ARE GAS-CORE NUCLEAR ROCKETS ATTAINABLE?

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Abstract

In order to evaluate an advanced nuclear engine concept, it must be compared with other concepts and with engine requirements. This paper describes a way to make such comparisons for open-cycle, gaseous-fueled nuclear rocket engines. Engine requirements are expressed in terms of two parameters. One parameter is the fraction of the engine cavity volume that is occupied by gaseous nuclear fuel. The other parameter is the ratio of mass flow rates, hydrogen-to-uranium, that is entering (and, therefore, leaving) the engine. These parameters are used to define engine performance goals and to compare experimental data for existing concepts. It is shown that a fuel volume fraction of 0.2 is a minimum requirement for any gas-core concept. Experimental data indicate that straight, axial flow through the reactor cavity is somewhat better than a rotating "vortex" flow pattern. No experimental data have yet been reported that correspond to high engine performance. Present information does indicate that a gas-core engine could be built that would produce a steady thrust of 250,000 pounds at a specific impulse of 1500 seconds or higher. However, there is not enough information to determine whether this first engine would be acceptable in terms of uranium loss rate, engine weight, and reliability.

I. Introduction

The advantage of using a gaseous nuclear fuel in a rocket engine to produce a specific impulse as high as 3000 seconds is clear. How to do it is not so obvious. Some ways have been proposed, and research is underway to provide tools for feasibility assessments. The status of this work has been recently reviewed in Ref. 1. It is concluded in Ref. 1 that substantial progress has been made toward solving complex problems of fluid flow, heat transfer, and reactor physics. It is necessary to solve these problems in order to be able to describe and predict engine performance characteristics.

It is also necessary, and at least equally important, to establish what kind of engine characteristics are desired. This would then allow a comparison of predicted engine performance with a clearly defined goal. A way to make such a comparison is described in this paper.

The work reported here has two objectives. One objective is to define what conditions must be met in order to have a high performance gaseous nuclear rocket engine. The second objective is to show what conditions have been achieved in gas-core fluid mechanics experiments to date. The over-riding objective, of course, is to answer the title question: Are gas-core nuclear rockets attainable?

The approach taken is to determine the important engine variables, use them to construct an engine performance "map," and then put the available experimental data on this map. Figure 1 shows a sketch that depicts the major features of the open-cycle, gas-core engine considered in this paper. An externally moderated cavity contains a centrally located region of gaseous nuclear fuel. The hydrogen propellant flows around the fuel. The fission-generated heat is transferred as thermal radiation. The hydrogen is made absorptive by adding some appropriate "seeding" material in the form of particles or gases.

Putting experimental data from various fluid mechanics tests on an engine performance map allows two comparisons. One comparison is between the data and engine goals. The other comparison is among the various concepts. Both comparisons are of interest.

II. Basic Engine Characteristics

The identification and calculation of basic engine characteristics are presented in this section. The engine model used is shown in Fig. 1. It is an open-cycle engine; that is, there is a steady flow of hydrogen and nuclear fuel into and out of the engine cavity. The fuel is contained in a central, "effective," fuel volume, around which flows the hydrogen propellant.

In an actual engine, of course, the fuel would be distributed throughout the reactor cavity. The exact distribution would be determined by the flow pattern of the particular concept. To obtain the effective fuel volume, we gather all of the fuel into a central volume that contains only pure fuel. The fuel is still at its original operating temperature. The reactor pressure is therefore unchanged, because the total mass of fuel in the cavity has not been changed.

For a given geometry and hydrogen and fuel flow rates, the concept with the largest fuel volume in the cavity will have the lowest pressure. Thus the fuel volume is a direct measure of engine performance. It is helpful to express this fuel volume as a fraction of the reactor cavity.

In order to calculate engine pressure, it is necessary to know the critical mass and the average fuel temperature. The average fuel temperature is shown in Fig. 2 as a function of reactor pressure and engine thrust. [2] These temperatures should be pretty much the same for any reasonable gas-core flow pattern. The fuel would be more or less centrally located with the hydrogen flowing between it and the wall in any concept. The fuel region is so thick, optically, that changes in edge conditions have virtually no influence on the temperature of most of the fuel.[2] It would be possible to reduce the fuel temperature by substantially increasing the amount of fuel surface. However, the penalty of increased mixing that would result would more than offset the hoped-for reduction in pressure. Therefore, it appears that the fuel temperatures obtained for this central fuel volume model should be practically independent of a particular concept.

The reactor pressure is also affected by fuel ionization. This effect can be expressed simply and easily in terms of an effective or average molecular weight of the fuel plasma. The molecular weight of a gaseous mixture of uranium nuclei and electrons would be less than that of pure uranium. This is shown in Fig. 3.[2] As the temperature goes up, so does the degree of ionization, and the average molecular weight decreases.

The effect of fuel volume fraction on reactor pressure is shown in Fig. 4. These curves are for particular values of thrust, specific impulse, and reactor, but the values used are pretty much representative of gas-core engines of interest. Critical mass is treated as a parameter because calculational techniques have not yet been experimentally verified for the many extreme conditions that would exist in a gas-core engine. Forty kilograms is the best guess for the example engine used to obtain Fig. 4.

It is apparent from Fig. 4 that a fuel volume fraction of at least 0.2 is necessary to keep the reactor pressure below 1000 atmospheres. A critical mass of 20 or 60 kilograms changes this threshold value to 0.1 or 0.3, but a good rule of thumb seems to be that about 20 percent of the reactor cavity must be available to contain fuel. Changes in the reactor size, thrust, or specific impulse are not likely to change this conclusion appreciably.

III. Engine Performance Map

For a given engine configuration, the major influence on the fuel volume fraction will be the relative flow rates of hydrogen and uranium entering the cavity. As the experiments to be discussed will show, an increase in the ratio of hydrogen-to-uranium flow rates tends to decrease the fuel volume fraction. Unfortunately, this trend is opposite to what is desired in terms of engine performance. Good engine performance occurs at large values of both fuel volume fraction and hydrogen-to-uranium flow rate ratio. Since both are not generally available together, some sort of a trade-off must be considered, where fuel volume fraction can be increased at the price of decreasing the hydrogen-to-uranium flow rate ratio. Another way of saying the same thing is that the reactor pressure can be decreased by increasing the uranium loss rate.

Fuel loss from an engine is undesirable for a number of reasons. Most or all of them have been mentioned before. They are:

(1) increased mission cost
(2) on-board storage of tons of uranium
(3) inefficient use of a natural resource
(4) political unattractiveness
(5) reactor ground test difficulties
(6) contamination of space
(7) plume radiation to crew
(8) fallout from orbital startup
(9) engine will not deliver high I_{sp}

It is obviously impossible to assign some importance number to each of these reasons. It is doubtful that they could even be arranged in some order of importance. The reason for this is that most of these penalties turn out to involve a matter of judgment. That is, they relate to <u>how well</u> an engine would work, and not to <u>whether</u> the engine would work. Here the word "work" is used in the following sense - a gas-core engine works if it can produce a steady thrust of 250,000 pounds and a specific impulse of 1500 seconds or higher.

From this veiwpoint, reason number 9 stands out from the rest. It can be evaluated quantitatively from existing information, and does not involve any speculation as to future needs or values. If there is too much uranium exhausted with the hydrogen, the engine simply will not produce a specific impulse substantially above a solid-core value of about 900 seconds. Although this threshold specific impulse cannot be fixed precisely, 1500 seconds is a reasonable number.

On the basis of the foregoing considerations, fuel volume fraction and hydrogen-to-uranium flow rate ratio were chosen as the engine variables with which to describe engine performance goals. Fuel volume fraction was selected because it is independent of engine concept, it affords a clear physical picture of conditions in the cavity, and it can be directly related to engine pressure. Hydrogen-to-uranium flow rate ratio was chosen because it is a measure of the most important undesirable engine characteristic (fuel loss), it can be quantitatively related to specific impulse, and it would truly be the independent variable in an engine test. These two variables were used to construct an engine performance map.

A gas-core performance map was obtained by plotting fuel volume fraction as the dependent variable and hydrogen-to-uranium mass flow rate ratio as the independent variable. The map is shown as Fig. 5. The words light and heavy are used instead of hydrogen and uranium in order to avoid confusion when later comparisons are made with experimental data obtained with other gases. The reactor pressure that corresponds to a given fuel volume fraction is taken directly from Fig. 4 for a critical mass of 40 kilograms. The percent of the pure hydrogen specific impulse is shown at the corresponding values of hydrogen-to-uranium flow rate ratio.

Regions of high performance and low performance are indicated. There is no sharp dividing line between these two regions, since a certain amount of judgment or opinion is involved as to how to trade off between reactor pressure and fuel loss. That is the reason for the region labeled intermediate performance. Though there is even some temptation to scrutinize the boundaries of this region, that is a rather unproductive exercise. The important point of this figure lies in the variables used and in the direction to the region of high performance in terms of these coordinates. It is also quite useful that the results of simple, room temperature flow experiments can be presented using these same variables. Thus, experimental data can be used to compare various concepts with each other and with engine performance goals.

IV. The Experimental Observations

The available experimental data are shown on Fig. 6. The coordinates are the same as those of Fig. 5. The region of intermediate performance is repeated to permit easy comparison with Fig. 5. The areas outlined indicate where data have been obtained by various investigators in studies of coaxial and vortex flow patterns. Altogether, the data represent results of four investigators, using seven different gases and more than six different test sections.

The density ratio, $\bar{\rho}$, is an important parameter; it will be discussed before going into each set of data. In order to relate experiments to engine conditions, it is necessary to estimate what density ratio would be encountered in an engine. In an engine the uranium would be much hotter than the hydrogen. Therefore a representative density ratio would be less than the ratio of molecular weights. If the hydrogen density is evaluated at its average (inlet plus outlet divided by 2) temperature, 7000^{o} R, and the fuel density is evaluated at its average temperature of $80,000^{o}$ R, the density ratio is 4. Although all of the complicated effects due to density gradients cannot be precisely represented by such a simple average, it is a reasonable first approximation. Thus, there is some reason to expect that that data obtained for density ratios of 1 and 5 should be representative of engine conditions.

The largest data area on Fig. 6 is that labeled vortex flow, $\bar{\rho} = 1$ to 5. These representative data were kindly supplied by George McLafferty of United Aircraft Research Laboratories. These results were obtained as a part of an extensive study of vortex flows with superimposed axial flow of the light gas in a number of vortex chambers.[3 to 6] Some of these experiments were also performed with density ratios of 0.17 and 14, but the results have not been used here. The results for a density ratio of 0.17 were obtained as a part of a study of a closed cycle, nuclear "light bulb" concept.[1] The data for a density ratio of 14 were not used here because they fall pretty much within the same area as 1 to 5, and because similar data were not available for any other study.

The data labeled vortex flow, $\bar{\rho} = 50$, was reported in Ref. 7. These data were obtained at the highest mass flow ratio, and they show the lowest fuel volume fraction. They were also obtained with the highest density ratio gases. These extremes are probably related. In other words, one might expect that a decrease in density ratio would result in higher fuel volume fractions. This is speculation, of course, but it is the direction in which one might intuitively expect the influence of density ratio to operate.

The data enclosed in the area labeled coaxial flow, $\bar{\rho} = 1$ to 5, are reported in Ref. 8. These data cover a wide range of geometry and flow conditions. The fuel volume fraction was determined from the total mass of heavy gas in the cavity. This total mass, in turn, was obtained from a detailed mapping of the heavy gas distribution throughout the cavity. Other experiments have been performed on coaxial flows.[9] Those results cannot be presented on the coordinates of Fig. 6, however, because they were for a free jet, and therefore there is no way to determine a "cavity" volume.

The data area labeled heated coaxial flow, $\bar{\rho} = 2$, are from experiments described in Ref. 10. These are the only data obtained with combined heat transfer and fluid mixing. A central argon plasma was heated inductively from a copper coil surrounding the flow channel. Hydrogen flowed in the annular space between the central plasma and the cavity wall. The fuel volume fractions were obtained from photographs in which the bright, central plasma has a relatively sharp, distinct, boundary. It is assumed that this volume is occupied by pure argon, or "fuel." This assumption will have to be substantiated by actual concentration measurements. These experiments are underway. The assumption should not be grossly in error because hydrogen is much more difficult to ionize than argon. Therefore, the region of heat generation would tend to restrict itself to a central, argon-rich volume.

The information in Fig. 6 indicates two things. Straight, axial flow of the gases through is somewhat better than a rotating, "vortex" flow. The other obvious fact is that none of the data fall in the region corresponding to high engine performance.

Both coaxial and vortex flow are close enough for some conditions, though, that it is interesting to speculate on ways to improve performance by a factor of 2 to 5. Heated coaxial flow experiments are presently underway to increase the mass flow ratio without decreasing the heavy gas volume fraction.

Probably the most valuable aspect of Fig. 6 is that it allows a quantitative comparison of engine concepts with each other and with engine performance goals. It is likely that some important parameters are absent from Fig. 6. Reynolds number may be a relevant parameter. Froude number, or some other buoyancy criterion, should be considered. As future information discloses deficiencies in Fig. 5 or 6, they can be modified or amended. This will improve their utility. Likewise, the present form of Figs. 5 and 6 may suggest some new and better construction. It is to be hoped that such changes and improvements will occur. This will allow better quantitative comparisons between concepts and engine goals.

One remaining point of interest is the effect of different density ratios on the fuel volume fraction. There is enough data for vortex flow and coaxial flow so that such effects can be displayed. The data for these two flow patterns is shown in Fig. 7(a) for a density ratio of

5. Higher density ratios give lower fuel volume fractions, as might be expected.

Figure 8 shows a replot of the data from Fig. 6. Here the abscissa variable is the light-to-heavy gas volume flow ratio rather than the mass flow ratio. There is no important change from Fig. 6. Therefore, it does not appear that density ratio effects can simply be incorporated into the flow rate parameter. The available data do not clearly indicate any advantage of using volume flows over mass flows as a variable. Therefore, mass flow ratio is probably the better one to use because engine thrust and fuel loss are more readily described in terms of mass flow rates.

V. Conclusions

It is important to define advanced nuclear rocket engine performance goals so that progress can be clearly and quantitatively measured. A necessary first step to this end is to identify what variables best describe engine performance. On the basis of a relatively simple and general model of an open-cycle gas-core engine, the following conclusions have been reached:

1. Fuel volume fraction and hydrogen-to-uranium mass flow ratio clearly and concisely describe engine performance.

2. Any concept must provide a fuel volume fraction of at least 0.20 in order to be of interest.

These same variables allow experimental data to be used to compare various concepts with each other and with engine performance goals. This comparison led to the following conclusions:

3. No experimental data have been reported that correspond to "high" engine performance, though some is reasonably close.

4. Straight axial flow of the propellant and fuel through the reactor appears somewhat better than a rotating, "vortex" flow pattern, especially at higher density ratios.

Finally, one is led to consider the title question. Are gas-core nuclear rockets attainable? It is tempting to dodge the issue by answering: Maybe. It does appear, however, that another answer can be made on the basis of existing information. And that answer is: Yes, but.

Both of these words have to be put into some kind of context. The yes answer means that it does appear that a gas-core engine could be built that would produce a steady thrust of 250,000 pounds at a specific impulse of 1500 seconds or higher. Fluid mechanics data indicate that the reactor pressure would be 1000 atmospheres. That is high, but is probably achievable. Certainly there are many potential problems that would be encountered in actually trying to build a gas-core engine. Reactor control, fuel delivery, and nozzle cooling are some of them. It is, of course, possible that any one of these problems could turn out to be insurmountable. There is, however, no present indication that this is so. It seems, therefore, that the weight of evidence, although incomplete, favors a yes answer.

The second half of the answer "Yes, but" is a reminder that even if an engine works, it is necessary to consider whether it works well enough to be desirable. In fact, how well the engine works becomes important only if it works. Even though this first engine works, it is obvious that some features need substantial improvement before it would become acceptable for space propulsion. There would be about 1 pound of uranium for every 10 pounds of hydrogen in the exhaust stream. The engine would probably weigh more than 250,000 pounds, perhaps as high as 500,000 pounds. This would restrict engine use to very ambitious missions.

In order to quantitatively measure how well a gas-core engine would work is indeed difficult. Much more information is required than now exists. Future mission requirements, uranium availability and cost, the prospects for competing schemes such as electric propulsion, are some of the areas that will require attention. In parallel with this, continued laboratory research studies will increase the understanding of gas-core process and, hopefully, lead to improved performance.

VI. References

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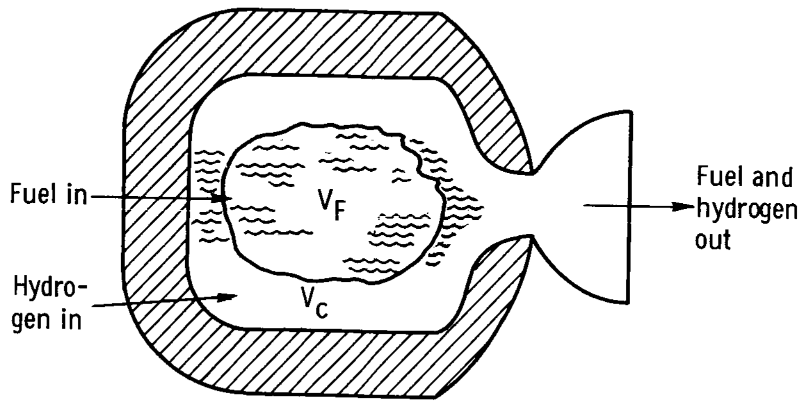

Figure 1. - Gas-core reactor model.

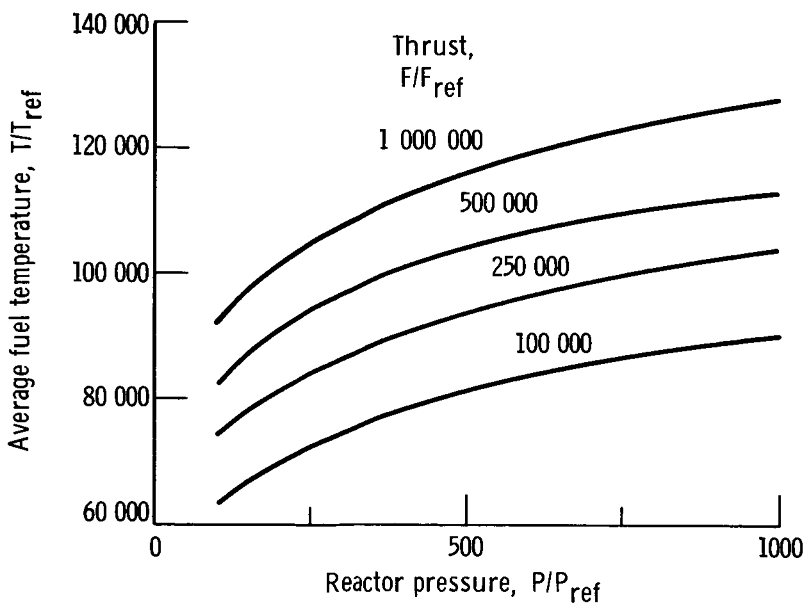

Figure 2. - Average fuel temperature. Specific impulse = 1° R (0.556° K), P_{ref} = 1 atm (10.1 N/cm^2), F_{ref} = 1 lb (4.45 N).

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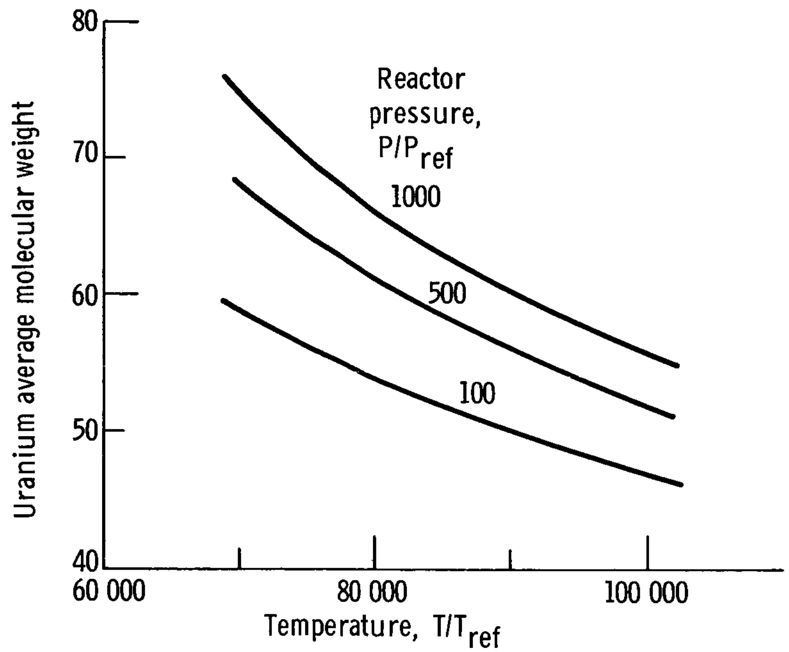


Figure 3. - Uranium average molecular weight. T_{ref} = 1° R (0.556° K), P_{ref} = 1 atm (10.1 N/cm^2).

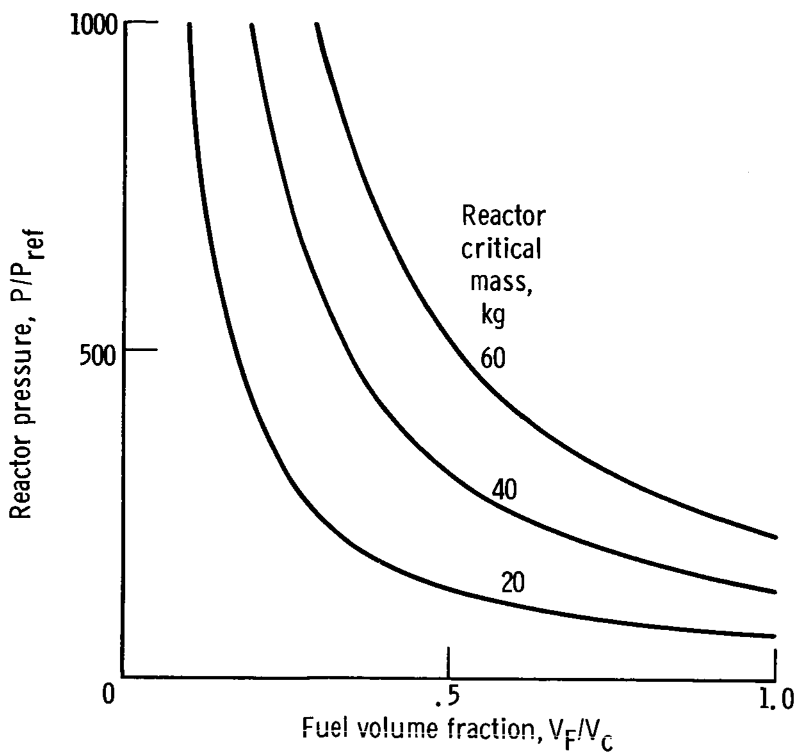


Figure 4. - Required reactor pressure in a 10-foot diameter, 8-foot long cavity. Thrust = 250 000 lb (1 110 000 N) specific impulse = 1500 sec, P_{ref} = 1 atm (10.1 N/cm^2).

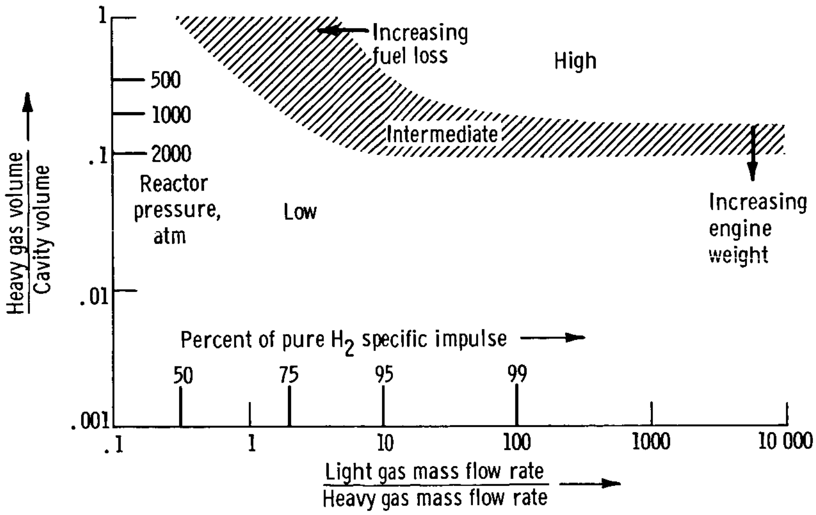


Figure 5. - Gas-core reactor performance map.

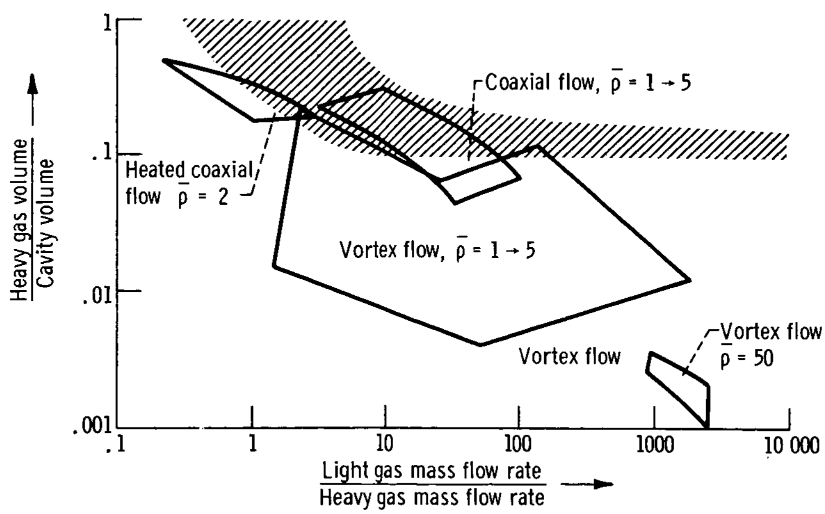
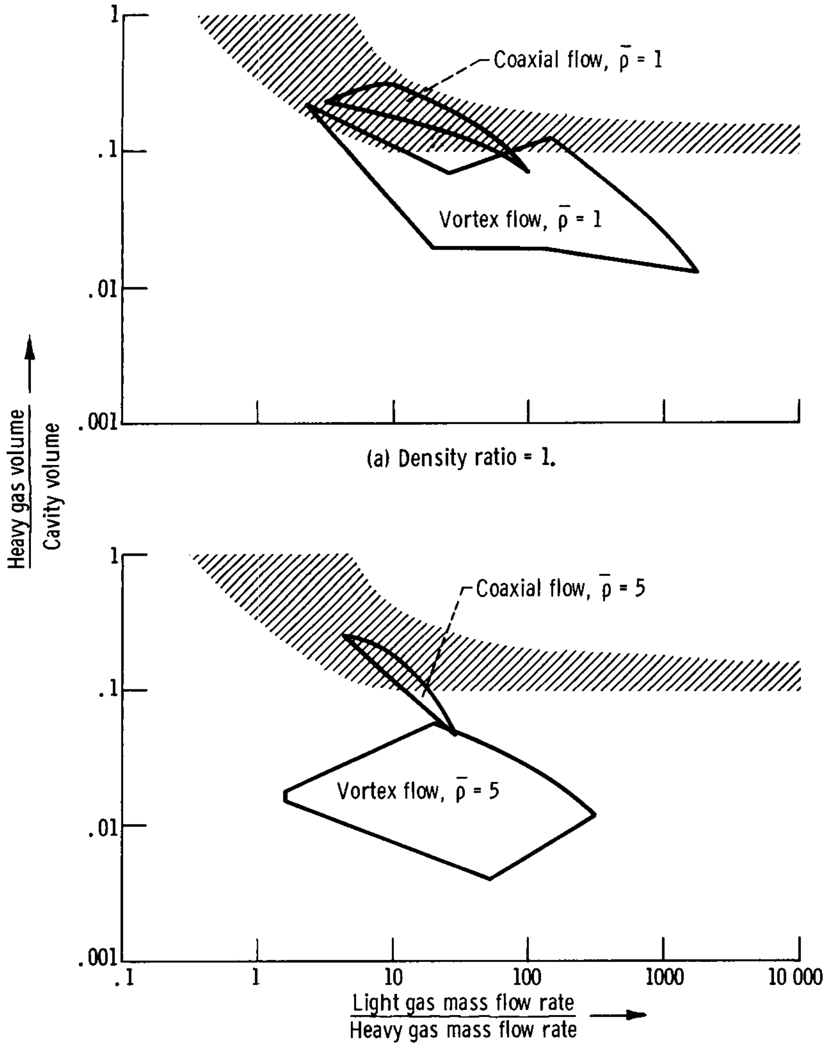


Figure 6. - Gas core fluid mechanics data. $\bar{\rho}$ = heavy to light gas density ratio.



(a) Density ratio = 1.

(b) Density ratio = 5.

Figure 7. - Comparison of coaxial and vortex flow.

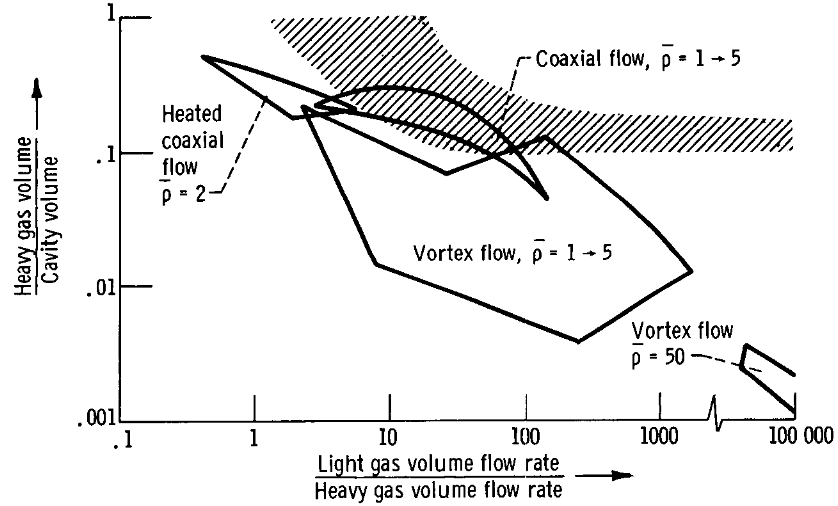


Figure 8. - Data comparison on volume flow basis.