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Conceptual Design Studies and Experiments Related to Cavity Exhaust Systems for Nuclear Light Bulb Configurations

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UNITED AIRCRAFT CORPORATION

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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. (Present Report)

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.

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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 x 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.

INTRODUCTION

Investigations of various phases of gaseous nuclear rocket technology have been conducted at the United Aircraft Research Laboratories under Contract SNPC-70 administered by the joint AEC-NASA Space Nuclear Systems Office. Previous investigations were conducted under NASA Contracts NASw-847, NASw-768, and NAS3-3382; under Air Force Contracts AF 04(611)-7448 and AF 04(611)-8189; and under Corporate sponsorship.

The principal research efforts have recently been directed toward the closed-cycle, vortex-stabilized nuclear light bulb engine and toward a small-scale fissioning uranium plasma experiment that could be conducted in the Los Alamos Scientific Laboratory's Nuclear Furnace (Figs. 1(a) and 1(b), respectively). The engine concept is based on the transfer of energy by thermal radiation from gaseous fissioning uranium, through a transparent wall, to hydrogen propellant. The reference engine configuration shown in Fig. 1(a) is comprised of seven unit cavities, each having its own fuel, transparent wall and propellant duct. The basic design of the engine is described in detail in Ref. 1. Subsequent studies performed to supplement and investigate the basic design are reported in Refs. 2 through 4. Summaries of other nuclear light bulb research programs conducted through September 1972 are included in Refs. 5 and 6.

As presently designed, a mixture of buffer gas, fuel and fission fragments is exhausted from each unit cavity of the reference engine through a 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. This condensation and separation at the thru-flow exhaust ducts, therefore, is an important consideration in demonstrating the feasibility of the closed-cycle concept. In the Nuclear Furnace tests (described in Ref. 4), flow will be removed from the cavity in a similar manner through one or two exhaust ducts (Fig. 1(b)). 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.

Previous research directed toward defining and understanding these requirements is reported in Refs. 7 and 8. In Ref. 7, results of limited theoretical investigations and initial exploratory tests on the condensation of iodine-vapor/gas mixtures and zinc-vapor/gas mixtures in flowing streams are presented. An analysis of the coolant recycle system of the nuclear light bulb is presented in Ref. 8.

The objective of the analyses and experiments described herein was to obtain additional information needed for a preliminary design of a thru-flow duct and separator system for the engine and a thru-flow duct for an in-reactor test model for the Nuclear Furnace.

FUEL EXHAUST SYSTEM FOR REFERENCE NUCLEAR LIGHT BULB ENGINE

Overall Configuration

The overall configuration for the seven-unit-cavity reference nuclear light bulb engine is shown in Fig. 1(a). Each unit cavity of the engine contains a 500-atm fissioning uranium plasma in a vortex driven by the tangential injection of neon gas at the inside of a cylindrical transparent wall. A mixture of the neon which drives the vortex, fission products, a small amount of silicon vapor (introduced into the cavity with the buffer gas to protect the transparent wall from uv radiation), and entrained uranium vapor exits from the cavity through an exhaust port in the end wall. To operate the engine continuously for long periods of time, it is necessary to remove the uranium and silicon which is entrained in the neon, and to recycle the uranium and neon in separate flow circuits. The components for the fuel exhaust system would be located within the region of the engine indicated in Fig. 1(a); Fig. 2 is a preliminary layout showing in more detail the possible locations of exhaust system components. Additional descriptions of the flow and coolant circuits for the engine are presented in Refs. 3 and 9.

Figure 3 is a schematic which indicates typical weight flow rates and temperatures at key points in the exhaust system for the engine design in Ref. 3*. The mixture leaves the cavity at a mixed mean temperature of approximately 6550°K. The mixture flows through the exhaust ports and is cooled by the addition of neon along the length of the exhaust duct to a temperature of 1500°K. At this temperature, all but 1 part in 6×10^{10} of the uranium would be in the liquid state. The cold neon must be introduced in a manner such that the exhaust flow is quickly cooled to protect the exhaust duct from the high-temperature flow. Moreover, condensation of uranium in the stream, rather than on the duct walls, is desired. The length of these ducts is approximately 2 m (see Fig. 2). The mixture flows directly to a centrifugal separator (Fig. 3) where the uranium and silicon are separated from the neon buffer gas. A distillation process may be used to separate the silicon from the uranium (see Ref. 9). The fuel distillation canister (Fig. 3) would be used for the process.

*Further calculations of the heat balance and flow requirements in the reference engine are reported in Ref. 9. As discussed there, the thru-flow port inlet conditions in Ref. 3 are satisfactory for conceptual design purposes until additional studies are made (1) to determine the most favorable split between the amount of buffer gas withdrawn through an axial bypass duct (an annular duct around the periphery of the end wall) and the amount withdrawn through the thru-flow duct and (2) to evaluate the alternative of seeding the fuel with silicon, rather than seeding the buffer gas.

The neon, upon leaving the separator, flows to a heat exchanger where it is further cooled such that it can be reinjected 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. It is desirable to have the uranium remain in liquid form for transport to the fuel distillation canister. The total flow rate of neon passing through the separator (from the seven cavities) is 67.2 kg/sec.

Fuel Exhaust Ducts

The fuel exhaust ducts serve to carry the mixture of neon, uranium, fission products, and silicon out of the cavity, through the moderator and directly to the separator. There would be seven such ducts in the reference engine, one for each unit cavity, leading to a common separator.

A possible configuration for the inlet portion of the exhaust duct is shown in Fig. 4. This configuration was chosen based on the results of tests described in Ref. 7 and those described later in this report. In particular, the geometry is similar to the long cylindrical injector tested (Configuration IV; see discussion of experiments). The inlet portion of the duct is configured such that neon bypass flow is injected with swirl (i.e., circumferentially) at the duct wall, along the entire length, if necessary, to reduce the mixed-mean temperature of the mixture exiting the cavity from approximately 6550°K to 1500°K (still above the melting temperature of uranium) and to prevent deposition of uranium on the duct walls. The latter consideration is especially important within the moderator regions where the neutron flux remains high and considerable fission heating occurs (see Ref. 9). It is not desirable to shield the exhaust ducts with poison material within the moderator due to the increase in critical mass which would result. These portions of the duct outside of the moderator region could, however, be poisoned.

The primary reason for maintaining the uranium in liquid form is to reduce the potential for solids forming on the walls which would result in clogging of the tubes. The flow velocity is intentionally kept high in the duct to further reduce this potential; if the cross-sectional area of the duct remains constant along the length, then the mean flow velocity would increase from 50 m/sec at the inlet to approximately 70 m/sec at the outlet. The duct inner diameter shown in Fig. 4 was sized at 4.75 cm to provide the 50 m/sec entrance velocity for the 1.6 kg/sec of neon.

Fuel Separator

Figure 5 shows a preliminary conceptual design for the centrifugal fuel separator for the reference engine. The mixture from the seven unit cavities enters the separator at the left end. A small plenum is provided which serves to distribute the flow to two injection slots at the periphery of the separator inner wall. The mixture enters the 50-cm-i.d., 45-cm-long separator cavity with a velocity of 500 m/sec through slots approximately 0.2-cm high which run the entire length of the separator inner wall. The uranium is then centrifugally separated from the mixture and is removed through screens and collector tubes located in the separator inner wall (see Fig. 5). The separated uranium droplets are then conveyed to the fuel distillation canister shown in Figs. 2 and 3. The neon, with the uranium removed, is withdrawn through a single port located in the opposite end wall. The neon effluent then flows to the hydrogen-neon heat exchanger as indicated in the diagram in Fig. 3.

The 500-m/sec velocity required for the mixture entering the separator was estimated on the basis of calculations of the radial velocities attained by small droplets in centrifugal acceleration fields. At the inlet, the initial centrifugal acceleration is about 100,000 g's. The g-level increases as the flow spirals inward (this is a key difference between the radial-inflow vortex separator and the conventional centrifuge with its rotating peripheral wall).

To obtain satisfactory separation, the initial terminal velocity of the droplets must be large relative to the initial radial velocity of the mixture (the latter is 116 cm/sec for this design) as it flows from the peripheral wall in toward the center of the separator. Figure 6 shows the effect of tangential velocity at the peripheral wall on the initial radial acceleration produced in the 50-cm-diam separator. Figure 7 shows the terminal radial velocity which would be achieved by uranium droplets having different diameters in the separation region, calculated assuming Stokes drag law (this drag law is valid if the Reynolds number based on droplet diameter is 1.0 or less). It can be seen from Fig. 7 that even relatively small droplets, i.e., d_p less than 5×10^{-5} cm or 0.5μ, would achieve relative terminal radial velocities significantly greater than the initial radial velocity of the mixture. For example, near the separator wall, where the radial acceleration would be approximately 100,000 g's, a 5×10^{-5}-cm-diam droplet would have a velocity relative to the neon flow of approximately 240 cm/sec, while the mean radial inward velocity of the neon in the flow is 116 cm/sec. Thus, the net outward velocity of the droplet would be 124 cm/sec.

Separation of the uranium from the neon in liquid form is desirable so that potential problems due to plating and clogging of the injection slot are minimized. In the present design, the separator has to operate at a pressure of about 500 atm and a temperature of 1500°K. This pressure does not present a materials or structural problem because the separator housing does not have to withstand a full

500-atm pressure differential; as shown in Figs. 1 and 2, the accessory region is within the engine pressure vessel and is, therefore, at the engine operating pressure. However, the structure will have to withstand a pressure drop of 50 atm across the separator from the periphery to the exhaust port radius.

The key problem is likely to be the inner peripheral wall and end walls of the separator which must be maintained at or above 1500°K. The material used will also have to be chemically compatible with liquid uranium. It is expected that materials technology developed in solid-core nuclear rocket research programs, particularly in the area of coatings for graphite, will be applicable here.

The inlet mixture to the separator will also contain a small amount of silicon, or silicon-uranium compounds, in particulate form. These particulates leave the separator with the separated uranium. As indicated previously, a distillation process could be used to remove the silicon. This process would involve use of afterheat to boil off the silicon from the liquid uranium in the fuel distillation canister. The method is discussed in Ref. 9; consideration of this component is not within the scope of the present investigation.

FUEL EXHAUST SYSTEM FOR NUCLEAR FURNACE UNIT CELL

A similar analysis was made to define a conceptual design for an exhaust duct for the Nuclear Furnace in-reactor test unit cell shown in Fig. 1(b). This cell, like the engine, operates at a pressure of 500 atm. Argon is used as the buffer gas and uranium as the fuel. There is no requirement for silicon seeds due to the lower operating temperature. The requirements for the design are that the mixed-mean temperature of the effluent leaving the unit cell must be reduced from approximately 1590°K (possibly slightly lower; see Ref. 10) to approximately 350°K at the exit of the core of the Nuclear Furnace. A further requirement is that the potential for deposition of uranium on the duct walls and clogging within the reactor core must be minimized.

The overall configuration for the Nuclear Furnace installation, as currently envisioned, is shown in Fig. 8; a detailed drawing of the unit cell test region is shown in Fig. 9. The test region would be approximately 6.6-cm in diameter and 17.8-cm long and would be located at about the center of the core in the Nuclear Furnace. The distances from the cell exit to the core ends would be approximately 58.5 cm. The effluent leaving the top of the reactor travels a total length of 82 cm before it leaves the Nuclear Furnace pressure shell. As described in Ref. 10, it is now believed desirable to provide a separate scrubber external to the reactor to process and remove fission products and uranium from the test cell effluent, rather than to exhaust this effluent into the existing Nuclear Furnace scrubber. Table I gives the estimated weights of gases and coolant fluids required for an approximately 10-min-long test.

The exhaust duct geometry is also shown in Fig. 9. The ducts would have an i.d. of approximately 0.5 cm and would be 58 cm and 82 cm long. Based on results of experiments described in the following section, it appears that use could be made of the end-wall coolant gas to provide injection along the entire length of the duct within the core of the Nuclear Furnace to isolate the mixture of argon and uranium from the duct walls. Sufficient bypass coolant (argon or hydrogen) would be introduced to reduce the mixed-mean temperature of the gases at the duct exit from 1590°K to approximately 350°K. The uranium at the duct exit would be in solid particle form.

In the Nuclear Furnace test configuration, the fuel is injected through a probe located along the centerline of the cavity region (see Fig. 9). Thus, at the duct entrance, an annular flow passage is used. The length of this annular passage must be as short as possible to reduce or eliminate the requirement for transpiration cooling of the fuel injection probe. The probe could be designed such that its surface temperature is above the uranium melting point, i.e., above approximately 1450°K. This would insure that no significant amount of fuel deposition would occur on the probe. In the experiments conducted to date, the presence of this probe and its effects on the flow and on deposition in the exhaust duct has not been investigated.

The average velocity of the mixture within the duct at the design point would be approximately 75 m/sec. This would lead to a dwell time within the Nuclear Furnace core region of approximately 8 msec.

Because it is expected that the first nuclear tests would likely employ uranium hexafluoride as the fuel, provisions must be made in the design for the handling of fluorine gases in the effluent. Although it is not expected that this will be a major problem, additional design considerations will be required to insure adequate material compatibility with the fluorine environment.

RESULTS OF EXHAUST DUCT CONFIGURATION EXPERIMENTS

Additional experiments were conducted, using metal-vapor/heated-gas mixtures flowing into inlets and long ducts, to explore methods for obtaining condensation of the vapor with minimum coating of the inlets and ducts. Little is known about the heat transfer and condensation processes that occur when cold bypass flow is added to the central swirling mixture containing the vapor. The results of initial experiments in this area are reported in Ref. 7. The specific objectives of the present tests were (1) to identify suitable inlet and bypass-flow injector geometries and (2) to observe the effects of changes in the ratio of bypass flow rate to inlet mixture flow rate on deposition on the inlet and duct walls. The findings, although qualitative, were used as a basis for the preliminary conceptual designs of the reference engine and in-reactor test exhaust ducts discussed in the previous sections.

Test Equipment

The basic test equipment used is shown in the sketch in Fig. 10. At the upstream end, a dc arc plasma torch (details in Fig. 11) was used to heat a flow of argon gas (simulated buffer gas). The hot argon then entered a vaporizer section in which zinc (simulated fuel) was added to the flow to form a vapor/gas mixture. The mixture left the vaporizer through a port and entered a 60-cm long pyrex tube, simulating the ducts in the reference engine and in the in-reactor test model. Interchangeable inlets were also provided at the upstream end of the duct for injection of cold argon bypass flow (Fig. 12). Both the argon entering the torch and the bypass flow could be injected with swirl. Four adjustable injectors in the torch base permitted the injection angle there to be varied from direct radial inflow to 60° from the radial (see section A-A in Fig. 11).

In all tests, thermocouples were used to measure the temperatures at the vaporizer exit and exhaust duct exit. In some tests, a thermocouple was provided at the torch exit. Radial traverses to determine temperature distributions were also made at several axial stations in the exhaust duct; the pyrex tube was replaced by a copper tube with holes to allow the probes to be inserted in these tests.

Plasma Torch Calibration Tests

Initially, the dc arc plasma torch was operated over a wide range of conditions to determine its operating characteristics. The torch was operated with approximately 0.4 to 6.7 kW being deposited in the argon flow. The argon flow rate through the torch was varied from 1.0 g/sec to 4.2 g/sec and the injection angle was varied from

4° to 40°. In some tests, the argon gas temperature at the exit of the vaporizer duct (the diameter and length of this duct were 2.5 cm and 15 cm, respectively) was measured. The variation of vaporizer exit temperature (measured at the centerline of the duct) with torch input power is shown in Fig. 13(a). In these tests, the maximum temperature measured was 1940°K. In one test, the radial distribution of temperature at the vaporizer exit was measured (Fig. 13(b)). The highest temperature obtained was approximately 450°K higher than the maximum temperature achieved in the tests reported in Ref. 7. This increased temperature allowed higher levels of zinc partial pressure in the vaporizer to better simulate the mass flow ratio (ratio of fuel vapor flow rate to buffer- and carrier-gas flow rate) expected in the in-reactor test and in the reference engine.

Tests to determine the operating characteristics of the torch with a bypass inlet configuration (Configuration I; see Fig. 12(a)) attached were also conducted. The pyrex test section was replaced with a copper tube having an inner diameter of 2.54 cm. At four axial stations along this tube, approximately 4.1, 6.6, 9.1, and 11.7 cm downstream of the bypass-flow exit (see sketch in Fig. 14), thermocouples were used to measure the radial temperature distribution.

In one series of tests, torch power, argon flow rate to the torch, and bypass inlet argon flow rate were varied. The flow rate ratio (ratio of bypass flow to torch flow) was varied from 1.6 to 3.8. The torch inlet and bypass-inlet injection angles were 30° and 60°, respectively. The thermocouple junctions were fixed at radial locations corresponding to $r/D = 0$, 0.25, 0.375, and 0.437. Typical radial temperature profiles which were obtained, assuming no variation of temperature along the test section between probes, are shown in Fig. 14.

Simulated-Fuel Condensation Tests

Tests were conducted using the four bypass-flow inlet configurations shown in Fig. 12 at the test conditions given in Table II. After each test, the bypass flow inlet and the exhaust duct were examined to determine qualitatively the relative amounts of zinc deposited on the walls.

Tests with Inlet Configuration I

In tests employing Configuration I (see Fig. 12(a)), the torch flow rate was 2 g/sec and the flow was injected at 30° from the radial direction (i.e., with a little swirl). The bypass flow rate was 7.7 g/sec; the flow was injected at 60° from the radial direction in Tests 1 and 2 and at 30° in Test 3. Mixed-mean temperatures at the vaporizer exit and at the downstream end of the long pyrex exhaust duct ranged from 1560 to 1740°K and 545 to 600°K, respectively. The zinc partial pressure ranged from 1.7 to 3.3×10^{-3} atm at the vaporizer exit. (The zinc partial pressure was determined using the measured argon flow rates and the average zinc flow rate based on the weight of zinc evaporated during the test.) During these tests, the exhaust duct wall did not remain free of zinc. The zinc deposited appeared to be distributed uniformly on the wall and rendered the duct opaque. Zinc was also deposited on the internal surfaces of the bypass inlet, indicating that rapid mixing occurred between the torch and bypass flow in the bypass inlet.

Tests with Inlet Configuration II

Bypass-flow inlet Configuration II, shown in Fig. 12(b), was designed to prevent this rapid mixing between the bypass flow and the hot flow containing the zinc vapor within the bypass flow inlet. In the test with Configuration II, the torch flow rate was 2 g/sec and the flow was injected at 30° from the radial direction. The bypass flow rate was 7.7 g/sec and the flow was injected at 60° from the radial direction. A cylindrical flow guide (shown in Fig. 12(b)) was used to prevent mixing between the torch flow and bypass flow in the bypass flow inlet; it protruded approximately 1.0 cm into the exhaust duct. The bypass flow entered the exhaust duct through the annulus between the exhaust duct wall and the flow guide. The mixed-mean temperatures at the vaporizer exit and downstream end of the exhaust duct were 1830 and 602°K, respectively. The zinc partial pressure at the vaporizer exit was 2.7×10^{-3} atm.

In the test, some zinc was deposited on the exhaust duct wall between the bypass inlet location (at the downstream end of the flow guide) and the end of the duct. Deposition of zinc was not uniform and increased with distance downstream in the duct.

Tests with Inlet Configuration III

Bypass-flow inlet Configuration III, shown in Fig. 12(c), was used in Tests 5 through 10. The bypass flow was injected tangent to the exhaust duct wall through forty 0.15-cm-diam injection ports. These tests were conducted with torch flow rates between 2.0 and 4.2 g/sec. The torch flow was injected either radially or 30° from the radial direction. The bypass flow rate ranged from 2.9 to 7.7 g/sec. In Configuration III tests, the 2.54-cm-diam disk with a 1.27-cm-diam port, located at the upstream end of the injector, was not used. The section of the exhaust duct formed by the internal wall of the injector remained relatively free of zinc deposits and the deposition of zinc in the exhaust duct downstream of the injector again appeared to increase with distance downstream. However, the bypass flow caused recirculation to occur in the vaporizer which reduced the temperature measured at the vaporizer exit and also cooled the vaporizer wall near the exit, causing zinc to be condensed within the vaporizer. The amount of zinc deposited on the injector wall increased in Test 10, which was conducted with a low (2.9 g/sec) bypass flow rate. During these tests, the vaporizer exit temperature ranged from 704 to 1770°K. The zinc partial pressure at the exit of the vaporizer ranged from a low value of 2.6×10^{-3} atm.

Tests with Inlet Configuration IV

Short Bypass Injector (3.0 cm)

Configuration IV for Tests 11 through 14 was identical to Configuration III except for the 2.5-cm-diam disk having a 1.27-cm-diam port placed at the upstream end of the inlet (see Fig. 12(c)). The disk was designed to decrease the recirculation flow which occurred in the vaporizer at high bypass flow rates. The tests were conducted with a torch flow rate of 2.0 g/sec and with the flow injected 30° from the radial direction. The bypass flow rate ranged from 4.2 to 9.8 g/sec, and the flow was again injected through ports in the injector tangent to the exhaust duct wall. The zinc partial pressure at the exit of the vaporizer ranged from 1.9 to 10.3 x 10^{-3} atm. In these tests (except for Test 12 which was conducted at a reduced bypass flow rate), there appeared to be almost no zinc deposited on the injector wall. Some zinc was deposited along the length of the pyrex portion of the exhaust duct; however, deposition increased with distance downstream, and for these tests the upstream portion of the pyrex exhaust duct was lightly coated. The zinc deposited on the duct walls could be removed by wiping with a clean cloth. This indicates the particles were formed within the gas stream prior to being deposited on the duct wall.

Long Bypass Injector (13.5 cm)

In the final test series, Configuration IV (shown in Fig. 12(c)) was modified by increasing the length of the cylindrical injector from about 3.0 to 13.5 cm. These tests (Tests 15 through 17) were conducted with the torch flow injected 30° from the radial direction. Figure 15 is a photograph of the cylindrical injector for Configuration IV.

In Test 15, the torch and bypass-inlet flow rates were 2.0 and 14.5 g/sec, respectively. Zinc was deposited on the injector wall and along the length of the pyrex portion of the exhaust duct. The deposition of zinc on the cylindrical injector wall was attributed to a bypass flow injection velocity which was small compared with that used in tests with the 3.0-cm-long injector (bypass inlet flow was increased to 150 percent relative to the highest flows with the 3.0-cm-long injector; however, the injection area of the 13.5-cm-long injector was approximately 400 percent greater).

In Test 16, the torch flow rate was 2.0 g/sec and the bypass-inlet flow rate was increased to 35.4 g/sec. Visual inspection of the injector wall after Test 16 indicated that less zinc had been deposited on the wall than in Test 15. However, zinc deposited on the downstream end of the vaporizer indicated that the increased bypass-inlet flow rate had again caused recirculation to occur in the vaporizer.

In Test 17, the torch flow rate was increased to 3.9 g/sec, which reduced the recirculation in the vaporizer. The bypass-inlet flow rate was 36.3 g/sec and the mixed-mean vaporizer exit temperature was 2020°K. The zinc partial pressure at the exit of the vaporizer was 14.3×10^{-3} atm. The amount of zinc deposited on the injector wall was measured (using chemical techniques) to be 0.014 g. This is 0.15 percent of the 9.5 g of zinc which was vaporized in the vaporizer during this test. The length of the test period was 2 min. Some zinc was deposited along the length of the exhaust duct; the duct was lightly coated for about 5 cm, opaque for about 25 cm, and lightly coated over the remainder (20 cm) of its length.

The performance of Configuration IV was significantly better than any of the other configurations tested. It is believed that by injecting over the entire duct length using a flow injector geometry similar to that used in Configuration IV, the entire duct may be maintained relatively free of zinc deposition.

In the nuclear light bulb engine and in-reactor test configuration, it is important that deposition of fuel on the thru-flow duct walls be as small as possible. The results of tests with Configuration IV indicate injection of bypass flow at the duct wall with swirl may be a feasible method to use to prevent occurrence of local deposition of fuel.

Satisfactory results were obtained with this injector geometry at a bypass coolant-to-torch flow ratio equal to 9.3. However, to obtain a better estimate of the amount of bypass coolant required to prevent fuel deposition in the engine or in-reactor test model exhaust ducts probably would require use of a full-scale mock-up of the specific duct configuration in tests with uranium rather than zinc. This is beyond the scope of the present investigation.

Recommendations for Further Experiments

The experiments discussed herein were preliminary in nature. The results should be verified by additional experiments with Configuration-IV-type bypass inlets over the same operating range, with concentration of effort on more detailed measurements of the particle size, wall coating, velocity distributions, and temperature distributions within the duct and at the duct wall. For these tests, the models should more closely simulate the geometries resulting from the preliminary conceptual designs for the reference engine and Nuclear Furnace configuration. These experiments should be conducted using uranium/argon and uranium-hexafluoride/argon mixtures to better simulate the conditions expected in the engine and the in-reactor test. Also, a mock-up of a vortex separator for separating the particles or liquid droplets and gas should be tested at the end of an exhaust duct.

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LIST OF SYMBOLS

a_r	Radial acceleration, g's
d_p	Particle diameter, cm
d_1	Diameter of separator inner wall, $2r_1$, cm
D	Diameter of exhaust duct, cm
G	Volume flow rate, cm^3/sec
l	Length of separator chamber, cm
P_{ZV}	Vapor pressure of zinc in vaporizer, atm
P_{ZTS}	Vapor pressure of zinc in test section, atm
Q_I	Plasma torch input power, kW
r	Radial distance, cm
r_1	Radius of separator inner wall, cm
Re_p	Reynolds number of flow around fuel particles, $V_r d_p/\nu$, dimensionless
T	Temperature, °K
$\bar{T}$	Average or mixed-mean temperature, °K
V	Velocity, m/sec
V_r	Velocity of droplets relative to the neon (see Fig. 7), cm/sec
$V_{r,N}$	Initial radial velocity of neon (see Fig. 7), cm/sec
$V_{\phi 1}$	Tangential injection velocity in separator
W	Weight flow rate, g/sec or kg/sec
W_B	Bypass flow rate, g/sec
W_T	DC arc plasma torch flow rate, g/sec
ν	Kinematic viscosity, cm^2/sec

TABLE I

CALCULATED TOTAL WEIGHT OF MATERIAL EXPENDED DURING EACH TEST RUN

Small Test Cell Installed In Nuclear Furnace

Test Time = 10 min

Test Sequence Described in Ref. 4

Flow Circuit	Total Weight, g
Nuclear Furnace Hydrogen*	3.0×10^5
Argon Buffer Gas	1.91×10^4
Liner and End-Wall Coolant, Argon	4.32×10^6
Liner and End-Wall Coolant, Hydrogen	1.44×10^5
U-235 Fuel (Uranium In UF_6 and Particles)	3.90×10^2
Argon Carrier Gas for UF_6-Argon System	5.71×10^2
Fluorine Contained In UF_6 for UF_6-Argon System	2.6×10^1
Fluorine Contained In UF_6 for All-UF_6 System	2.98×10^2

*Coolant required to remove neutron and gamma ray heating when test cell not in operation.

TABLE II

TEST CONDITIONS FOR SIMULATED-FUEL CONDENSATION TESTS

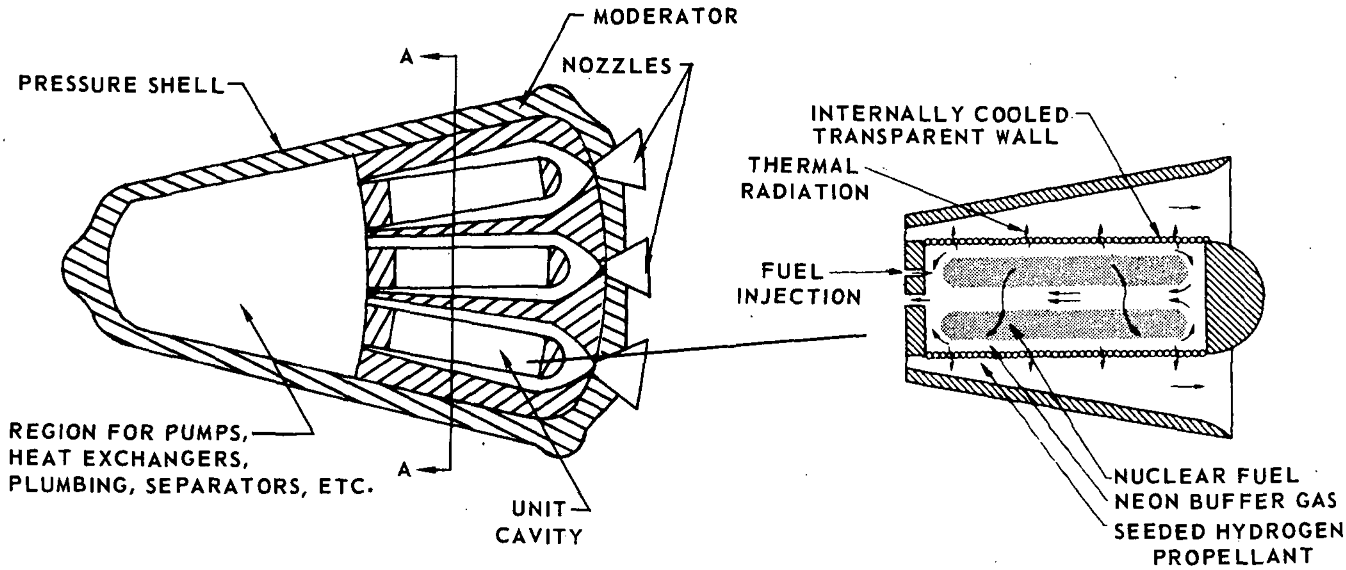
See Fig. 12 for Bypass Inlet Geometries

Test Number	Test Configuration (see Fig. 12)	Torch Flow Rate, W_T g/sec	Bypass Flow Rate, W_3 g/sec	Flow Rate Ratio, W_B/W_T	Power To Gas, kW	Vaporizer Exit Temp., °K	Exhaust Duct Exit Temp., °K	Duration of Run, min	Torch Swirl Angle, deg	Bypass Swirl Angle, deg	Vaporizer Zn Vapor Pressure, P_{ZV}-atm	Test Section Zn Vapor Pressure, P_{ZTS}-atm	Power To Torch, kW
1	I	2.0	7.7	3.9	2.3	1740	600	7.0	30	60	1.7×10^{-3}	3.5×10^{-4}	5.1
2	I	2.0	7.7	3.9	2.3	1670	545	1.9	30	60	2.2	3.8	5.1
3	I	2.0	7.7	3.9	2.3	1560	552	2.1	30	30	3.3	6.8	5.1
4	II	2.0	7.7	3.9	2.3	1830	602	2.0	30	60	2.7	5.6	5.1
5	III	2.0	6.4	3.2	2.3	1355	---	1.6	30	90	1.4	3.2	5.1
6	III	2.0	7.7	3.9	2.3	704	704	1.9	30	90	0	0	5.1
7	III	2.0	7.7	3.9	2.3	1410	---	1.7	30	90	1.9	3.9	5.1
8	III	4.2	7.7	1.8	2.3	835	518	2.4	0	90	0	0	5.0
9	III	3.3	7.7	2.3	2.9	990	586	2.6	0	90	0.34	1.0	6.4
10	III	2.0	2.9	1.4	2.3	1770	729	1.8	30	90	2.6	10.4	5.1
11	IV	2.0	7.7	3.9	2.3	1850	589	2.0	30	90	2.0	4.0	5.1
12	IV	2.0	4.2	2.1	2.3	1850	660	2.1	30	90	2.4	7.7	5.1
13	IV	2.0	9.8	4.9	2.3	1830	550	2.1	30	90	1.9	3.2	5.1
14	IV	2.0	9.8	4.9	3.1	----	---	2.1	30	90	10.3	17.4	8.4
15	IV	2.0	14.5	7.3	2.3	----	483	2.5	30	90	3.0	3.7	5.1
16	IV	2.0	35.4	17.8	2.3	1970	426	2.0	30	90	11.0	5.9	5.1
17	IV	3.9	36.3	9.3	4.5	2020	530	2.0	30	90	14.3	13.6	11

GEOMETRY OF NUCLEAR LIGHT BULB ENGINE AND NUCLEAR FURNACE IN-REACTOR TEST CONFIGURATIONS

(a) REFERENCE ENGINE CONFIGURATION

DIMENSIONS OF UNIT CAVITY: 49-CM I.D. ×183-CM LONG



DETAIL OF UNIT CAVITY

(b) NUCLEAR FURNACE IN-REACTOR TEST CONFIGURATION

I.D. OF TEST HOLE CASING = 8.4 CM

DIMENSIONS OF CYLINDRICAL CAVITY REGION: 6.6-CM I.D. × 17.8-CM LONG

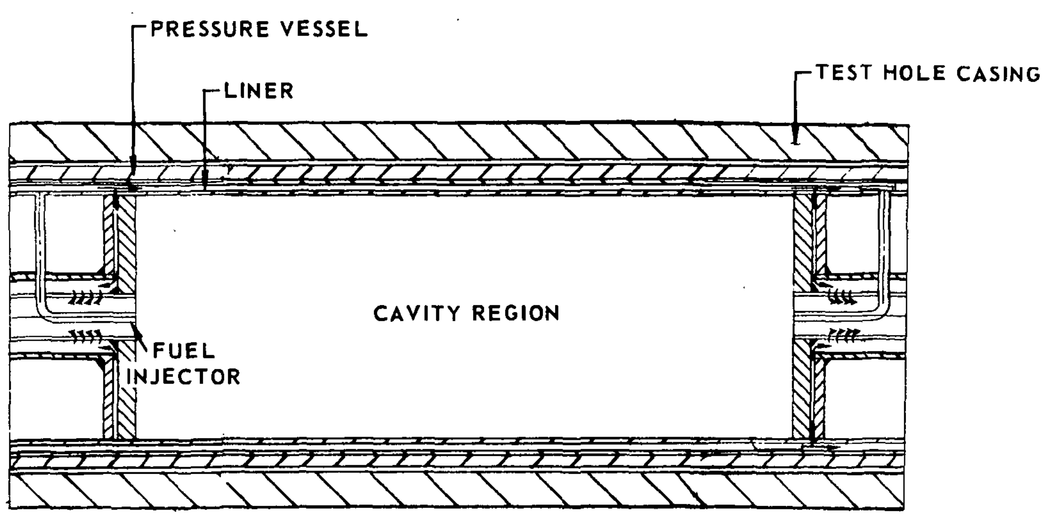
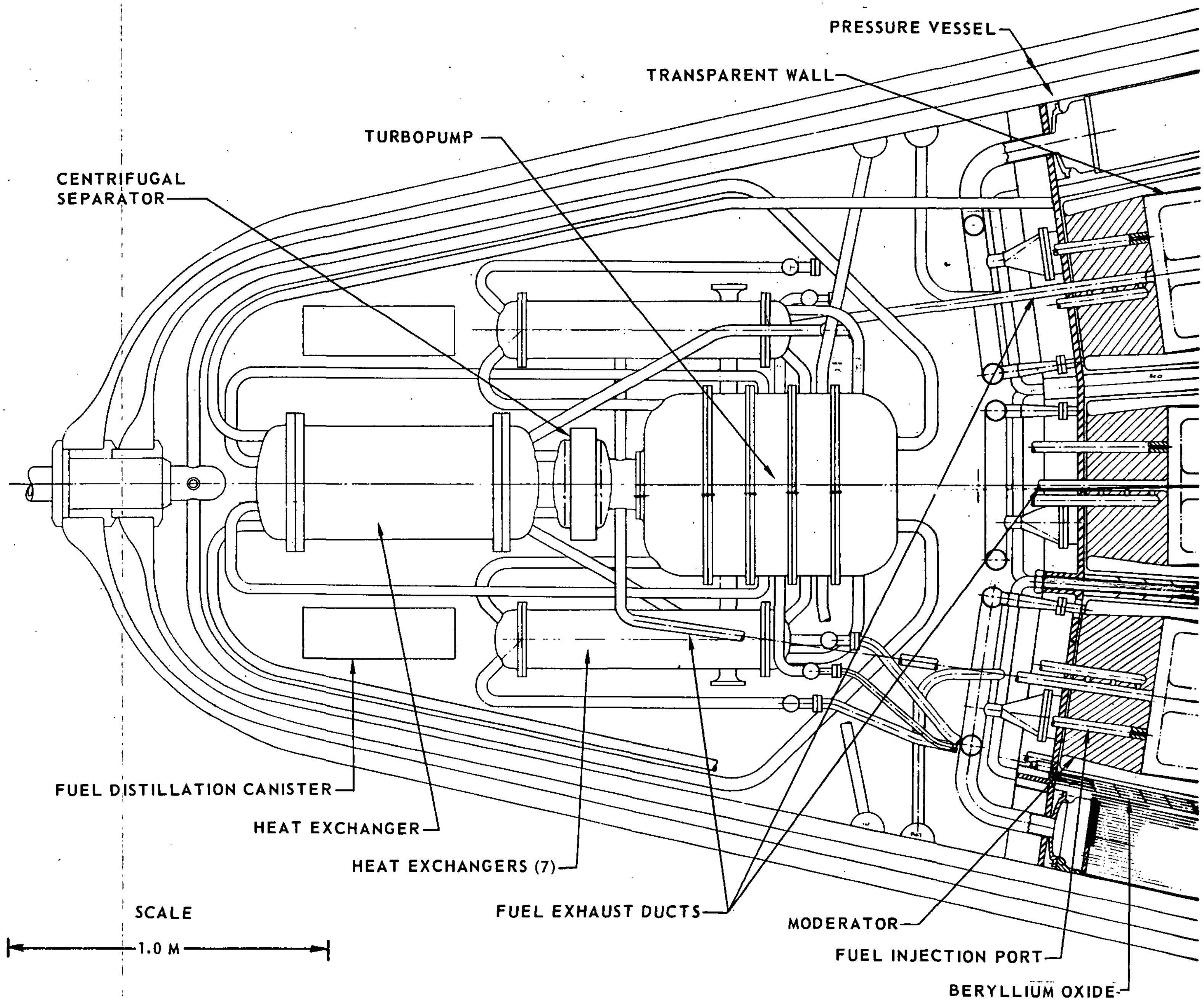


FIG. 2

PRELIMINARY LAYOUT OF EXHAUST SYSTEM AND OTHER COMPONENTS FOR REFERENCE NUCLEAR LIGHT BULB ENGINE



TYPICAL WEIGHT FLOW RATES AND TEMPERATURES IN FUEL EXHAUST SYSTEM OF NUCLEAR LIGHT BULB ENGINE

VALUES SHOWN ARE FOR REFERENCE ENGINE CONFIGURATION DESCRIBED IN REF. 3
ENGINE POWER LEVEL = 4600 MW
PRESSURE = 500 ATM
FLOW OF FISSION PRODUCTS AND SILICON SEED NOT SHOWN (SEE TEXT)
NOT TO SCALE
G = VOLUME FLOW RATE

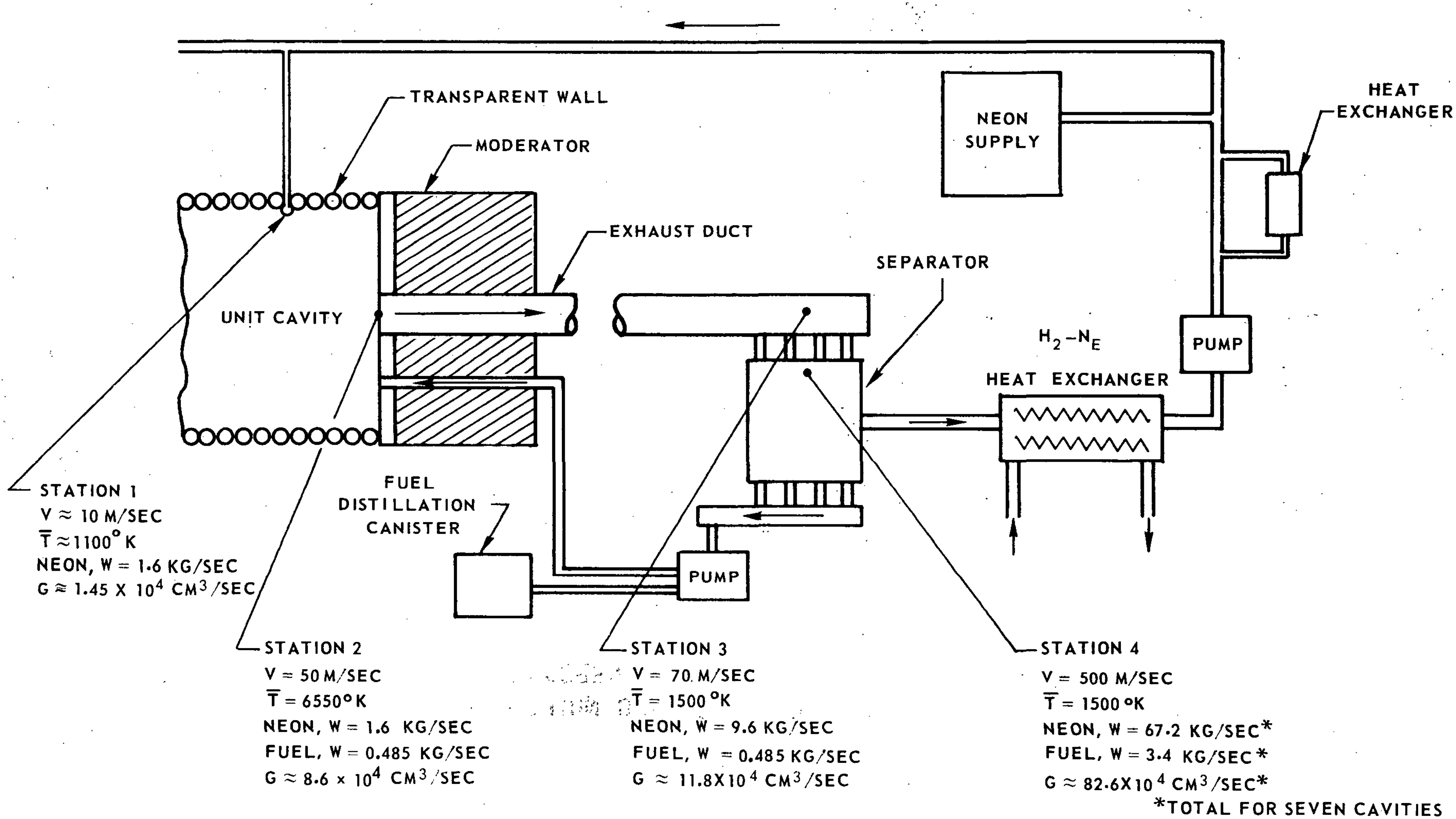
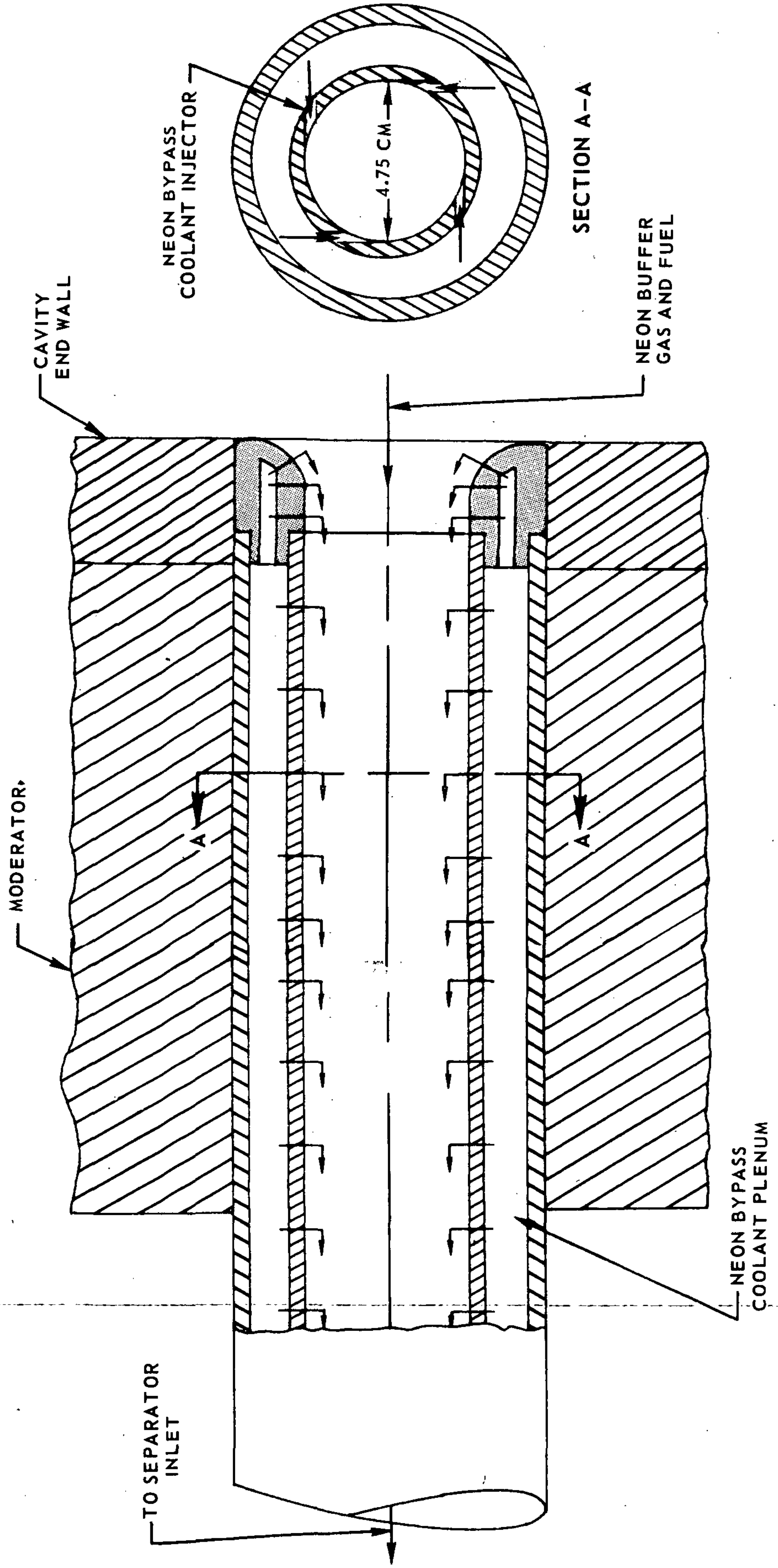
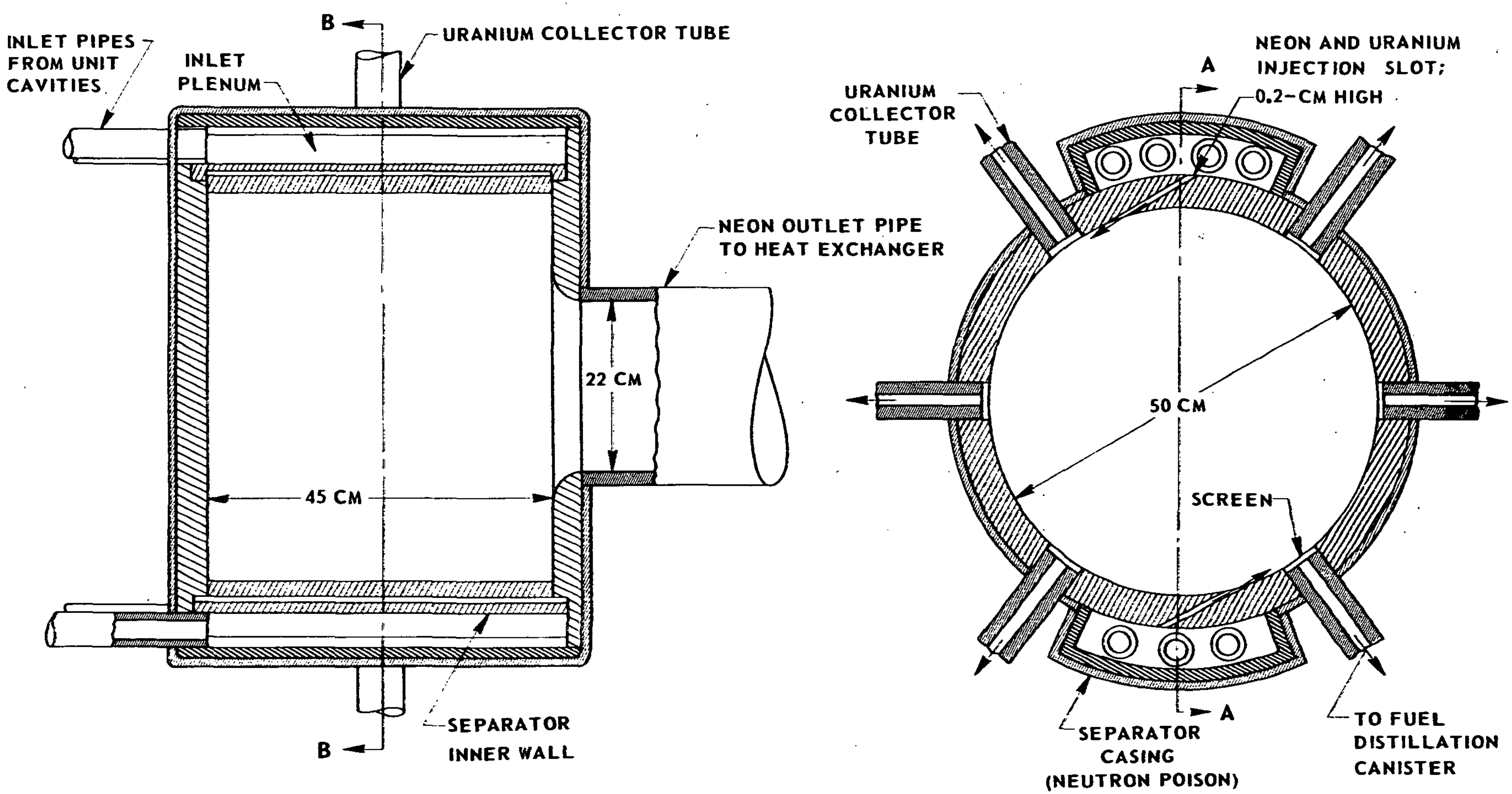


FIG. 3

SKETCH OF INLET PORTION OF FUEL EXHAUST DUCT FOR UNIT CAVITY OF REFERENCE ENGINE CONFIGURATION



PRELIMINARY CONCEPTUAL DESIGN OF FUEL SEPARATOR FOR REFERENCE ENGINE CONFIGURATION



SECTION A–A

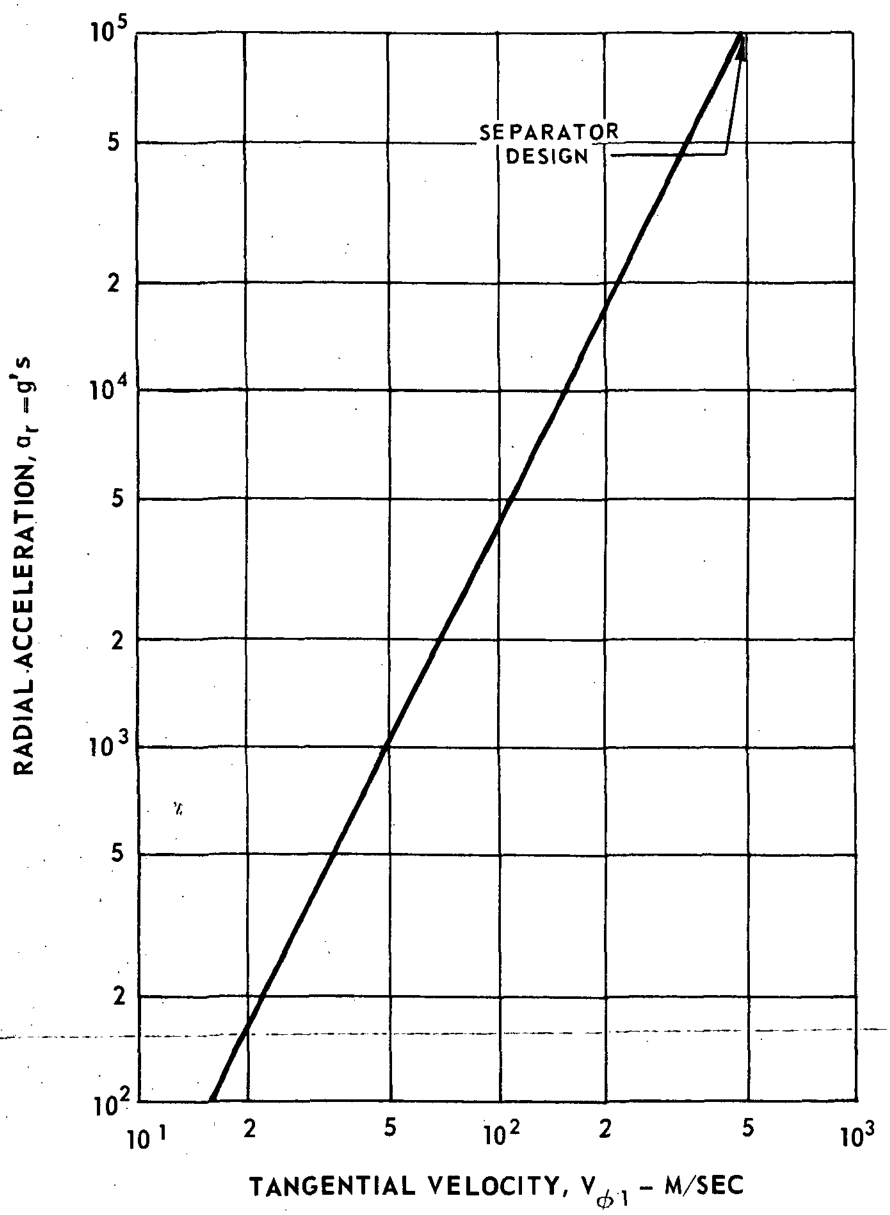
SECTION B–B

FIG. 5

EFFECT OF TANGENTIAL VELOCITY AT PERIPHERAL WALL ON INITIAL RADIAL ACCELERATION PRODUCED IN FUEL SEPARATOR

SEPARATOR I.D. = 50 CM $(2r_1)$

$$a_r = \frac{V_{\phi 1}^2 \times 10^4}{r_1 \times 980}$$



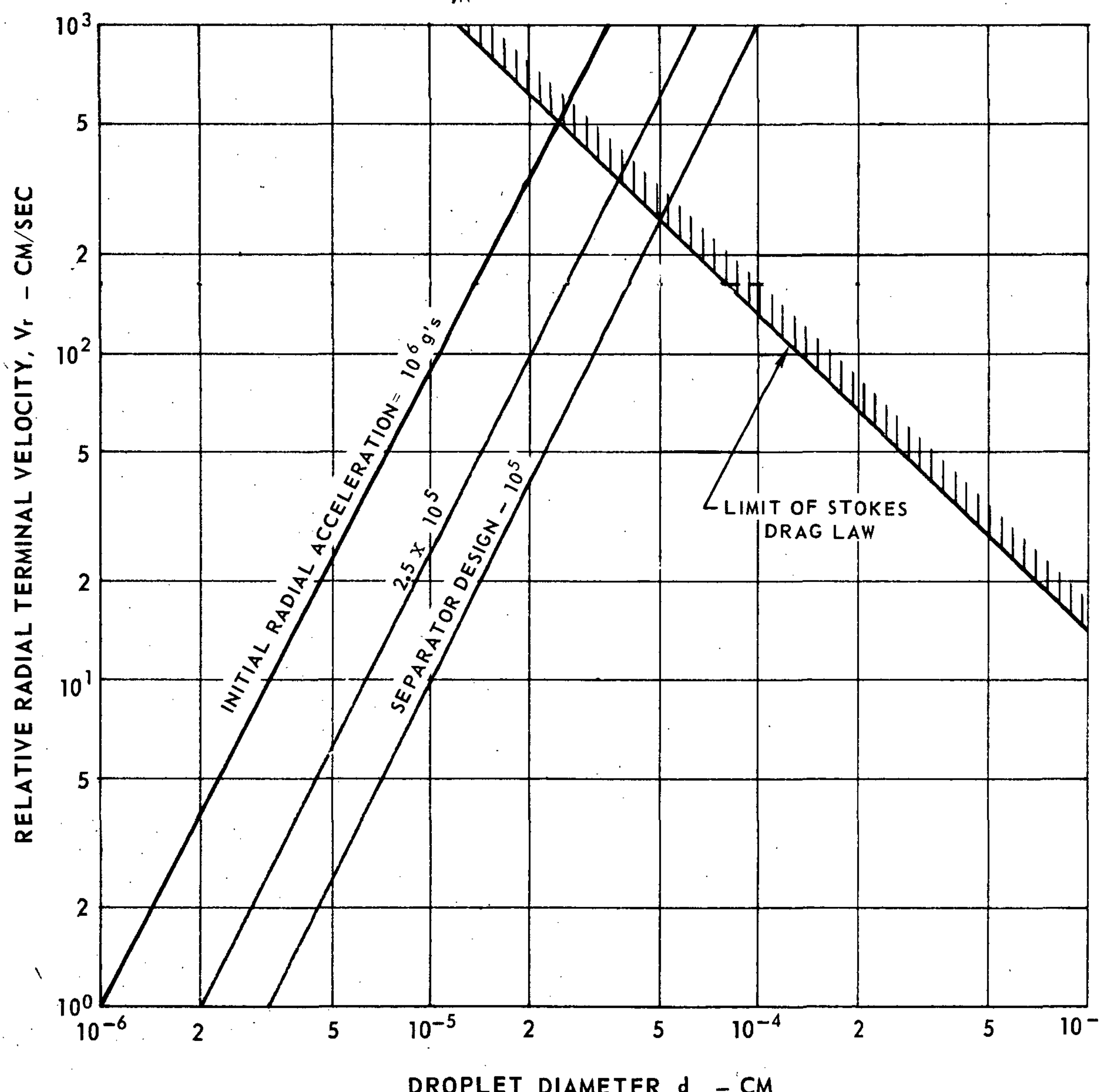
VARIATION OF TERMINAL VELOCITY OF FUEL DROPLETS WITH DROPLET DIAMETER

STOKES FLOW ASSUMED

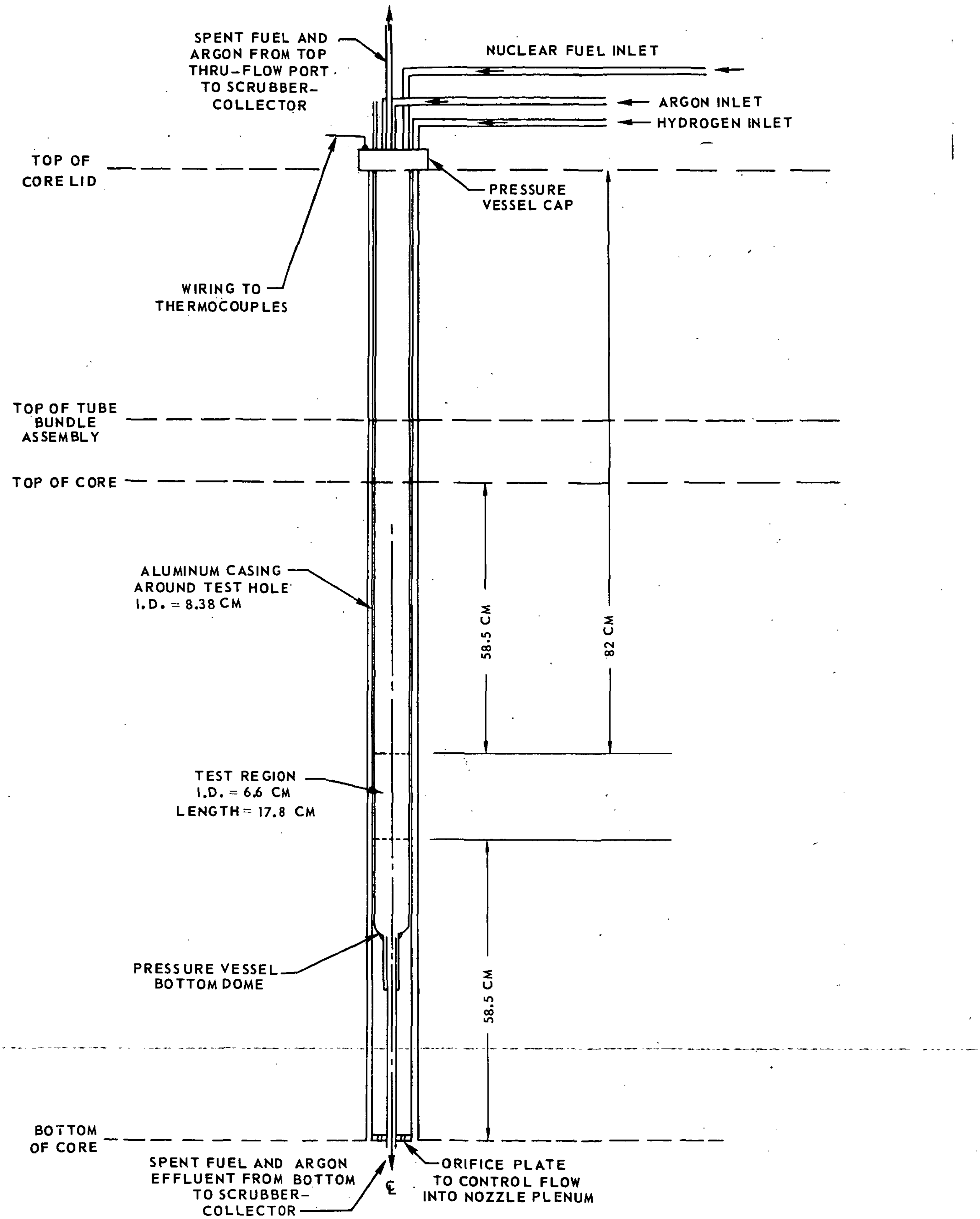
VELOCITY OF DROPLETS RELATIVE TO THE NEON, $V_r = \frac{a_r \rho_P d_p^2 g}{18 \mu_N}$

INITIAL RADIAL VELOCITY OF NEON, $\bar{V}_{r,N} = \frac{W_N}{\rho_N \pi d_1 \ell}$

FOR SEPARATOR DESIGN POINT, $\bar{V}_{r,N}$ = 116 CM/SEC



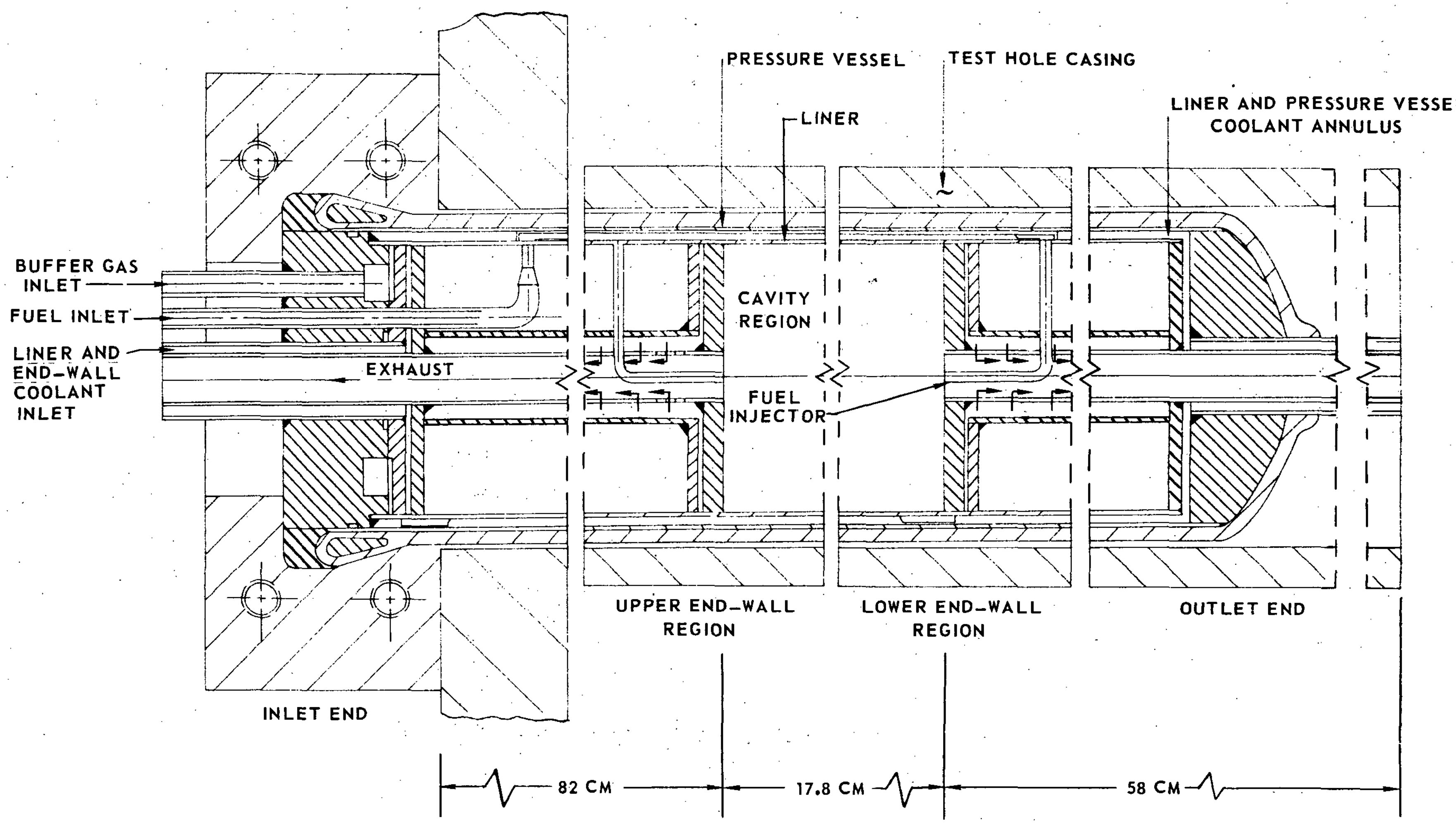
SKETCH SHOWING LOCATION OF IN-REACTOR TEST UNIT CELL IN NUCLEAR FURNACE



PRELIMINARY LAYOUT OF IN-REACTOR TEST CELL FOR NUCLEAR FURNACE

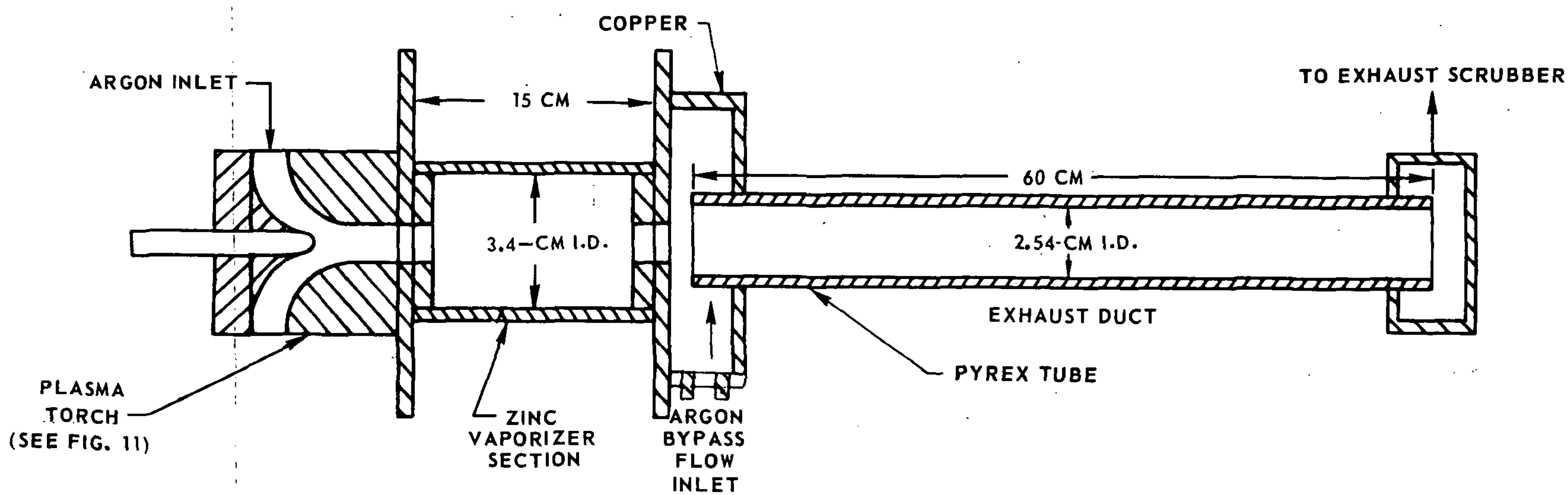
I.D. OF TEST HOLE CASING = 8.4 CM

DIMENSIONS OF CYLINDRICAL CAVITY REGION: 6.6-CM I.D. X 17.8-CM LONG

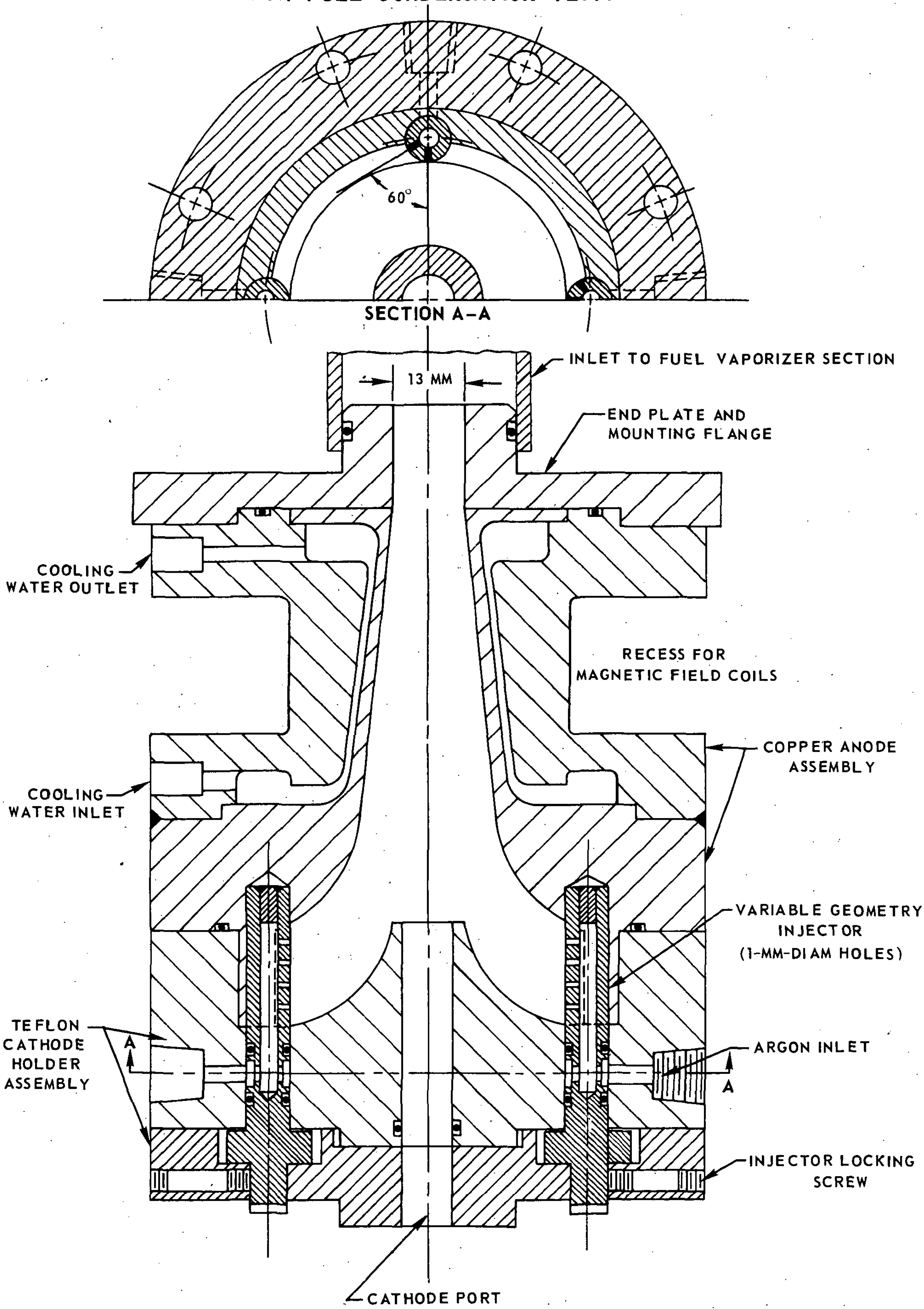


SKETCH OF EQUIPMENT FOR ZINC/ARGON TESTS

SEE FIG. 12 FOR INLET GEOMETRIES

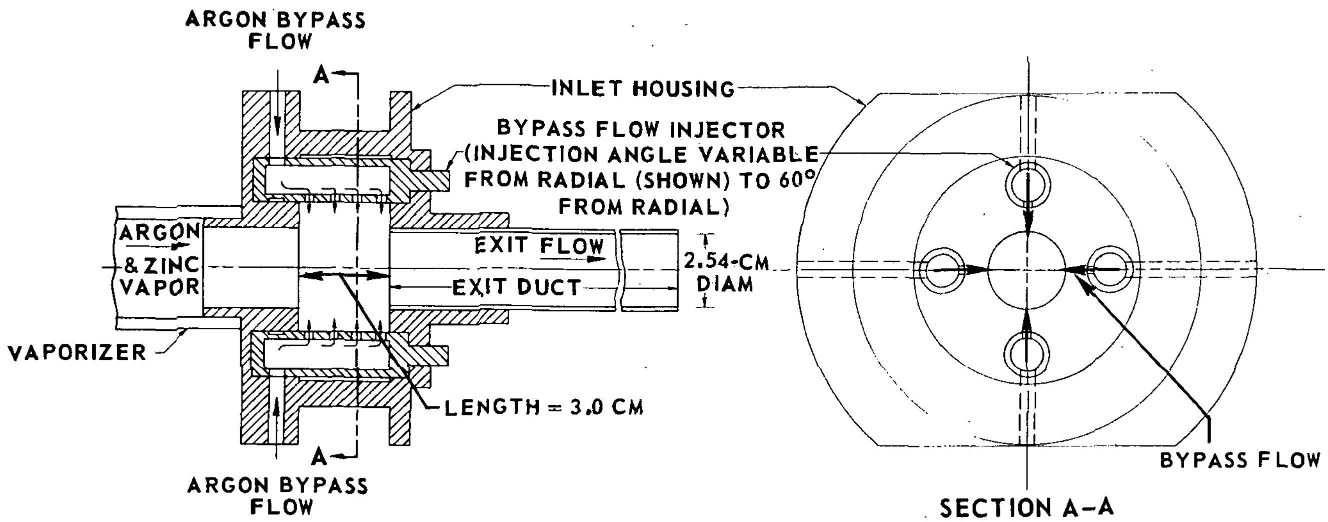


DC ARC PLASMA TORCH WITH VARIABLE INJECTOR GEOMETRY FOR FUEL CONDENSATION TESTS

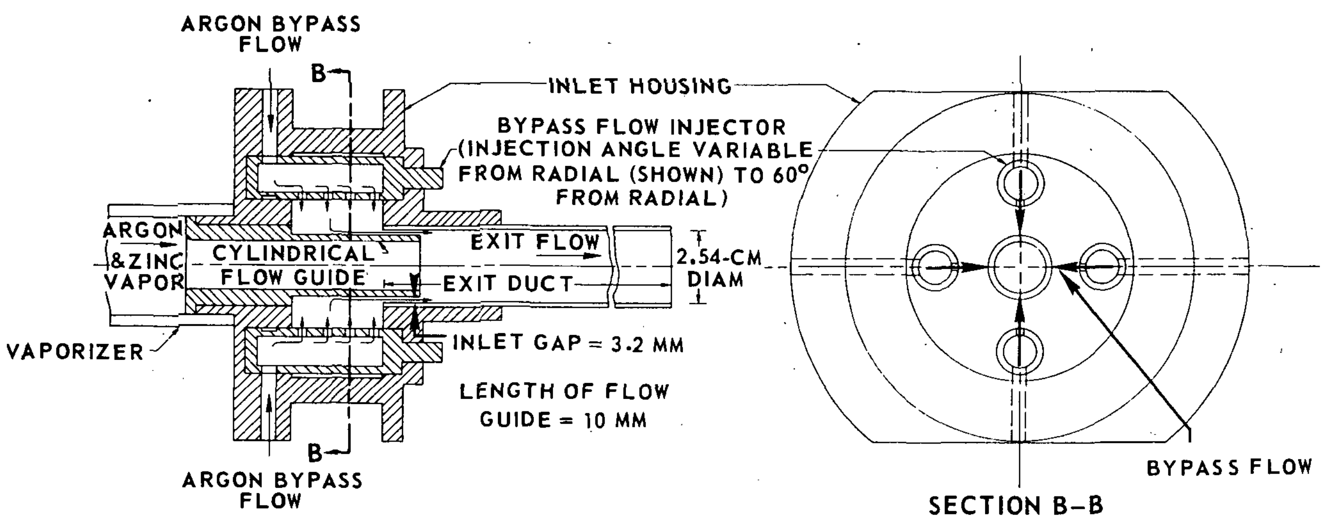


BYPASS-FLOW INLET GEOMETRIES USED IN FUEL-CONDENSATION TESTS

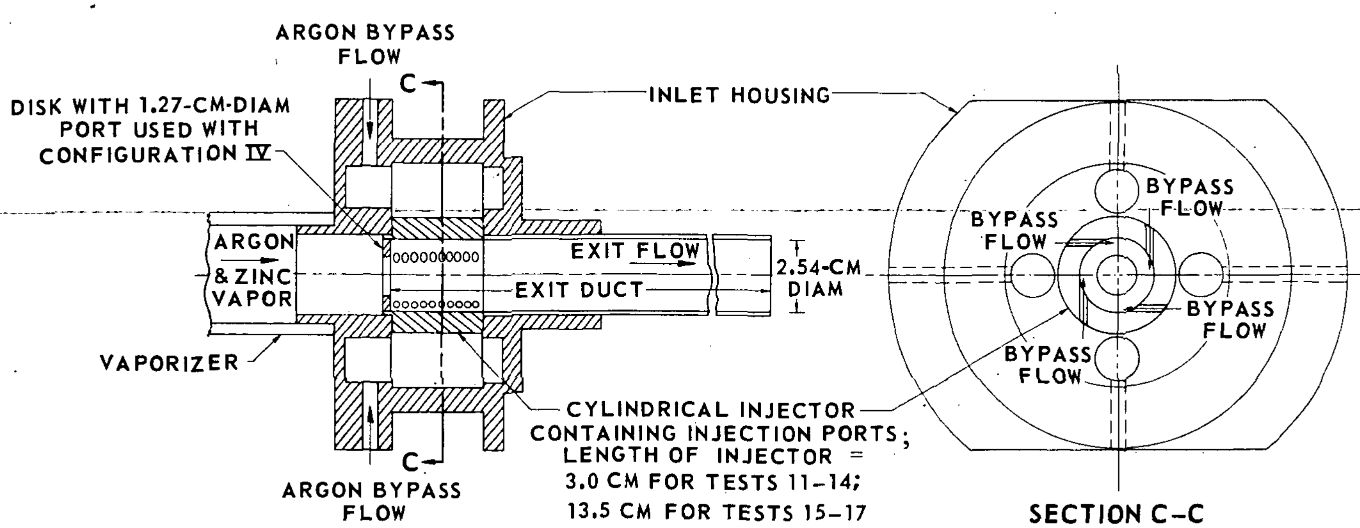
(a) CONFIGURATION I



(b) CONFIGURATION II



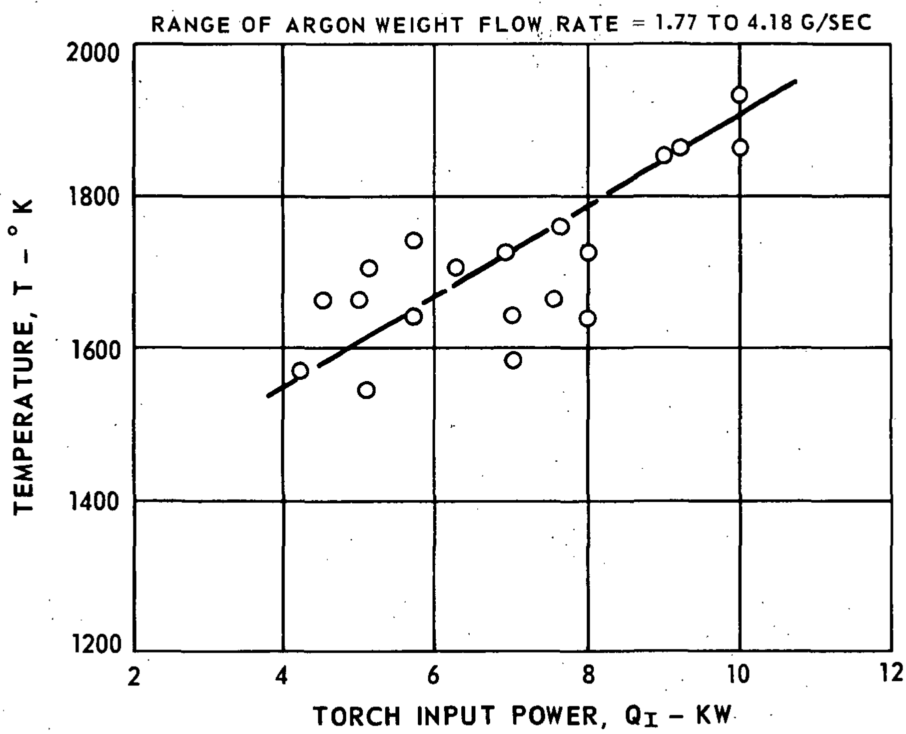
(c) CONFIGURATIONS III & IV



TEMPERATURE OF DC-ARC-HEATED ARGON AT EXIT OF SIMULATED-FUEL VAPORIZER

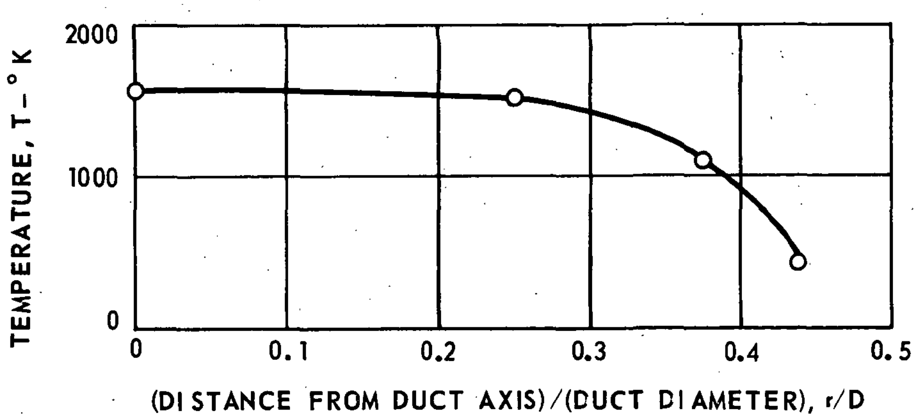
SEE FIG. 10 FOR TEST SECTION SCHEMATIC
SIMULATED FUEL NOT PRESENT IN VAPORIZER

(a) VARIATION OF MEASURED EXIT TEMPERATURE (ON VAPORIZER AXIS) WITH TORCH INPUT POWER



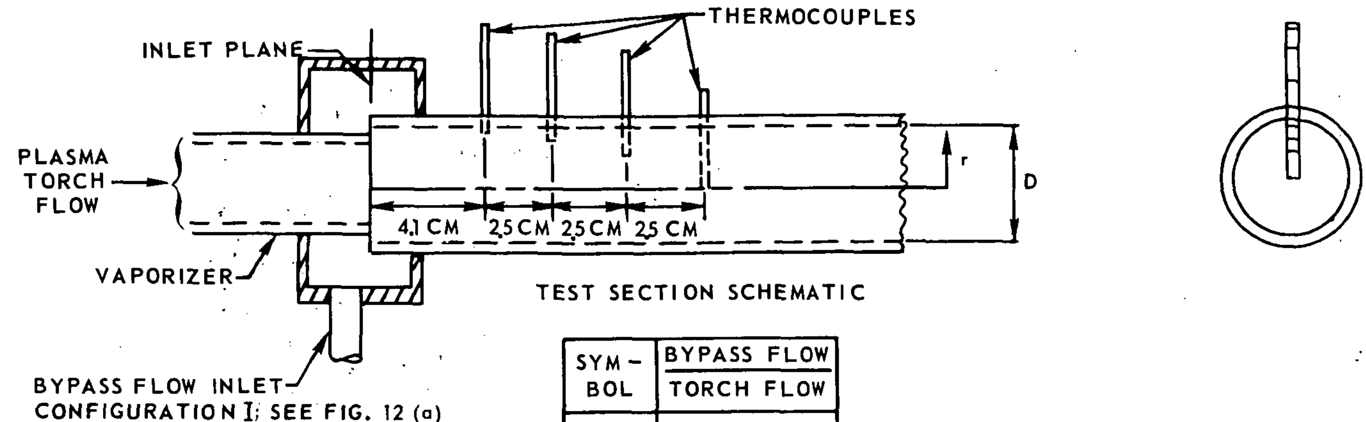
(b) RADIAL DISTRIBUTION OF TEMPERATURE AT EXIT OF VAPORIZER

TORCH INPUT POWER = 6.5 KW
ARGON WEIGHT FLOW RATE = 2.6 G/SEC
INJECTION ANGLE = 25° (SEE TEXT)



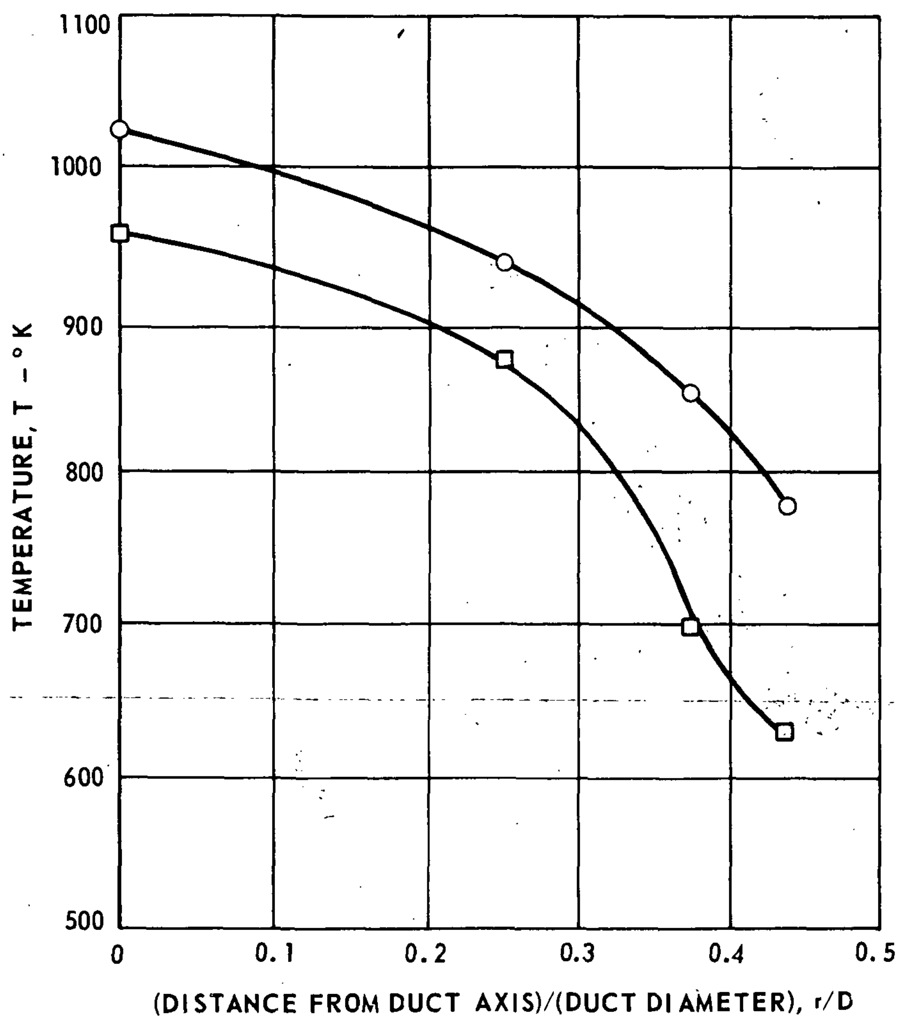
TYPICAL RADIAL TEMPERATURE DISTRIBUTIONS IN TEST SECTION EMPLOYED IN FUEL CONDENSATION TESTS

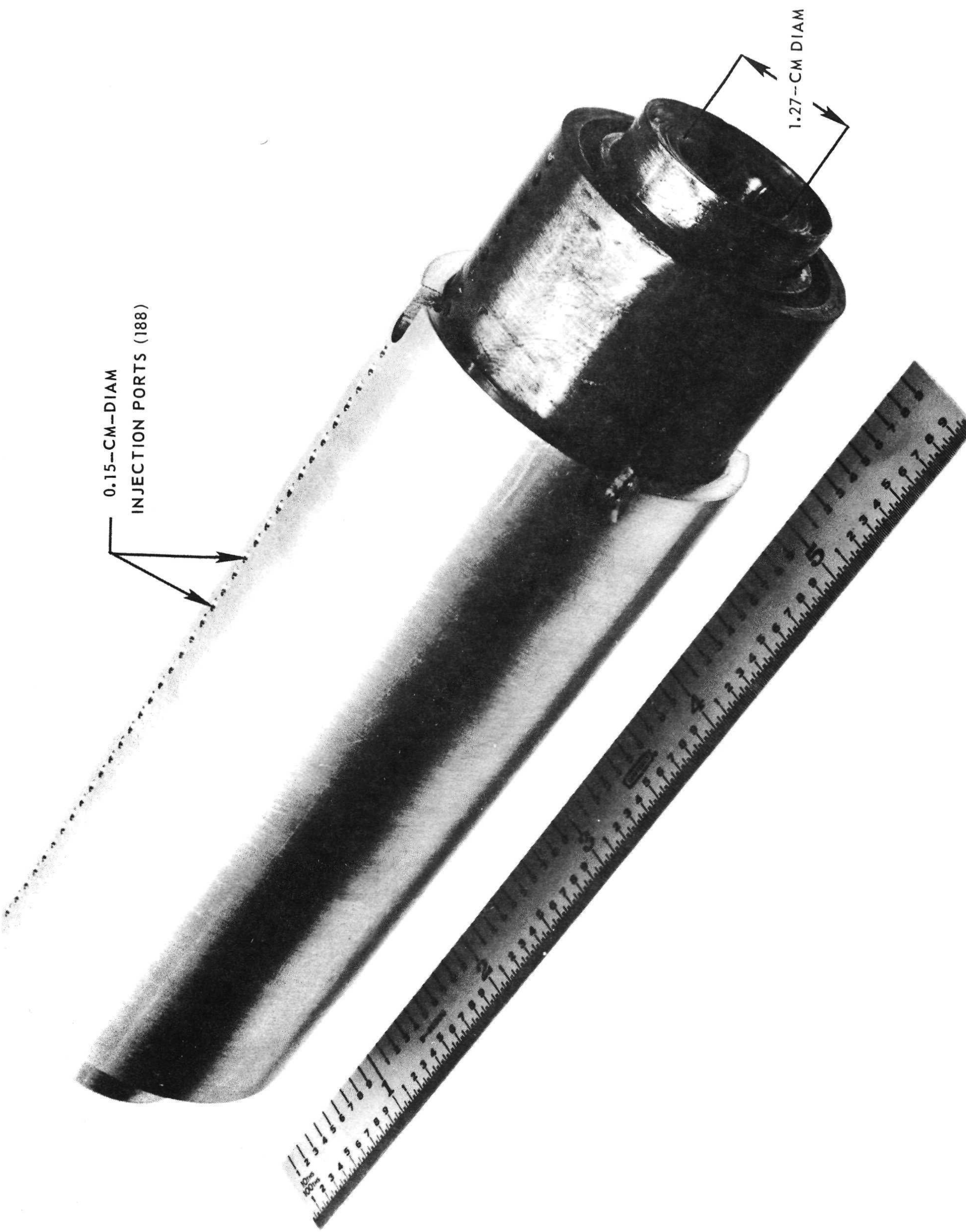
SIMULATED FUEL NOT PRESENT IN VAPORIZER
TORCH INPUT POWER = 10 KW
VAPORIZER EXIT TEMPERATURE = 1935 °K
ARGON WEIGHT FLOW RATE FOR (TORCH) = 2.6 G/SEC



TEST SECTION SCHEMATIC

SYM-BOL	BYPASS FLOW / TORCH FLOW
○	1.6
□	2.9





PHOTOGRAPH OF CYLINDRICAL INJECTOR USED IN FUEL CONDENSATION TESTS

DETAILS OF DUCT ASSEMBLY SHOWN FIG. 12(C)

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U

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A

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