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EXPLORATORY STUDY OF THE EFFECTS OF INJECTION CONFIGURATIONS AND INLET FLOW CONDITIONS ON THE CHARACTERISTICS OF FLOW IN SPHERICAL CHAMBERS

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16. Abstract

Flow visualization studies were conducted to evaluate techniques for injecting simulated-fuel and simulated-propellant gases into a spherical cavity for application to open-cycle gaseous-core nuclear rockets. Preliminary studies were conducted with six simulated-fuel injectors and eight simulated-propellant injection configurations. Additional tests were conducted with the best configuration to determine the effect of weight-flow ratio, gas density ratio, injector location, and flow distribution on the simulated-fuel containment characteristics.

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Exploratory Study of the Effects of Injection Configurations

And Inlet Flow Conditions on the Characteristics

Of Flow in Spherical Chambers

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SUMMARY

Flow visualization studies were conducted to evaluate techniques for injecting gases into a spherical cavity for application to the open-cycle gaseous-core nuclear rocket engine. The inner gas was injected into the cavity from a small diameter 'point' source to simulate gaseous nuclear fuel. The outer stream was injected from the peripheral wall to simulate the propellant. The study was concerned with developing injection configurations that would result in good simulated-fuel containment characteristics, i.e., more than twenty percent of the cavity filled with inner gas for ratios of outer-stream flow rate to inner-stream flow rate greater than 100. A major portion of the tests were conducted in a spherical chamber with maximum diameter and length of 12 in. (30.5 cm) and 15 in. (38.1 cm), respectively, which terminated with an exhaust nozzle having a throat diameter of 2 in. (5.1 cm). The outer gas was air for all tests and the inner gases were air and Freon-11. Flow visualization was obtained by coloring the inner gas with iodine gas and photographing the flow with a still camera, real-time motion pictures, and high-speed motion pictures.

A preliminary study was conducted with six inner-gas and eight outer-stream injection configurations to develop a suitable injection configuration. Additional tests were conducted with the best configuration from the preliminary tests to determine the effect of the outer-to-inner-stream weight-flow ratio, the inner-gas injector location, the inner gas, and the outer-stream flow distribution on the estimated inner-gas containment volume. Approximately 25 percent of the spherical cavity was filled with a high concentration of the simulated fuel for a weight-flow ratio of 100 with air as the inner gas. For tests with Freon-11 as the inner gas (inner to outer stream density ratio equal 4.7), and a weight-flow ratio of 20, approximately 22 percent of the cavity was filled with a high concentration of the inner gas. Further development of the outer-stream injection configuration is required to obtain desirable simulated-fuel containment characteristics with ratios of simulated-fuel density to simulated-propellant density greater than one.

INTRODUCTION

The goal of developing a gaseous-core nuclear rocket engine is desirable because the potential specific impulse obtainable is high (between 1500 and 5000 sec) and because the potential engine thrust-to-weight ratio is greater than one. Because of this potential, analytical and experimental studies to determine the feasibility of several open-cycle and closed-cycle versions of the gaseous-core nuclear rocket have been conducted at NASA-Lewis Research Center, the United Aircraft Research Laboratories, and elsewhere since approximately 1957. For the open-cycle gaseous-core rockets, the nuclear fuel and the propellant are both exhausted from the engine through the nozzle. For the closed-cycle gaseous nuclear rockets, the nuclear fuel is separated from the propellant by a transparent wall inside the engine and is not exhausted with the propellant. The fluid mechanics study reported herein is applicable to the open-cycle concept.

The original open-cycle coaxial-flow concept, outlined in Ref. 1, has been modified and refined such that the reactor chamber presently envisioned has an approximately spherical shape rather than the original cylindrical shape. Descriptions of the current concepts, estimates of the performance and component requirements, and a survey of previous work on open cycle concepts are presented in Refs. 2 and 3. In all of these concepts the nuclear fuel and propellant are injected into the reactor chamber at different locations and exhausted together from the reactor chamber through the nozzle. The energy generated from nuclear fissions in the gaseous fuel is transferred to the propellant by thermal radiation. The fluid mechanics requirements are that (1) a large fraction of the reactor chamber be filled with gaseous nuclear fuel, i.e., high containment, and (2) the ratio of the propellant weight-flow rate to the gaseous nuclear fuel weight-flow rate be large.

Background Information

Coaxial Flow Studies. - Most of the previous experimental and analytical investigations of the fluid mechanics for the coaxial-flow gaseous-nuclear rocket (GNR) engine have studied coaxial jets issuing into a chamber with a sharp discontinuity between the fast moving simulated propellant in the outer stream and the slow moving simulated fuel of the inner jet. These previous studies at Lewis Research Center, Illinois Institute of Technology, and United Aircraft Research Laboratories are summarized or cited in Ref. 3. These studies were thought to be applicable to the coaxial-flow region of the engine (see Fig. 1). However, the flow, which resulted from these inlet flow conditions had large or moderate scale turbulent mixing and had poor containment characteristics with respect to that required for economical operation of the rocket engine.

A flow visualization study (Ref. 4) of some of the coaxial jets described above indicated that the large eddy structure developed rapidly near the inlet plane. When these results were related to the results of previous and concurrent analytical and experimental studies of the growth of wave-like disturbances in shear layers (Refs. 5 through 7), a method of improving the containment characteristics for the coaxial-flow region was proposed (Ref. 8). This method consisted of providing a larger shear layer width at the coaxial-flow region inlet plane; the transition from the high-velocity outer stream to the lower-velocity inner jet being gradual, rather than abrupt. The flow visualization studies of Ref. 8 indicated qualitatively that a more desirable flow could be obtained with this inlet condition. The large-scale eddies found for many flow conditions in Ref. 4 were suppressed by suitable modification of the inlet geometry. The suppression of these large-scale eddies is desirable for a full-scale reactor since this reduces mixing between fuel and propellant.

Concentration measurements of a two-component coaxial flow in a cylindrical cavity (Ref. 9) indicate that a simulated-fuel volume fraction of approximately 20 percent was obtained at ratios of simulated-propellant flow rate to simulated-fuel flow rate greater than 200 by reducing the scale and intensity of the turbulent transport between the simulated fuel and simulated propellant to a sufficiently low level. The application of the information obtained from these and previous coaxial-flow tests at Lewis Research Center and the Illinois Institute of Technology is limited to the coaxial-flow region of the engine chamber.

Tear-Drop Cavity Studies. - Recent studies have been directed toward obtaining desirable containment flow conditions in a two-dimensional tear-drop cavity with small-diameter 'line' sources. These studies have been exploratory and qualitative in that most of the effort has been directed toward obtaining a desirably appearing flow rather than obtaining detail flow measurements. The first study employing a tear-drop shaped chamber with cylindrical porous walls was conducted at Lewis Research Center (Ref. 10). This study is currently being extended to include two component flows in a larger cavity at Idaho Nuclear Corporation.

Objectives of this Study

At present, parametric studies on the nucleonics, fluid mechanics, and heat transfer for the open-cycle reactor are being conducted or directed by the NASA-Lewis Research Center. Models for each aspect of the reactor are continuously being revised, studied, and evaluated in order to provide information (e.g., Refs. 4 and 8 through 13) for parametric system studies to determine the "trade-offs" and feasibility of the reactor concept (Refs. 14 through 16). Therefore, the general purposes of the present study are

(1) to improve the fluid mechanics characteristics in the chamber with respect to the previously mentioned fluid mechanics requirements, and (2) to provide qualitative data concerning the chamber containment characteristics.

The present study is the first which employs flow in the geometry envisioned for use in the full-scale engine. For all the tests in this study, the simulated fuel was injected into the chamber from a small 'point' source rather than being injected from a relatively large 'disc' source as in the previous coaxial studies or from a 'line' source as in the two-dimensional studies. A major problem in the current experiment is to produce favorable conditions for the expansion of the simulated fuel by properly choosing the injection velocities and flow rate of the simulated-propellant in the developing flow region. This expansion from a small source is required in order to obtain a volume of nuclear fuel large enough for nuclear criticality with reasonable cavity pressures.

The exploratory study described in this report deviated from the original plan to extensively study the flow characteristics in a chamber with porous walls. Rather than explore the effects of many possible inlet flow conditions with the porous wall configuration, the effort was redirected toward developing the outer-stream injection geometry which would result in larger inner gas containment volume fractions. Several inner-gas injectors and outer-stream injection configurations were fabricated and tested during this phase of the study. Tests to document the effects of flow injection conditions were conducted with the injection configuration for which the best containment characteristics were obtained during the preliminary tests. This report contains a summary of the work done to date to obtain desirable containment characteristics in the spherical cavity. The injection configuration for which parametric tests were conducted should be considered as an intermediate step in the path toward an acceptable configuration for the open-cycle engine rather than a configuration to be employed for the rocket development.

DESCRIPTION OF EQUIPMENT AND PROCEDURES

Equipment

Flow System. - A photograph of the spherical cavity test apparatus employed in the major portion of this study is shown in Fig. 2. Two gas streams were supplied to this apparatus: an inner stream to simulate the gaseous nuclear fuel and an outer stream to simulate the propellant. The inner stream was ducted directly to the inner-gas injector which was attached to the vertical tube shown in Fig. 3 at the upper end of the disassembled cavity. The outer stream was ducted through variable area flowmeters, valves, and hoses to the plenum chamber inlet ducts. A particular outer-stream injection configuration was attached to the plates separating the plenums in Fig. 3. To supply the desired combinations of inner-jet and outer-stream gases and gas weight-flow rates to the test apparatus, a combination of gas generators, heaters, and compressors were used. Air flow for the outer stream was drawn into the cavity using the Research Laboratories vacuum system. The total flow rate for the outer stream was measured with a nozzle located in the outer-stream supply lines. The inner-stream gas flow rate was measured with a variable area flowmeter. The outer stream was heated to approximately 203 deg F (95 deg C) using the 'light-gas' supply system described in Ref. 17. The inner-jet gases used were air and Freon-11. The air was obtained from the 400 psi (2.76×10^6 Nt/m^2) air supply and heated to 250 deg F (120 deg C) in a conventional tube-and-shell heat exchanger. The Freon-11 was vaporized on the shell side of a tube-and-shell heat exchanger and superheated in the air superheater. The average cavity pressure was approximately 14 psia (9.3×10^4 Nt/m^2).

Inner-Stream Injector Configurations. - Sketches of the inner-stream injection configurations employed in the study are shown in Fig. 4 a-f. These configurations are designated (a) Sintered Metal Sphere, (b) Sintered Metal Hemisphere, (c) Ceramic Filter Cylinder with Porous End, (d) Ceramic Filter Cylinder with Solid End, (e) Ceramic Filter Cup, and (f) Foam and Drill Tube Injectors. The materials, dimensions, and construction details for each injector are shown in Fig. 4. The injection areas for these configurations vary from 4 to 12 sq in. (25 to 75 sq cm). For a typical flow condition with a weight flow ratio, W_O/W_I, equal 100 and air as the inner gas, typical inner gas flow conditions have flow rates of 0.005 lb/sec (0.0023 kg/sec) and density of 0.050 lb/ft^3 (0.8 mg/cc). The velocities at the injection surface vary from 1.2 to 4.8 ft/sec (0.42 to 1.7 m/sec).

A sketch of the apparatus employed in the Inner-Gas Source Region tests is shown in Fig. 5. This apparatus was constructed from parts used in the coaxial-flow studies described in Refs. 8 and 9. The dimensions and construction notes are shown in Fig. 5. The inner-stream gas was heated, colored with iodine vapor, and metered for all tests. The outer-stream gas was drawn into the cylindrical cavity from the laboratory without metering, through a porous plate and foam inlet similar to that employed in Ref. 9. The flow rate was estimated from pressure drop information and was maintained constant for the preliminary tests by opening exhaust flow control valves to identical positions.

Outer-Stream Injection Configurations. - The eight outer-stream injection configurations employed during tests in the spherical cavity were made of combinations of three downstream configurations and six upstream configurations. These configurations were employed in the combinations given in TABLE I for the preliminary tests. Sketches of the downstream configuration and four upstream configurations and construction notes are shown in Figs. 6a-h. The Porous Wall Cavity (PW) (Figs. 6a and 6b) injection surface was constructed of transparent lexan sheet punched with 1/4 to 3/8-in. (0.65 to 0.92-cm)-dia holes and covered with 1/4-in. (0.65-cm)-thick foam. The Conical Wall Jet-I (CJ-I) upstream and the Conical Wall Jet (CJ) downstream configuration are shown in Figs. 6c and 6d. The Conical Wall Jet-II (CJ-II) upstream configuration was constructed by removing the perforated plate and foam inlet from plenum 1 and the wall jets from plenums 2 and 3 and replacing them with a single foam and porous plate inlet located at the downstream end of plenum 3. For the Coaxial Flow (CF) configuration, the Conical Wall Jet-II configuration was modified by installing a 10.0-in. (25.4-cm)-dia cylinder of lexan sheet from the plate between plenums 3 and 4 to the plate between plenums 9 and 10. This configuration was nearly identical to the cylindrical chamber and inlet shown in Fig. 5. The Annular Wall Jet-I (AJ-I) upstream configuration (Fig. 6e) had the foam and perforated plate inlet at the downstream side of plenum 3 used in the Conical Wall Jet-II and Coaxial Flow cavities and annular wall jets at plenums 4 and 5. The Conical Wall (CW) downstream section was constructed of lexan sheet as shown in Fig. 6f. The configuration used for the parametric study is shown in Fig. 6g,h. The upstream configuration, designated Annular Wall Jet-II (AJ-II), was obtained by modifying the Annular Wall Jet-I configuration to obtain a more spherical shape. The Conical Wall Jet (CJ) configuration was used for the downstream section.

For most of the tests, the outer stream flow rate was 0.5 lb/sec (0.23 kg/sec) with approximately 0.055 lb/sec (0.025 kg/sec) through each of the nine plenums. With gas density of approximately 0.05 lb/ft^3 (0.8 mg/cc), the total outer stream volumetric flow rate was approximately 10 cu ft/sec (28 liter/sec). Because the injection area varies for each plenum, the outer stream injection velocity varied from approximately 10 to 100 ft/sec (3.2 to 32 m/sec) for the flow from plenums 3 through 10.

Procedures

Flow Visualization. - A schematic of the optical system used for the flow visualization photography of the containment tests is shown in Fig. 7. Light was supplied by tungsten-halogen (bromine) quartz lamps and diffused with drawing vellum to provide uniform background illumination. Iodine was used to color the inner-jet gas for all of the flow visualization tests. For the black and white photographs, light to the films was filtered at a wavelength absorbed by the iodine vapor to obtain good contrast between the regions with and without iodine colored inner gas. Type 7241 EF Kodak Ektachrome film was used for all motion pictures obtained. Film sequences were obtained with Fastax and Miliken cameras at 24 to 500 frames per second.

Containment Estimating Technique. - The volume fraction of inner gas within the spherical cavity was estimated from color motion picture frames. The frame was projected to drafting paper and the outline of the dense and the lighter inner-gas regions and of several geometrical parts was drawn. The density of the inner gas in each region was estimated by the author based on previous experience and previous comparisons between results obtained by flow visualization concentration measurement techniques (Ref. 9).

PRELIMINARY EVALUATION OF VARIOUS INNER-STREAM AND OUTER-STREAM INJECTION CONFIGURATIONS

A series of exploratory tests were conducted to develop an injection configuration with which good containment characteristics could be obtained in the spherical chamber. The first problem was to obtain expansion of the inner gas from a small diameter 'point' source. Consequently, a series of tests were conducted early in the program to determine how best to simulate a point source and to obtain uniform nonmixing expansion of the inner gas from that source. These tests are described in the Inner-Gas Source Region Tests section. A second series of tests were conducted to develop an acceptable outer-stream injection configuration. These tests are described in the Outer-Stream Injection Tests section. During the evaluation and redesign of the outer-stream injection configurations, an effort was made to keep the cavity as spherical as possible so that the configuration developed would be compatible with nuclear criticality and weight requirements for the full-scale engine. The outer-stream injection configuration developed during these tests should be considered an interim configuration because, although the containment characteristics obtained with it are better than those obtained with the initial configuration, they probably are not sufficiently good for the full-scale engine.

Inner-Gas Source Region Tests

Flow visualization tests were conducted to determine the effect of inner-stream injector configuration on the inner-stream flow characteristics and to determine what outer-stream flow characteristics are required near the inner-stream injector to obtain a uniform nonmixing expansion of the inner-stream from a small source. For these tests, the inner gas (air) was heated to approximately 250 deg F (120 deg C) and colored with iodine gas and the outer-stream gas was drawn into the apparatus from the laboratory.

Inner-Gas Injector Tests. - The first series of tests were conducted to determine the inner-gas flow characteristics near the injector. These tests were conducted in the cylindrical chamber apparatus (Fig. 5) with L_C = 30 in. (76 cm) and D_B = 7.1 in. (18.0 cm). The flow from the Sintered Metal Sphere (Fig. 4a), the Sintered Metal Hemisphere (Fig. 4b), and the Ceramic Filter Cylinder with Porous End (Fig. 4c) was uniform and appeared 'laminar like'. The flow from the Foam and Drilled Tube (Fig. 4f) was less uniformly injected and appeared turbulent near the injector. Although the Sintered Metal Sphere (Fig. 4a) and the Sintered Metal Hemisphere (Fig. 4b) were constructed of nickel which is very resistant to iodine corrosion, these injectors became clogged after several hours operation. When the Sintered Metal injectors were clogged (indicated by increased pressure drop across injector), the flow rate was less uniform about the sphere and hemisphere but appeared laminar. These nonuniformities caused undesirable asymmetries in the flow within the cavity. The Ceramic Filter Cylinder with Porous End also became clogged and ruptured after the source region tests and after several tests in the spherical cavity. As a result of these difficulties, a filter system was installed upstream of the injectors to remove any iodine 'rust' particles from the air stream. A ceramic Filter Cylinder with Solid End (Fig. 4d) was fabricated from the remaining stock of the porous cylinder. The inner gas injected from this configuration was also uniform and 'laminar like'. However, at higher inner-gas flow rates, the inner-gas stream issuing from this injector had a radial jet characteristic (radial outward flow at a high rate) without any of the inner gas flowing downstream. In order to obtain axial as well as radial flow from the inner stream source, an alternate inner-gas small diameter source was sought. A ceramic automobile gasoline line filter was found to have these characteristics. Flow from the Ceramic Filter Cup (Fig. 4e) injector was uniform and appeared laminar near the injector.

Source Region Outer-Stream Flow Tests. - A second set of tests were conducted to determine the effects of the outer-stream flow distribution on the expansion of the inner-gas from the injector to the containment region. These tests also were conducted in the apparatus shown in Fig. 5 with L_C = 8.0 in. (20.3 cm) and the Ceramic Filter Cylinder with Solid End injector (Fig. 4d). The outer-stream flow was drawn into the cavity from the laboratory and was maintained approximately constant at about 0.5 lb/sec (0.23 kg/sec) for the six tests. Outer stream injection was tailored by varying the blockage diameter D_B (see Fig. 5). The inner-stream flow was varied to obtain ratios of W_O/W_I equal approximately 20, 30, and 60. The outer-stream injection configurations had the blockage diameters of D_B = 3.0, 7.1, and 8.5 in. (7.6, 18.0, and 21.6 cm). For tests with D_B = 3.0 in. (7.6 cm), the inner gas flowed axially from the injector and resulted in a small diameter cylinder of inner gas near the center of the chamber. When the blockage diameter, D_B, was increased to 7.1 and 8.5 in. (18.0 and 21.6 cm), the outer stream entrained the inner gas from the injector and formed a large diameter region of inner gas in the upstream end of the chamber. For the tests with D_B = 7.1 in. (18.0 cm), increasing the inner-gas flow rate to decrease W_O/W_I from 60 to 30, increased the amount of inner gas in the region near the injector. A further increase in W_I to decrease W_O/W_I to 20, did not further increase the amount of inner gas within the chamber. Rather, the inner gas became more turbulent, more mixing occurred between the inner and outer streams, and recirculation occurred upstream of the exhaust nozzle. For tests with D_B = 8.5 in. (21.0 cm), the inner-gas region was larger than for tests with D_B = 7.1 in. (18.0 cm) but less dense because some recirculation occurred for all the flow ratios. Increasing the inner-gas flow rate also increased the strength of the inner-gas recirculation cell; some of this recirculation may have been due to the lack of axial flow from this injector as mentioned in the previous paragraph.

Concluding Remarks. - Following are the conclusions from the Inner-Gas Source Region tests with air as both the inner and outer gases: (1) with the proper outer-stream flow distribution, it is possible to obtain a large volume of inner gas in the upstream end of the chamber when the inner gas is injected through a small diameter source; (2) the inner-gas injector should have provision for axial as well as radial flow to simulate spherical point source characteristics in the cavity and to prevent recirculation cells from forming near the injector when the inner gas is injected at relatively high flow rates; (3) nonuniformities of flow through the injector causes flow asymmetries in the cavity; and (4) the sintered metal injectors are more subject to corrosion or clogging than were the ceramic injectors (ceramic porous injectors are more suitable for use in further flow visualization tests when iodine is employed as a trace gas).

Outer-Stream Injection Tests

A summary of preliminary tests conducted in the spherical cavity during the development of the outer-stream injection configuration is given in TABLE I. Changes to the injection configurations were based on information obtained during the test program and from the Inner-Gas Source Region tests. The inner gas containment was evaluated with air as the inner gas because the first several wall jet configurations had strong recirculation cells and large-scale mixing. The containment results were undesirable with either air or Freon-11 as the inner-jet gases. For these tests, the outer-stream air was heated and metered with the High Reynolds Number Facility Equipment.

Porous Wall Cavity (PW). - The first series of tests (Runs 4a, etc.) were conducted with the porous wall cavity (Fig. 6a,b) oriented to exhaust upward. The outer stream was injected into the cavity through conical porous wall sections from ten plenums. The flow to each plenum was controlled and was measured with a variable-area flowmeter. The cavity surface area fed by each plenum, Numbers 3 through 10 (10 is nearest the exhaust nozzle), was approximately equal to the surface area fed by plenums Numbers 1 and 2 combined. The Ceramic Filter Cylinder with Porous End Injector (Fig. 4c) was employed with the center approximately 2 in. (5.1 cm) from the upstream end of the cavity. The best containment characteristics were obtained by setting the flow rate through the four upstream plenums at approximately 10, 20, 30, and 30 percent, respectively, of the average flow rate (i.e., total flow rate/10) and the flow rate through the remaining six plenums at higher than average flow rates. For tests with W_O/W_I greater than 20, the inner-gas concentration was diluted when the flow reached the center of the chamber. The tests with this configuration were terminated when the unsteady characteristics of the flow increased markedly. Examination of the inner-stream injector showed a break in the ceramic porous wall. A second set of tests (Runs 5 and 6) were conducted with the Foam and Drilled Tube Injector (Fig. 4f) and the outer-stream injection configuration employed in the first series of tests. Air and Freon-11 were used as the inner-stream gases. Because the cavity was positioned with the flow exhausted upward, an increase in containment volume due to buoyancy effects was expected for tests with Freon-11 as the inner-stream gas. However, the use of Freon-11 did not improve the containment characteristics which were approximately the same as for tests using air as the inner-stream gas. A third set of tests (Runs 14 through 21) were conducted with the cavity oriented to exhaust downward and using the Ceramic Filter Cylinder with Solid End Injector and with both air or Freon-11 as the inner-jet gas. The containment resulting with this injection configuration was the same as for Runs 4 to 6. The conclusion from these tests was that the inner-gas containment was low and consequently that the Porous Wall Injector configuration tested is not suitable for use in the full-scale engine.

Conical Wall Jet Cavity I (CJ-I,CJ). A series of tests (A, C, D) were conducted with the outer-stream injection configuration shown in Figs. 6c and 6d. The conical wall jet angles were designed, using a momentum integral analysis, for constant flow per unit length along the cavity. The tangential momentum added at each axial location was designed to entrain the flow injected upstream and keep the outer gas near the peripheral wall. Attempts to obtain this type of flow in the cavity were unsatisfactory because a large axisymmetric recirculation cell occurred in the chamber. Although the outer gas flowed near the peripheral wall, sufficient mixing between the outer stream and inner stream occured so that the average inner-gas density was low.

Conical Wall Jet Cavity II (CJ-II,CJ). - The upstream half of the outer-stream injection configuration described in the previous paragraph was modified by removing the conical wall jets from plenums 2 and 3 and placing a foam covered porous plate at the base of plenum 3. Although the inner gas filled a larger fraction of the cavity for these tests (Runs Nos. 37 through 40) than with the first wall jet configuration, a large amount of mixing between the inner stream and the outer stream occurred.

Coaxial Flow Cavity. - A series of tests (Runs B) were conducted with a cylindrical chamber similar to that shown in Fig. 5 inside the spherical cavity. These tests were carried out to determine if the flow patterns obtained in the Inner-Gas Source Region Tests could be obtained in the spherical cavity. This question arose during the tests with the Conical Wall Jet Cavity-I which produced large-scale mixing and large recirculation cells. A cylinder of lucite sheet was rolled to a 10 in. inside diameter and fastened inside the spherical cavity. The outer-stream gas was injected from plenums 1 to 3 through the foam and perforated plate inlet used for the modified wall jet tests. Flow patterns like those obtained in the Source Region Outer-Stream Flow tests were also obtained from these tests. The conclusion after tests B with the Coaxial Flow Cavity and additional tests (Runs 37 through 46) with the Conical Wall Jet Cavity-I was that the Conical Wall Jet-I injection system was causing the undesirable flow characteristics and that improvements were required in the outer-stream injection configuration.

Annular Wall Jet Cavity I (AJ-I,CJ). - The downstream half of the injection configuration for the cavity was the same as used for the conical wall jet cavities. The upstream half of the cavity consisted of annular wall jets injecting flow from plenums 4 and 5 and of a foam covered perforated plate at the lower end of plenum 3 injecting flow from plenums 1 to 3. No flow was injected from plenum 6. The flow characteristics obtained with this configuration (Runs 51 through 58) were similar to those obtained with the previously discussed coaxial-flow configuration. The inner-stream gas region was approximately axisymmetric and filled approximately one-fourth of the upper half of the cavity. The inner-stream concentration was diluted in the downstream half of the chamber due to recirculation.

Annular Wall Jet Cavity II (AJ-II,CJ). - The upstream half of the Annular Wall Jet Cavity I was modified by adding a third annular jet for injecting flow from plenum 3 and by decreasing the diameter of the foam and perforated plate for injecting flow from plenums 1 and 2 (Fig. 6e). A series of exploratory tests (Runs 61 through 67) were conducted with this outer-stream injection configuration and the Ceramic Filter Cylinder with Solid End Injector (Fig. 4d). The containment characteristics of the flow in the chamber with this outer-stream injection configuration was improved compared to that obtained in the previously described tests. The region near the inner-gas injector was filled with inner gas, had relatively low turbulent intensities, and had a relatively small amount of turbulent mixing between the inner gas and outer gas. The downstream half of the chamber contained recirculating flow with a low inner-gas concentration. The flow characteristics obtained with this configuration are described in detail in a following section.

Conical Exhaust Cavity (AJ-II,Cone). - The lower half of the Annular Wall Jet Cavity II was modified by installing a conical section in the downstream half of the chamber (Fig. 6f). For these tests, flow was injected only in the upstream half of the cavity. The flow characteristics of this cavity were similar to those obtained with the Annular Wall Jet Cavity I. Recirculation and mixing occurred in the downstream half of the chamber at flow ratios W_O/W_I of 80 and 133. Consequently, the inner-gas concentration was low in that region. For the same weight-flow ratios, no improvement over the apparent containment obtained with the Annular Wall Jet Cavity II could be discerned.

EVALUATION OF ANNULAR WALL JET CAVITY II

A series of tests were conducted with the injection configuration for which the best apparent inner-gas containment characteristics were obtained during the preliminary evaluation tests described in the previous section, i.e., the Annular Wall Jet Cavity II (Fig. 6g,h) and the Ceramic Filter Cup (Fig. 4e). For these tests, the flow was exhausted downward from the chamber, the outer-stream flow rate was held approximately constant and the inner-stream flow rate, the inner-stream injection location, the inner-stream gas, and the outer-stream flow distribution through the plenums was varied. The amount of inner gas contained in the cavity was estimated by determining the volumes of the dark inner-gas regions and the lighter inner-gas regions for a frame of high-speed motion pictures. The iodine colored gas concentration is easier to estimate from the color motion pictures than from the black and white photographs. This occurs because shadows and light reflections cause decreases or increases in the light intensity which must also be interpreted for iodine concentrations. Based on previous experience with iodine density measurements and flow visualization studies (Refs. 4 and 9), the dark inner-gas region was estimated to contain 80 to 100 percent inner gas and the light region was estimated to contain 10 to 80 percent inner gas. Average values of 80 percent concentration for the dark regions and 20 percent for the light region were considered conservative reasonable values and were used in estimating the containment volume. A summary of the inlet flow conditions and the apparent inner-gas containment results for these tests is given in TABLE II. (A concentration measured, obtained after the work reported herein was completed, showed that for a flow condition with recirculation, the inner gas concentration was less than estimated in this report. The flow conditions for which recirculation was apparent are noted in TABLE II, Fig. 12 and Fig. 14.)

The effect of inner-stream weight-flow rate and the inner-stream gas injection locations on the containment characteristics is shown in Figs. 8 and 9 for tests with air and Freon-11, respectively, as the inner-stream gas. For tests with air, the volume fraction of inner gas contained in the cavity is greatest for a weight-flow ratio W_O/W_I = 50 and with the inner-gas injector adjacent to the upstream end of the cavity. The apparent containment volume decreased with increased weight-flow ratio, W_O/W_I, and with increased distance of the inner-gas injector from the upstream end. The volume of the light region increased with an increase in W_O/W_I from 50 to 100 for the inner-gas injection adjacent to and 1.0 in. (2.5 cm) from the upstream end. This was apparently due to an increase in recirculation or mixing in the downstream end of the cavity. The intensity of the recirculation flow appeared to decrease as the inner gas injector location was moved to 2.0 in. (5.1 cm) downstream from the foam. The apparent containment results from tests with Freon-11 as the inner gas show the same trends as the results with air. However, the same containment volumes are obtained at higher values of W_I or lower ratios of W_O/W_I. The effect of buoyancy on the inner-gas containment characteristics is apparent from Run Nos. 104, 108, and 109 (Fig. 9). The Freon-11 forms an axisymmetric column from the injection location to the upstream edge of plenum No. 8. Downstream of this location the Freon-11 concentration decreases due to mixing and recirculation.

The flow distribution through the outer-stream plenums was then varied as shown in Fig. 10. The 'standard' flow distribution was that employed in the tests described in the previous paragraph. Runs 94 and 95 have increased flow in the upstream half of the cavity and have decreased and zero flow, respectively, on the downstream half of the cavity. Run 96 has decreased flow on the upstream half of the cavity and increased flow on the downstream half of the cavity. The time exposure photographs do not show significant changes in the containment characteristics; small differences in the containment characteristics were estimated from the color motion pictures. For Run 96, the containment in the upper portion of the cavity increased compared to that obtained for Run 92 with the standard flow distributions which resulted in an increased estimated containment volume fraction of inner gas in the cavity.

A graphic summary of the estimated containment results obtained with this cavity are shown in Fig. 12 as variations of the estimated volume fraction of inner gas with the weight-flow ratio, W_O/W_I. (Arrows at some data points indicate flow conditions with recirculation. The estimated containment volumes for one of these flow conditions was greater than obtained from recent concentration measurements.) Inner-gas volume fractions greater than 0.2 were obtained for weight-flow ratios, W_O/W_I, less than 150 for air and 23 for Freon-11 as the inner gases. For tests with air as the inner-gas, the containment volume decreases slightly with increasing weight-flow ratio, W_O/W_I. For tests with Freon-11, the decrease in containment volume with increasing weight-flow ratio is more pronounced. The conclusion from the tests with Freon-11 is that buoyancy causes the inner gas to accelerate downward faster than the outer-stream can entrain it and form a large inner-gas volume. For the tests with air, the buoyancy effects are negligible and the inner gas is entrained toward the outer-stream shear layer and consequently forms the larger inner-gas containment volume.

CALCULATED STREAMLINE DISTRIBUTION OF FLOW IN SPHERICAL CAVITY

The streamline distribution within a spherical cavity was calculated for several sets of boundary conditions using a modified version of the Basic Computer Program described in Ref. 18. The Navier-Stokes equations of motion are formulated in finite-difference form as second-order equations with the stream function and the vorticity as dependent variables. These equations are solved subject to the injection and exhaust boundary conditions by an iterative method of successive substitutions. Modifications were made to the Basic Computer Program which enable the calculation of flows with the following boundary conditions:

1. Arbitrary tangential and radial velocity distribution around the peripheral wall.

2. A point source of inner-stream fluid placed on the axis of symmetry at an arbitrary distance from the upstream end.

3. A conical exhaust nozzle attached to the spherical chamber.

The streamline distributions, calculated for three sets of boundary conditions and flow properties, are shown in Fig. 13. For these three cases, (1) the radial velocity and density of the flow injected from the peripheral wall were constant at 1 ft/sec (30.5 cm/sec) and 0.075 lb/ft^3 (1.20 kg/m^3), respectively, (2) the inner-gas source strength was 5 percent of the flow injected from the peripheral wall, (3) the inner gas was the same density as the outer gas. The cavity diameter was equal to one foot. For case (a) the kinematic viscosity was arbitrarily chosen high, 13.3 ft^2/sec (0.124 m^2/sec) and the tangential wall velocity was zero. The inner-stream gas expands from the point source in the upstream portion of the chamber but contracts as the flow approaches the exhaust nozzle. These flow characteristics were observed in the experimental tests with the Porous Wall Cavity. For case (b), the kinematic viscosity was the same as for case (a) and the tangential velocity was varied from zero at the upstream end of the chamber to 40 ft/sec (12.2 m/sec) directed toward the exhaust nozzle at the edge of the exhaust nozzle. A strong recirculation cell formed in the spherical cavity for these boundary conditions. The flow injected from the peripheral wall remain close to the wall. The flow from the point source flowed between the recirculation cell and the wall flow similar to the recirculation flow experimentally observed in the spherical cavity for the tests with the Conical Wall Jet I injection configuration. For the experimental tests, the concentration of the inner gas was low because of mixing between the streams which indicated that this flow condition is not desirable. For case (c), the kinematic viscosity was decreased to 0.1 ft^2/sec (93 x 10^{-3} m^2/sec) which is probably closer to the value in the spherical chamber. The tangential wall velocity was also decreased in an attempt to obtain flow in the cavity which would not recirculate. These modifications to the flow conditions and properties caused the gas flow from the inner-gas source to expand to fill a large fraction of the chamber and exit from the chamber through the ehxaust nozzle without recirculating. The present opinion of the author is that flow conditions like those oi case (c) will be required to experimentally obtain high average inner gas concentrations in the spherical chamber. The conclusion from this study was that the calculations of flow in a spherical cavity can be made which predict the flow patterns in the spherical cavity and which will assist in the design or redesign of outer-stream injection configuration to obtain improved cavity containment characteristics.

COMPARISON OF RESULTS WITH COAXIAL FLOW RESULTS AND CURRENT REQUIREMENTS

The estimated inner-gas containment results obtained with the inner-gas injector adjacent to the upstream end of the chamber are compared in Fig. 14 with previous results from coaxial-flow studies and with the GNR open-cycle fluid mechanics requirements. The upper range of the present spherical cavity results with air as the inner gas are well within the containment region of interest designated on the graph. However, the present spherical cavity results with Freon-11 as the inner gas are lower than recently deemed sufficient for use in the full-scale engine. Further effort will be required to develop an injection configuration which is effective in producing desirable flow characteristics with the density ratio and buoyancy parameters expected in the full-scale engine.

SUMMARY OF RESULTS

1. Approximately 25 percent of the spherical cavity was filled with a high concentration of the simulated fuel injected from a small diameter source. For this test with the Annular Wall Jet Cavity the ratio of simulated propellant flow rate to simulated fuel flow rate, W_O/W_I, was equal to 100, air was employed as both the simulated fuel and propellant.

2. A ratio of W_O/W_I equal 20 was required to fill approximately 22 percent of the spherical cavity with Freon-11 (Mol $_{wt} \approx 140$) employed as the simulated fuel.

3. The general flow characteristics in the spherical cavity were predicted by numerical solutions of the Navier-Stokes equations for boundary conditions similar to those employed in the experiment.

4. Further development of the outer-stream injection configuration is required to obtain desirable simulated-fuel containment characteristics with ratios of simulated-fuel density to simulated-propellant density greater than one.

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LIST OF SYMBOLS

D_B Diameter of outer-stream blockage on foam and porous plate inlets, ft (m)

L_C Length of cylindrical chamber, ft (m)

Q Volume flow rate, ft^3/sec (m^3/sec)

R Maximum radius of axisymmetric cavity, ft (m)

Re_Z Axial flow Reynolds number, dimensionless

U_R Radial injection velocity at cavity wall, ft/sec (m/sec)

U_θ Tangential injection velocity at cavity wall, ft/sec (m/sec)

V Volume of cavity, ft^3 (m^3)

V_I Volume of inner gas in cavity, ft^3 (m^3)

W_F Weight-flow rate of simulated fuel, lb/sec (kg/sec)

W_I Weight-flow rate of inner-jet gas, lb/sec (kg/sec)

W_O Weight-flow rate of outer-stream gas, lb/sec (kg/sec)

W_P Weight-flow rate of simulated propellant, lb/sec (kg/sec)

ρ_I Inner-gas density, lb/ft^3 (kg/m^3)

ρ_O Outer-stream gas density, lb/ft^3 (kg/m^3)

TABLE I

SUMMARY OF PRELIMINARY TESTS IN SPHERICAL CAVITY DURING DEVELOPMENT OF OUTER-STREAM INJECTION CONFIGURATION

See Figs. 4 and 6 for description of inner-stream and outer-stream injection configurations.

TB: Timed Exposure; Black and White Film
TC: Timed Exposure; Color Film
M: High Speed Motion Pictures

Run No.	Injection Configuration					Inner Stream Gas	Documentation	Comments
	Inner Stream Configuration	Outer Stream Configuration: Up-Stream Half	Outer Stream Configuration: Down-Stream Half	Flow Direction	Configuration Notes			
4a,b,c,d	c	PW	PW	UP		Air	TB	Additional tests will be required to determine containment obtainable with Freon-11.
5a,b,c,d	f					Freon-11	TB	
6a,b,c,d	f					Air	TB	
14-21	d			DOWN	Air Leak to Plenum	Air	M	
Aa,b,c,d	d	CJI	CJ			Air	None	
Ba,b,c,d	d	CF	CF			Air	None	Flow patterns obtained in cylindrical chamber reproduced in spherical cavity
37-40	f	CJII	CJ			Air	TC	
41-43	f					Freon-11	TC	
44-46						Air	TC	
51-54	f	AJ-I	CJ		Swirl in Plenums	Air	M	
55-58						Freon-11	M	
Ca,b,c,d	f	CJI	CJ			Air	None	
Da,b,c,d	f	CJI	CJ			Air	None	
61-64	d	AJII	CJ		No Swirl in Plenum	Air	M	Containment characteristics obtained with this configuration best obtained thus far.
65-67						Freon-11	M	
71-74	e	AJII	Cone			Air	M	For a given ratio of W_O/W_I
75-79						Freon-11	M	
80						Air	TB	

TABLE II

SUMMARY OF INLET FLOW CONDITIONS AND APPARENT INNER-GAS CONTAINMENT RESULTS FOR TESTS WITH ANNULAR WALL JET CAVITY II

$W_O \approx 0.51$ lb/sec for all tests

Estimated volume fraction of inner gas equal 0.8 x dark volume fraction plus 2 x light volume fraction.

*Probably lower due to recirculation. A concentration measurement obtained after this study indicates lower inner-gas concentration than estimated when recirculation occurs.

Run No.	Inlet Flow Condition				Apparent Inner-Gas Containment Results		
	Inner Stream Gas	Weight Flow Ratio, W_O/W_I	Inner Stream Injector Location	Outer Stream Injector Distribution	Dark Volume Fraction	Dark and Light Volume Fraction	Estimated Volume Fraction of Inner Gas
91	Air	51	Adjacent to Foam	Standard-Approximately Uniform Axially	0.30	0.47	0.28
92	Air	101			0.20	0.50	0.26*
93	Air	194			0.16	0.49	0.18*
94	Air	107		Increased on Upstream Half	0.23	0.039	0.22*
95	Air	101		Zero on Downstream Half	0.23	0.46	0.23*
96	Air	101		Increased on Downstream Half	0.29	0.50	0.28*
97	Freon-11	20		Standard-Approximately Uniform Axially	0.24	0.41	0.23
98	Freon-11	38			0.11	0.32	0.13
99	Freon-11	12			0.31	0.50	0.28
100	Air	109			0.25	0.40	0.23*
101	Air	55	1.0 in. Downstream of Foam		0.22	0.35	0.20
102	Air	107			0.21	0.43	0.21*
103	Air	214			0.12	0.35	0.14*
104	Freon-11	40			0.036	0.18	0.058
105	Air	55	2.0 in. Downstream from Foam		0.18	0.44	0.20
106	Air	107			0.14	0.27	0.16*
107	Air	215			0.10	0.29	0.12*
108	Freon-11	40			0.036	0.18	0.057
109	Freon-11	82	Adjacent to Foam		0.028	0.18	0.054

SKETCH OF OPEN CYCLE GASEOUS - CORE NUCLEAR ROCKET ENGINE SHOWING FLUID MECHANICS ASPECTS

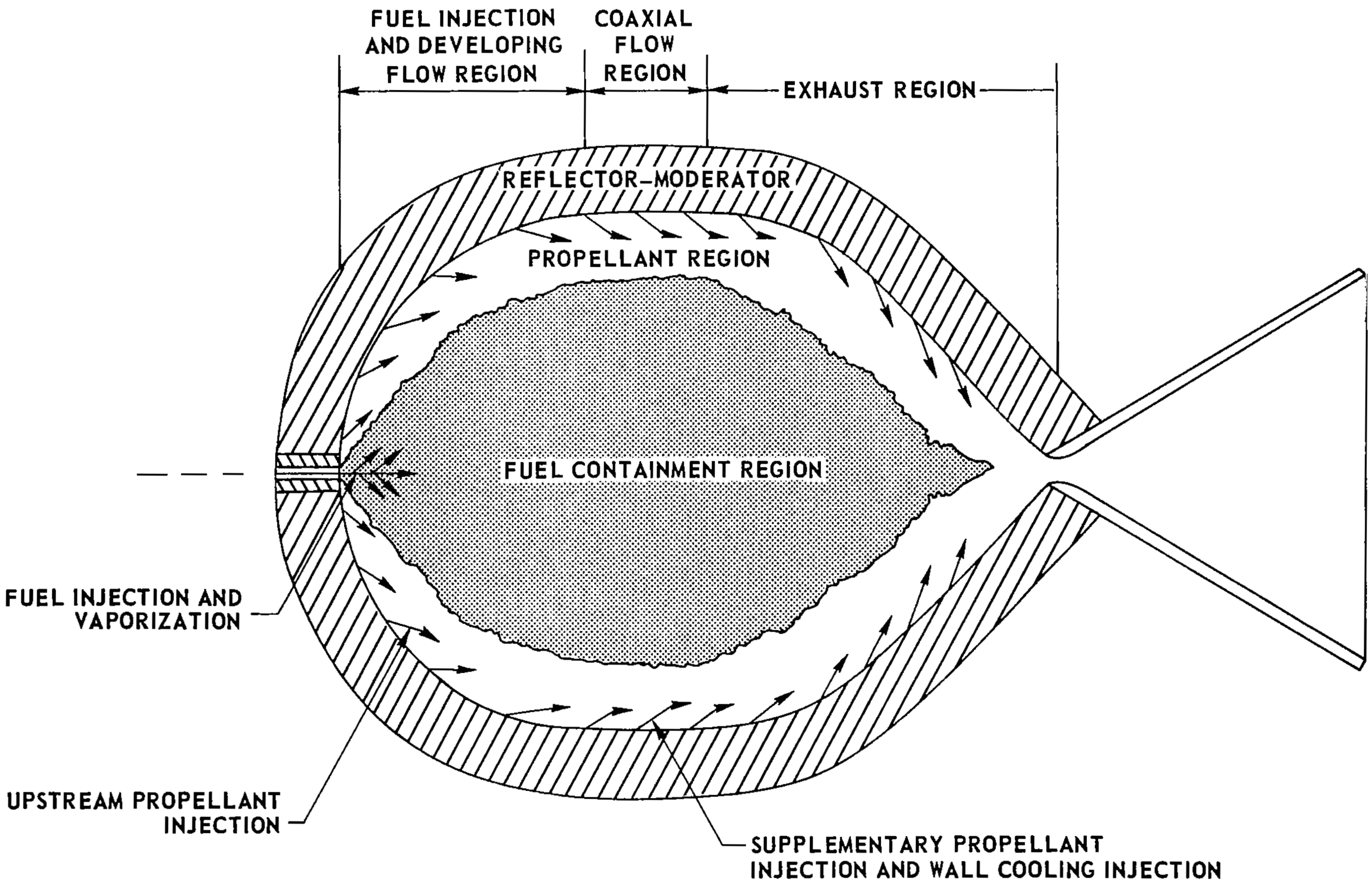


FIG. 2

PHOTOGRAPH OF SPHERICAL CAVITY TEST APPARATUS

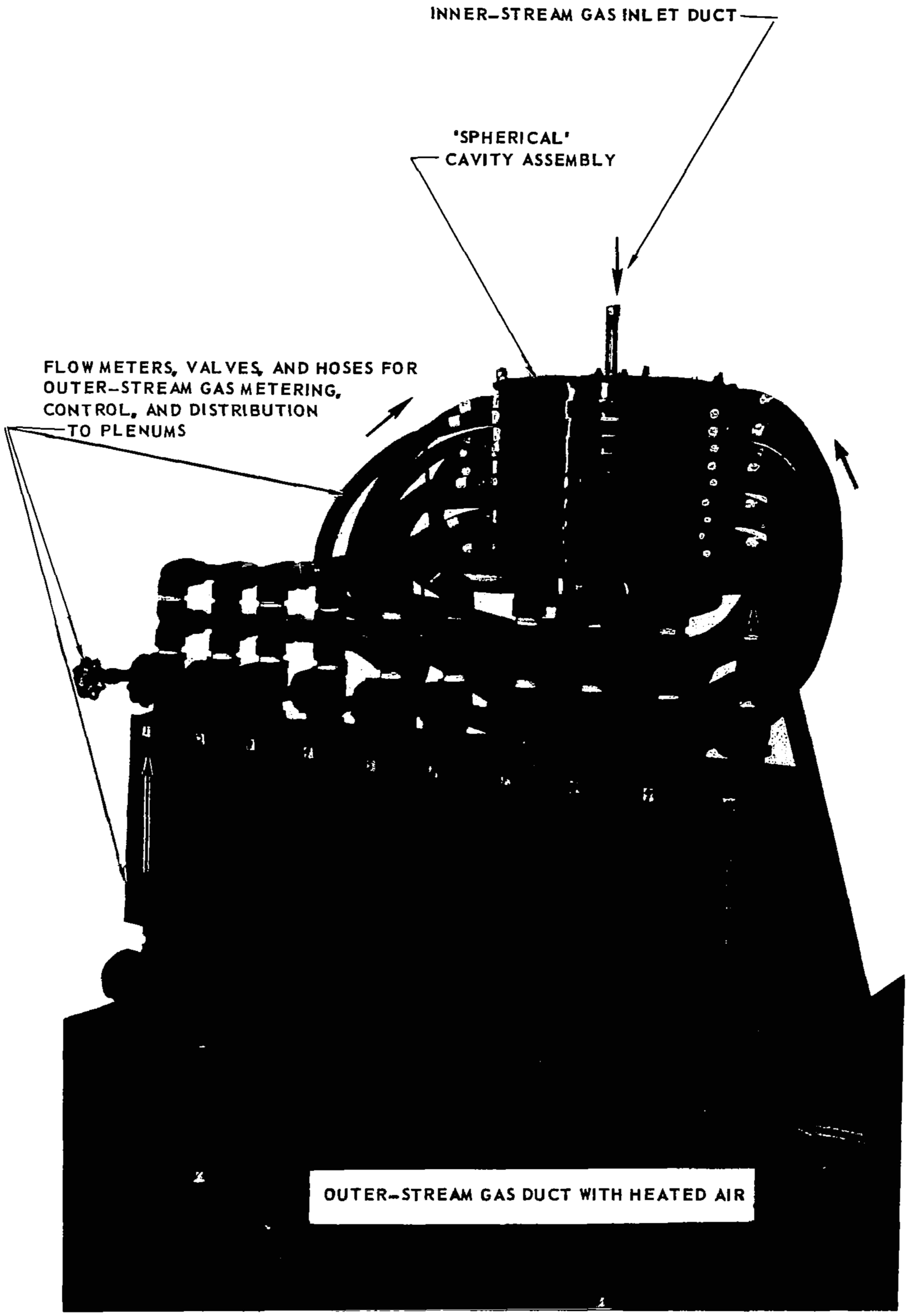
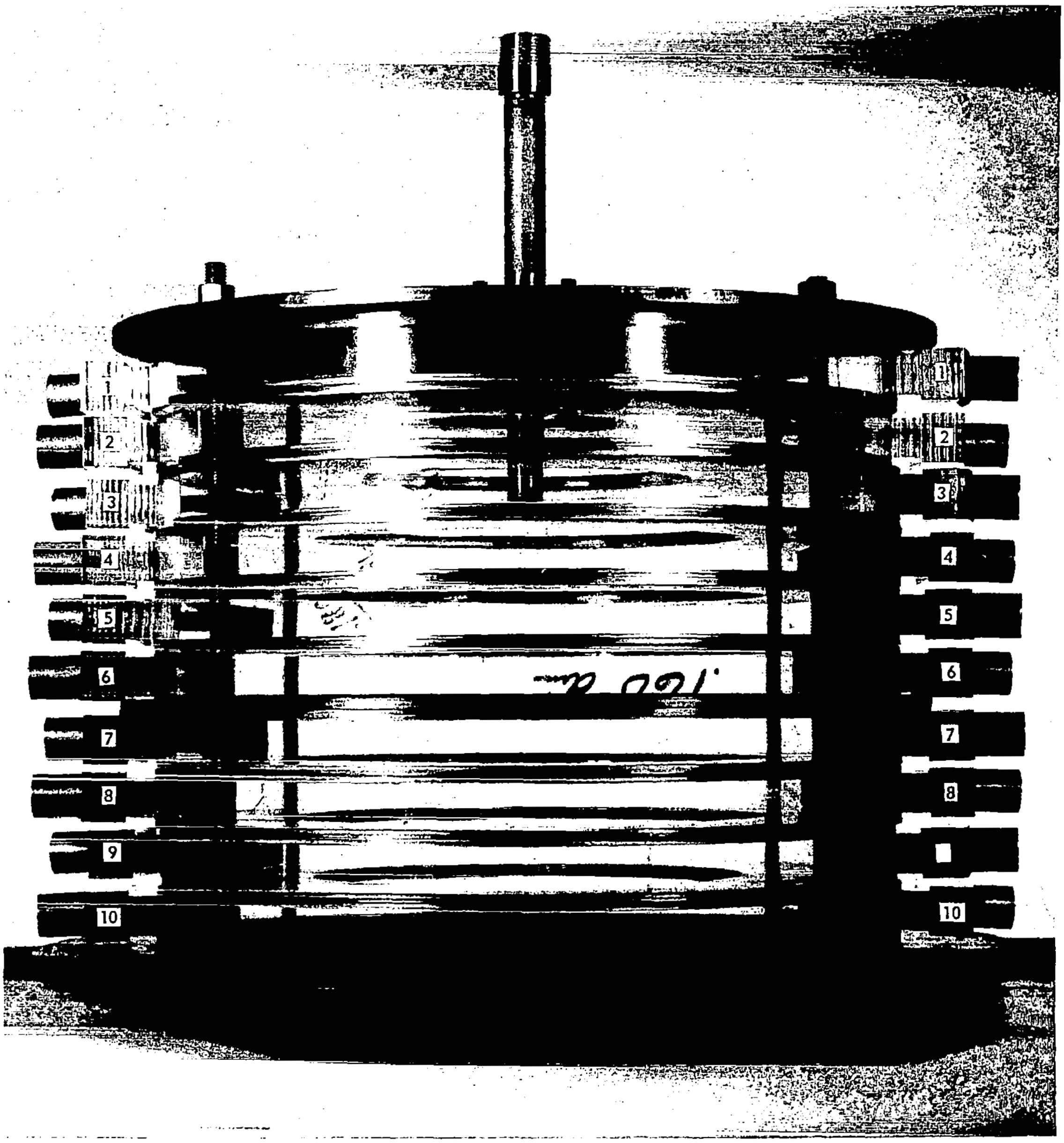


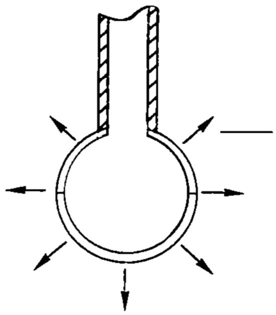
FIG. 3

PHOTOGRAPH OF SPHERICAL CAVITY ASSEMBLED WITHOUT INJECTION CONFIGURATIONS

SECTIONS ABOVE AND BELOW THE DOUBLE PLATE
NEAR CENTER ARE CYLINDRICAL SECTIONS.



SKETCHES OF INNER-STREAM INJECTION CONFIGURATIONS

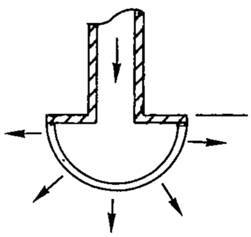


(a) SINTERED METAL SPHERE

MATERIAL:
NICKEL

DIMENSIONS:
OUTSIDE DIAMETER – 2.0 IN.
INSIDE DIAMETER – 1.75 IN.

CONSTRUCTION:
UPPER AND LOWER HEMISPHERE CEMENTED TOGETHER AND CEMENTED TO TUBE

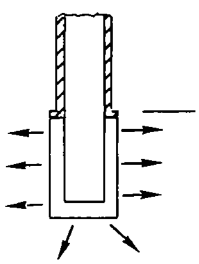


(b) SINTERED METAL HEMISPHERE

MATERIAL:
NICKEL

DIMENSIONS:
OUTSIDE DIAMETER – 2.0 IN.
INSIDE DIAMETER – 1.75 IN.

CONSTRUCTION:
HEMISPHERE CEMENTED TO PLATE AND TUBE



(c) CERAMIC FILTER CYLINDER WITH POROUS END

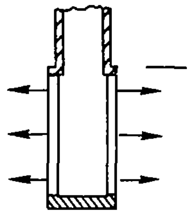
MATERIAL:
COORS PORCELAIN COMPANY POROUS CERAMIC P–100

DIMENSIONS:
OUTSIDE DIAMETER – 1.0 IN.
LENGTH – 1.25 IN.

CONSTRUCTION:
POROUS TUBE CEMENTED TO ADAPTER AND TUBE

CONTINUED

SKETCHES OF INNER–STREAM INJECTION CONFIGURATIONS



(d) CERAMIC FILTER CYLINDER WITH SOLID END

MATERIAL:

COORS PORCELAIN COMPANY POROUS CERAMIC P–100

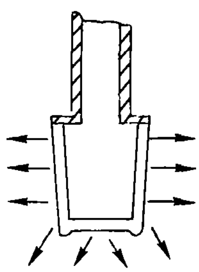
DIMENSIONS:

DIAMETER – 1.0 IN.

LENGTH – 2.0 IN.

CONSTRUCTION:

BOTTOM PLATE OF POROUS TO BE CEMENTED TO CYLINDER SECTION. POROUS TUBE CEMENTED TO ADAPTER AND INLET TUBE.



(e) CERAMIC FILTER CUP

MATERIAL:

CARTER AUTOMOBILE FILTER CUP NUMBER

DIMENSIONS:

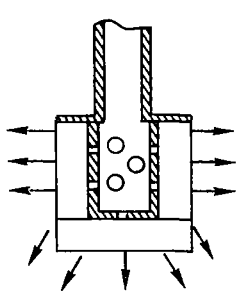
UPSTREAM DIAMETER – 1.45 IN.

DOWNSTREAM DIAMETER – 1.27 IN.

LENGTH – 1.78 IN.

CONSTRUCTION:

CUP CEMENTED TO PLATE AND INLET TUBE



(f) FOAM AND DRILLED TUBE

MATERIAL:

SCOTT INDUSTRIAL FOAM 20 PORES PER INCH

DIMENSIONS:

FOAM OUTSIDE DIAMETER – 2.0 IN.

FOAM LENGTH – 2.0 IN.

TUBE DIAMETER – 1.0 IN.

TUBE LENGTH – 1.5 IN.

CONSTRUCTION:

FOAM CYLINDER AND END CEMENTED TOGETHER. FOAM CEMENTED TO DRILLED TUBE.

SKETCH OF APPARATUS EMPLOYED IN INNER–GAS SOURCE REGION TESTS

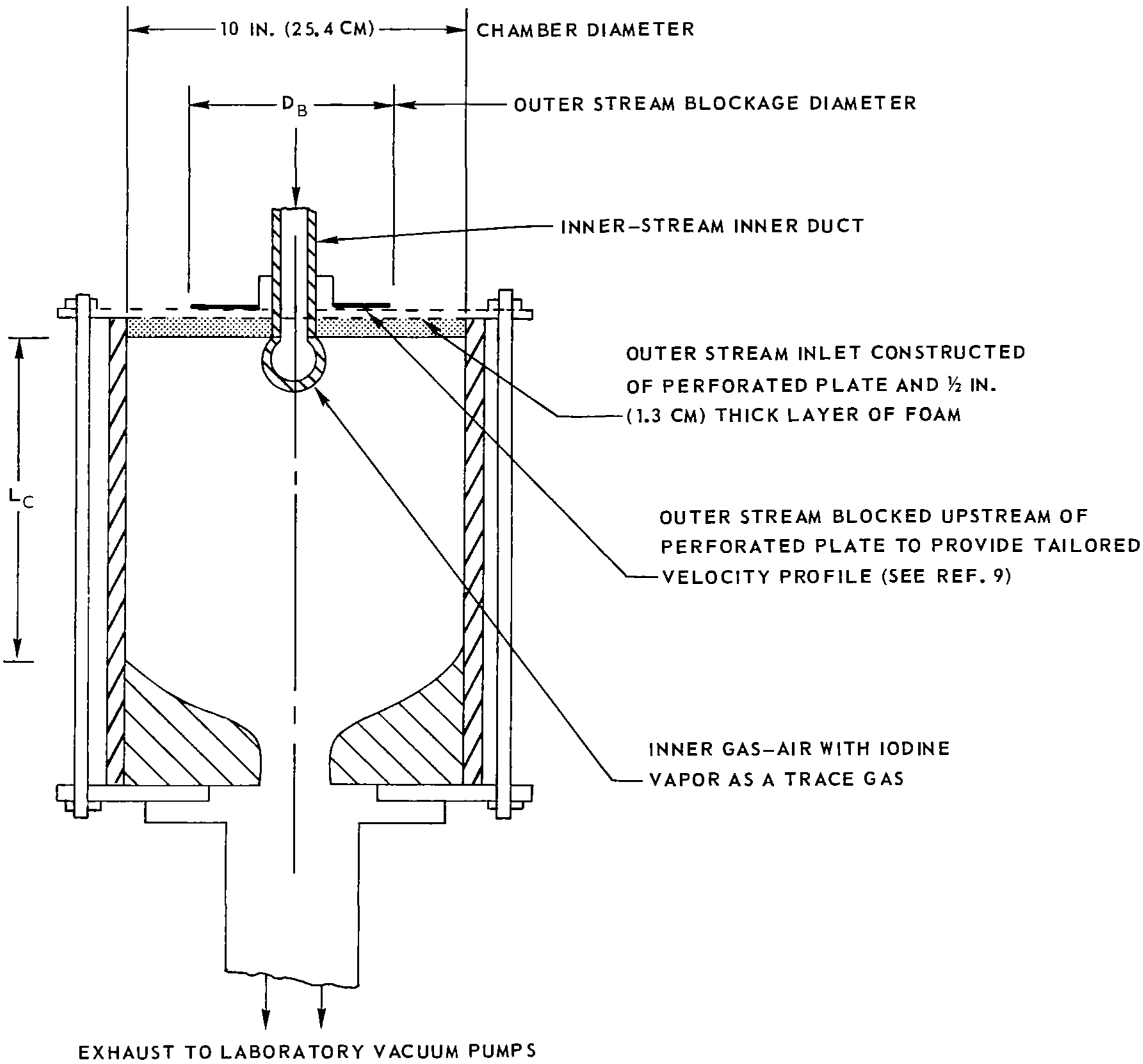


FIG. 6a,b

SKETCHES OF 'SPHERICAL' CAVITY OUTER-STREAM INJECTION CONFIGURATIONS

UPSTREAM CONFIGURATION – POROUS WALL (PW)
DOWNSTREAM CONFIGURATION – POROUS WALL (PW)

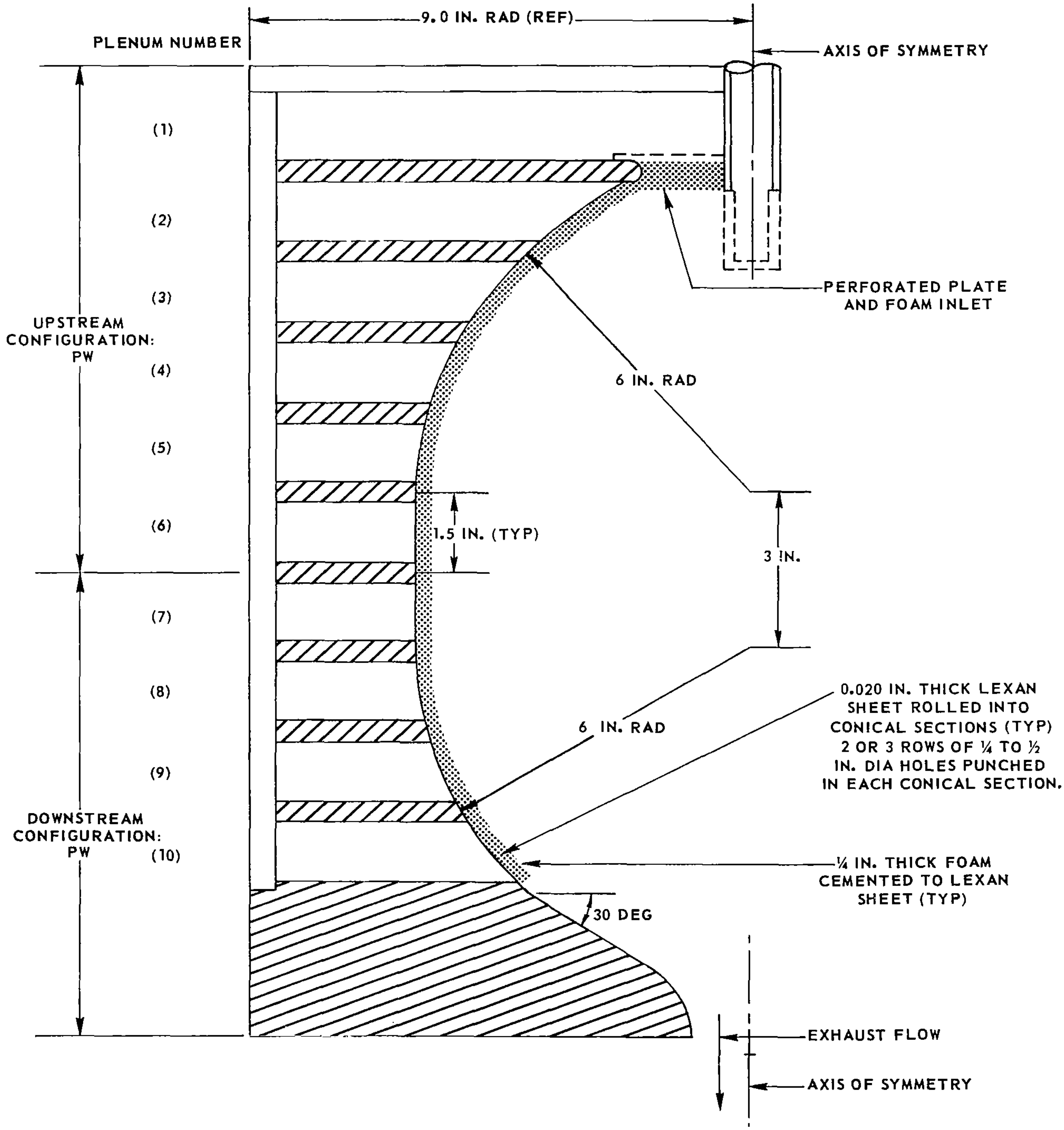


FIG. 6c,d

SKETCHES OF 'SPHERICAL' CAVITY OUTER-STREAM INJECTION CONFIGURATIONS

UPSTREAM CONFIGURATION – CONICAL WALL JET I (CJ–I)
DOWNSTREAM CONFIGURATION – CONICAL WALL JET (CJ)

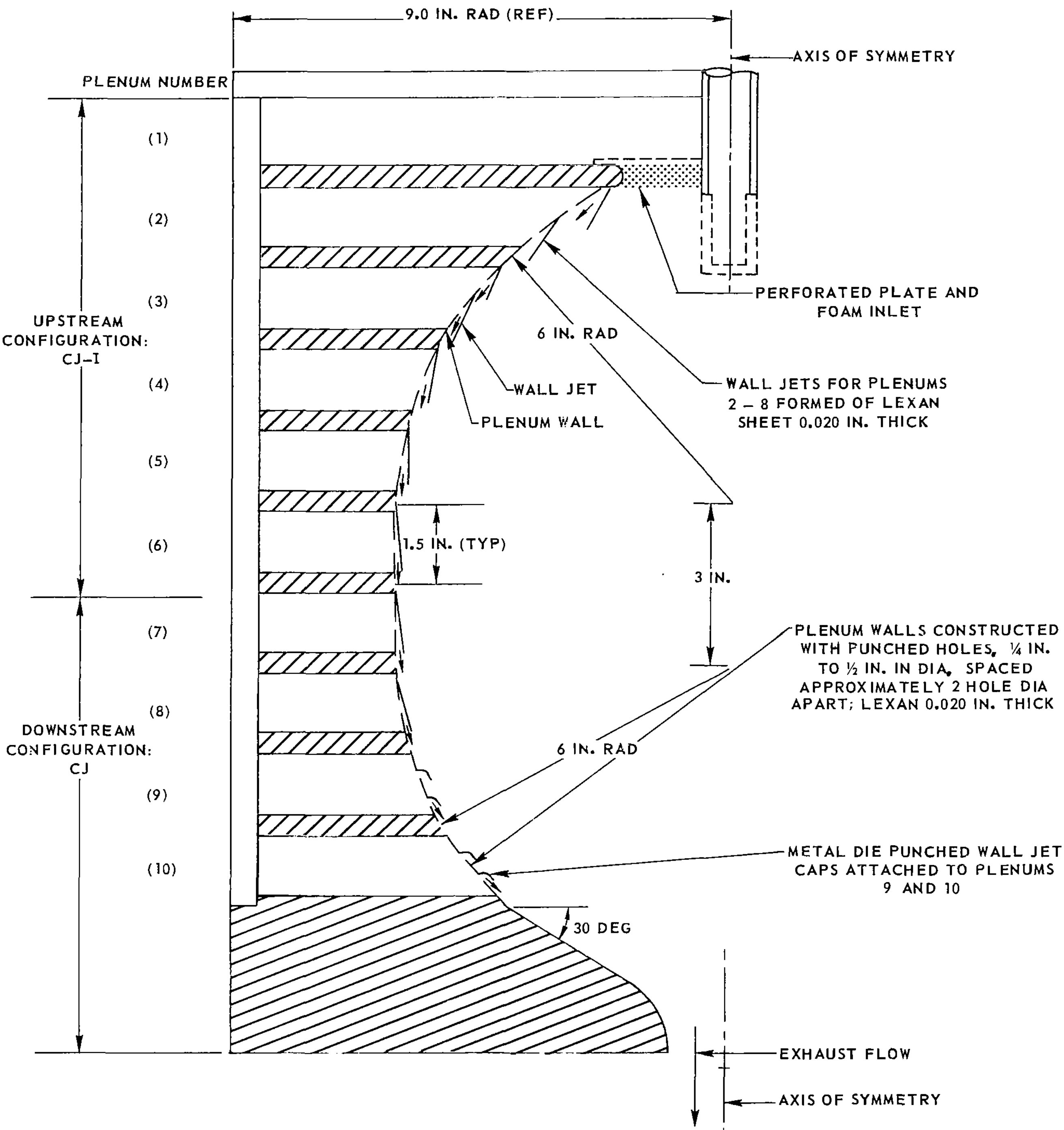


FIG. 6e,f

SKETCHES OF 'SPHERICAL' CAVITY OUTER-STREAM INJECTION CONFIGURATIONS

UPSTREAM CONFIGURATION–ANNULAR WALL JET I (AJ–I)

DOWNSTREAM CONFIGURATION–CONICAL WALL JET (CW)

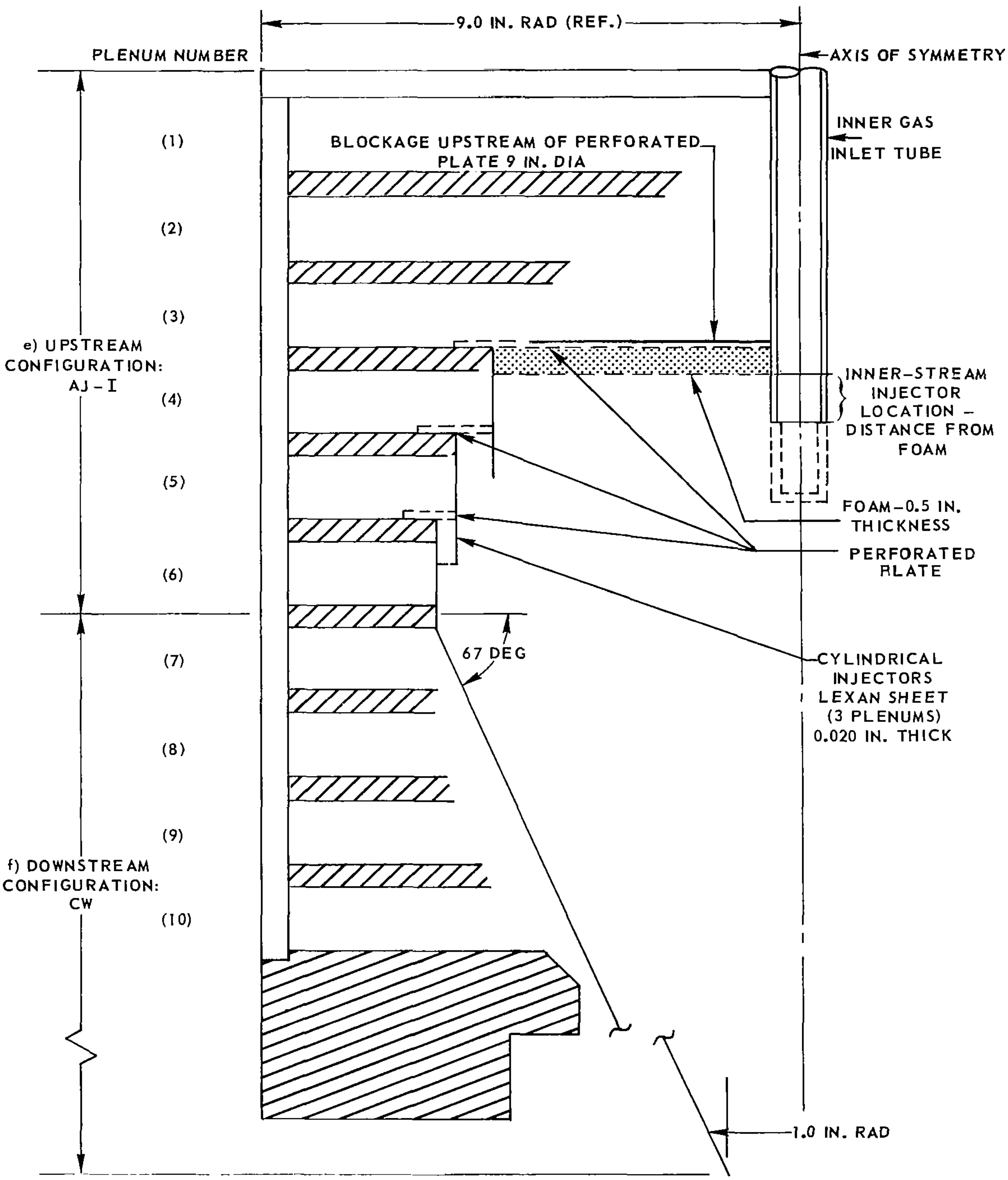


FIG. 6g,h

SKETCHES OF 'SPHERICAL' CAVITY OUTER-STREAM INJECTION CONFIGURATIONS

CONFIGURATION USED FOR PARAMETRIC STUDY

UPSTREAM CONFIGURATION–ANNULAR WALL JET II (AJ–II)
DOWNSTREAM CONFIGURATION–CONICAL WALL JET (CW)

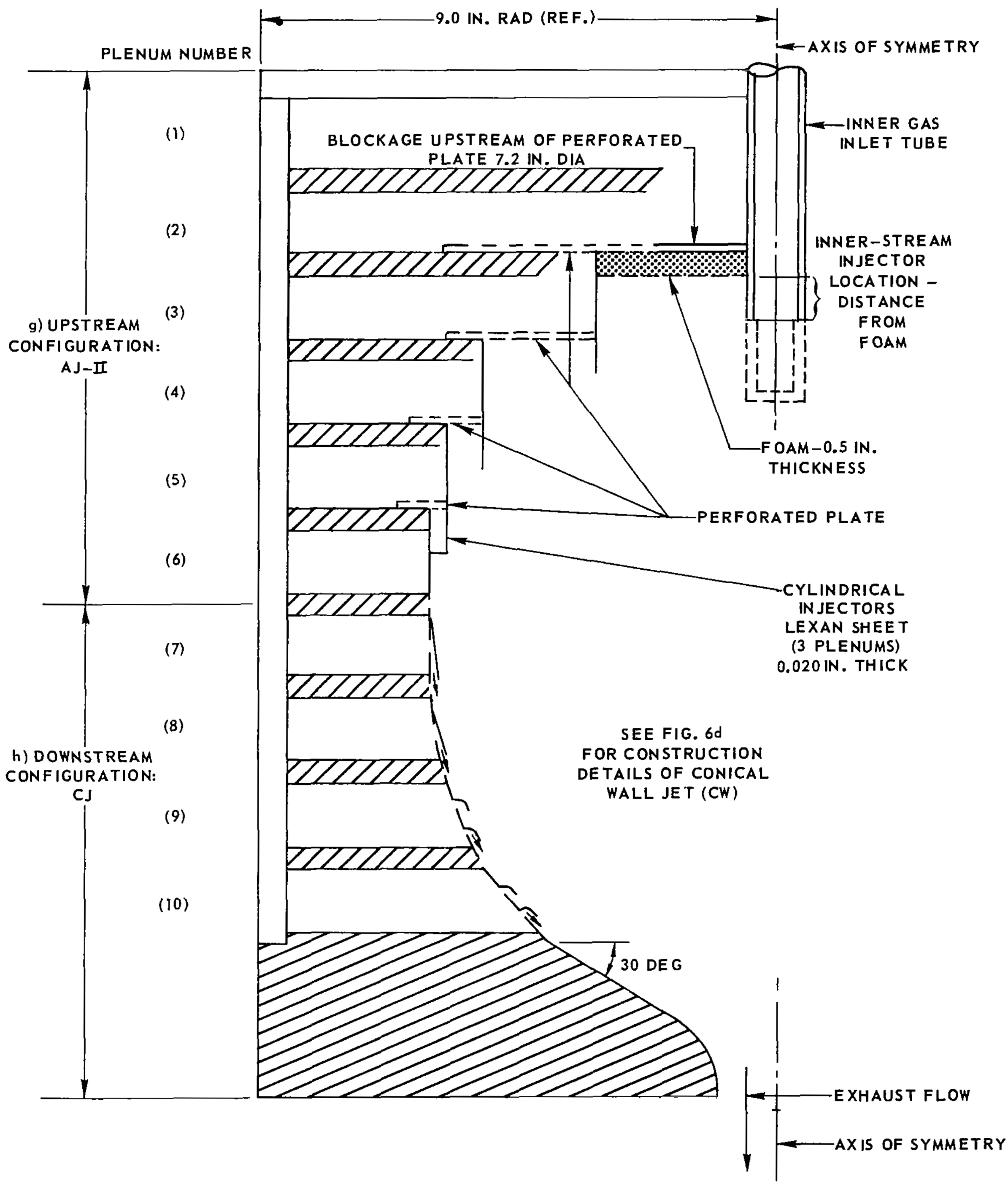


FIG. 7

SCHEMATIC OF OPTICAL SYSTEM FOR FLOW VISUALIZATION PHOTOGRAPHY

TOP VIEW

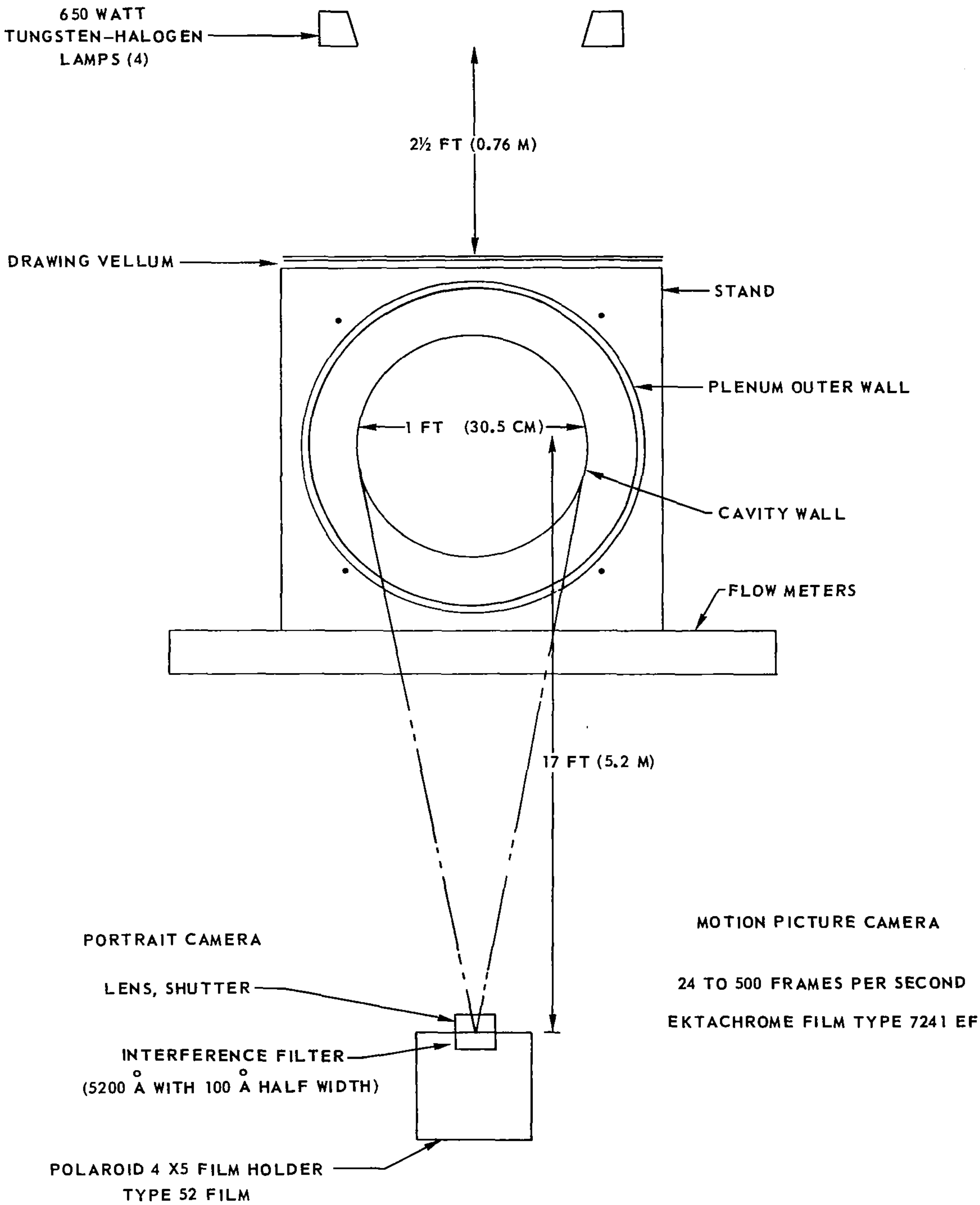


FIG. 8

EFFECT OF WEIGHT FLOW RATE AND INJECTOR LOCATION ON FLOW CHARACTERISTICS WITH AIR AS INNER STREAM GAS

ANNULAR WALL JET CAVITY II

SEE TABLE II, FIGS. 4 AND 6 FOR DETAILS OF FLOW CONDITIONS AND GEOMETRIC FLOW CONFIGURATIONS

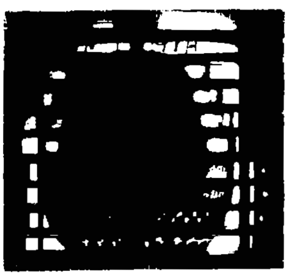
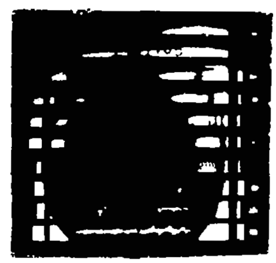
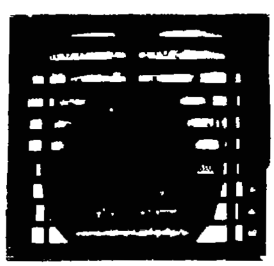
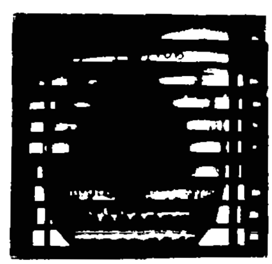
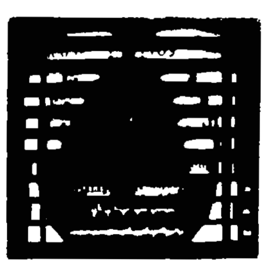
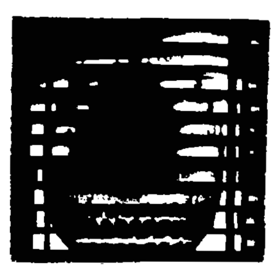
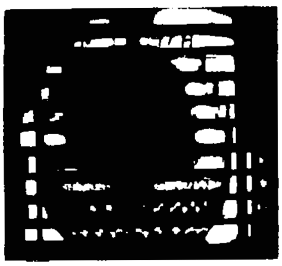
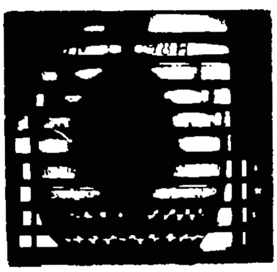
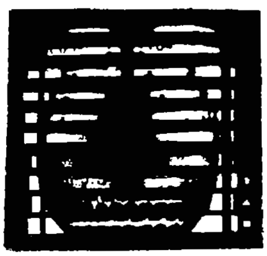
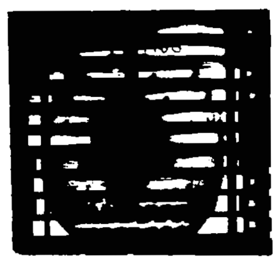
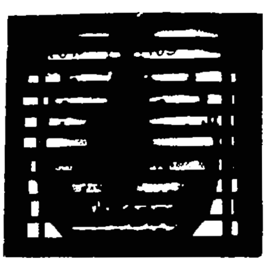
INNER STREAM INJECTOR LOCATION			
ADJACENT TO FOAM	1.0 IN. DOWNSTREAM OF FOAM	2.0 IN. DOWNSTREAM OF FOAM	WEIGHT FLOW RATIO, W_O/W_I
			50
			100
			200

FIG. 9

EFFECT OF WEIGHT FLOW RATIO AND INJECTOR LOCATION ON FLOW CHARACTERISTICS WITH FREON-11 AS INNER-STREAM GAS

ANNULAR WALL JET CAVITY II

INNER STREAM INJECTOR LOCATION			
ADJACENT TO FOAM	1.0 IN. DOWNSTREAM OF FOAM	2.0 IN. DOWNSTREAM OF FOAM	WEIGHT FLOW RATIO, W_O/W_I
			20
			40
			80

DISTRIBUTION OF OUTER STREAM FLOW THROUGH PLENUMS

ANNULAR WALL JET CAVITY II

$W_O \approx 0.5$ LB/SEC (0.23 KG/SEC)

SYMBOL	—○—	- -△- -	- -□- -	···◇···
RUN NO.	92 (STD)	94	95	96

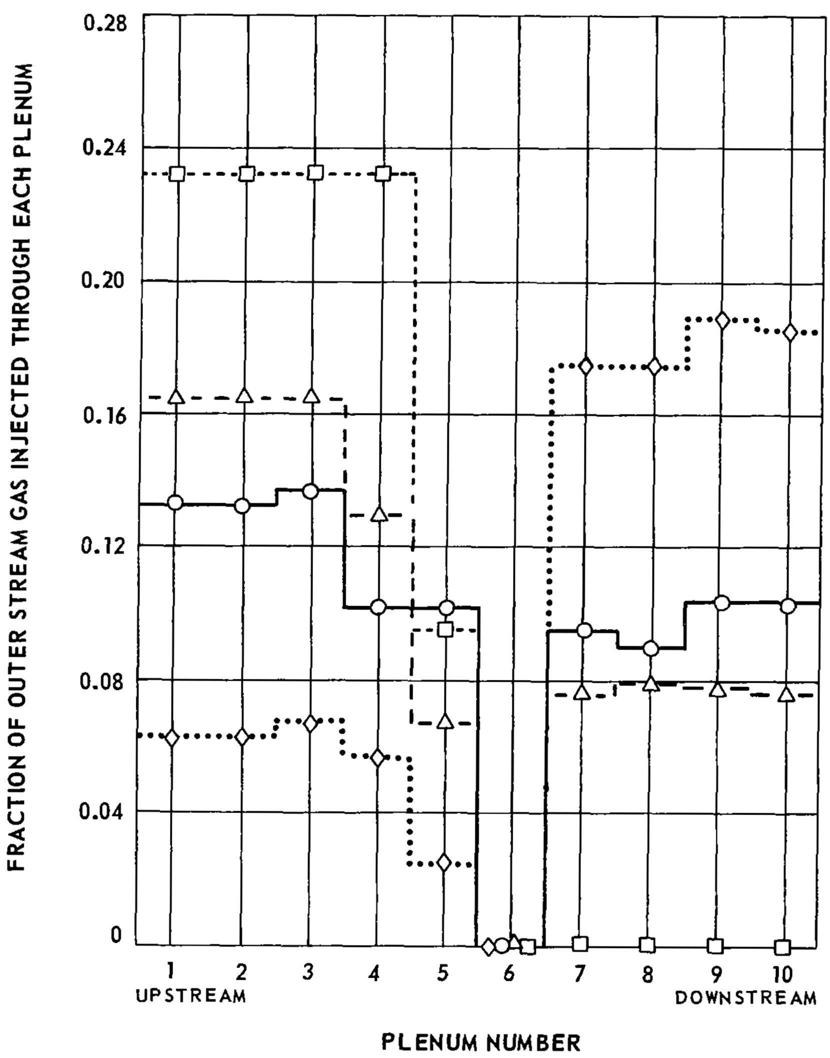


FIG. 11

EFFECT OF FLOW RATE DISTRIBUTION ON FLOW CHARACTERISTICS

ANNULAR WALL JET CAVITY II

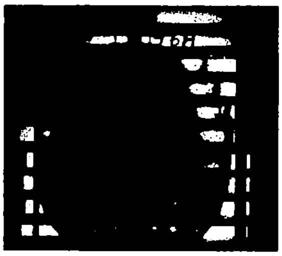
SEE FIG. 10 FOR FLOW RATE DISTRIBUTIONS

INNER STREAM GAS – AIR

OUTERSTREAM INJECTION DISTRIBUTION

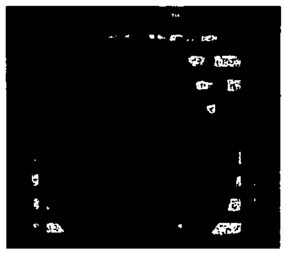
(a) RUN 96

INCREASED ON DOWNSTREAM HALF,
DECREASED ON UPSTREAM HALF



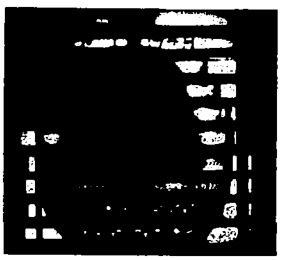
(b) RUN 92 (STANDARD)

APPROXIMATELY UNIFORM AXIALLY



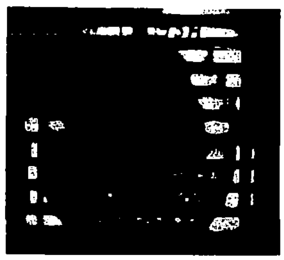
(c) RUN 94

INCREASED ON DOWNSTREAM HALF



(d) RUN 95

ZERO ON DOWNSTREAM HALF
INCREASED ON UPSTREAM HALF



SUMMARY OF ESTIMATED INNER GAS CONTAINMENT RESULTS OBTAINED IN ANNULAR WALL JET CAVITY II

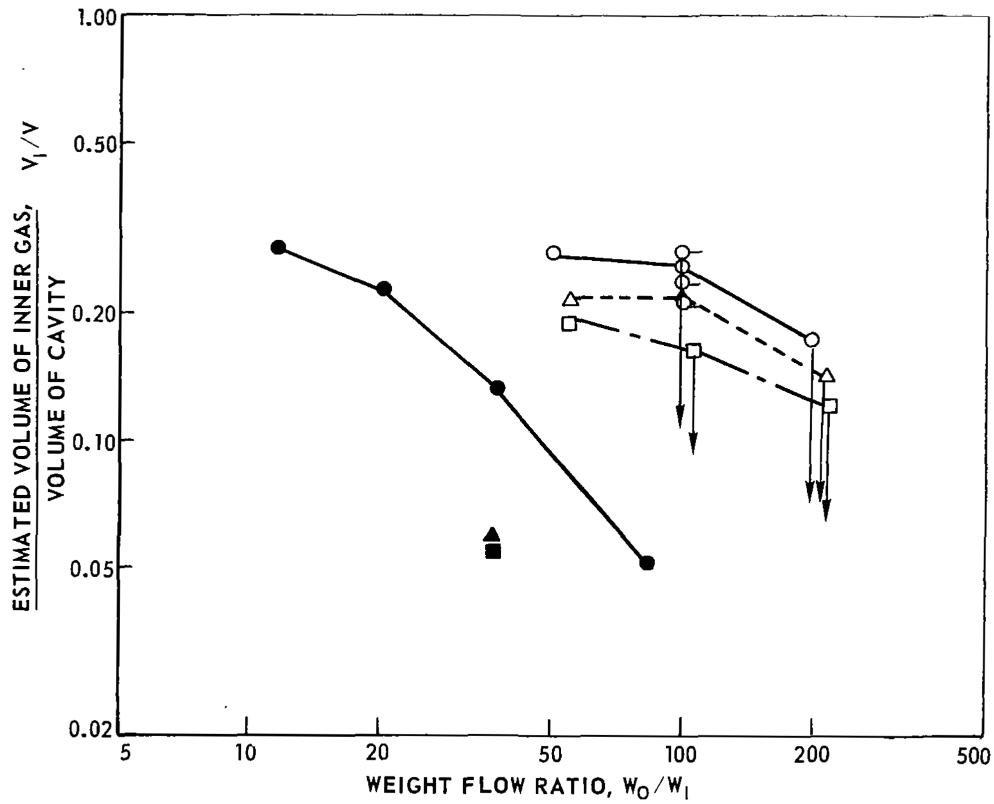
INNER-GAS VOLUME FRACTION ESTIMATED FROM HIGH-SPEED COLOR MOTION PICTURE FRAME

SEE FIG. 6g,h FOR DETAILS OF CAVITY CONSTRUCTION

SYMBOL	INNER GAS	INNER-STREAM INJECTOR
○——○	AIR	ADJACENT TO FOAM AT UPSTREAM END
●——●	FREON-11	
△- - -△	AIR	1.0 IN. (2.5 CM) DOWNSTREAM FROM FOAM
▲- - -▲	FREON-11	
□—-—□	AIR	2.0 IN. (5.1 CM) DOWNSTREAM FROM FOAM
■—·—■	FREON-11	

SYMBOLS WITH ARROWS INDICATE FLOW CONDITIONS WITH RECIRCULATION

FLAGGED AND UNFLAGGED SYMBOLS INDICATE AXIAL NONUNIFORMITY AND AXIAL UNIFORMITY, RESPECTIVELY, IN OUTER-STREAM INJECTION DISTRIBUTION.



STREAMLINE PATTERNS FOR FLOW IN SPHERICAL CAVITY

STREAMLINES FED BY POINT SOURCE

STREAMLINES ENCLOSED BY FLUID FROM POINT SOURCE

CAVITY DIAMETER = 1.0 FT (30.5 CM)

PERIPHERAL WALL RADIAL VELOCITY, $U_R = -1.0$ FT/SEC (−30.5 CM/SEC)

POINT SOURCE LOCATED 0.5 IN. (1.2 CM) FROM UPSTREAM END WITH STRENGTH EQUAL 5 PERCENT OF FLOW FROM PERIPHERAL WALL

$Re_z = 2\ Q/R\pi\nu \approx -8\ U_R R/\nu$

(a) $U_\theta = 0$
$\nu = 13.3\ FT^2/SEC$
$Re_z = 0.3$

(b) $0 < U_\theta < -40$ FT/SEC
$\nu = 13.3\ FT^2/SEC$
$Re_z = 0.3$

(c) $0 < U_\theta < -30$ FT/SEC
$\nu = 0.1\ FT^2/SEC$
$Re_z = 40$

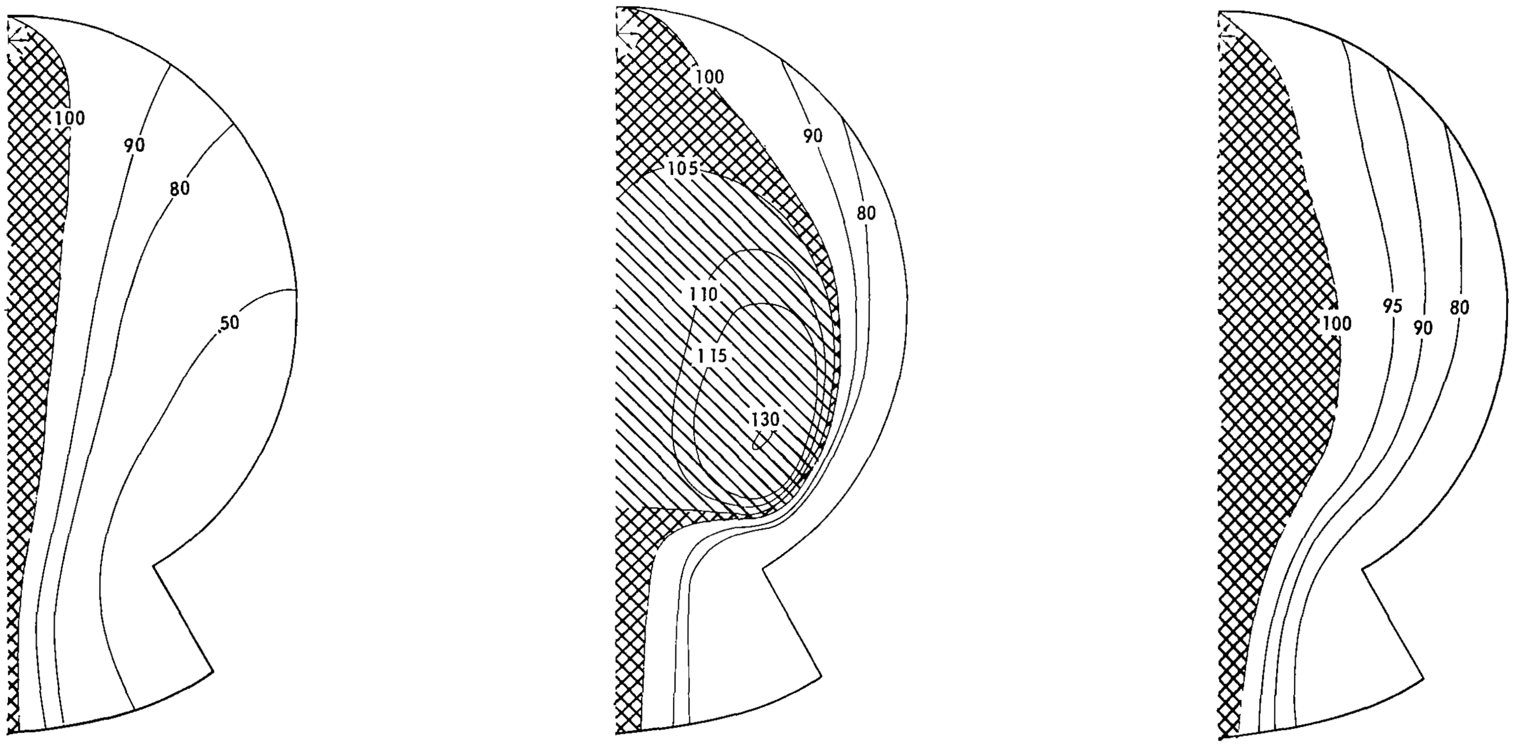


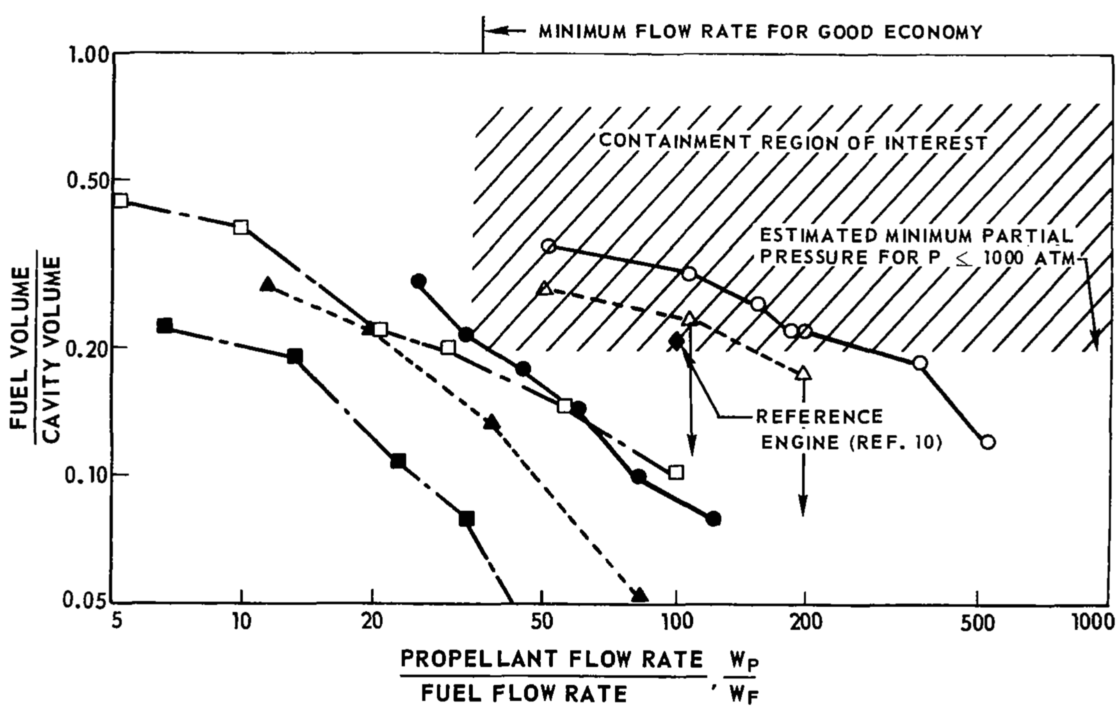
FIG. 13

COMPARISON OF PRESENT SPHERICAL CAVITY AND PREVIOUS COAXIAL FLOW CONTAINMENT RESULTS WITH GNR OPEN-CYCLE FLUID MECHANICS REQUIREMENTS

BEST CONTAINMENT RESULTS FROM EACH SOURCE USED IN COMPARISON

SYMBOL	INNER GAS	P_I/P_O	CAVITY SHAPE	SOURCE	MEASUREMENT TECHNIQUES
△----△	AIR	1.0	'SPHERICAL'- AJ-II	PRESENT WORK	ESTIMATED FROM MOTION PICTURE FRAMES
▲----▲	FREON-11	4.7			
○——○	AIR	1.0	CYLINDRICAL- FOAM INLET COAXIAL FLOW	REF. 9	CHORDAL LIGHT ABSORPTOMETER
●——●	FREON-11	4.7			
□-·-□	AIR	1.0	CYLINDRICAL- SCREEN INLET COAXIAL FLOW	REF. 4	
■-·-■	FREON-11	4.7			

SYMBOLS WITH ARROWS INDICATE FLOW CONDITIONS WITH RECIRCULATION



NASA-Langley, 1972 —— 1? E-6633