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A FLOW EXPERIMENT ON A CURVED-POROUS-WALL GAS-CORE REACTOR GEOMETRY

by Chester D. Lanzo

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

An air-air fluid flow experiment was conducted to determine the merit of a curved, porous wall gas-core reactor concept. Photographs of the flow are shown, and fuel concentration profiles are presented. The fuel volume fraction varied from 0.51 to 0.28 as the propellant-to-fuel mass flow ratio was increased from 25 up to 100. The concept looks useful and merits further research.

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SUMMARY

An air-air experiment was carried out to evaluate a new gas-core reactor flow pattern. The tests were exploratory in nature, and did not delve in great detail into the flow mechanisms. The objective of the work was to determine the general character of the flow, and to obtain some overall, quantitative measurements of its potential for gas-core reactor application.

The geometry tested was made up of a curved, porous wall, through which the propellant (clear air in the experiment) was introduced. The fuel (smoky air) was injected at one end of the cavity. Both gases exited through a subsonic exhaust port at the opposite end of the cavity.

Still and motion pictures were taken to study the qualitative nature of the flow. Densitometer traces of the smoke patterns on the film negatives were used to obtain fuel concentration distributions. Experiments were performed for propellant-to-fuel mass flow rate ratios from 25 to 100.

The general conclusion that emerges from these experiments is that a relatively large, stagnant fuel volume forms in the reactor cavity for propellant to-fuel flow rate ratios as high as 100. Specifically, at this mass flow rate ratio, the "effective" fuel volume is about 28 percent of the total cavity volume.

The conditions of this experiment did not properly mockup some important engine parameters and conditions, such as heat generation, density ratios, and Reynolds numbers. The concept is promising enough to now explore these factors in further experiments.

INTRODUCTION

Both the advantage and disadvantage of a gas-core nuclear engine result from the gaseous state of the uranium. The advantage is higher specific impulse than can be produced by a solid-core engine. The disadvantage is that the fuel can move during engine operation. Thus, it must either be contained within a solid transparent wall (so the heat can be radiated to the hydrogen propellant outside) or allowed to be exhausted with the propellant. Thus, one has the choice of a materials problem or a fluid flow problem. The transparent material approach, a "nuclear light bulb," is being pursued at United Aircraft Research Laboratory, as described in references 1 and 2. The alternate approach is to devise a fluid mechanics flow pattern that produces an acceptably low uranium loss rate from the engine while maintaining a critical mass within the reactor cavity. An experiment on a new flow pattern is the subject of this report.

Most of the gas-core work at Lewis Research Center has centered around a coaxial-flow concept. References 3 and 4 summarize this work. The initial experiments on coaxial flow two-gas mixing were carried out in a cylindrical geometry.

Although it is more convenient for analysis and for basic coaxial flow experiments, a simple cylindrical geometry would probably not be practical for an actual engine configuration. Because of such things as wall cooling requirements and pressure shell design, a spherical design is more likely. This train of thought leads to the notion that all of the propellant would not be injected in a coaxial stream immediately adjacent to the

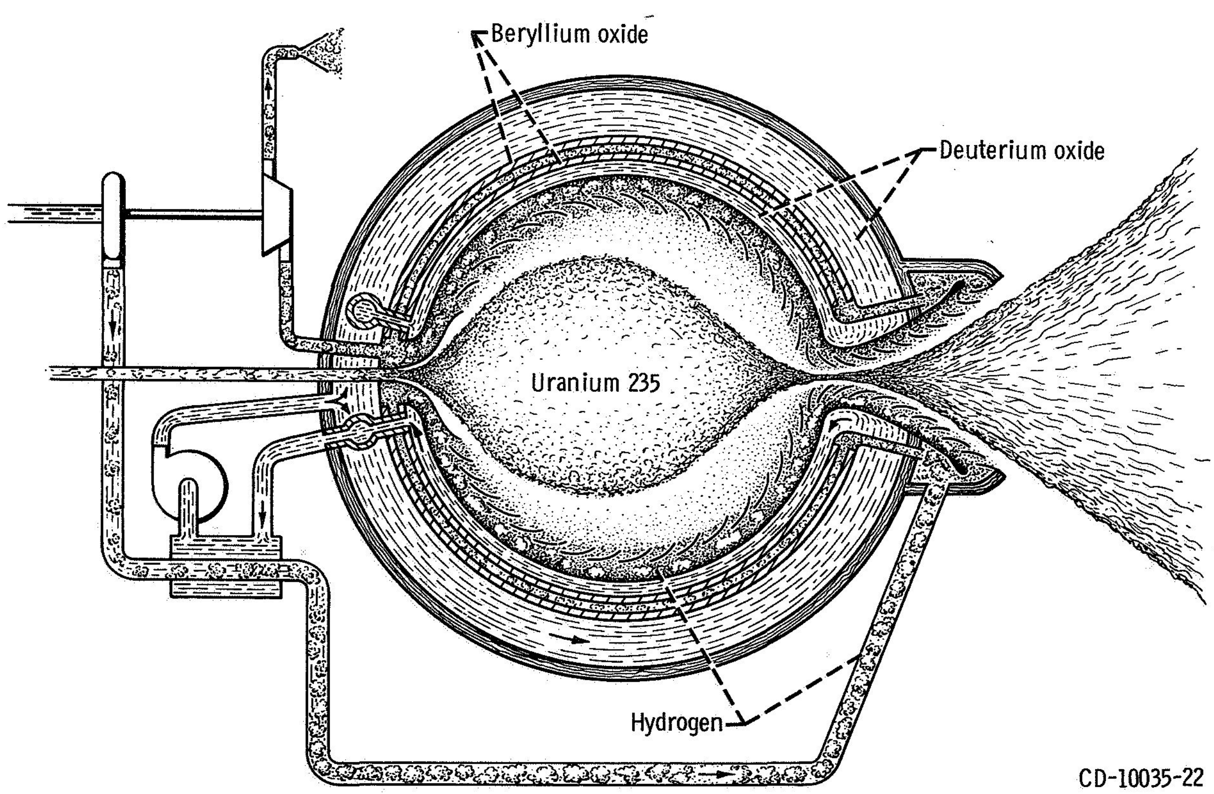

Figure 1. - Conceptual gas-core nuclear rocket engine.

fuel injection location. More likely, the propellant would be introduced all along the cavity wall, with some distribution dictated by a trade-off between wall cooling requirements and the effects of such an injection on the flow pattern within the cavity. Figure 1 depicts a conceptual representation of an engine with these features. The main new fluid mechanics characteristic seen here is that the wall is curved and that propellant is introduced all along its length.

An experiment was carried out on such a flow pattern. There were two objectives, one qualitative and the other quantitative. The first objective was simply to display the general character of the flow and to see if it appeared favorable for gas-core reactor application. The second objective was to measure the distribution and total amount of fuel in the cavity, and to see how this was affected by varying the fuel flow rate into the cavity. The amount of fuel in the cavity is expressed as a volume fraction of the entire cavity. Reference 4 has shown that a "fuel volume fraction" in the range of 0.1 to 0.2 is necessary to be of much interest for a gas-core reactor.

The tests reported here are exploratory in nature. The flow was not studied in depth. For example, there was no systematic and detailed measurement of the fine structure of the velocity field. The experiment was not aimed at explaining the flow mechanisms. It was aimed at answering the question: Is this flow concept promising enough to explore further?

EXPERIMENTAL PROCEDURE

A flow experiment was carried out on a two dimensional model of the geometry shown in figure 1. A schematic of the test section is displayed in figure 2. The

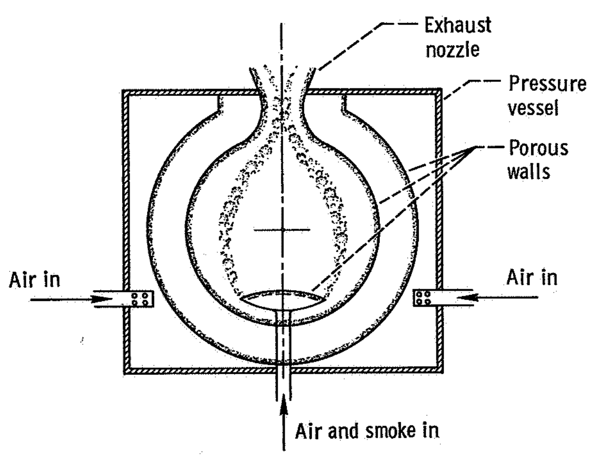

Figure 2. - Schematic drawing of porous wall experiment.

"pressure vessel" provided the plenum for the propellant gas. The outer porous wall was constructed in the form of a series of adjustable vanes, or slots, that were used to control the distribution of propellant flow through the inner porous wall.

The study was conducted at room temperature and atmospheric pressure. Air was used to simulate the propellant. Air with smoke added to make it visible was used to simulate the gaseous uranium fuel. A two-dimensional mockup of the spherical geometry was used so that the flow pattern could be visually observed through flat transparent sides. A photograph of the experimental set-up is shown in figure 3. The diameter of the cavity is 9 inches and the two parallel, flat sides are 6 inches apart.

The propellant-simulating clear air was introduced through the curved porous side walls. The side walls are constructed of brass sheet metal that had holes drilled through it (see fig. 4). The metal was 0.025-inch thick. The holes were about 0.010-

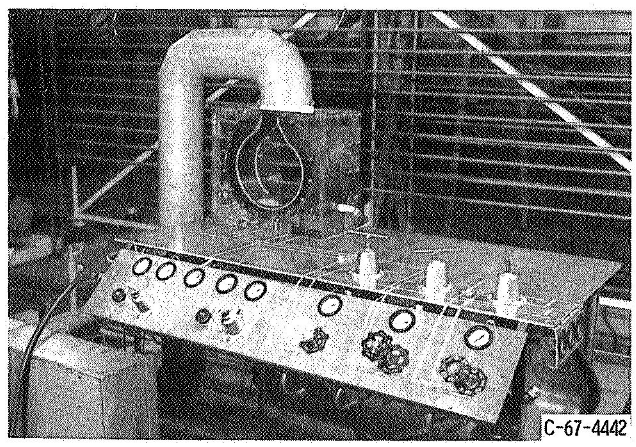

Figure 3. - Curved porous wall rig.

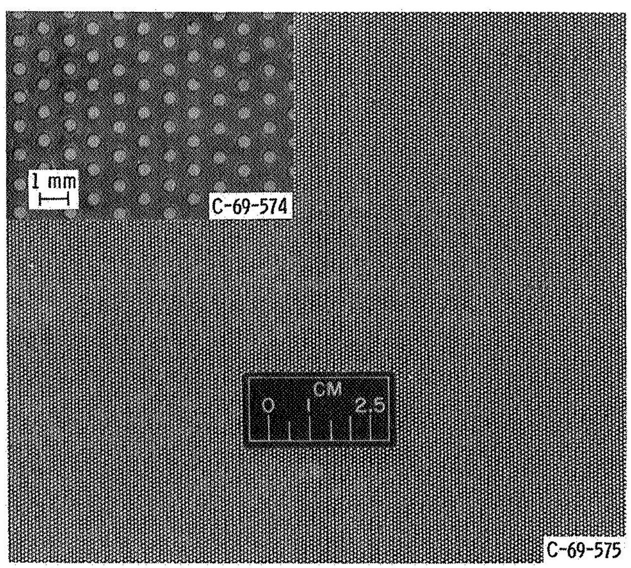

Figure 4. - Porous wall material.

inch in diameter. The overall porosity, or open area fraction, of the wall material was about 0.25.

A shower-head type fuel injector was used to introduce the smoky air into the cavity. The general idea behind this geometry is that it may somewhat represent the expanding flow that would occur in an engine due to heat generation in the uranium as it enters the cavity. The showerhead surface is constructed of the same material as is the walls. The fuel gas is injected at one end of the cavity, and the propellant is introduced all along the curved side walls. Both gases then exit through a subsonic nozzle at the end opposing the fuel entrance. This can be seen in figures 2 and 3.

The independent variable of the experiment was the flow rate of the "fuel" gas. The outer, propellant-simulating air flow rate was set at 352 standard cubic feet per hour for all tests. The inner gas flow rate was set at 3.5, 4.7, 7, and 14 standard cubic feet per hour. This gave propellant-to-fuel flow rate ratios of 100, 75, 50, and 25.

Three kinds of data were obtained. First, a shrouded hot-wire probe was used to measure the incoming propellant velocity distribution around the curved cavity wall. Second, still and motion pictures were taken to obtain a qualitative description of the flow. Finally, the negatives of the still photographs were used to obtain concentration profiles of the fuel in the cavity volume.

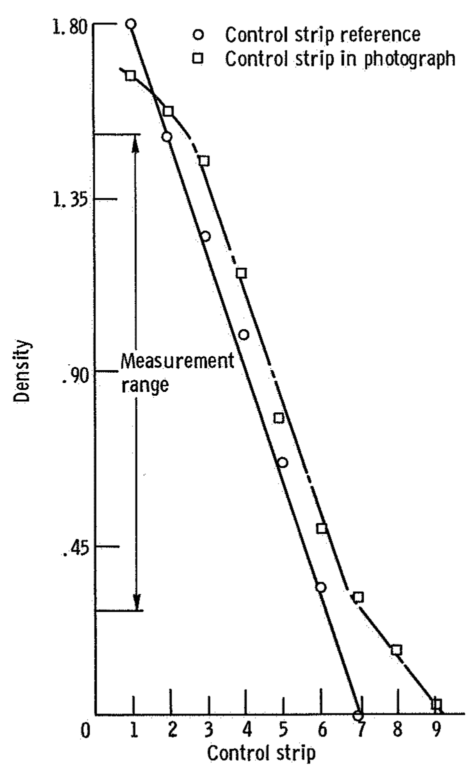

Figure 5. - Usefull range of photographic negatives for concentration measurements.

The photographic negative was used to produce concentration profiles through the use of a microdensitometer. The densitometer traces actually measure the film density, which is taken to be proportional to the amount of smoke, or "fuel" that was between the back lighting and the camera. This assumes many things such as uniform light intensity over the flow field, linear film response, and an exponential variation of light absorption with smoke density. The overall linearity of the instrumentation system was checked by including a calibration film strip of known density variation in each photograph.

Typical results of such a calibration check are shown in figure 5. The circle-symbol data were obtained with a densitometer trace along the actual control film strip. Each control strip number along the abscissa represents a known film density. The control strip is linear, as it should be. The square-symbols were obtained by tracing along the image of the control strip on a negative of a photograph of it in place on the test section. It is still linear. The range of film exposures over which all the data were obtained is shown on the ordinate of figure 5. Thus, no nonlinearities were introduced into the relative concentration distributions obtained by the film density technique.

DISCUSSION OF RESULTS

Inlet Propellant Flow Distribution

Before taking data, the outer control vanes were adjusted to give a relatively uniform distribution of air along the curved porous wall. Figure 6 shows the velocity

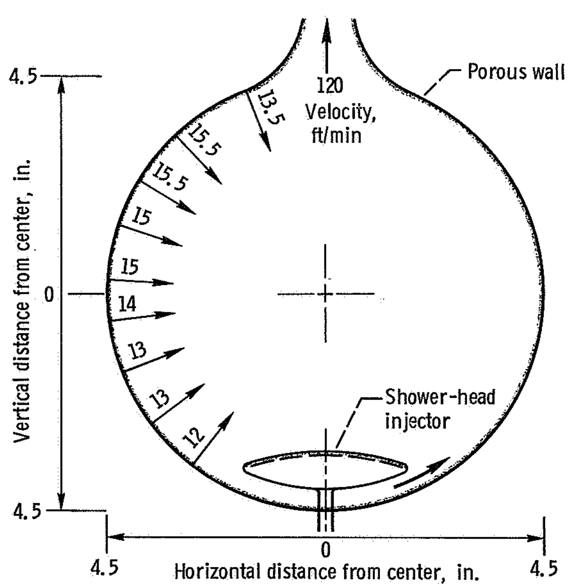

Figure 6. - Velocity profiles with hot wire anemometer.

distribution at the inner surface of the porous wall. It is fairly uniform. There are some perturbations near the inlet end due to the showerhead. The mass flow rate obtained by integrating the velocity profile agreed within 10 percent with the rotameter measured value.

Flow Visualization Tests

Photographs were taken of the flow at propellant-to-fuel flow rate ratios of 25, 50, 75, and 100. The photographs taken were time exposures. This was done to obtain an "average" representation of the flow. Instantaneous photos showed the fine structure better, but that was not under study here. Typically, a time exposure of about 13 seconds was used.

Figures 7 to 10 show the appearance of the flow at the indicated flow ratios. Two characteristics are immediately apparent. First, the smoky "fuel" region occupies a fairly large portion of the cavity. Second, there is an increasing degree of dilution of the fuel region as the flow rate ratio increases. These pictures give a reasonably accurate impression of the actual flow behavior that was observed. Movies of the flow show some of the unsteady or periodic character of the flow pattern, but these are not dominant features.

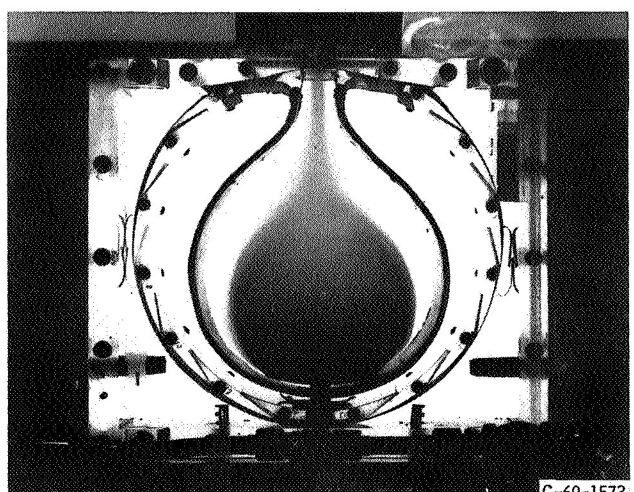

Figure 7. - Time exposure at flow rate ratio of 25.

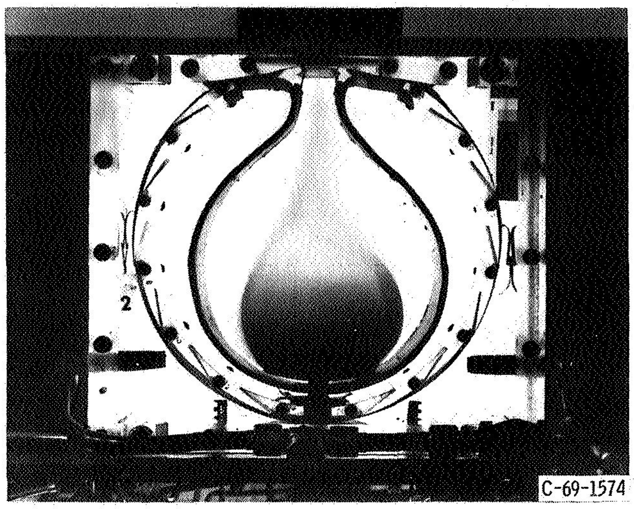

Figure 8. - Time exposure at flow rate ratio of 50.

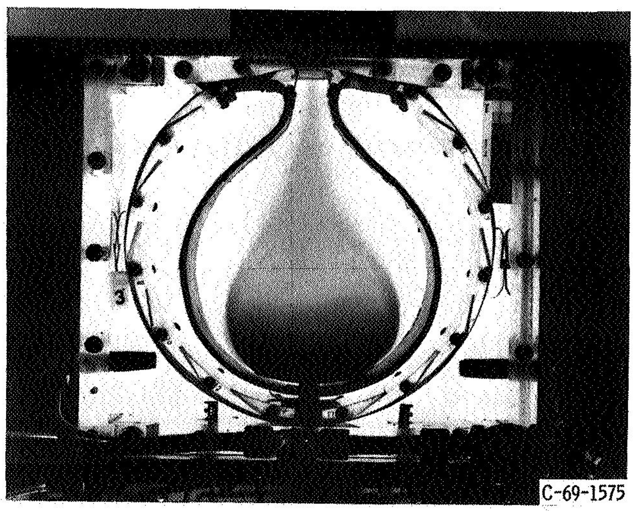

Figure 9. - Time exposure at flow rate ratio of 75.

Fuel Concentration Measurements

Densitometer traces were made from the film negatives of the photos shown in figures 7 to 10. The calibration film density strip used to check linearity can be seen in the upper right hand corner of the test section in these photos. Horizontal traces were obtained, from the centerline to the wall, at various vertical positions from the fuel inlet to the exhaust.

The fuel distribution within the cavity is shown in figure 11 for a flow rate ratio of 100. The concentration is a relative one - it is normalized to the value at the fuel in-

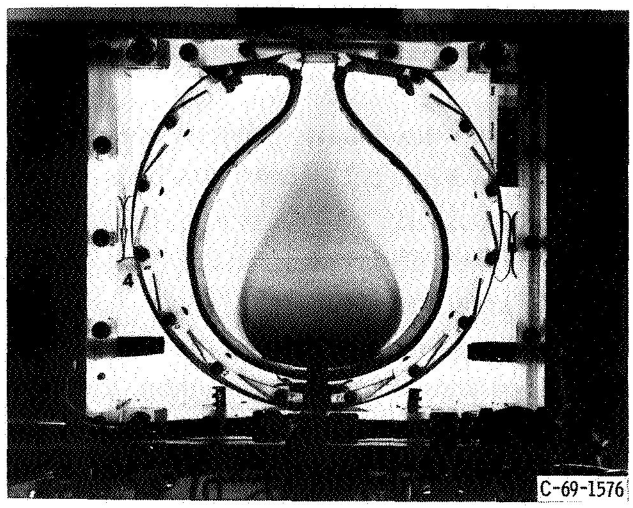

Figure 10. - Time exposure at flow rate ratio of 100.

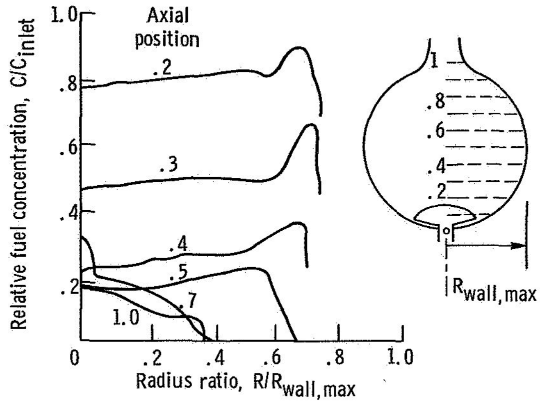

Figure 11. - Fuel distribution in curved porous wall rig at mass flow ratio of 100.

jector face. Thus, 1.0 represents pure fuel, and 0.5 represents a weight fraction of half fuel and half propellant. Figure 11 shows that the fuel concentration is uniform horizontally, but that it falls off fairly rapidly in the vertical direction. At the center of the cavity, for example, the fuel concentration if about twenty percent of the inlet value. The remaining 80 percent is propellant. Similar profiles were obtained for mass flow ratios of 25, 50, and 75.

Centerline concentration variation gives a good indication of the entire flow field because the profiles are rather flat horizontally. Centerline concentration as a function of vertical location is shown in figure 12 for mass flow ratios of 25 and 100. As the photographs indicate, the concentration falls off rapidly in the first half of the cavity, for a flow rate ratio of 100. At a mass flow ratio of 25, the fuel dilution occurs at a

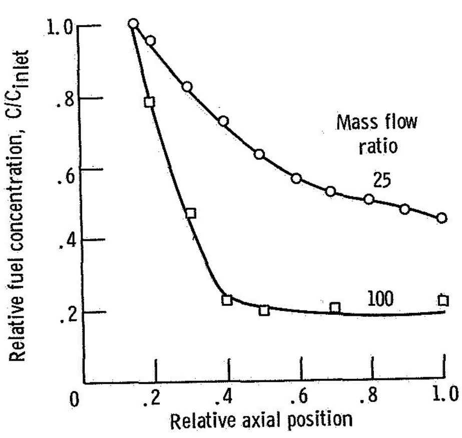

Figure 12. - Centerline fuel concentration.

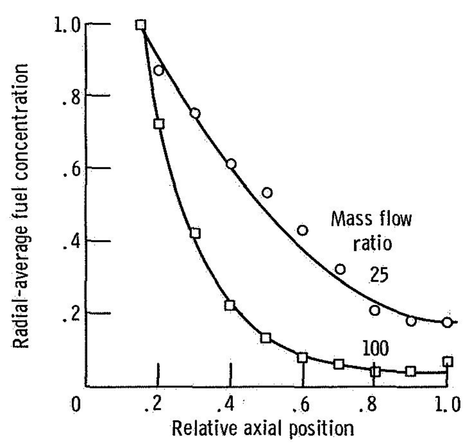

Figure 13. - Radial-average fuel concentration.

more constant rate throughout the cavity. It is obvious from a comparison of figures 7 and 10, and also from the data of figure 12 that there is less fuel in the cavity at the higher mass flow ratio.

The horizontal concentration profiles obtained from the densitometer traces were integrated to give a horizontal average concentration. Figure 11 shows how this average concentration varies from the inlet to the outlet of the cavity. Again it is clear that the fuel concentration falls off faster at the higher flow rate ratio. Similar curves for 50 and 75 were obtained, and they fall between the two shown in figure 13.

The vertical concentration curves were integrated to obtain a cavity-average concentration. For a mass flow ratio of 25, the average concentration throughout the cavity was 0.51. That is, if the fuel were distributed uniformly throughout the cavity, the concentration would be 0.51. Or, if all the fuel were collected into a region that was pure fuel, the volume of that region would be 0.51 of the entire cavity. Table I lists the fuel

TABLE I. - FUEL VOLUME FRACTIONS

Flow rate, cu ft/hr		Flow rate ratio	Fuel volume fraction
Outer	Inner		
350	14	25	0.51
350	7	50	.32
350	4.7	75	.31
350	3.5	100	.28

volume fractions for the four mass flow ratios. At a mass flow ratio of 100, the fuel volume fraction is 0.28.

Fuel volume fraction plotted against mass flow ratio was used in reference 4 to characterize gaseous reactor performance areas. Figure 14 shows this kind of a plot. The vortex and coaxial flow regions show where previous data has been reported from other gas-core fluid mechanics experiments. These data and the experiments are discussed in reference 4.

The data from this study are also shown in figure 14. The data show higher fuel volume fractions than have been previously reported in the mass flow ratio range of 25 to 100. It is the only data in the "high performance" region. The fuel volume fraction does decrease with increases in mass flow ratio, but it is only a square root variation. That is, an increase of mass flow ratio by a factor of 4, would only decrease the fuel volume fraction by a factor of 2.

These high fuel volume fractions, at these relatively high mass flow ratios, make this flow pattern quite attractive. Obviously, these are preliminary tests and additional

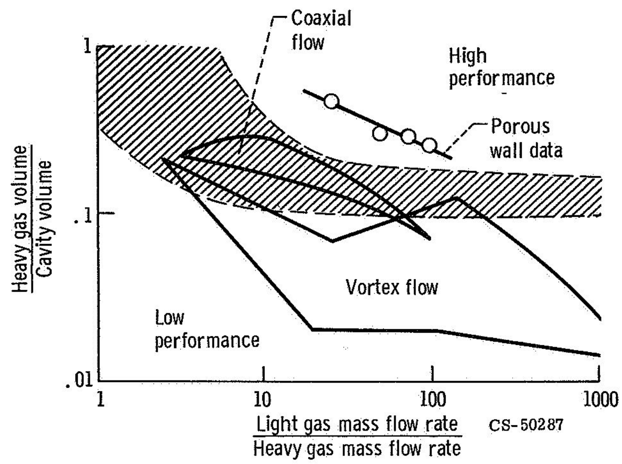

Figure 14. - Porous wall data on gas-core performance map.

work is required. For example, the experiments were conducted at the relatively low Reynolds number of 1100. It will be necessary to establish that the present flow pattern, or one just as good, will exist at higher Reynolds numbers. The effect of using two different gases (density difference), and the effect of heat generation on the flow pattern must also be studied. The general result that has emerged to date from these tests is that the flow pattern appears to be useful for gaseous reactor application, and that for the air-air simulation, has provided the best fuel volume fractions that have been reported.

SUMMARY OF RESULTS

An experiment was carried out to determine the flow characteristics of a curved, porous wall gas-core reactor concept. The experiments were performed at room temperature and atmospheric pressure. Air was used to simulate the flow of both the hydrogen propellant and the uranium fuel.

The "fuel" air contained smoke to make it visible and to allow photographic measurements of its relative distribution in the test cavity. These tests have produced three results which are summarized below.

1. The qualitative indication is that this geometry merits further investigation.

2. The fuel occupies 28 to 51 percent of the cavity volume for propellant-to-fuel flow rate ratios of 100 and 25, respectively.

3. The fuel volume fraction decreases inversely with the square root of the mass flow rate ratio.

These tests were exploratory in nature. Mainly, they have disclosed a flow

pattern that appears applicable to a gas core nuclear reactor. Obviously, more extensive tests are needed. Higher Reynolds numbers, heat addition, two-gas flow, and 3-D geometry are features that would be present in an engine but were absent in the experiment. The present results justify doing these more difficult experiments.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 11, 1969,
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