September 1971.

SUMMARY

An exploratory experimental study of the condensation of a metal vapor carried in a flowing stream of non-condensable gas in a duct was conducted to provide information which could be used in the design of the cavity exhaust ports of a nuclear light bulb engine and an in-reactor test unit. Condensation was initiated by adding a sufficient quantity of cold non-condensable gas to a heated vapor/gas mixture to reduce the mixed mean temperature to a level below the melting point of the condensable material. It is desired to have condensation occur in the flowing gas with minimum deposition of condensable material on the duct walls.

A series of preliminary tests were conducted using iodine and air as the vapor/gas mixture. The air and iodine were heated electrically in an oven to produce the heated vapor/gas mixture which was then cooled by mixing with additional cold air at the inlet to a 1.0-m (39.4-in.)-long pyrex tube test section. Subsequent test series were conducted using zinc and argon as the vapor/gas mixture. Argon was preheated using a d-c arc plasma torch and was then passed through a vaporizer section containing zinc. At the test section, cold argon was used to cool the mixture. Two inlet configurations for the cold gas were used, one with direct radial inflow (no swirl) and one with rotating inflow (swirl). In addition, tests were conducted with heated and unheated test section walls.

In the iodine/air tests, condensation on the test section walls could be eliminated by maintaining the test section walls at a temperature approximately 10 to 15 K above the mixed-mean temperature of the flow in the tube. In the zinc/argon tests, heating of the tube walls had no observable effect on the amount of deposition on the tube walls. This difference is believed to be due to the different amounts of mixture sub-cooling present in the tests. A weight flow of cold argon gas equal to at least 10 times the weight flow of vapor/gas mixture was required to rapidly condense the zinc vapor into particulate form away from the test section walls.

The results of these exploratory tests indicate the need for additional experiments in which measurements of particle size, amount of wall coating, velocity distributions, and temperature distributions within the duct and at the duct wall are made. These experiments should concentrate on the zinc/argon system or other metal-vapor/gas systems, rather than on the iodine/air system because the operating conditions of such tests would more closely simulate the heat transfer and condensation processes in nuclear light bulb reactor exhaust ducts.

Rodgers, R. J., T. S. Latham and H. E. Bauer: Analytical Studies of Nuclear Light Bulb Engine Radiant Heat Transfer and Performance Characteristics. UARL Report K-910900-10, September 1971.

SUMMARY

The analytical studies of nuclear light bulb engine characteristics were divided into two major sections: (1) a continuing analysis of engine operating and transient response characteristics, with an emphasis on engine shutdown and (2) a detailed study of the radiation heat transfer characteristics of the fuel and buffer-gas regions. Emphasis in the radiation heat transfer calculations was placed on calculations of the spectral distribution of radiated energy emitted from the nuclear fuel region over a wide range of engine power levels and calculations of the effectiveness of seed systems in altering the spectral distribution of radiant energy.

It was determined that engine shutdown may be accomplished by stopping the fuel injection to the cavity region. Total power drops to 10 percent of the steady-state value in approximately 0.2 sec and decreases to zero in 6 sec. The propellant flow rate may be reduced to 10 percent of its steady-state value in 36 sec, but must be maintained at that value for approximately 160 sec in order to avoid overtemperatures in the beryllium oxide regions. Residual heat remaining after approximately 200 sec may be rejected by means of a space radiator.

The investigations of the dynamic response of the controlled engine to various perturbations indicated that a control response proportional to the difference between the instantaneous value of the neutron flux level and the desired steady-state value resulted in smaller variations in power than the control response proportional to the rate-of-change of neutron flux previously investigated. The studies also indicated that changes in the heat loads due to radiation and conduction in the moderator and structure will necessitate revisions to the order in which principal engine components are cooled. These modifications, plus the inclusion of a space radiator circuit, should be incorporated in the dynamic simulation program so that any variations in the responses to various perturbations during steady-state operation may be determined.

Spectral distributions of radiant energy emitted from the nuclear fuel region and incident on the transparent wall structure were calculated using a neutron transport theory code. The spectral heat fluxes and corresponding radial temperature distributions were used to calculate the heat loads in the buffer gas and

transparent walls due to absorption of radiant energy. These calculations were limited to the special case in which the temperature at the edge of the fuel with buffer seed is set approximately equal to the calculated edge-of-fuel temperature without buffer seed, the nuclear fuel partial pressure distribution within the nominal edge-of-fuel region is fixed, and convection takes place in the buffer-gas region bounded by the transparent wall and the nominal edge-of-fuel region. The fraction of ultraviolet energy incident on the transparent walls increases with increasing power level. For the reference engine power level of 4600 megw, it is necessary to either increase propellant flow rate or employ space radiators to reject the ultraviolet radiated energy absorbed by the transparent walls. This ultraviolet energy can be blocked by employing nitric oxide and oxygen seed gases in the fuel and buffer-gas regions. However, this results in increased ultraviolet absorption in the buffer gas which also requires either an increase in propellant flow rate or space radiators to reject the heat load. An increase in propellant flow rate reduces specific impulse and increases engine thrust-to-weight ratio, whereas the addition of space radiators allows specific impulse to remain constant and the engine thrust-to-weight ratio to decrease. It is concluded that investigations of seeding systems for the fuel and buffer-gas regions should be continued to identify seeds which will block ultraviolet radiation emitted from the fuel region more effectively than the nitric oxide and oxygen seed gases, and thereby minimize both the convection heat load in the buffer gas and the radiation absorption by the transparent walls.

Latham, T. S. and H. E. Bauer: Analytical Design Studies of In-Reactor Tests of a Nuclear Light Bulb Unit Cell. UARL Report K-910900-11, September 1971.

SUMMARY

Analytical design studies were continued to determine the design characteristics and performance of a small-scale model of a nuclear light bulb unit cell suitable for testing in a nuclear reactor. The test reactor considered was the Nuclear Furnace, a solid-core nuclear rocket fuel element test reactor. The Nuclear Furnace can provide a specific fission power level in the test region ranging from 25 to 40 kw/gm of U-235 fuel.

The results of the study indicate that a meaningful series of in-reactor demonstration tests of fuel containment, transparent-wall performance, and propellant heating could be conducted using the Nuclear Furnace reactor. Tests conducted with a configuration having reflecting walls and operating at a pressure of 500 atm could result in thermal radiation fluxes corresponding to black-body radiating temperatures ranging from 5800 to 6300 K. Tests could also be conducted to demonstrate that internally cooled transparent walls are capable of withstanding both the nuclear radiation and thermal environments anticipated for a nuclear light bulb engine and that seeded propellant can be heated to exhaust temperatures in the range of 3300 to 3700 K.

Simulation tests of models similar in geometry to those anticipated for in-reactor demonstration tests have been performed using the UARL r-f induction heater and d-c arc facilities. It is recommended that thorough development and testing of in-reactor test models at power levels and operating conditions anticipated for in-reactor tests be performed using these facilities prior to nuclear testing.

Krascella, N. L.: Spectral Absorption Coefficients of Helium and Neon Buffer Gases and Nitric Oxide-Oxygen Seed Gas Mixture. UARL Report K-910904-2, September 1971.

SUMMARY

A theoretical investigation was conducted to ascertain the spectral properties of helium and neon as a function of pressure, temperature and wave number. The spectral properties of these gases has a strong influence on radiative energy transfer in the buffer gas region of nuclear light bulb rocket engines.

A computer program was formulated and used to calculate spectral absorption coefficients of helium and neon at total pressures of 50, 100, 250, 500, 750 and 1000 atm in the temperature interval between 1,000 and 30,000 K. At each pressure and temperature, spectral properties were calculated for 47 wave numbers in the interval between 1000 cm^{-1} and $1,000,000 \text{ cm}^{-1}$.

In addition, previous estimates of spectral characteristics of a nitric oxide-oxygen seed mixture were extended to temperatures below 10,650 R.

Palma, G. E. and R. M. Gagosz: Effect of 1.5 Mev Electron Irradiation on the Transmission of Optical Materials. UARL Report K-990929-2, September 1971.

SUMMARY

A program of experiments was conducted to measure the optical transmission of several transparent materials before, during, and immediately after 1.5 Mev electron irradiation. These experiments were conducted at the Space Radiation Effects Laboratory of the NASA Langley Research Center using a Dynamitron electron accelerator as a source of 1.5 Mev electrons. A preliminary experiment was also conducted to evaluate the feasibility of using the Langley pulsed LINAC electron accelerator as a source of higher energy electrons (3-10 Mev) in future experiments. The Dynamitron experiments included a comparison of irradiation-induced optical absorption in three commercial grades of high-purity fused silica. It was found that the behavior of Corning 7940, Amersil, and Spectrosil high-purity grades of fused silica were similar with regard to the generation, annealing, and optical bleaching of the irradiation-induced optical absorption in the wavelength interval 2000 to 3000 Å. In addition, measurements of the optical transmission of single crystal specimens of aluminum oxide, magnesium fluoride, barium fluoride, lithium fluoride, and beryllium oxide were made during 1.5 Mev electron irradiation in the wavelength interval 2000 to 3000 Å.

Roman, W. C. and J. F. Jaminet: Development of RF Plasma Simulations of In-Reactor Tests of Small Models of the Nuclear Light Bulb Fuel Region. UARL Report L-910900-12, September 1972.

SUMMARY

Experiments were conducted to develop test configurations and technology necessary to simulate the thermal environment and fuel region expected to exist in in-reactor tests of small models of nuclear light bulb configurations. Particular emphasis was directed at rf plasma tests of approximately full-scale models of an in-reactor cell suitable for tests in Los Alamos Scientific Laboratory's Nuclear Furnace. The in-reactor tests will involve vortex-stabilized fissioning uranium plasmas of approximately 200-kW power, 500-atm pressure and equivalent black-body radiating temperatures between 3220 and 3510°K.

The test program was conducted using the UARL 1.2-MW rf induction heater operating with 8.6-cm-i.d. work coils at approximately 5.4 MHz. One portion of the program employed a fused silica pressure vessel in the test configuration --- a 15.5-cm-long chamber with an inside diameter of 5.7 cm. The end walls of this chamber were made of copper; they were water cooled and were polished to increase surface reflectivity. Argon gas, injected at the periphery of each end wall, was used to drive the vortex. Chamber pressures up to 42 atm, rf plasma power levels up to 180 kW, and equivalent black-body radiating temperatures up to 4320°K were attained. In other rf tests, an opaque fiberglass filament-wound pressure vessel was used. These tests demonstrated the structural integrity of the vessel in the rf electrical and thermal environments at pressures up to 43 atm and total power levels up to 203 kW. Similar vessels have previously been hydrostatically tested to 550 atm; i.e., above the pressure level expected to be required in future rf and in-reactor tests.

The maximum operating pressure levels in the rf plasma tests were limited primarily by the water pumps and plumbing installed at the 1.2-MW rf heater facility. A gas and water-cooling system which can be used for future rf plasma tests up to 500 atm has been developed and is now available. The maximum power levels were determined by operating limits on the dc current from the 1.2-MW power supply; these limits permitted achieving the goals of the present program. The limits can be increased, if required, for future tests.

Another portion of the program involved tests with condensible simulated fuels --- micron-sized tungsten particles and gaseous uranium hexafluoride --- injected into the rf plasma. To permit injection of the particulate fuel in a steady and

controlled manner into the 40-atm rf plasma environment, a particle feeder system was developed and tested. This design can be extended for operation at 500 atm.

An important area of research in future rf tests is to contain sufficient amounts of fuel for simulating the nuclear tests. In preparation for these tests, an analytical investigation of several methods suitable for measuring the amount of simulated fuel in the plasma and, if possible, its density distribution, was conducted. Two methods were selected as most promising: a time-of-flight mass spectrometer technique and an x-ray absorption technique. These techniques are applicable to rf plasma tests up to 500 atm in which opaque filament-wound pressure vessels are used.

Additional tests were conducted with thin-walled fused-silica transparent walls similar to the transparent walls of a nuclear light bulb engine. Using axial tube wall thicknesses down to 0.125 mm, tests were conducted at pressures up to 35 atm and total discharge powers up to 193 kW. The walls were successfully cooled at total incident heat fluxes (radiation and conduction) up to 1.5 kW/cm², compared with an estimated 0.4 kW/cm² net radiant heat flux expected in in-reactor tests.

Klein, J. F.: Nuclear Light Bulb Propellant Heating Simulation Using a Tungsten/Argon Aerosol and Radiation from a DC Arc Surrounded by a Segmented Mirror Cavity. UARL Report L-910900-13, September 1972.

SUMMARY

Further experiments were conducted to simulate radiant heating of the propellant stream of a nuclear light bulb engine. As in previous experiments, the primary objective was to obtain high bulk exit temperatures in the flowing simulated propellant stream by absorption of large fractions of the incident thermal radiation.

A high-power, vortex-stabilized dc arc within an uncooled fused silica tube was used as the radiant energy source. It was surrounded by a mirror system to increase the radiation incident on the simulated propellant. The 12.7-cm-long by 2.3-cm-wide, diverging-duct test section had a transparent front wall and a reflecting rear wall. The central stream of seeded gas, a tungsten-particle/argon aerosol, had unseeded argon buffer layers on both sides to prevent coating of the duct walls. Arc operating times were approximately 0.5 sec with power levels up to 780 kW. Bulk exit temperatures were measured using a calorimeter downstream of the duct.

To reach higher exit temperatures than those obtained previously, the following changes were made in the arc and mirror cavity during the present program: (1) the maximum dc arc power was increased by operating the power supplies at an overload condition and (2) an improved water-cooled segmented mirror cavity was developed to replace the previous cylindrical cavity. These two changes resulted in a factor of two increase in the radiation incident on the simulated propellant. In addition, a tungsten-particle/argon aerosol was used instead of the carbon-particle/argon aerosol, with expected benefits in terms of higher seed melting and boiling points and higher opacity in the vapor state. The latter change required development of a unique new tungsten powder feeder.

The maximum simulated propellant bulk exit temperature obtained was 4515°K, compared with 3860°K in previous tests, 3300 to 3700°K expected in in-reactor tests in the Nuclear Furnace, and 6660°K in the reference nuclear light bulb engine. The maximum temperature in these tests was limited primarily by the amount of radiation incident on the test section (determined by the arc operating characteristics and the effectiveness of the mirror cavity).

Jaminet, J. F.: Development of a Model and Test Equipment for Cold-Flow Tests at 500 Atm of Small Nuclear Light Bulb Configurations. UARL Report L-910900-14, September 1972.

SUMMARY

A model and test equipment were developed and cold-flow-tested at greater than 500 atm in preparation for future high-pressure rf plasma experiments and in-reactor tests with small nuclear light bulb configurations. With minor exceptions, the model chamber is similar in design and dimensions to a proposed in-reactor geometry for tests with fissioning uranium plasmas in the Nuclear Furnace. The model and the equipment were designed for use with the UARL 1.2-MW rf induction heater in tests with rf plasmas at pressures up to 500 atm.

The model consists of (1) a 6.6-cm-diam, 17.8-cm-long vortex chamber formed by a fused silica tube with water-cooled copper and stainless-steel end walls, (2) a fiberglass filament-wound pressure vessel around the fused silica tube, and (3) a pair of stainless-steel split retainer flanges which transmit the axial pressure load from the end walls to the pressure vessel. Each 7.75-cm-o.d. end wall has seven 0.84-mm-i.d. injectors at its periphery through which argon is injected to drive the vortex and a 0.8-cm-i.d. thru-flow exhaust port at its center. Also, each end wall has a single 1.7-mm-i.d. off-axis fuel injector at a radius of approximately 1.0 cm and ten equally spaced 1.6-mm-i.d. ports at radii from 1.43 to 2.87 cm. The latter could be used as view ports for instrumentation for measuring the radial distribution of fuel in the chamber, or as static pressure taps. All components of the model were designed to withstand the heat loads expected in rf plasma tests with greater than 200 kW of power in the plasma.

The fiberglass filament-wound pressure vessel, which was designed for an operating pressure of 500 atm, has an inside diameter of 7.76 cm, a length of 28.1 cm, and a maximum wall thickness of approximately 5 mm. Alternate axial and hoop layers (a total of 28 layers) are used to provide the required strength. Immediately inside the filament-wound pressure vessel is a silicone rubber sealing liner. Cooling water flows in the annulus between the liner and the fused silica tube. This cooling water will contain dye in tests with plasmas to protect the liner and pressure vessel from the intense thermal radiation.

Equipment was assembled in a test facility adjacent to the UARL 1.2-MW rf induction heater for use with the model in cold-flow tests and in future high-pressure rf plasma tests. The gas flow system provides a metered flow of argon

at pressures up to 680 atm. At a chamber pressure of 500 atm, the maximum argon flow rate available is approximately 7.55 liter/sec (STP). A submerged pump in a pressure vessel provides up to 29 gal/min of cooling water at approximately the chamber pressure.

Initially, tests were conducted to verify the strength and reliability of the filament-wound pressure vessel design. One vessel was hydrostatically tested to 680 atm before it failed. Another was cycled more than 60 times between 0 and at least 545 atm before it developed a crack in the outer fiber layers.

A series of cold-flow tests of the model was then conducted at pressures up to about 510 atm. At 504 atm, the flow rates of argon and cooling water were 3.35 liter/sec (STP) and 26 gal/min, respectively. It was demonstrated that the model is capable of being operated for extended periods at the 500-atm pressure level and is, therefore, ready for use in initial high-pressure rf plasma experiments.

Kendall, J. S. and R. C. Stoeffler: Conceptual Design Studies and Experiments Related to Cavity Exhaust Systems for Nuclear Light Bulb Configurations. UARL Report L-910900-15, September 1972.

SUMMARY

Analyses were conducted to develop preliminary conceptual designs for exhaust system components for the nuclear light bulb reference engine and for a small Nuclear Furnace in-reactor test model. Experiments were also conducted to study the heat transfer and condensation processes of metal-vapor/heated-gas mixtures flowing into inlets and long ducts.

For the reference engine conceptual design, the components considered were the thru-flow exhaust duct and the fuel/buffer-gas separator. Approximately 2.1 kg/sec of a gaseous mixture of neon, uranium, fission products and silicon is exhausted from the fuel region in each of the seven unit cavities at a mixed-mean temperature of 6550°K and a pressure of 500 atm. Cold bypass neon is injected into the 2-m-long by 4.75-cm-diam exhaust duct to drop the temperature to 1500°K at the end of the duct. At this temperature, all but one part in 6×10^{10} of the uranium is in the form of liquid droplets. About 8 kg/sec of cold bypass neon is required to produce this drop in temperature. To reduce the potential for deposits forming on the wall, the bypass is injected with swirl (i.e., circumferentially) from ports along the entire length of the duct, and the duct wall is kept at a temperature of at least 1500°K. A single 50-cm-i.d., 45-cm-long vortex separator is used to centrifugally separate the liquid uranium droplets from the 1500°K mixture leaving the seven exhaust ducts. Approximately 3.4 kg/sec of uranium is separated from 70.7 kg/sec of mixture. The mixture is injected into the separator through two 0.2-cm-high slots running the length of the peripheral wall. The injection velocity is 500 m/sec and the initial radial acceleration field experienced by the droplets is about 100,000 g's; radially outward terminal velocities that are large relative to the initial radially inward neon velocity of 116 cm/sec are experienced by droplets having diameters greater than 0.5μ . The centrifuged liquid uranium is withdrawn through six ports in the peripheral wall, and the neon is removed through a 22-cm-i.d. thru-flow port at the center of one end wall.

For the Nuclear Furnace model conceptual design, the two 0.5-cm-i.d. by 58.5-cm-long (length within Nuclear Furnace core) thru-flow exhaust ducts are similar in concept to the ducts for the reference engine. Approximately 0.02 kg/sec of a mixture of gaseous argon, uranium and fission products enters each exhaust duct. The mixture is initially at a temperature of 1590°K and a pressure of 500 atm; 2.0 kg/sec of cold bypass argon (or 0.1 kg/sec of hydrogen) is injected with swirl from the wall of each duct to lower the exit temperature to about 350°K. The uranium leaving the ducts is in particulate form. As presently envisioned, the entire effluent from the model then enters a small external scrubber system where separation will take place.

To provide information for these conceptual design studies, testing which was started in a preceding program using models of exhaust ducts and zinc-vapor/argon-gas mixtures was continued. A swirling flow of argon was heated using a dc arc plasma torch, passed through a vaporizer section where zinc vapor was entrained and entered a bypass inlet section and then a 2.54-cm-diam by 60-cm-long pyrex exhaust duct. Cold bypass argon was injected with swirl through four different bypass inlet section geometries. Radial distributions of temperature were measured in some tests and observations were made of the deposition of zinc on the duct walls. These experiments led to the development of a bypass inlet geometry which appears capable of achieving condensation of the vapor in the flow, with very little deposition on the wall for long distances. In this inlet, bypass flow was injected with swirl from 188 ports in the 2.54-cm-i.d., 13.5-cm-long wall (47 ports in each of four rows spaced 90° apart around the circumference). In one test, only 0.15 percent of the 9.5 g of zinc vapor passing through the inlet in a 2-min test was deposited on the wall. The mixture flow rate in this test was 3.9 g/sec and the bypass flow rate was 36.3 g/sec; hence, the bypass ratio was 9.3.

To make further progress on the design of exhaust system components, it is recommended that further tests be conducted using models which more closely mock-up the entire lengths of the exhaust ducts developed in the conceptual design studies. These tests should employ uranium-vapor/argon-gas mixtures for closer simulation of the properties of the mixtures in the engine and in-reactor test model.

Rodgers, R. J. and T. S. Latham: Analytical Design and Performance Studies of the Nuclear Light Bulb Engine. UARL Report L-910900-16, September 1972.

SUMMARY

Analytical studies were conducted to investigate in detail the heat balance characteristics of the nuclear light bulb engine. Distributions of energy deposition to all engine components from the fission process, conduction and convection, and thermal radiation were considered. Where uncertainties in basic data or heat transfer characteristics were encountered, ranges of heat loads were calculated and reference values were selected. The influence of these heat loads on engine performance, space radiator requirements, and cooling sequence and cooling circuit designs was determined.

Reference heat balance conditions were chosen which resulted in an engine with a weight of 37,250 kg (82,000 lb), including a space radiator weight of 5500 kg (12,100 lb); a thrust of 409,000 N (92,000 lb); and a specific impulse of 1870 sec. The space radiator serves a dual purpose -- rejection of 118 MW of power from structural components of the system during steady-state operation and rejection of fission product decay heat and sensible heat from bulk moderator and structural components after engine shutdown.

The analyses resulted in revisions to the previously reported reference engine characteristics, principally in the heat loads to some engine components and in the cooling sequence. These revisions were incorporated in the engine dynamics digital computer simulation program. No significant changes occurred in the dynamic response of the engine to perturbations in fuel injection rate, reactivity or exhaust nozzle area.

Latham, T. S. and R. J. Rodgers: Analytical Design and Performance Studies of Nuclear Furnace Tests of Small Nuclear Light Bulb Models. UARL Report L-910900-17, September 1972.

SUMMARY

Analytical studies were continued to identify the design and performance characteristics of a small-scale model of a nuclear light bulb unit cell suitable for testing in the Nuclear Furnace reactor. Emphasis was placed on calculating performance characteristics based on detailed radiant heat transfer analyses, on designing the test assembly for ease of insertion, connection, and withdrawal at the reactor test cell, and on determining instrumentation and test effluent handling requirements. In addition, a review of candidate test reactors for future nuclear light bulb in-reactor tests was conducted.

The results of the study indicate that a meaningful series of in-reactor demonstration tests of fuel containment, transparent-wall performance, and propellant heating could be conducted using the Nuclear Furnace reactor. Processing of the effluent from an in-reactor test could be accomplished by flowing the exit gases through the Nuclear Furnace scrubber or by adding a separate scrubber loop to handle the in-reactor test effluent separately. The test cell design was chosen such that the test capsule could be inserted, connected, and withdrawn from a Nuclear Furnace without transporting the entire system by rail from the test cell to the remote Maintenance-Assembly-Disassembly (MAD) building. With this mode of operation, it is estimated that 10 to 20 test runs could be performed using one Nuclear Furnace core.

Results of detailed radiant heat transfer and performance analyses indicated that thermal radiation fluxes corresponding to black-body radiating temperatures on the order of 5420°K could be sustained in a fissioning uranium plasma in a test configuration having reflecting walls and operating at a pressure of 500 atm. Tests could also be conducted to demonstrate that internally-cooled transparent walls are capable of withstanding both the nuclear radiation and thermal environments anticipated for a nuclear light bulb engine and that seeded propellant can be heated to exhaust temperatures in the range of 3300 to 3700°K .

Simulation tests of models similar in geometry to those anticipated in in-reactor demonstration tests have been performed using the UARL 1.2-MW rf induction heater and dc arc facilities. To date, these tests have included successful injection of gaseous UF_6 and tungsten particles in argon carrier gas into rf plasmas operating at pressures up to about 40 atm with up to 125 kW of radiated power. Bulk exit temperatures of 4515°K have been measured in simulated propellant streams

heated by dc arc discharges. In addition, a fiberglass pressure vessel capable of operating in the 1.2-MW rf induction heater in future high-pressure tests has been designed, fabricated, and tested at pressures greater than 500 atm. It is recommended that thorough development and testing of in-reactor test models at power levels and operating conditions anticipated for in-reactor tests in the Nuclear Furnace be continued using these facilities.

Krascella, N. L.: Spectral Absorption Coefficients of Argon and Silicon and Spectral Reflectivity of Aluminum. UARL Report L-910904-3, September 1972.

SUMMARY

A theoretical investigation was conducted to estimate the spectral properties of argon as a function of pressure, temperature and wave number. The spectral characteristics of the argon buffer gas exert a strong influence on radiative energy transfer in the Nuclear Furnace in-reactor test configuration of the nuclear light bulb engine. An existing computer program was modified and used to calculate the spectral absorption coefficients of argon at total pressures of 50, 100, 250, 500, 750 and 1000 atm in the temperature interval between 1000 and 30,000°K. At each pressure and temperature, spectral properties were calculated for forty-seven wave numbers in the interval between 1000 and 1,000,000 cm^{-1} .

Estimates of the spectral absorption coefficients of silicon were made as part of an evaluation of silicon vapor as a possible buffer-gas seeding agent for the reference nuclear light bulb engine. Existing cross-section data were used to calculate the spectral characteristics of silicon at twenty-four temperatures in the interval between 2000 and 10,000°K. Calculations were made for partial pressures of silicon equal to the vapor pressures up to a temperature of 3700°K and equal to 10 atm above 3700°K. Spectral data for silicon were calculated at twenty-nine wave numbers at each temperature and partial pressure.

The spectral and angular dependence of the reflectivity of aluminum was also computed for subsequent use in determining radiative transfer characteristics of both the in-reactor-test configuration and the reference engine configuration. Reflectivities of aluminum were calculated at twenty-three wave numbers between 1000 and 1,000,000 cm^{-1} for six angles of incidence between 0 and 89.9°.

Palma, G. E.: Measurements of the UV and VUV Transmission of Optical Materials During High-Energy Electron Irradiation. UARL Report L-990929-3, September 1972.

SUMMARY

An experimental program was conducted in which the optical transmission of several transparent materials was measured during high-energy electron irradiation. These experiments were conducted at the Space Radiation Effects Laboratory of the NASA Langley Research Center using the Dynamitron electron accelerator as a continuous source of 1.5 MeV electrons and the LINAC electron accelerator as a pulsed source of 5-7 MeV electrons.

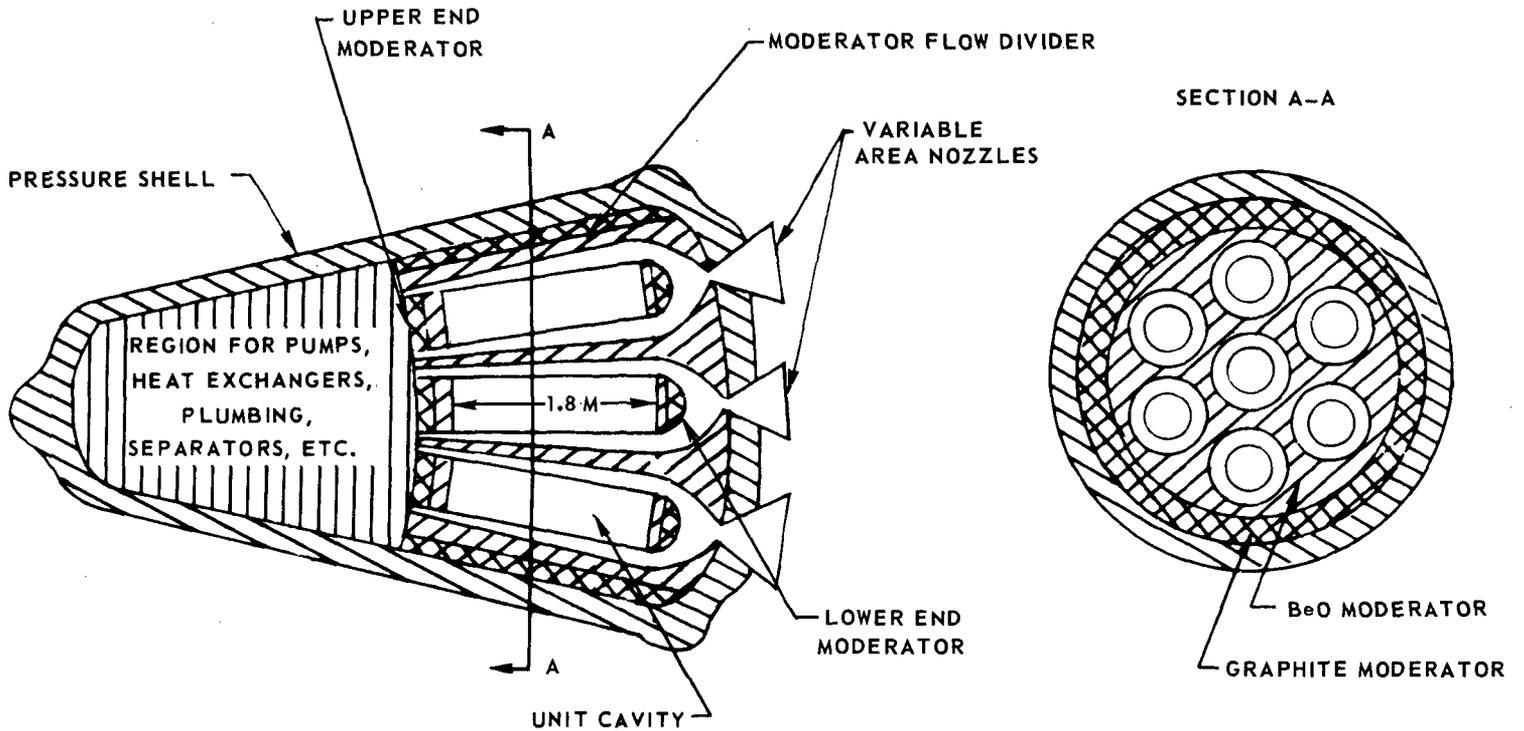
The experimental program consisted of three major portions. The first portion, the optical transmission of fused silica, BeO, MgF₂, and LiF was measured at vacuum ultraviolet wavelengths in the range 1550-2000Å during ambient-temperature, 1.5-MeV electron irradiation at ionizing dose rates to 0.5 Mrad/sec. In the second portion of the program, the optical transmission of fused silica and BeO was measured in the range 2000-3000Å during high-dose-rate, elevated-temperature 1.5-MeV electron irradiation. In particular, accurate measurements of the optical transmission were made at ionizing dose rates as high as 10 Mrad/sec. In the final portion of the program, the optical transmission of fused silica and BeO was measured in the wavelength range 2000-3000Å during pulsed 5- and 7-MeV electron irradiation from the LINAC accelerator. The maximum time-averaged ionizing dose rate was limited to 0.75 Mrad/sec due to accelerator limitations.

TABLE I
 TOPICS COVERED IN UARL TECHNICAL REPORTS ON GASEOUS NUCLEAR ROCKET TECHNOLOGY
 See Ref. 42 For List of 98 Reports Issued by Other Agencies

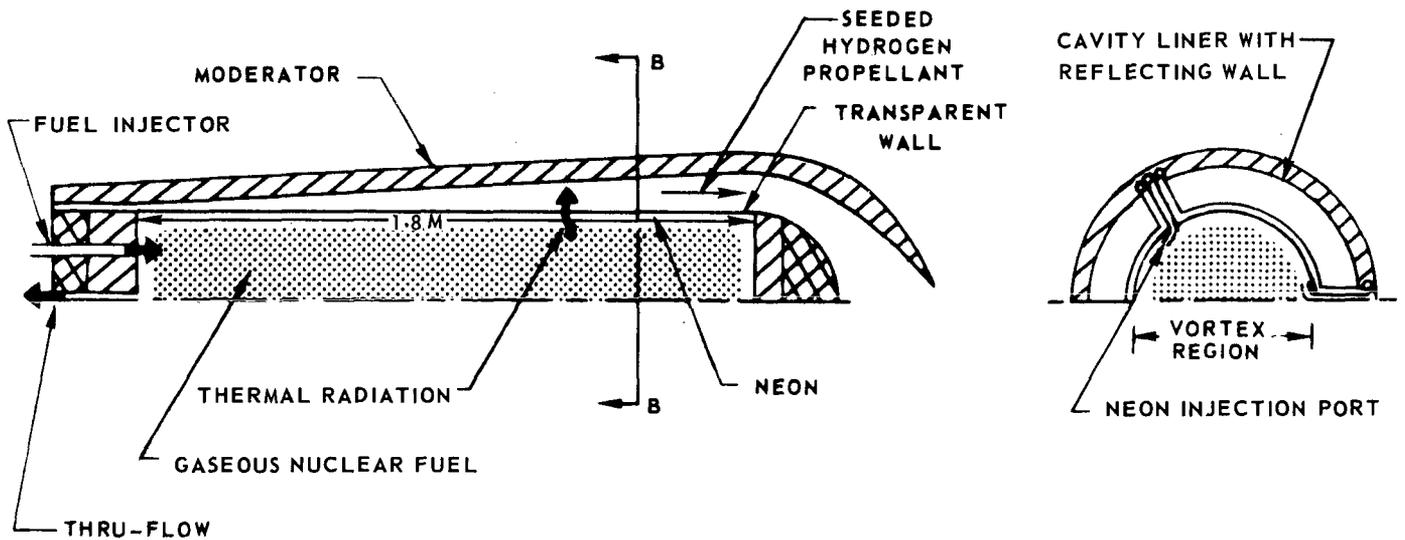
Topic	Reports Issued Under Contracts						
	SNPC-70	NASw-768	NASw-847	NAS3-13446 NAS3-13459	NAS3-3382	AF O4 (611)8189	AF O4 (611)7448
<u>Fluid Mechanics</u> Unheated Vortex Flow Heated Vortex Flow Unheated Coaxial Flow	3,17 1,9,17,18,19		45,46,57,62,63,64 72,74,75,76,83,84,85,86 44,45,49,50,52 48,55	93,94		96,98,104,105 98,99,100	107,108
<u>Radiant Heat Transfer</u> Propellant Heating Experiments Theoretical Analyses and Opacity Measurements	2,10,16 5,6,7,12,14,23		44 46,51,66,67,68,73,77,78,81,82 87,88,89,90,91		95	101,102,103	
<u>Radiation Damage to Transparent Materials</u>	8,15,22	41	43,54,58,59				
<u>Engine Design</u>	4,5,11,12,20		47,53,60,61,69,70,71,79,80,92				
<u>In-Reactor Tests</u>	4,6,11,13,21						
<u>Program Summary Report</u>	Present Report		42,65			97	106

SKETCHES ILLUSTRATING PRINCIPLE OF OPERATION OF NUCLEAR LIGHT BULB ENGINE

(a) OVERALL CONFIGURATION



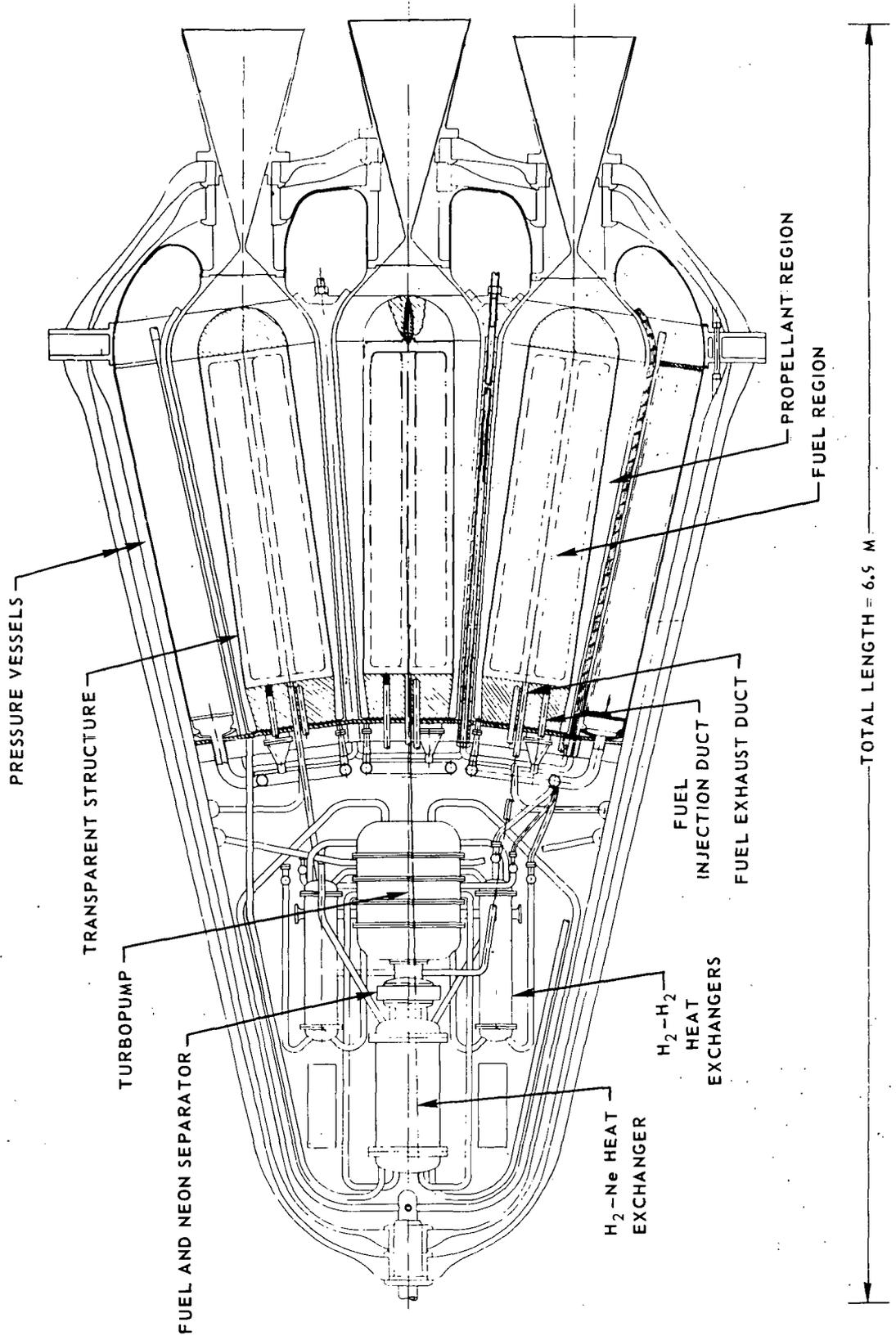
(b) CONFIGURATION OF UNIT CAVITY



SIDE VIEW OF NUCLEAR LIGHT BULB REFERENCE ENGINE CONFIGURATION

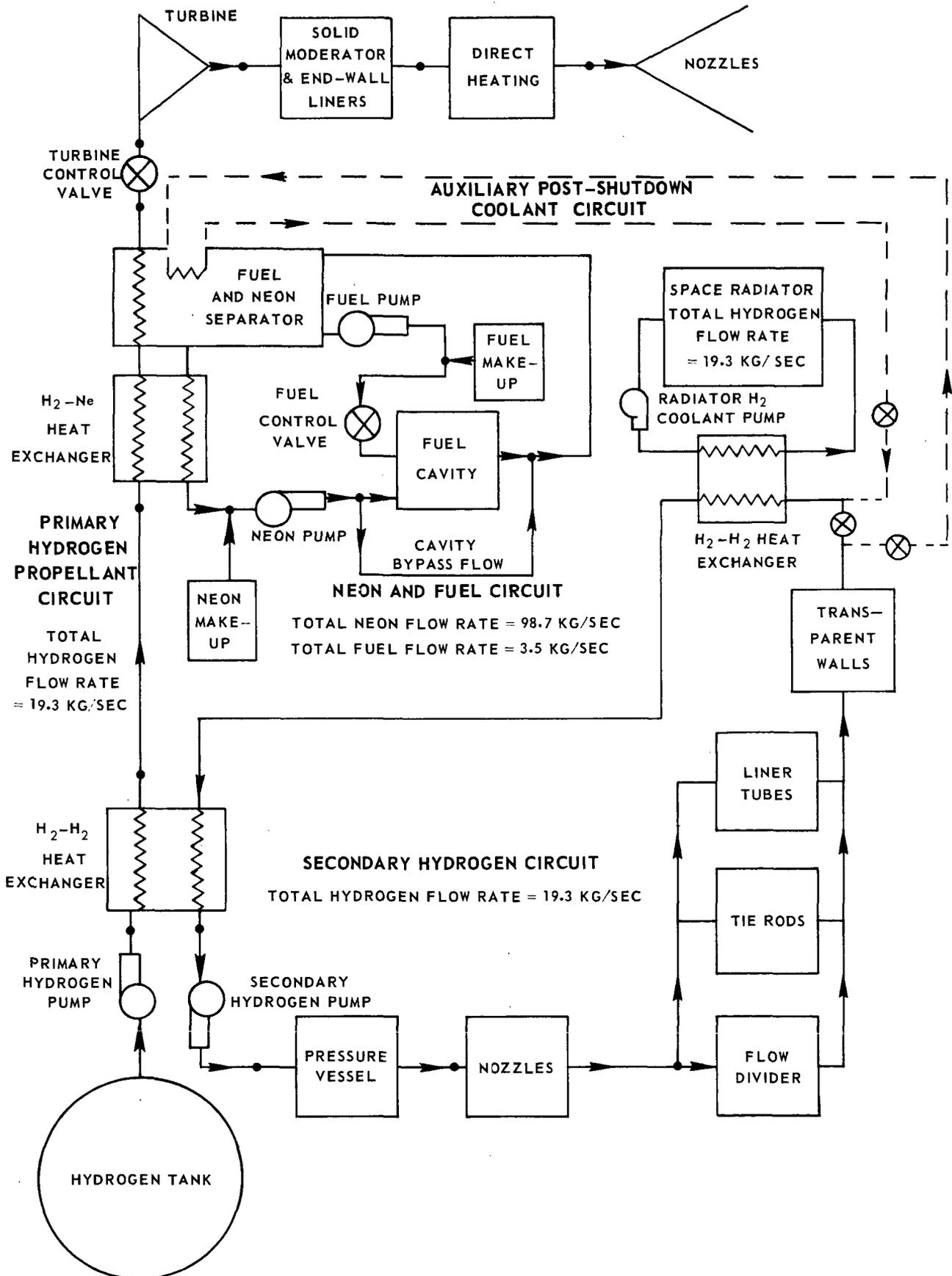
ENGINE POWER = 4600 MW

OPERATING PRESSURE = 500 ATM

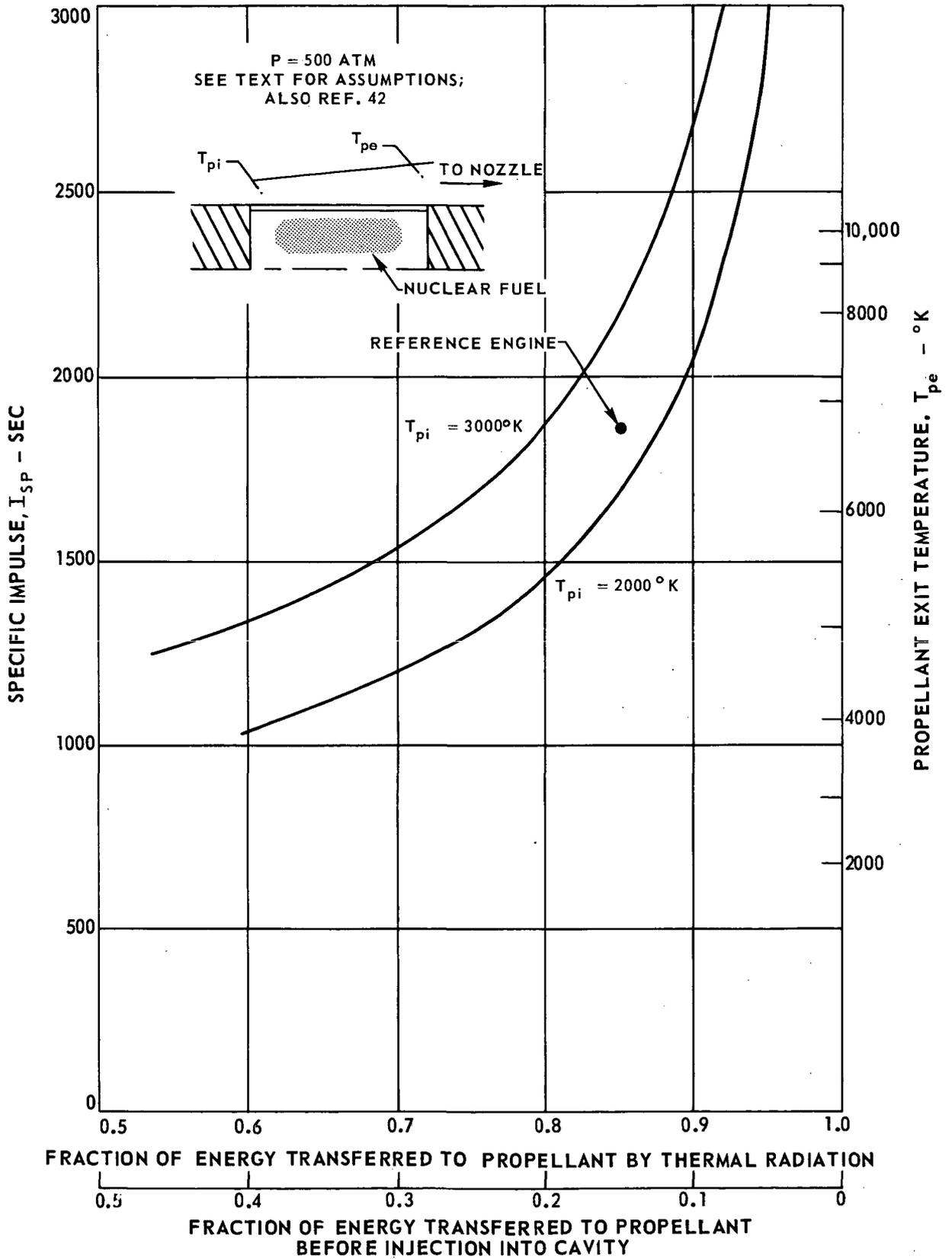


NUCLEAR LIGHT BULB FLOW DIAGRAM

FOR ADDITIONAL DETAILS SEE REF. 5.



EFFECT OF PROPELLANT HEATING MECHANISM AND PROPELLANT INLET TEMPERATURE ON SPECIFIC IMPULSE



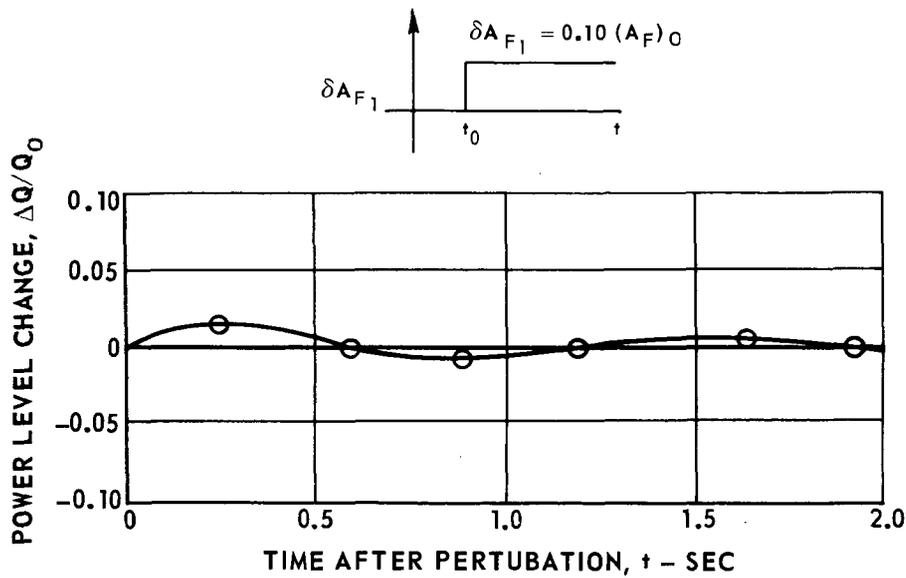
POWER LEVEL RESPONSES OF CONTROLLED ENGINE TO STEP CHANGES
IN FUEL INJECTION CONTROL VALVE AREA

$$W_F = K_F A_F \left(\frac{P_I - P_C}{0.25} \right)^{1/2}$$

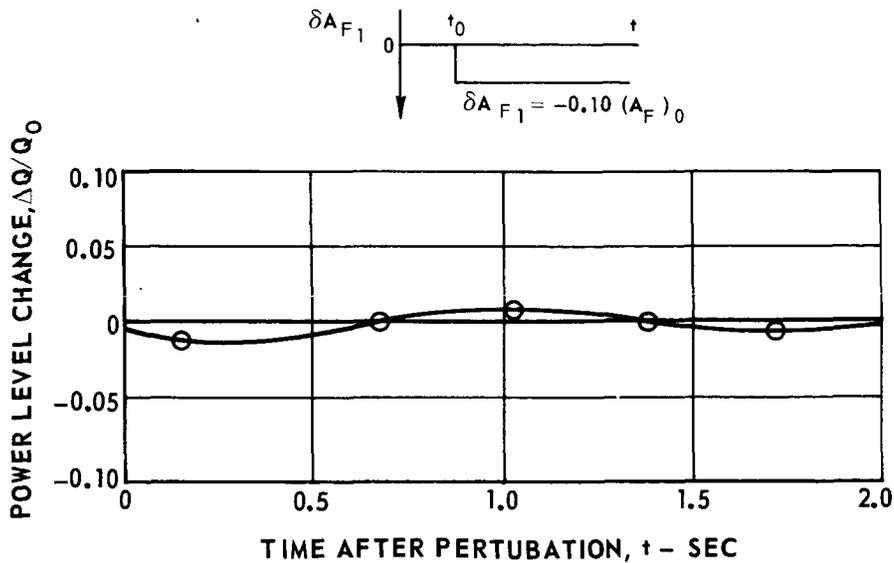
— CALCULATED RESPONSE FROM REF. 5

○ SYMBOL INDICATES CALCULATED RESPONSE FOR REVISED REFERENCE ENGINE

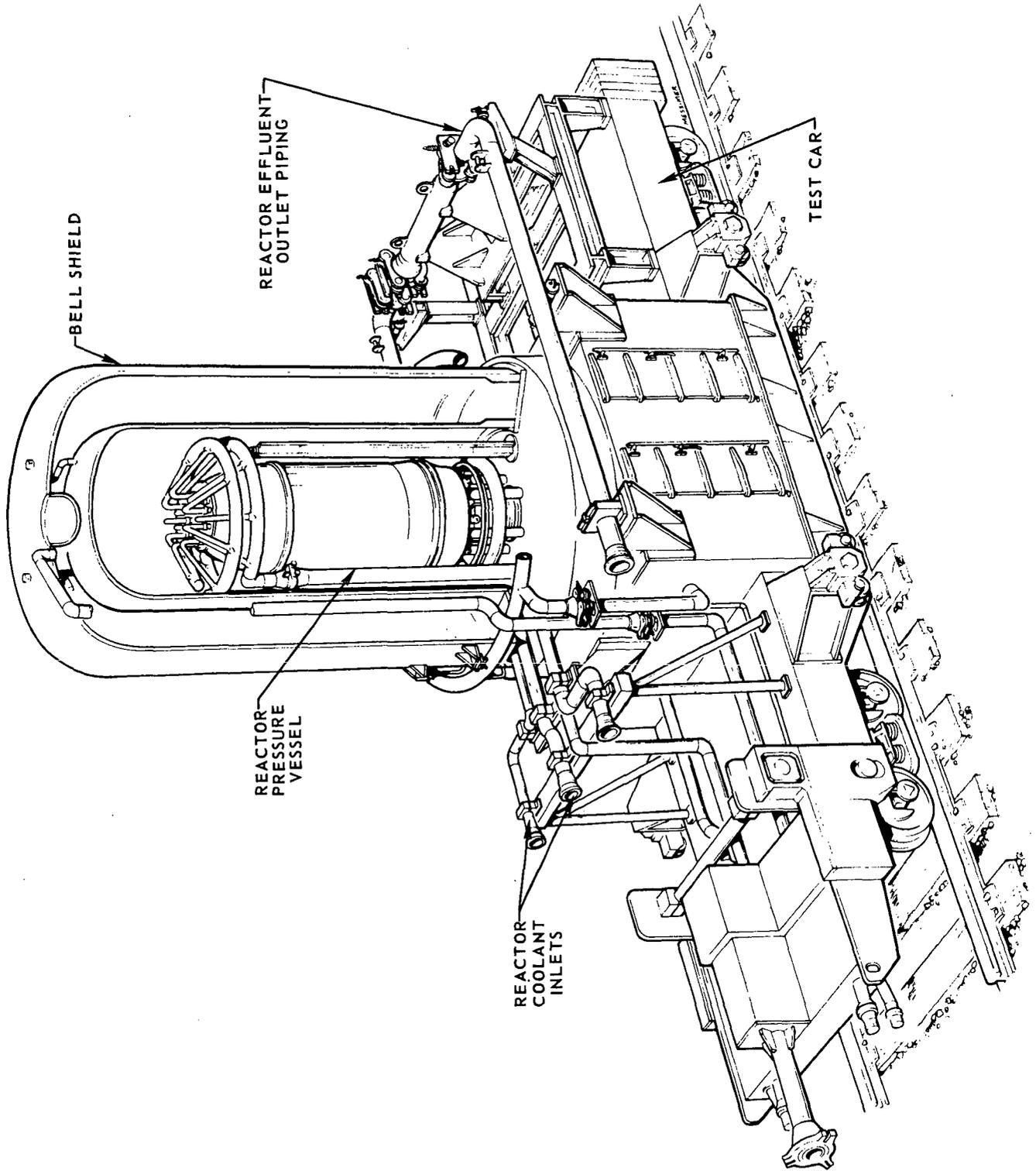
(a) INITIAL STEP INCREASE IN CONTROL VALVE AREA



(b) INITIAL STEP DECREASE IN CONTROL VALVE AREA



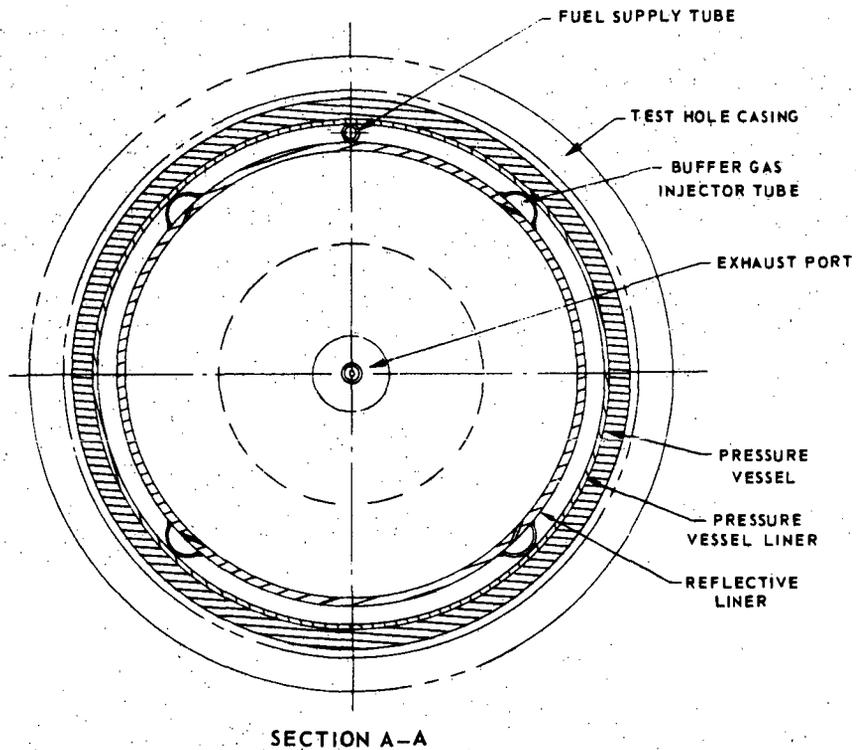
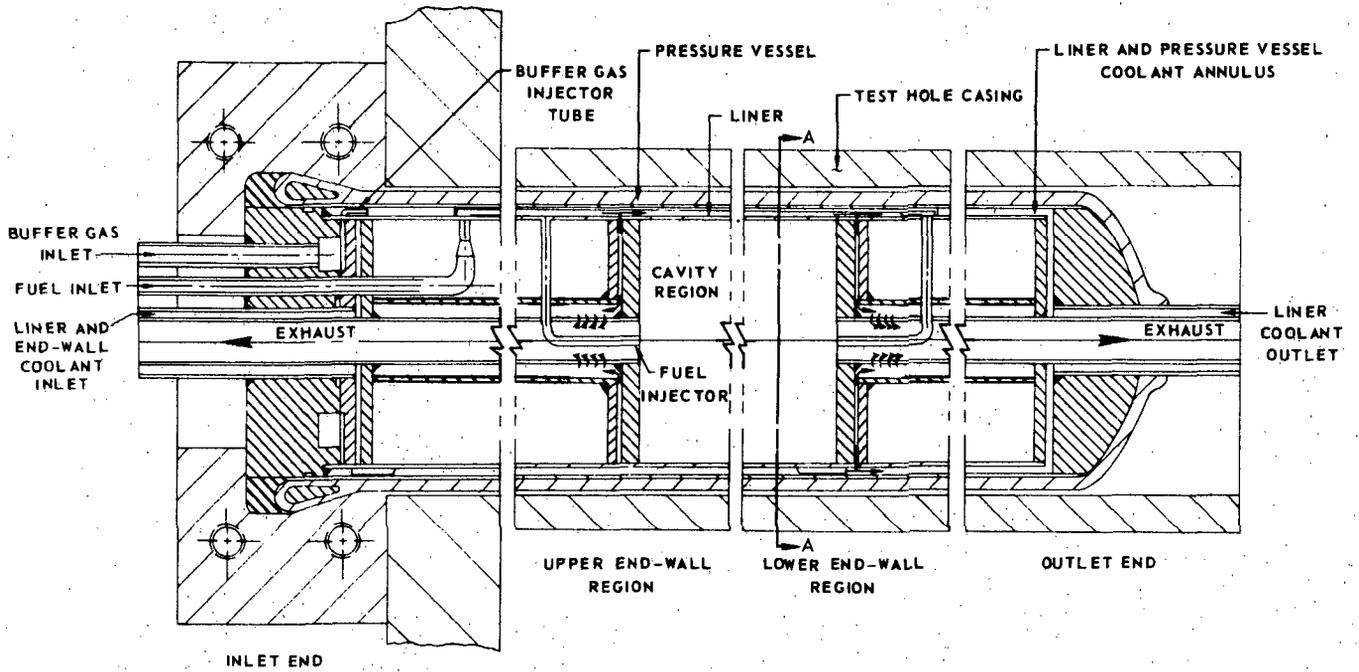
NUCLEAR FURNACE REACTOR ASSEMBLY
LASL SKETCH



PRELIMINARY LAYOUT OF TEST CELL FOR NUCLEAR FURNACE IN-REACTOR TEST

ID OF TEST HOLE CASING = 8.4 CM

DIMENSIONS OF CYLINDRICAL CAVITY REGION: 6.6-CM ID X 17.8-CM LONG



CALCULATED IN-REACTOR TEST PERFORMANCE

FISSIONING URANIUM PLASMA FACILITY (FUPF)

NUCLEAR FURNACE (NF)

HIGH-FLUX ISOTOPE REACTOR (HFIR)

KINETIC INTENSE NEUTRON GENERATOR (KING)

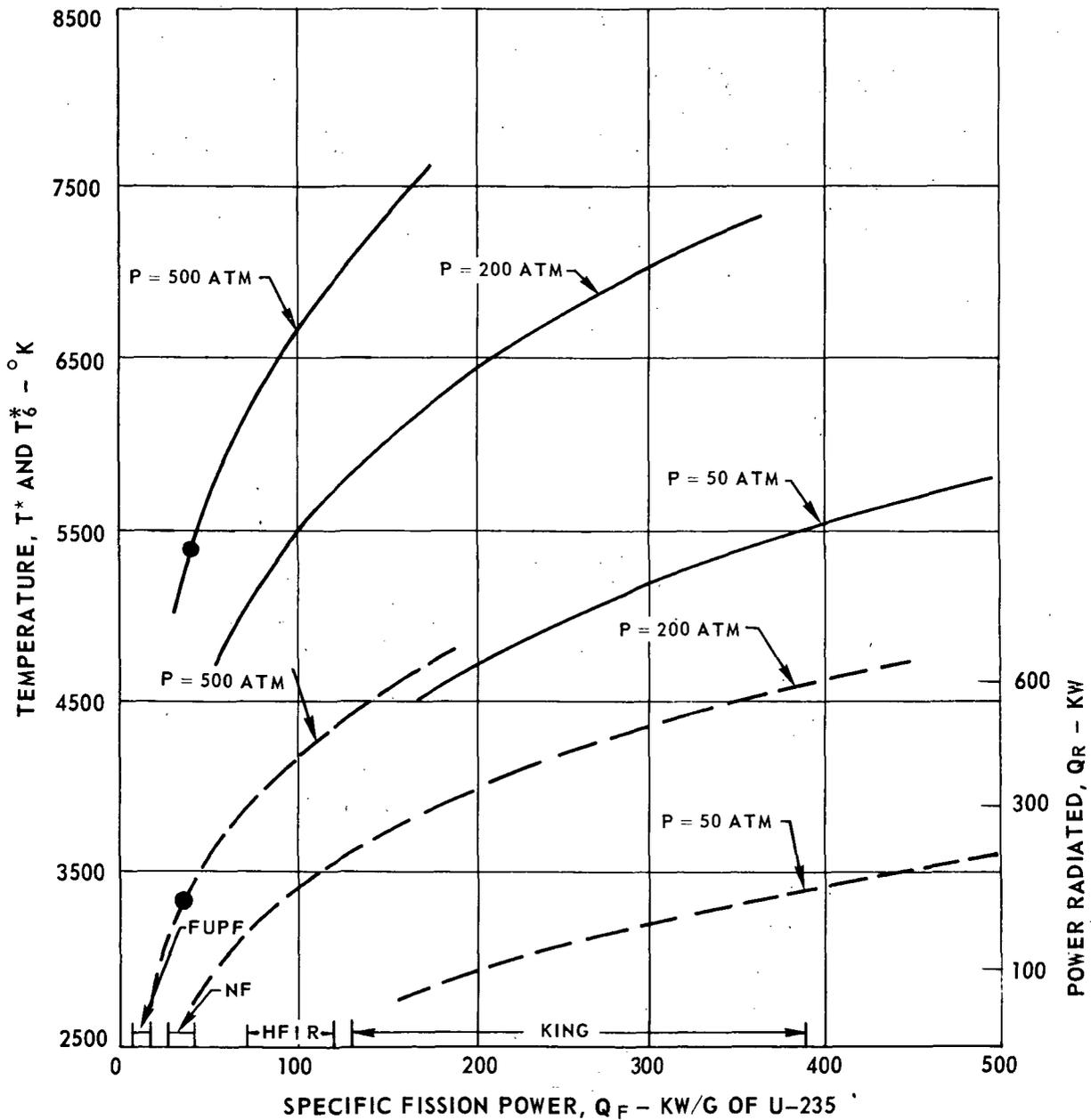
SEE FIG.7 FOR TEST CONFIGURATION DETAILS

REFLECTIVITY, $R = 0.855$

CONTAINMENT DENSITY RATIO, $\bar{\rho}_{F_6} / \rho_{B_6} = 0.6$

● DENOTES PERFORMANCE AT REFERENCE TEST CONDITION

— T_{δ}^* , EDGE OF FUEL
 - - - T^* , BLACKBODY



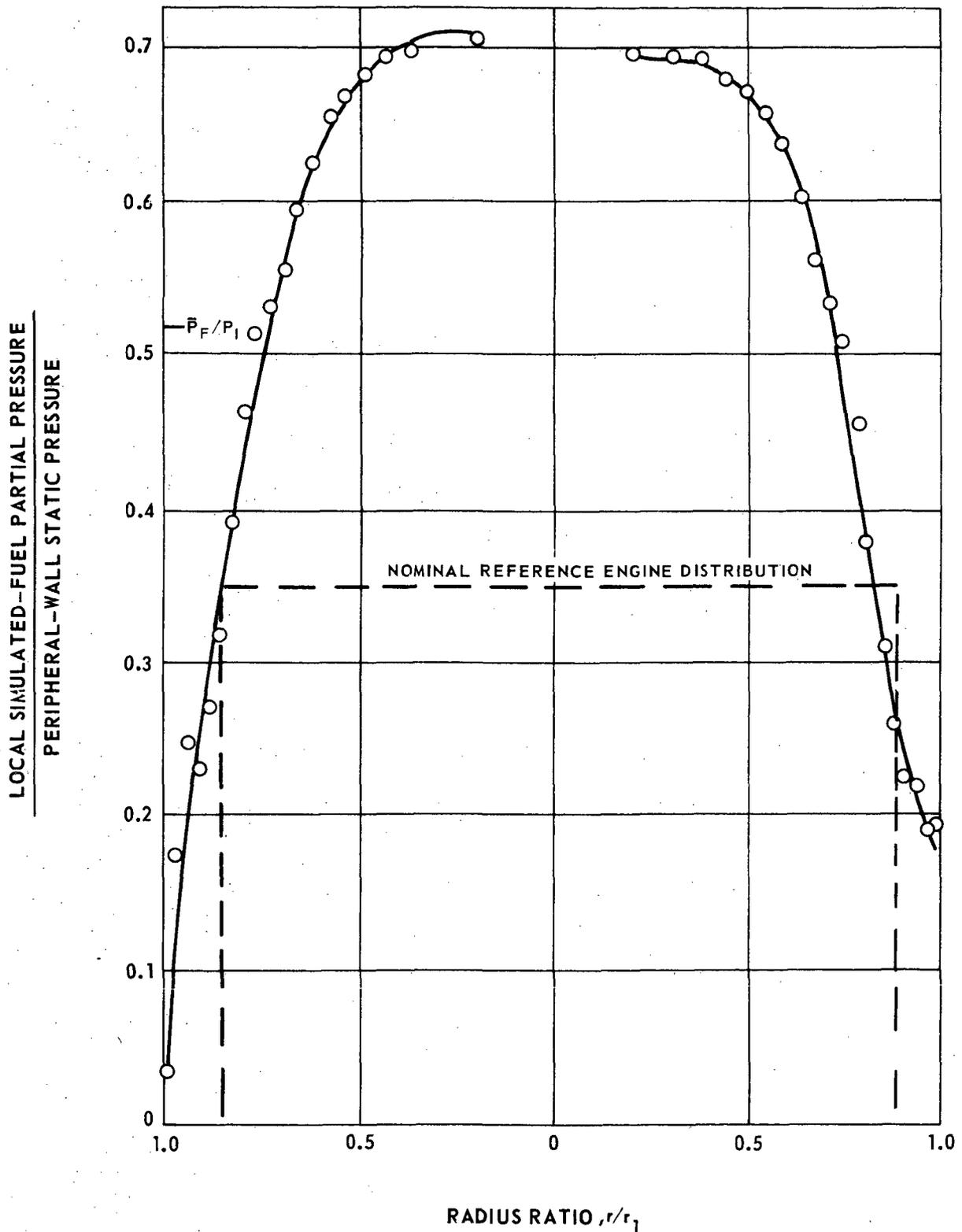
RADIAL DISTRIBUTION OF SIMULATED FUEL IN ISOTHERMAL VORTEX CONTAINMENT TEST

DIMENSIONS OF VORTEX CHAMBER: 25.4 - CM I.D. X 76.2-CM LONG

NITROGEN/IODINE SIMULATED FUEL

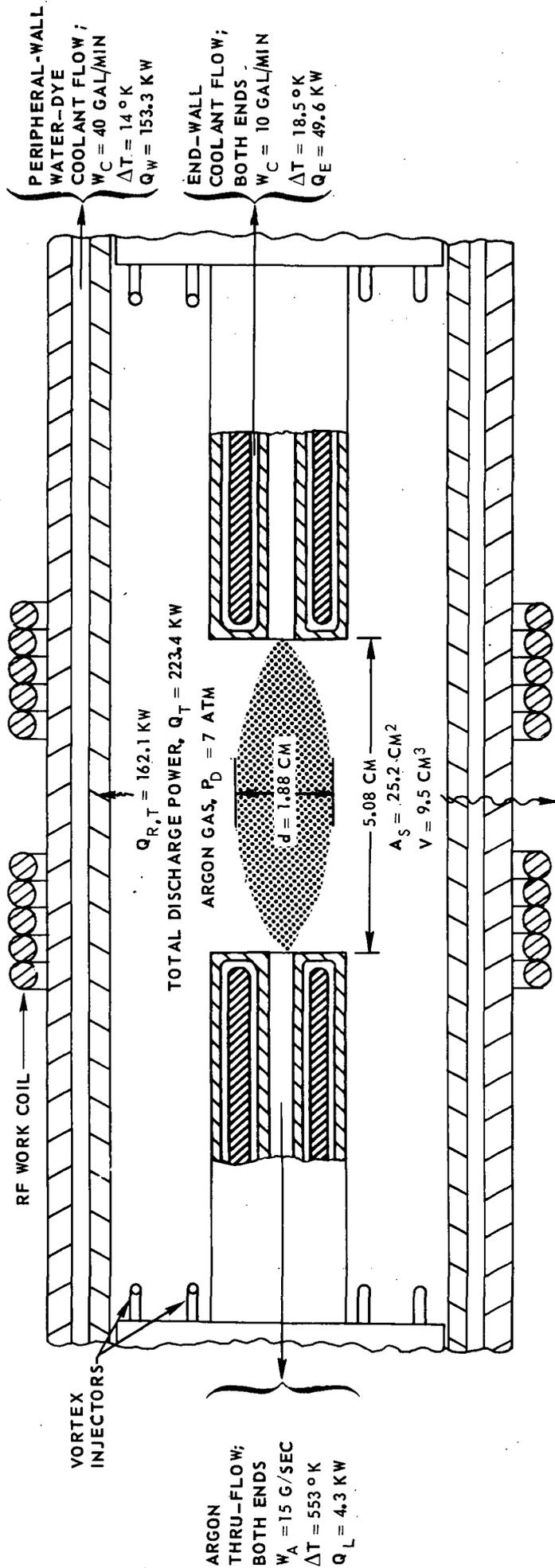
CHAMBER PRESSURE = 1.0 ATM

TEMPERATURE \approx 400° K



SKETCH OF RF RADIANT ENERGY SOURCE CONFIGURATION SHOWING POWER BREAKDOWN FOR HIGHEST-POWER OPERATING POINT

FOR ADDITIONAL DETAILS SEE REF. 19



RADIOMETER

READING = 1884 MV

$$Q_R = (8.6 \times 10^{-3} \text{ KW/MV}) (1884 \text{ MV}) = 16.2 \text{ KW}$$

TOTAL D-C INPUT POWER = 640 KW AT 5.5873 MHZ

$$\text{TOTAL DISCHARGE POWER, } Q_T = 16.2 + 153.4 + 49.6 + 4.3 = 223.4 \text{ KW}$$

$$\text{R-F SYSTEM COUPLING EFFICIENCY} = 223.4/640 = 34.9 \text{ PERCENT}$$

PROBABLE MAXIMUM POWER CONDUCTED THROUGH PERIPHERAL WALL = 7.5 KW

$$\text{TOTAL POWER RADIATED THROUGH INNER PERIPHERAL WALL, } Q_{R,T} = 153.4 - 7.5 + 16.2 = 162.1$$

$$\phi_R = Q_{R,T} / A_S = 162.1 / 25.2 = 6.43 \text{ KW/CM}^2 \quad (T^* = 5800^\circ \text{K})$$

$$\text{FRACTION OF DISCHARGE POWER RADIATED THROUGH INNER PERIPHERAL WALL, } Q_{R,T} / Q_T = 162.1 / 223.4 = 0.72$$

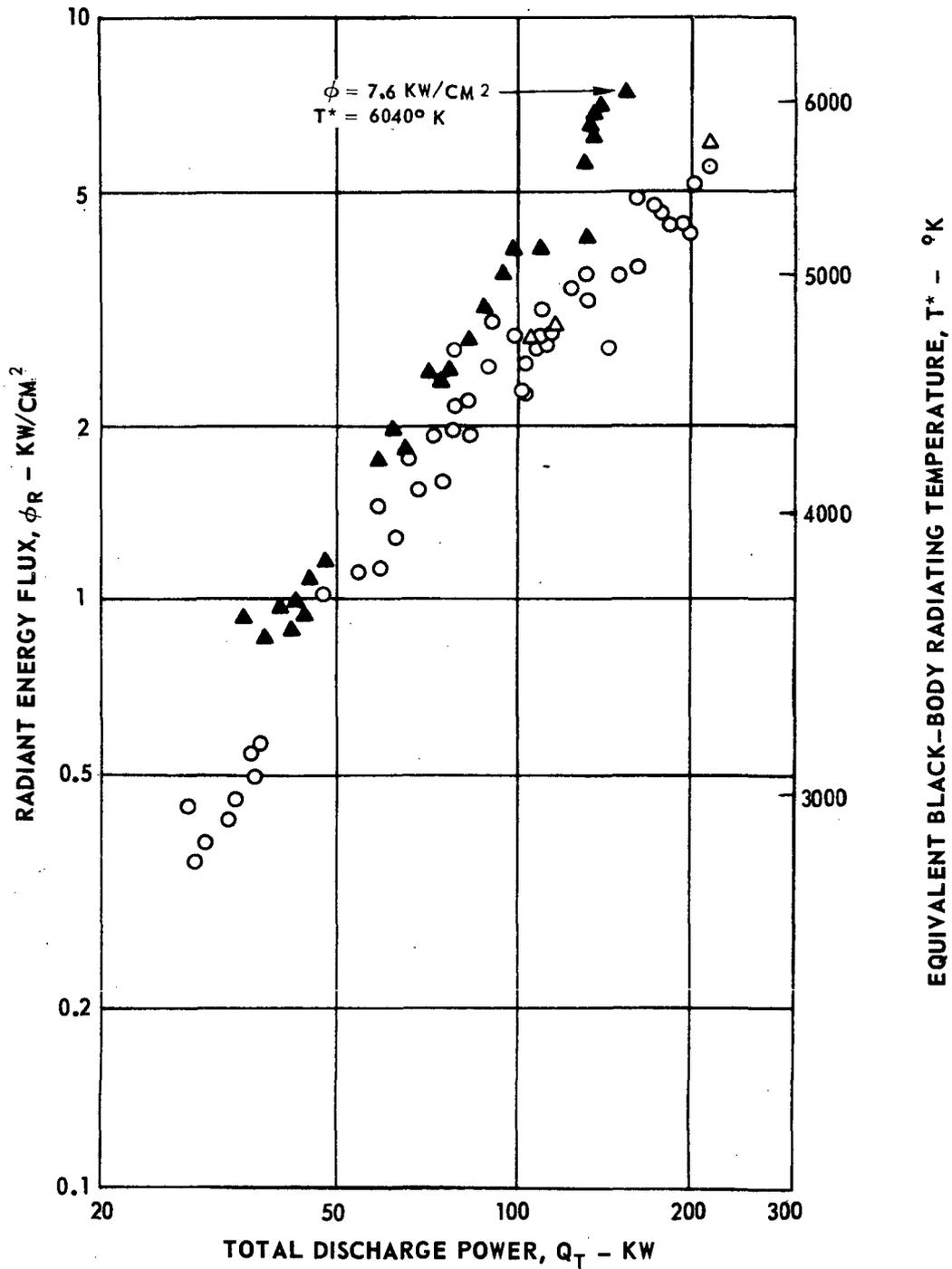
VARIATION OF RADIANT ENERGY FLUX WITH TOTAL DISCHARGE POWER

SEE FIG. 10 FOR DETAILS OF TEST CONFIGURATION ; ALSO REFS. 9 AND 19.

RANGE OF CHAMBER PRESSURE, $P_D = 2$ TO 19.2 ATM

- CONFIGURATION HAVING 8 VORTEX INJECTORS AT 0.72-IN. RADIUS
- ▲ CONFIGURATION HAVING 16 VORTEX INJECTORS AT TWO RADIAL LOCATIONS

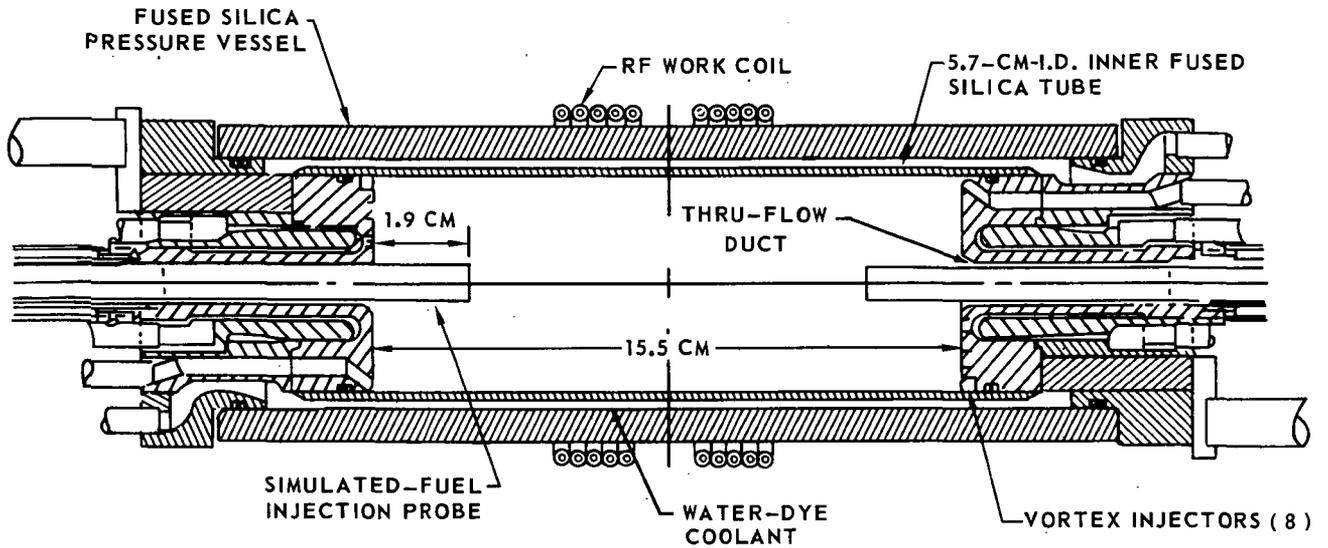
$$\phi_R = Q_{R,T} / A_S$$



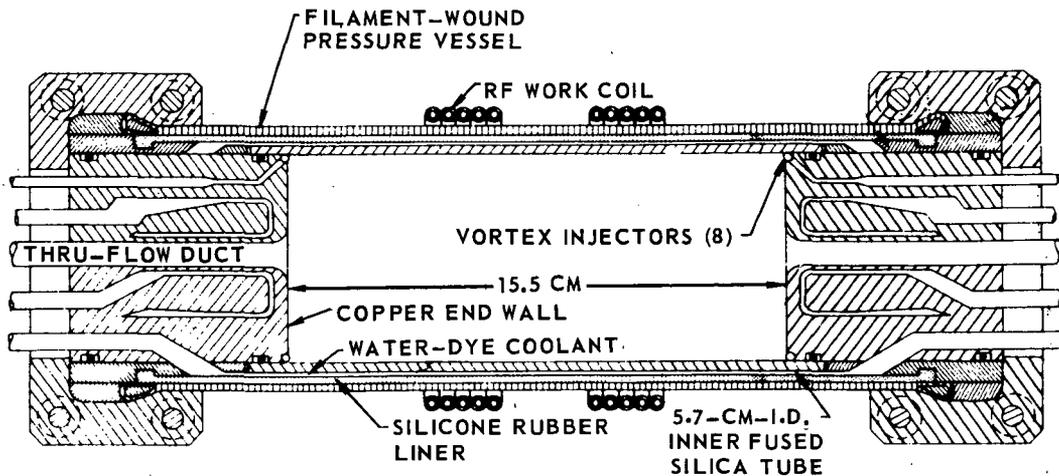
TEST CONFIGURATIONS USED FOR RF PLASMA SIMULATIONS OF IN-REACTOR TEST CONDITIONS

ADDITIONAL DETAILS GIVEN IN REF. 1

(a) CONFIGURATION FOR TESTS WITH FUSED SILICA TUBE PRESSURE VESSEL AND
SIMULATED -FUEL INJECTION



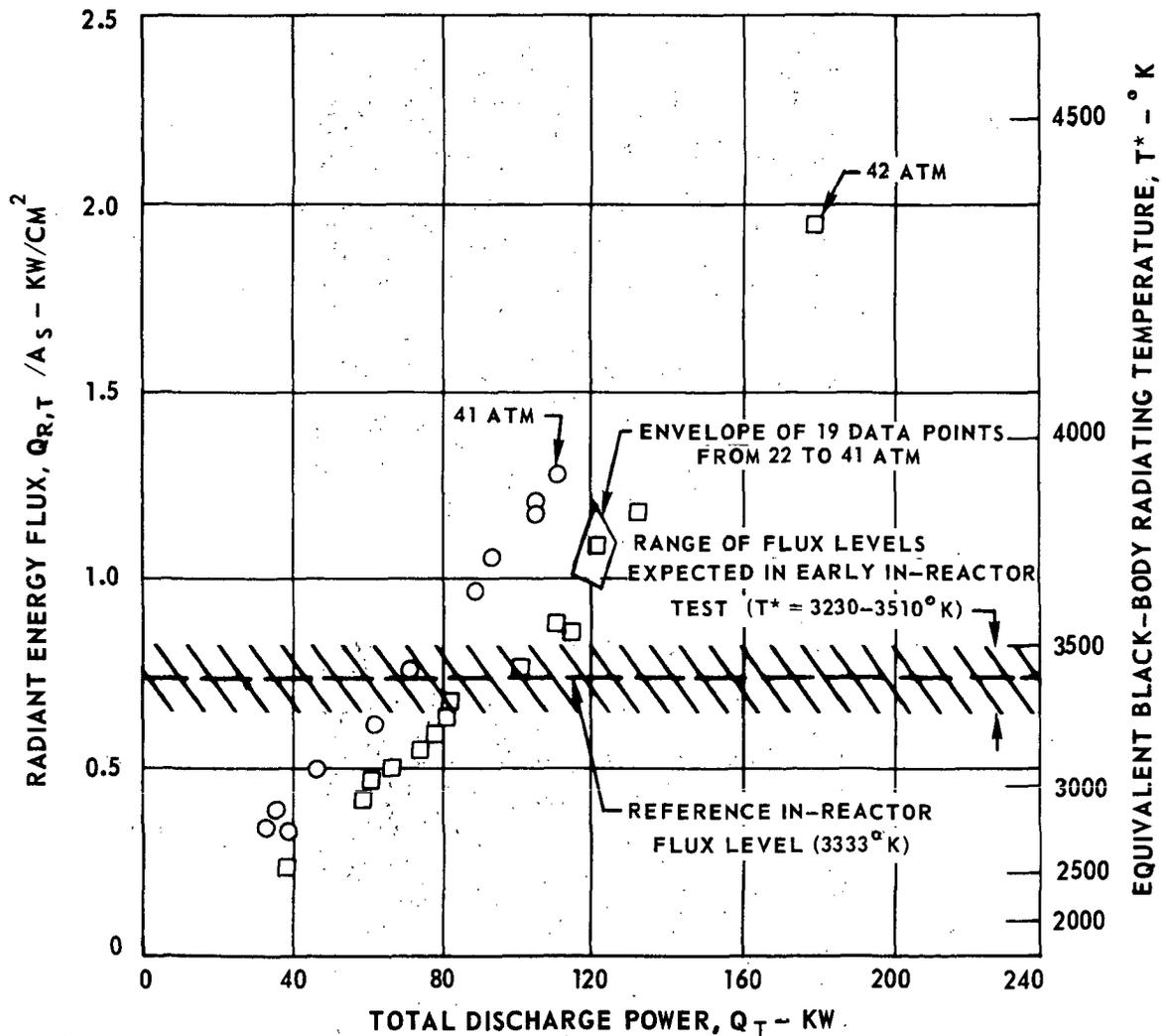
(b) CONFIGURATION FOR TESTS WITH FILAMENT-WOUND PRESSURE VESSEL



VARIATION OF RADIANT ENERGY FLUX WITH TOTAL DISCHARGE POWER OBTAINED IN RF IN-REACTOR FUEL REGION SIMULATION TESTS

FUSED SILICA PRESSURE VESSEL CONFIGURATION; SEE FIG. 12 (a)

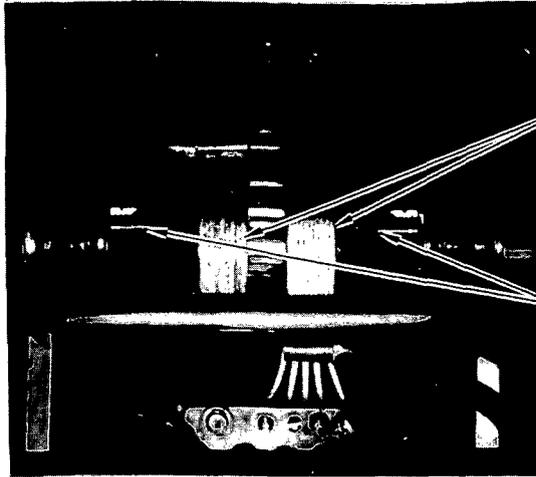
SYMBOL	CHAMBER PRESSURE, P_D - ATM	ARGON FLOW RATE, W_A - g /SEC	RF OPERATING FREQUENCY, f - MHz	SIMULATED-FUEL INJECTION PROBE AND THRU-FLOW DUCT DIAMETER
○	10 - 41	3.6 - 5.9	5.3996 - 5.4095	0.635-CM-O.D., 3 CONCENTRIC TUBE TYPE; 0.792-CM-DIAM DUCT
□	5 - 42	5.4 - 9.1	5.4001- 5.4358	0.89-CM-O.D., 4 CONCENTRIC TUBE TYPE; 1.14-CM-DIAM DUCT



PHOTOGRAPHS TAKEN DURING RF PLASMA TESTS WITH SIMULATED-FUEL INJECTION

(a) TEST CONFIGURATION WITH NO PLASMA PRESENT

SEE FIG. 12 (a) FOR
DETAILS OF TEST
CONFIGURATION



RF WORK COILS

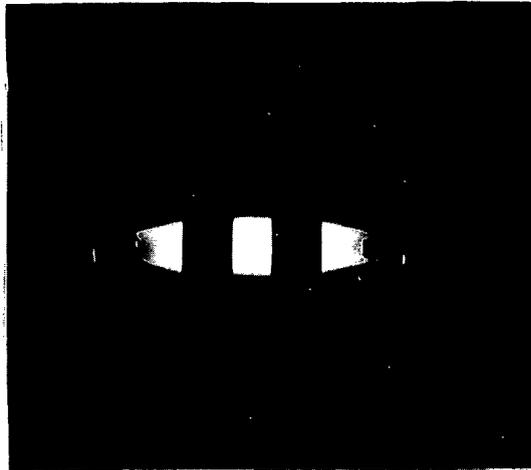
EXPOSURE DATA:
EKTACOLOR-ASA 100
f/8 AT 1/10 SEC

SIMULATED-FUEL
INJECTION PROBES

(b) WITH ARGON RF PLASMA PRESENT

TEST CONDITIONS:

$Q_T = 46 \text{ KW}$
 $P_D = 20 \text{ ATM}$
 $W_A = 6.5 \text{ g/SEC}$
 $T^* = 2800^\circ \text{K}$

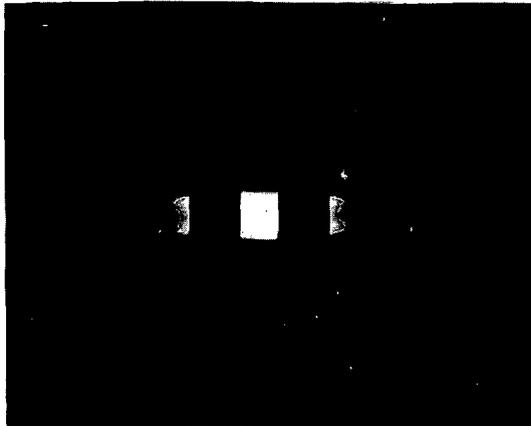


f/16 AT 1/250

(c) WITH 1 PERCENT UF_6 INJECTION

TEST CONDITIONS:

$Q_T = 84 \text{ KW}$
 $P_D = 20 \text{ ATM}$
 $W_A = 6.5 \text{ g/SEC}$
 $T^* = 3380^\circ \text{K}$



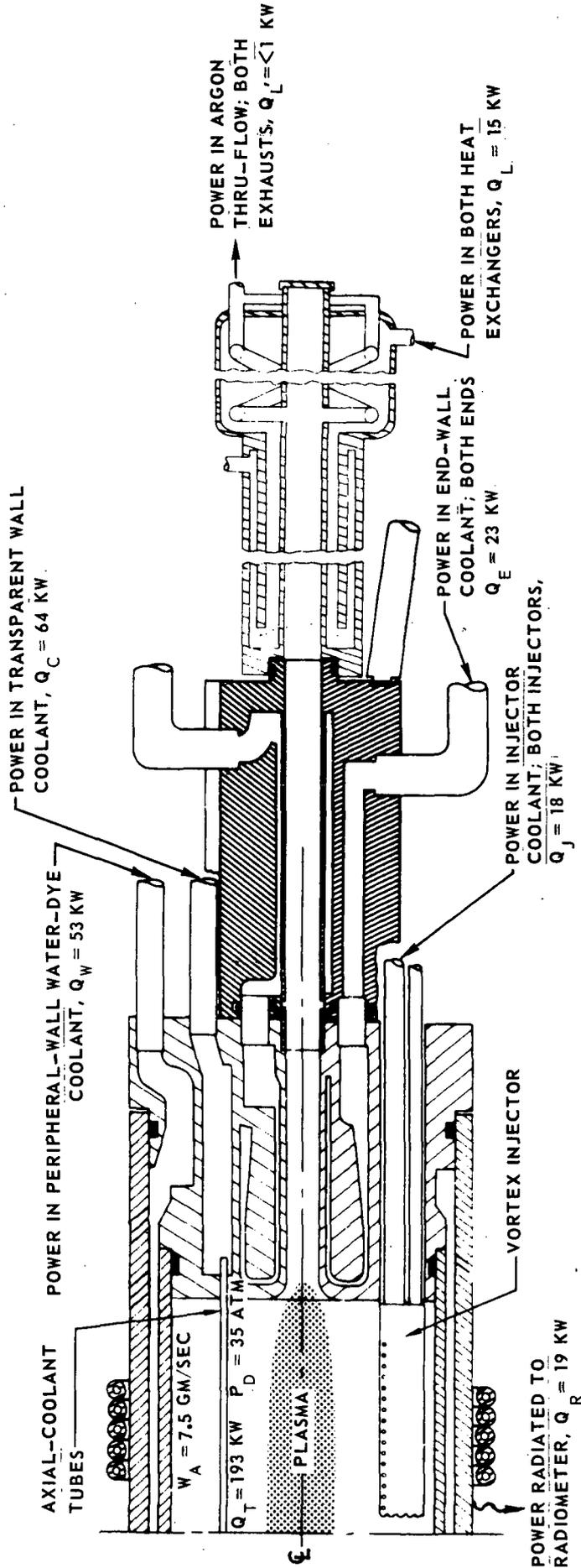
f/32 AT 1/250

PHOTOGRAPH OF CONFIGURATION FOR RF PLASMA IN-REACTOR SIMULATION
TESTS AT 500 ATM PRESSURE



SKETCH OF TRANSPARENT-WALL MODEL SHOWING POWER BREAKDOWN FOR HIGHEST-POWER/HIGHEST-PRESSURE OPERATING POINT

FOR ADDITIONAL DETAILS OF MODEL CONFIGURATION SEE REF. 1



TOTAL DC INPUT POWER = 590 KW AT 5.4824 MHZ

TOTAL DISCHARGE POWER, $Q_T = 193$ KW

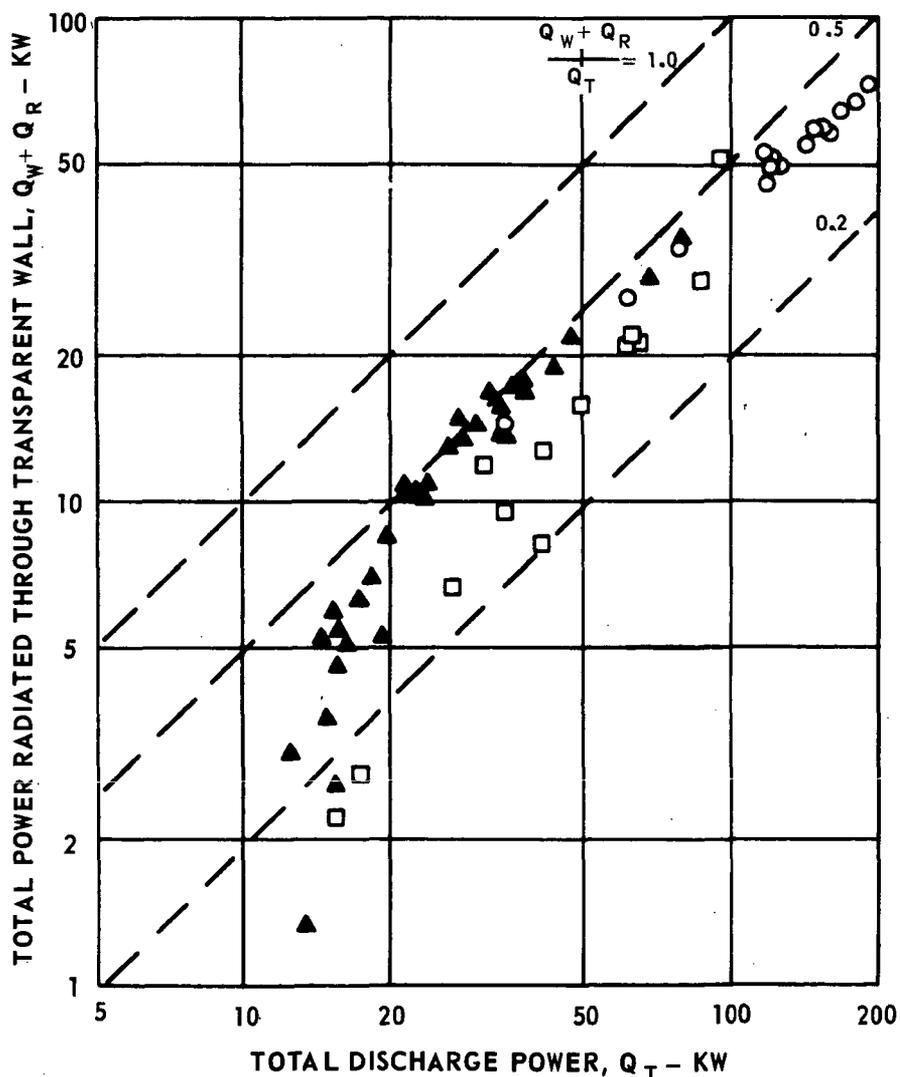
TOTAL POWER RADIATED THROUGH MODEL WALL, $Q_R + Q_W = 72$ KW

RADIANT ENERGY FLUX MODEL WALL, $Q_{R,T}/A_M = 1.4$ KW/CM²

VARIATION OF POWER RADIATED THROUGH AXIAL-COOLANT TUBES WITH TOTAL DISCHARGE POWER IN TRANSPARENT-WALL MODEL TESTS

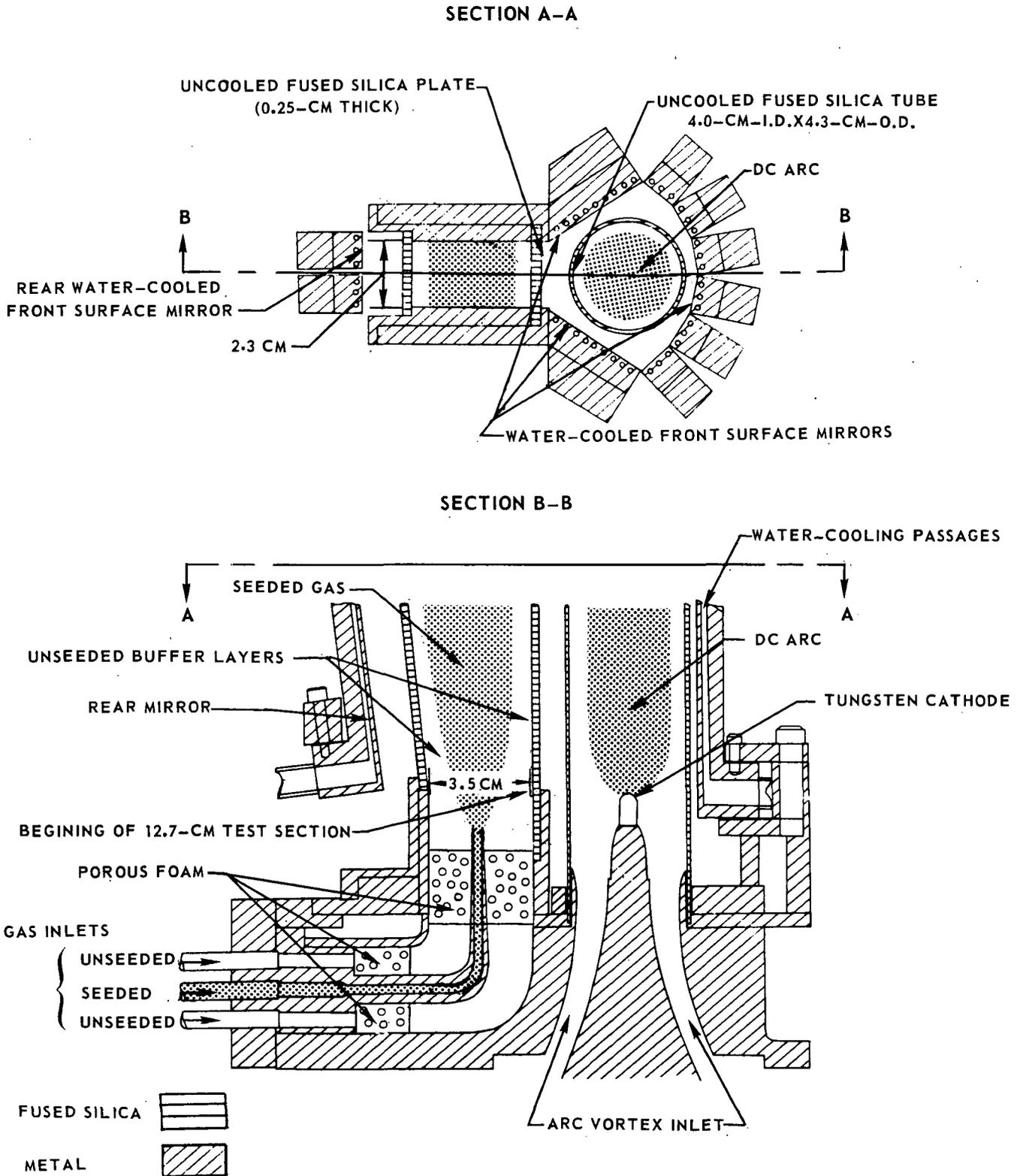
SEE FIG. 16 FOR DETAILS OF MODEL CONFIGURATION

SYMBOL	TRANSPARENT WALL THICKNESS, CM	CHAMBER PRESSURE, P_D - ATM	ARGON FLOW RATE W_A - g/SEC	DATA FROM REF.
○	0.0125	7-35	4.5-8.1	1
□	0.025	1-16.6	2.3-8.1	1
▲	0.0125	1-21	1.8-7.7	9



SKETCH OF PROPELLANT HEATING TEST CONFIGURATION

SEE REF. 2 FOR ADDITIONAL DETAILS OF CONFIGURATION



RESULTS OF SIMULATED PROPELLANT HEATING TESTS USING CARBON SEED MATERIAL

DATA FROM TESTS DESCRIBED IN REF. 10

NON-REFLECTING AND NON-DIVERGENT PROPELLANT DUCT WALLS

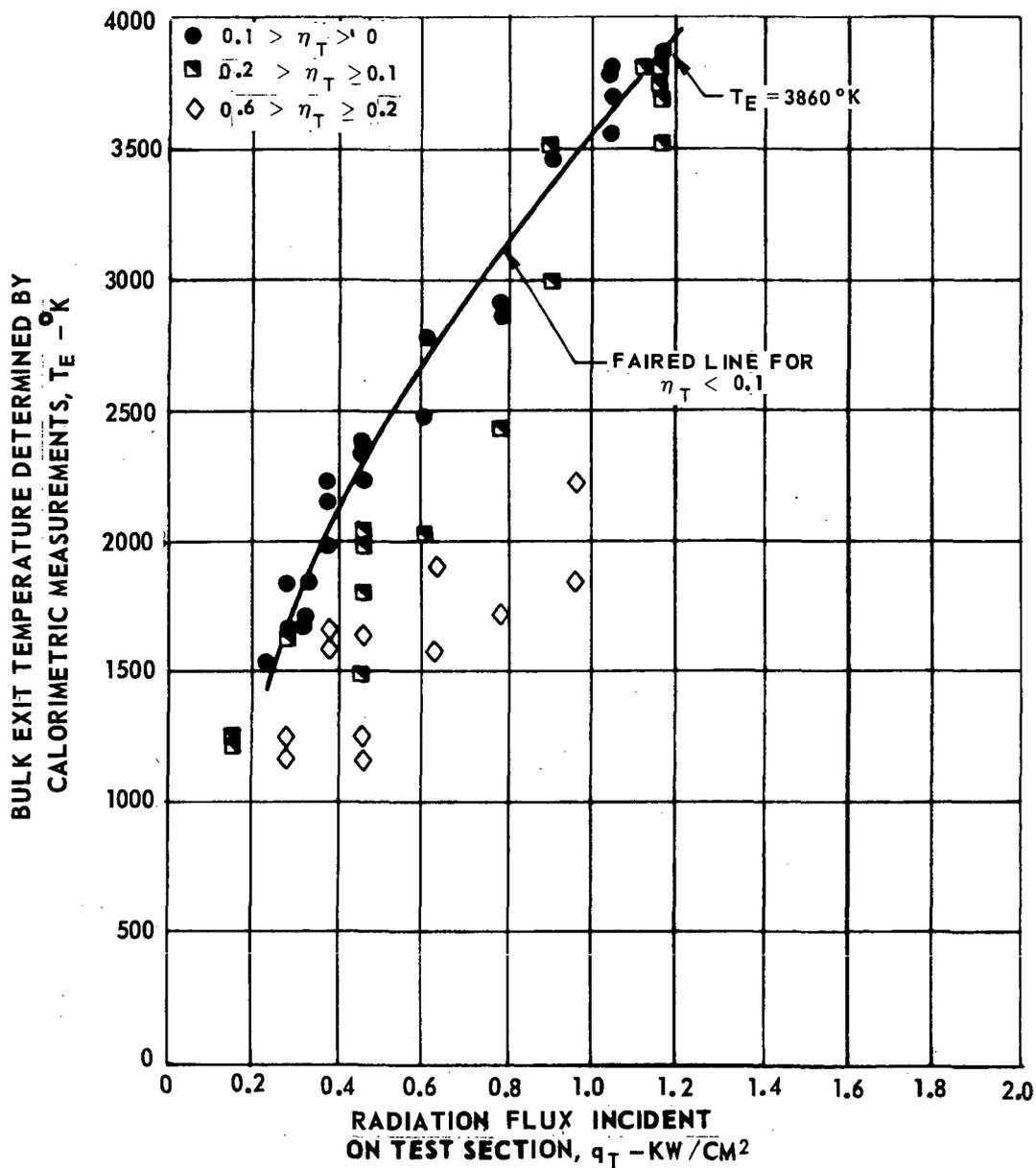
PROPELLANT DUCT PRESSURE \approx 1.0 ATM

SIMULATED PROPELLANT VELOCITY AT DUCT INLET = 0.8 M/SEC

TEST SECTION FRONTAL AREA = 29.2 CM²

$$q_I = \frac{\text{RADIATION INCIDENT ON TEST SECTION}}{\text{TEST SECTION FRONTAL AREA}}$$

$$\eta_T = \frac{\text{RADIATION TRANSMITTED THROUGH SEED}}{\text{RADIATION INCIDENT ON SEED}}$$



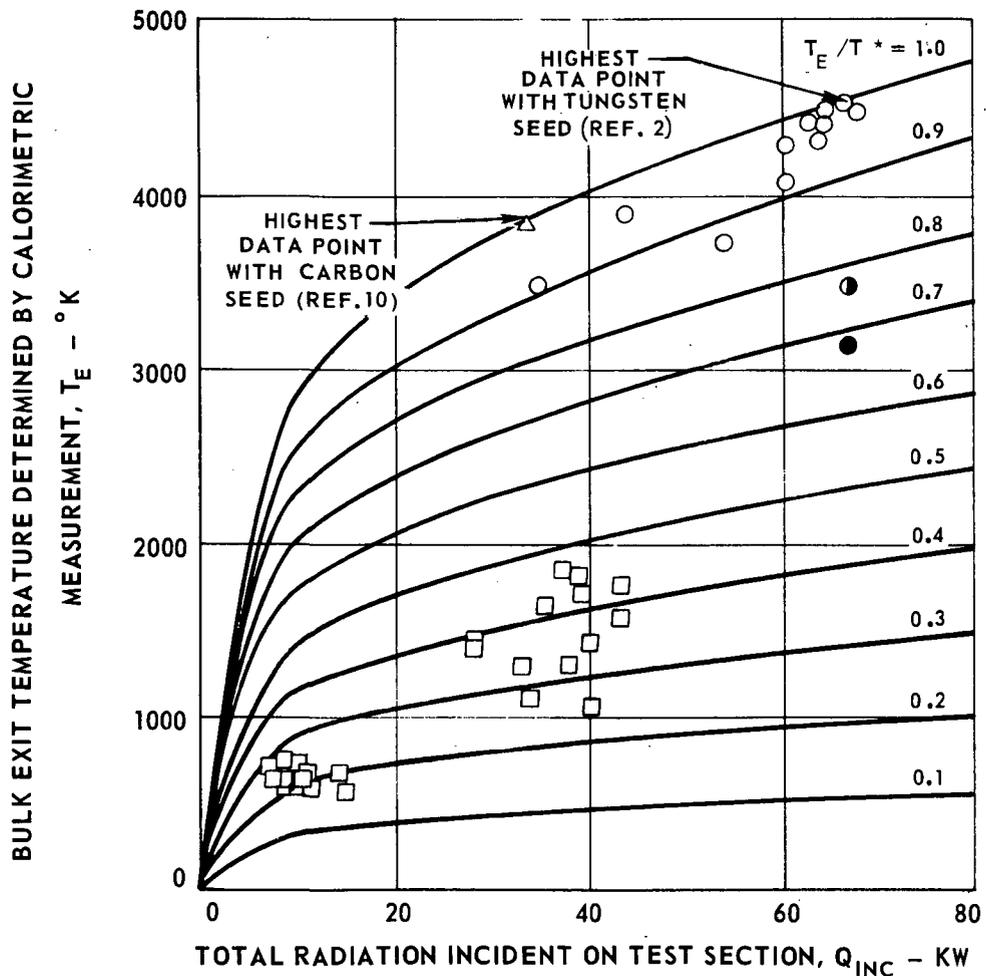
VARIATION OF BULK EXIT TEMPERATURE WITH RADIATION INCIDENT ON TEST SECTION FOR PROPELLANT HEATING TESTS

REFLECTOR AT OUTER WALL OF PROPELLANT DUCT

SEE FIG.18 FOR TEST CONFIGURATION

DATA FROM TESTS DESCRIBED IN REF. 2

SYMBOL	ARGON WEIGHT FLOW, W_A - G/SEC	TUNGSTEN WEIGHT FLOW, W_W - G/SEC
○	2.2	7.0
◐	4.4	7.0
●	8.8	7.0
□	8.8	5.0 AND 5.5

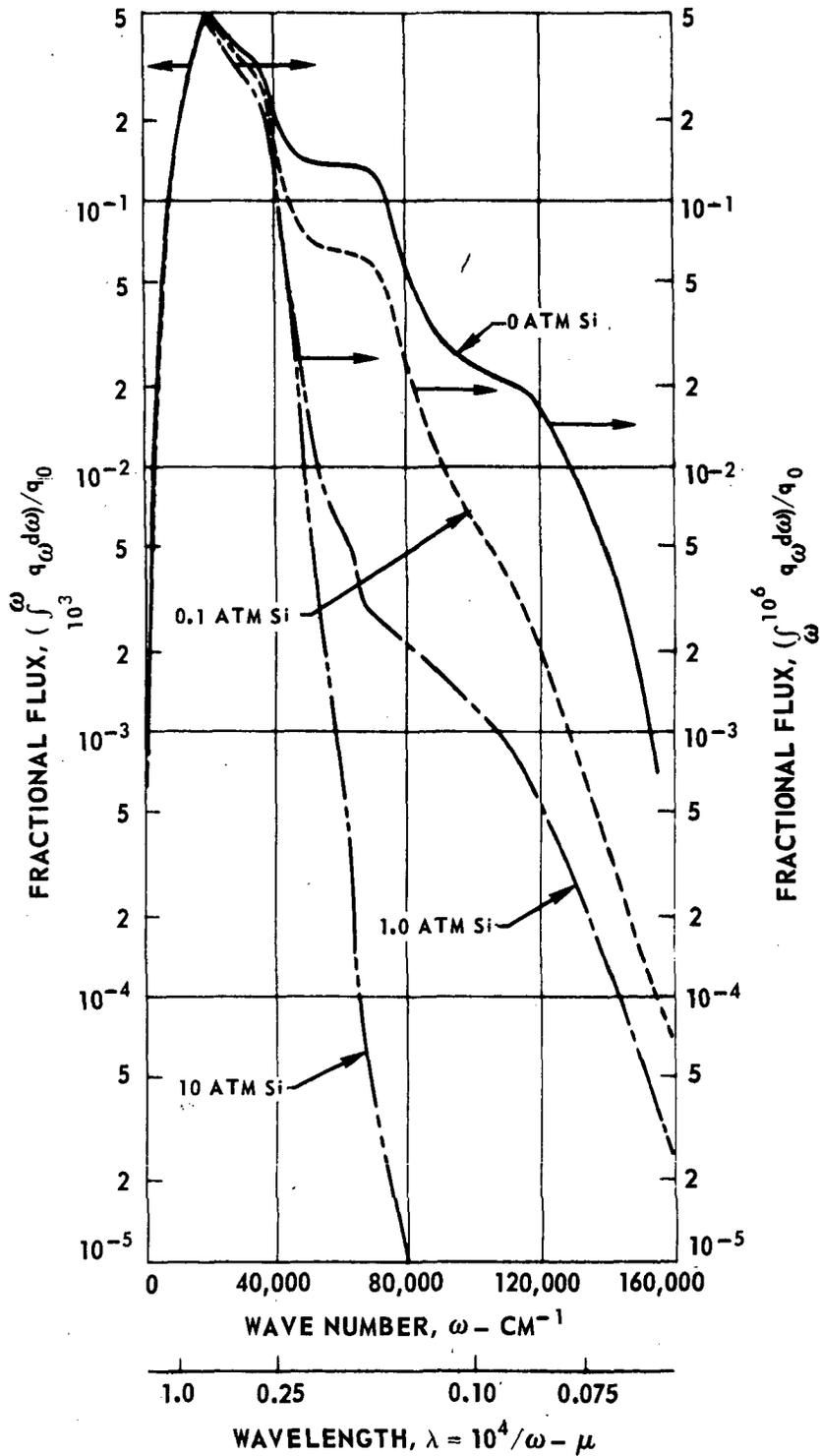


CALCULATED FRACTIONAL HEAT FLUX DISTRIBUTIONS EMITTED AT EDGE-OF-FUEL FOR REFERENCE ENGINE CONFIGURATION

SEE REF. 5 FOR CALCULATION METHOD USED

REFERENCE ENGINE PRESSURE = 500 ATM

$$q_0 = 2.73 \times 10^6 \text{ ERG/CM}^2 \text{ - SEC}$$

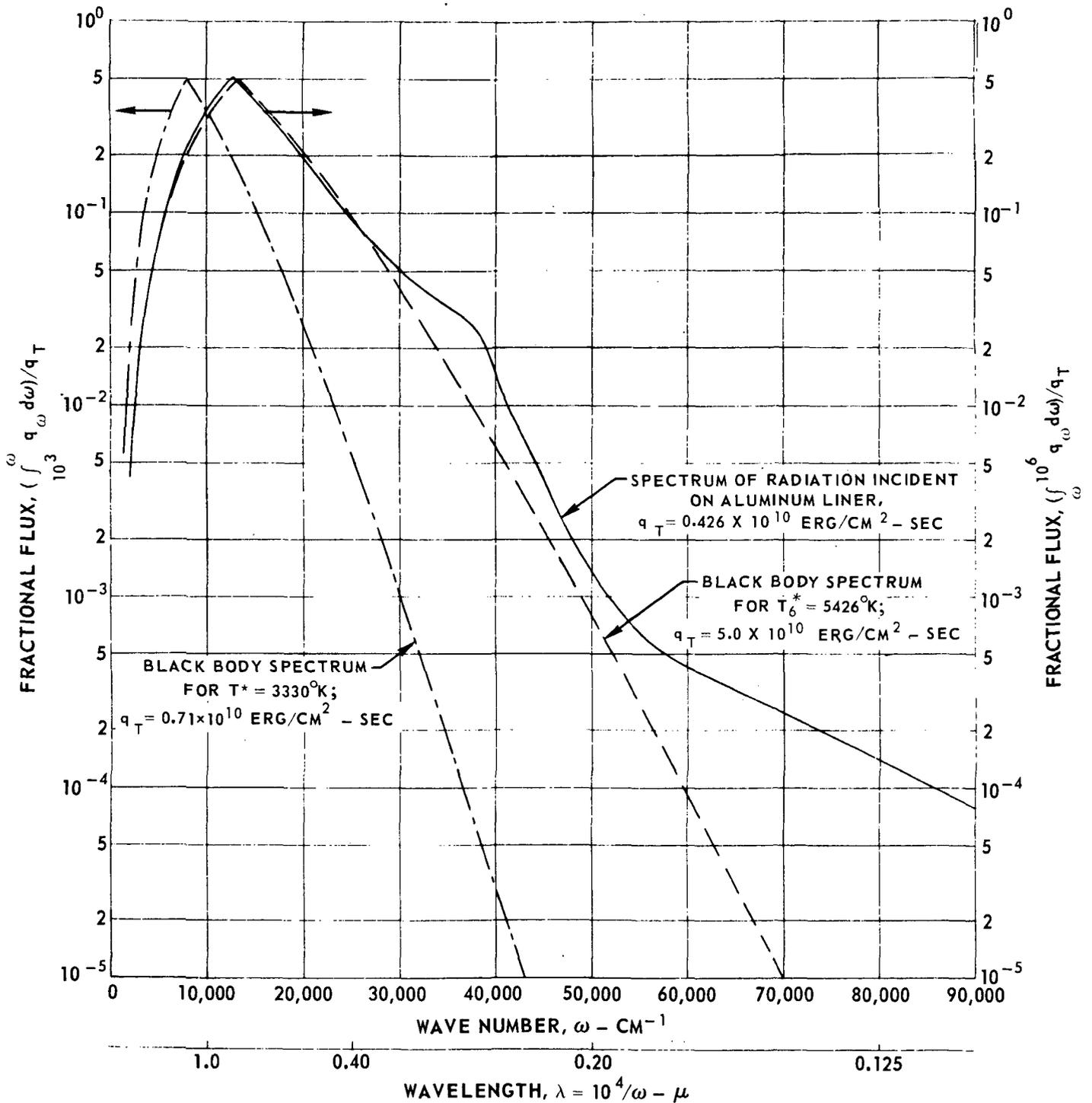


VARIATION OF FRACTIONAL HEAT FLUX AT ALUMINUM LINER WITH WAVE NUMBER FOR IN-REACTOR TEST CONFIGURATION

SEE FIG. 7 FOR TEST CONFIGURATION GEOMETRY

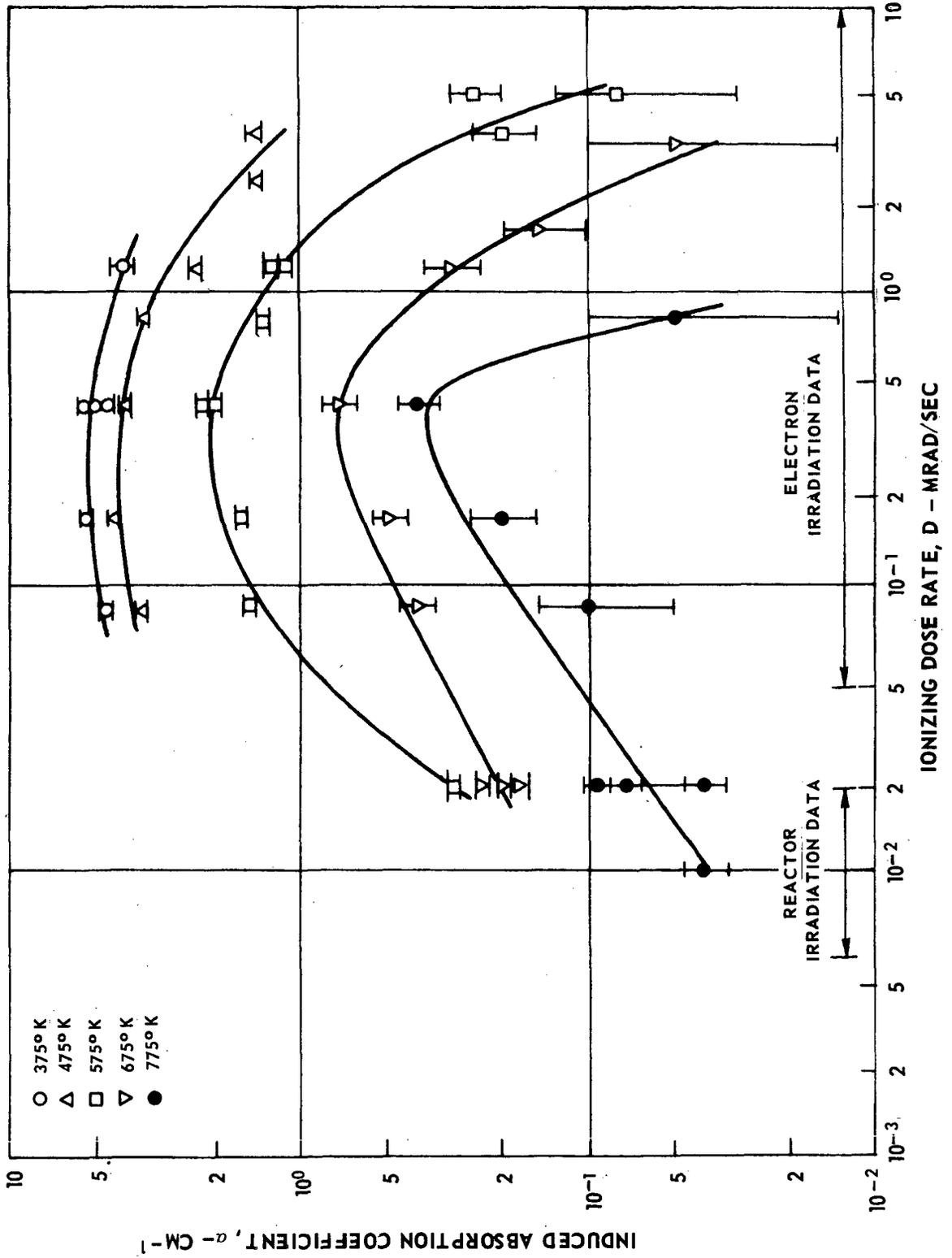
SEE REF. 6 FOR CALCULATION METHOD USED

IN-REACTOR TEST PRESSURE = 500 ATM



VARIATION OF STEADY - STATE ABSORPTION IN FUSED SILICA WITH IONIZING DOSE RATE

IONIZING DOSE RATE OF REFERENCE ENGINE = 5 MRAD/SEC
DATA OBTAINED IN TESTS USING 1.5-MEV DYNAMITRON ACCELERATOR; SEE REF. 15
WAVELENGTH, $\lambda = 0.215\mu$



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