Gas-Core Nuclear Rocket Engine Technology Status

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A review is presented of the status of research on the nuclear light bulb and coaxial-flow gaseous-core nuclear rocket engines. Both proposed engines are based on the transfer of energy by thermal radiation from gaseous nuclear fuel to seeded hydrogen propellant. Reference configurations for both engines are calculated to provide a specific impulse of ~1800 sec and a thrust-to-weight ratio of ~1.4. Two recently investigated flow configurations show promise of improving the containment of the gaseous nuclear fuel in a coaxial-flow engine. These configurations involve the use of foam inlets at the gas entrance to reduce the turbulence in the flow, and the use of a spherical, rather than a cylindrical, cavity. Substantial progress has been made in simulating the thermal environment of a nuclear light bulb engine during tests employing rf induction-heated and arc-heated plasmas. During one rf test, 85% of the energy deposited in the plasma was emitted as thermal radiation with a radiant flux of 48 kw/in.^{2}. This flux is slightly greater than the radiant flux at the surface of the sun, and is 20 times that which has been obtained from any other rf tests. Initial low-power arc tests have resulted in heating of seeded simulated propellant by thermal radiation to a temperature of ~2200°R.

Introduction

GAS-CORE nuclear rockets offer the potential of providing specific impulses between ~1500 and 2500 sec and thrust-to-weight ratios greater than unity. A number of different concepts have been proposed over the past 15 years, and many investigations have been conducted to provide the basic technological information required to evaluate these concepts. Most work on gaseous nuclear rocket (GNR) technology is now directed toward one or both of two concepts: the coaxial-flow reactor (under investigation at NASA Lewis Research Center) and the nuclear light bulb reactor (under investigation at United Aircraft Research Laboratories under Contract SNPC-70 with the joint AEC-NASA Space Nuclear Propulsion Office). The present paper is limited to these two concepts and the background technology which is of greatest importance in their evaluation, as reported since the survey of Ref. 1.

Reactor Concepts and Reference Engines

Coaxial-Flow Reactor

In this concept (Fig. 1), a low-velocity cloud of gaseous fissionable fuel is surrounded by a higher-velocity stream of seeded hydrogen propellant.[2,4–6] This seeded propellant is heated by thermal radiation from the hot gaseous nuclear fuel. The cavity containing the fuel and propellant is surrounded by a moderator region to reflect the neutrons created by the fission process back into the cavity to sustain the nuclear chain reaction. The hot hydrogen propellant, along with a small quantity of unburned nuclear fuel and fission products, is exhausted through a transpiration-cooled nozzle to provide thrust.

Extensive analyses have been conducted to optimize engine size, engine pressure, etc.[2,6] A representative configuration might employ a spherical chamber having a diameter of 12 ft and containing 50 kg of uranium-233. The total power created in the nuclear reaction, 22,000 Mw, would be sufficient to heat 222 lb/sec of hydrogen to a temperature which would result in a specific impulse of 1800 sec, thus providing a thrust of 400,000 lb. The required pressure within the cavity would be ~1000 atm, and the fuel loss rate would be ~1% of the hydrogen flow rate. The moderator surrounding the cavity would be composed of heavy water and beryllium oxide, with a total thickness of 2.5 ft. The total weight of this representative configuration is estimated to be 281,000 lb, which is made up of the following component weights: moderator, 120,000 lb; pressure shell, 140,000 lb; turbopump, 19,000 lb; and exhaust nozzle structure, 2000 lb.

Nuclear Light Bulb Reactor

The nuclear light bulb engine comprises seven separate unit cavities (Fig. 2a). Each cavity contains a region of hot gaseous nuclear fuel which, as in the coaxial-flow reactor, heats seeded hydrogen propellant by thermal radiation. However, an internally cooled transparent wall now is located between the fuel and the propellant regions (Fig. 2b). The gaseous nuclear fuel is isolated from the transparent wall by a neon vortex. This neon flow passes out through ports located on the centerline of the end wall of each cavity to a fuel recycle system, wherein nuclear fuel entrained in the neon is con-

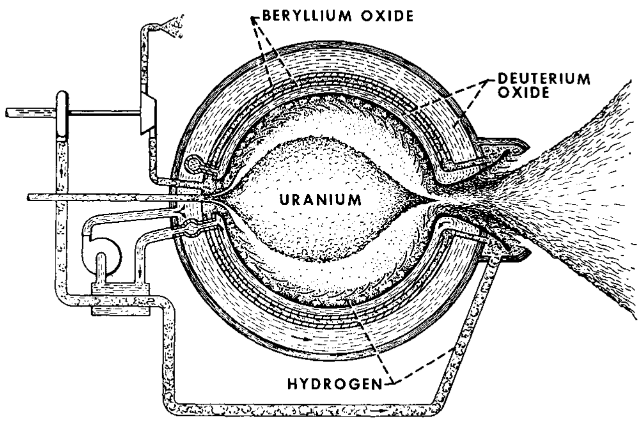

Fig. 1 NASA Lewis coaxial-flow gas-core nuclear rocket concept.

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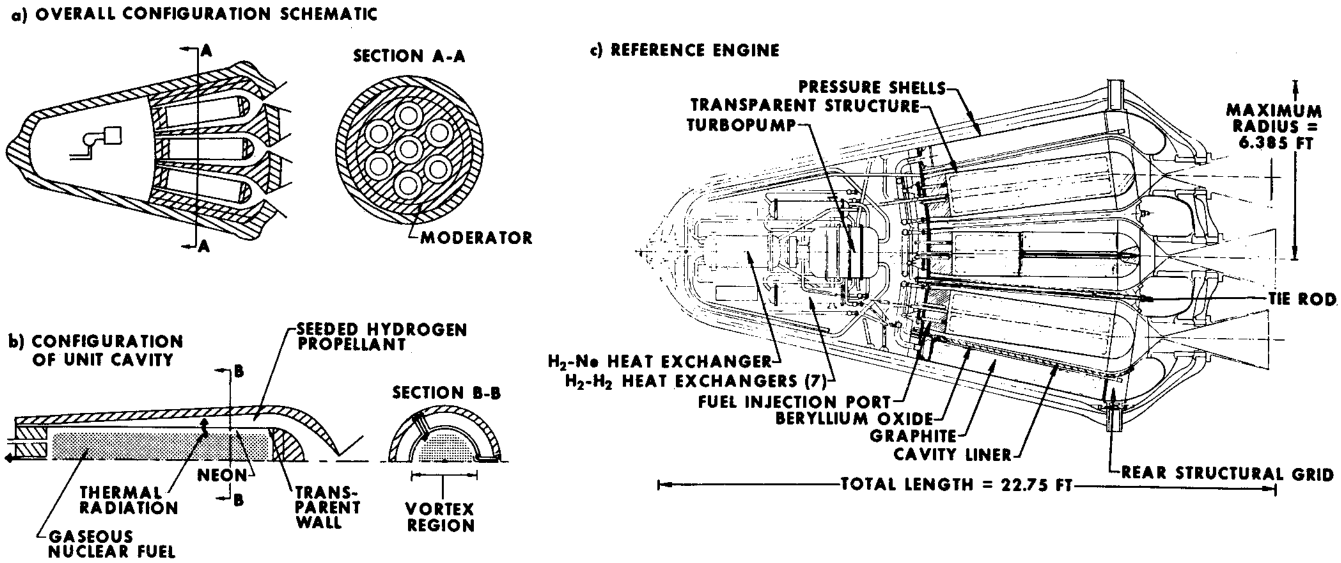

Fig. 2 Sketches illustrating principle of operation of nuclear light bulb engine.

densed to liquid form, centrifugally separated from the neon, and pumped back into the fuel region.

In the reference engine (Fig. 2c), each of the seven cavities has a length of 6 ft. The total volume of all seven cavities is equal to that for a single cylinder having a diameter of 6 ft and a length of 6 ft. The total amount of fuel contained within the seven cavities is ~14 kg, and the power is ~4600 Mw. The critical mass of 14 kg is less than that for the coaxial-flow reactor because of the reduced engine size and the beneficial effect of the moderating walls between the unit cavities. The total pressure in the cavity is estimated to be 500 atm. The reduced pressure in this engine relative to the coaxial-flow engine is due primarily to a reduction in the fuel region centerline temperature which, in turn, results from a lower radiant flux at the edge of the fuel and a reduced diameter of the fuel cloud region. The total hydrogen flow rate of 49 lb/sec is heated to 12,000°R, which will provide a specific impulse of 1870 sec. The resulting engine thrust is, therefore, 92,000 lb. The total weight is estimated to be 70,000 lb and is made up of the following component weights: moderator (graphite and beryllium oxide), 27,000 lb; pressure vessel, 30,000 lb; turbopumps, 3000 lb; and miscellaneous (including the fuel recycle system), 10,000 lb.

The nuclear light bulb engine offers the possibility of perfect containment of the gaseous nuclear fuel because of the presence of the internally cooled transparent wall between the fuel and the propellant, and because of the incorporation of a fuel recycle system in the engine.

Fluid Mechanics Research

Coaxial-Flow Reactor

The coaxial-flow reactor relies on fluid mechanics phenomena to provide preferential containment of the gaseous nuclear fuel. Two recent experiments have provided information on geometries which should provide improved fuel containment. One[4,5,8,9] (Fig. 3a) consisted of tests with and without foam material located at the entrance of the mixing region of the simulated-fuel and simulated-propellant streams. As is indicated in Figs. 3b and 3c, the introduction of a foam material resulted in a substantially increased average simulated-fuel density. It is believed that the presence of the foam material resulted in a reduction in the initial turbulence in both streams, thereby reducing the turbulence in the cavity which tends to mix the simulated fuel and the simulated propellant.

The second change in coaxial-flow geometry is illustrated in Fig. 4.[4,5] In these experiments, the cylindrical geometry employed in preceding tests was replaced by a spherical geometry. The average fuel concentrations in these tests were substantially higher than were obtained in preceding coaxial tests with the cylindrical geometry.

A third experiment of interest[4] is illustrated in Fig. 5 and was conducted at the Humphreys Corporation. Tests were conducted both with and without an rf discharge in the central region of the flow. The rf discharge produces a temperature rise in the argon gas which simulates the gaseous nuclear fuel.

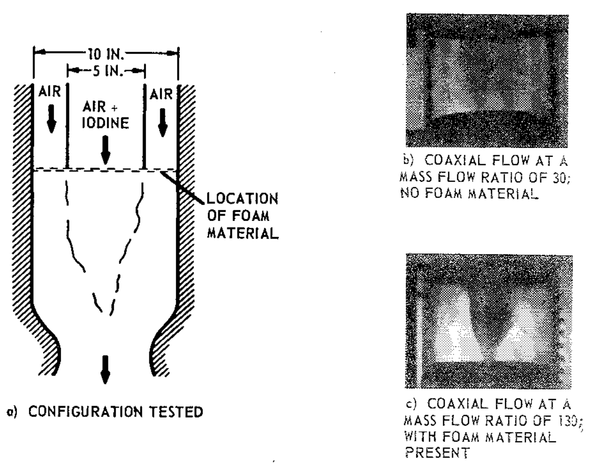

Fig. 3 Coaxial-flow experiments.

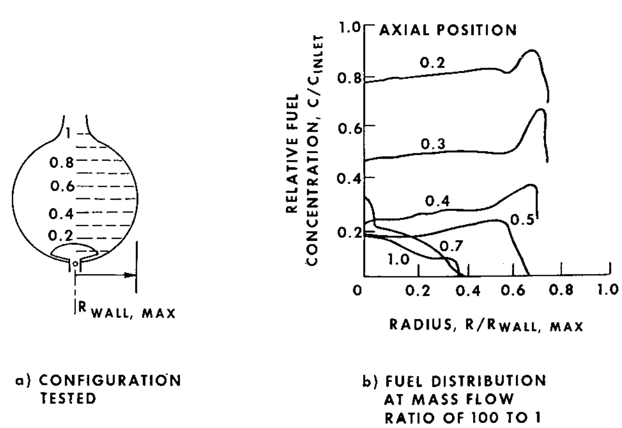

Fig. 4 Curved porous wall coaxial-flow test.

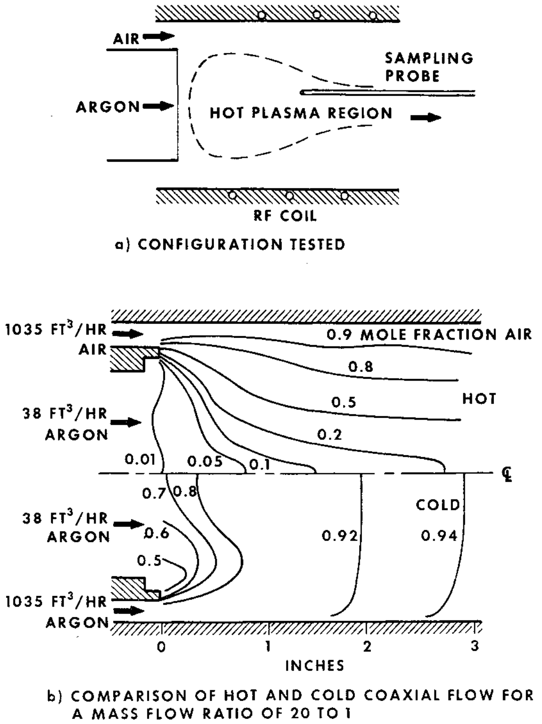

Fig. 5 The rf heated coaxial-flow test.

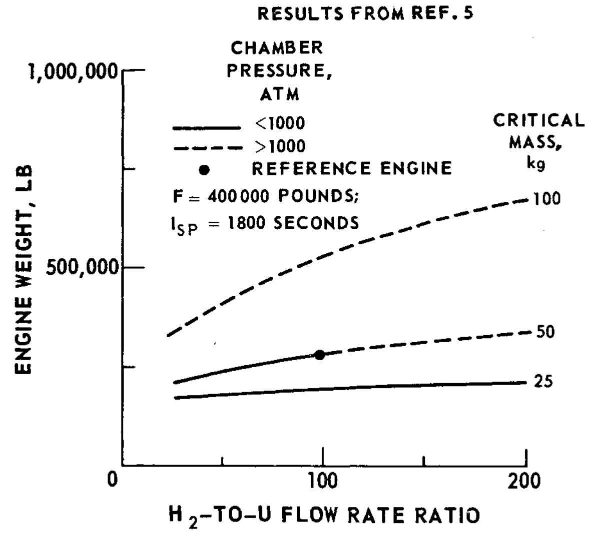

Fig. 7 Effect of uranium loss rate on engine weight for coaxial-flow engine.

The concentration profile results shown in Fig. 5b indicate that reduced mixing occurred when the argon gas was heated by the rf discharge. However, it is not known what portion of this reduction in mixing occurred because of the reduced velocity difference between the argon and air due to the thermal expansion of the heated argon, and what portion occurred due to other flow phenomena.

Studies have also been conducted at NASA Lewis to generalize the results obtained in the tests which are reported in Ref. 8 and which are shown in Fig. 3. This correlation is described in Ref. 9; some results are presented in Fig. 6. The technique employed to obtain the correlation shown in Fig. 6 has been used in the studies of Ref. 6 to calculate results such as those shown in Fig. 7. It can be seen from Fig. 7 that a change in the required ratio of hydrogen to uranium flow results in a relatively small change in engine weight.

Nuclear Light Bulb Reactor

One of the primary objectives of the fluid mechanics work being conducted under the nuclear light bulb program is to provide a flow geometry which will prevent condensation of the gaseous nuclear fuel on the transparent wall. Most of this work has been devoted to the use of vortex flow to provide such containment. Results obtained in unheated gas vortex tests using the equipment of Ref. 10 are presented in Fig. 8. The results shown indicate that the location of simulated fuel injection has a major effect on the partial pressure distribution of simulated fuel in the vortex tube. Moving the fuel injection port radially inward on the end wall results in an increase in simulated-fuel partial pressure near the centerline and a decrease in simulated-fuel partial pressure near the outer periphery; however, this also results in a decrease in the average simulated-fuel partial pressure within the vortex tube. It would appear from Fig. 8 that a radius ratio somewhere between 0.5 and 0.8 will result in a better combination of high average simulated-fuel partial pressure and low partial pressure of simulated fuel near the peripheral wall than any of the three injection configurations shown in Fig. 8. Tests have also been conducted with rf heated vortexes in which the radial temperature gradient near the outer periphery results in a further decrease in simulated-fuel partial pressure near the peripheral wall.

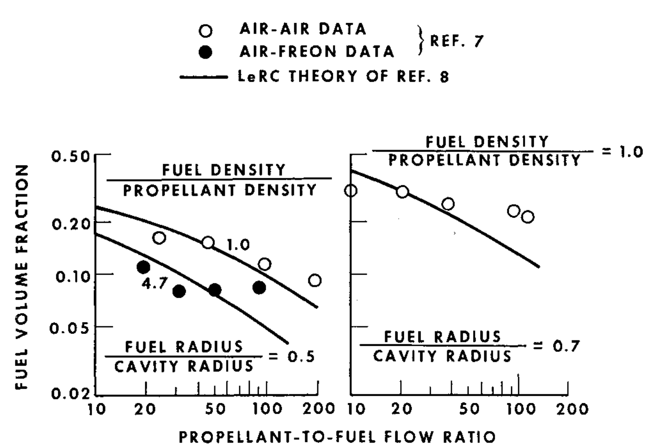

Fig. 6 Comparison of calculated and measured fuel volume fraction for coaxial-flow reactor.

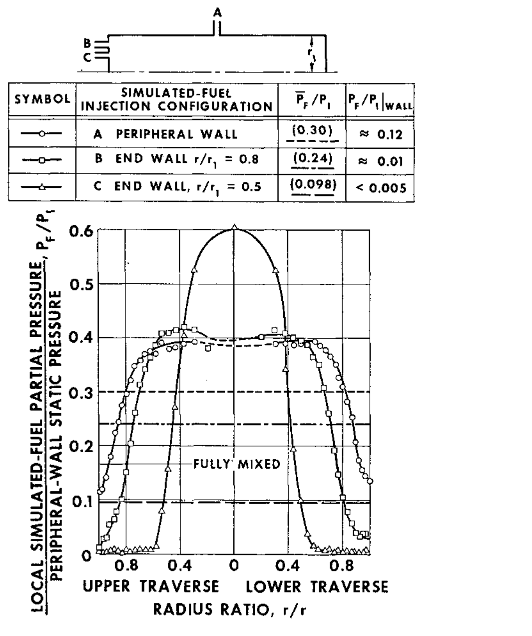

Fig. 8 Radial distributions of simulated fuel obtained in nuclear light bulb investigations.

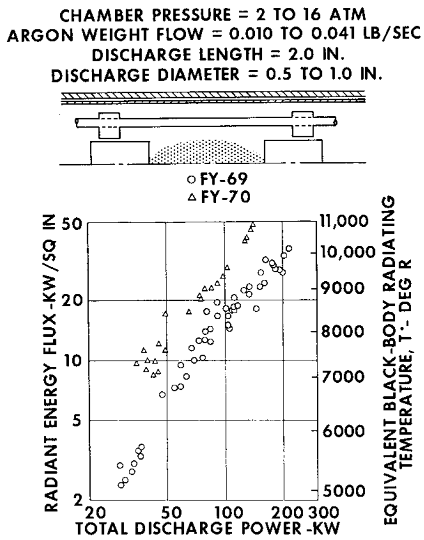

Fig. 9 Tests of rf radiant energy source for nuclear light bulb investigations.

The rf induction heating equipment at the United Aircraft Research Laboratories has been used to obtain a very intense radiation source for use in demonstrating that transparent wall structures can be successfully cooled, and for use in tests in which a simulated propellant is heated by thermal radiation. Results from some of these tests are given in Fig. 9. During tests conducted in 1969[11] a peak radiant flux at the edge of the rf discharge of 36 kw/in.^{2} was obtained from an ellipsoidal discharge region which was 2 in. long and which had a diameter of ~0.8 in. (corresponding radiated power of 156 kw and total deposited power of 216 kw). This radiant heat flux is equal to that from a blackbody at a temperature of 10,200°R (5650°K). Preliminary tests conducted in 1970 have resulted in a reduction in the diameter of the discharge, and a resulting increase in flux for a given power level. The peak flux obtained to date from these preliminary tests is 48 kw/in.^{2} (see Fig. 9), which corresponds to a blackbody radiating temperature of 10,800°R. This flux is slightly greater than the flux at the surface of the sun. The energy radiated from the plasma in this test was 85% of the energy deposited in the plasma. Additional tests to provide further increases in radiant flux are now being conducted.

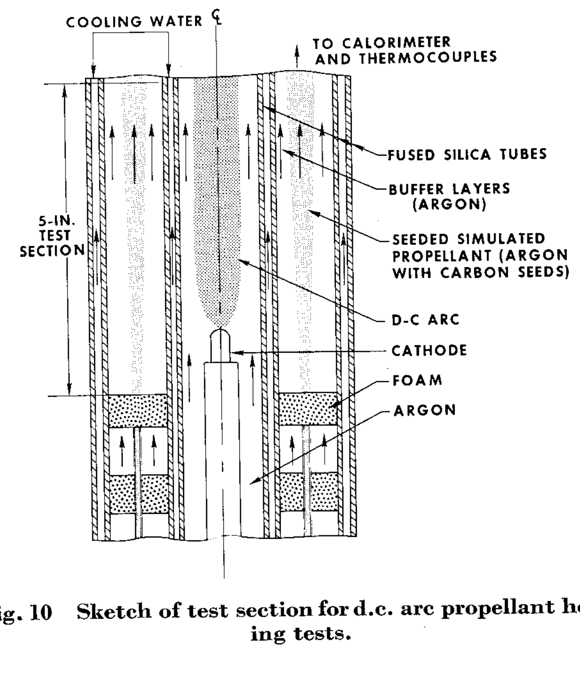

Fig. 10 Sketch of test section for d.c. arc propellant heating tests.

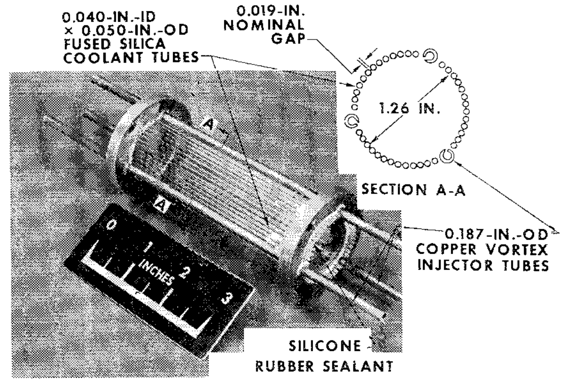

Fig. 11 Photograph of transparent-wall axial-coolant-tube model.

One of the objectives in generating the high-intensity radiant energy source shown in Fig. 9 is to permit tests to be conducted in which seeded simulated propellant is heated by radiation from the high-intensity source. In preparation for such tests, initial experiments are being conducted to heat seeded simulated propellant using the radiation from a low-power arc source. The configuration employed in these tests is illustrated in Fig. 10, and a more complete description of these tests is given in Ref. 12. Temperatures are determined from radiometer measurements, by calorimetric techniques, and by thermocouples located in the stream. During some tests conducted using this equipment, up to 90% of the radiant energy emitted from the radiant-energy source was attenuated by the seeds in the simulated propellant gas. The highest indicated bulk exit temperature obtained in tests to date was ~2200°R. Tests similar to those shown in Fig. 10 are planned for the immediate future for the rf induction heater. The total radiant power available in the rf induction heater is approximately fifteen times that for the arc heater illustrated in Fig. 10, and the length of the discharge region in the rf heater is approximately half of that in the arc heater. Therefore, substantially higher temperatures should be obtainable.

Internally cooled transparent walls are required in the nuclear light bulb engine, but not in the present version of the coaxial-flow concept. (It is also possible to employ a transparent wall to minimize the fuel loss rate in a coaxial-flow engine.) The transparent walls are usually assumed to be made of either fused silica or single-crystal beryllium oxide, with fused silica being considered in most studies because of its ready availability. However, because of the finite absorption of fused silica in the ultraviolet and its low thermal con-

Table 1 Comparison of results of fluid mechanics research with requirements of full-scale nuclear light bulb engine

Research area	Simulation parameter	Value for full-scale engine	Level achieved to date in research program
Propellant heating by thermal radiation	Exit temperature, °R	12,000	2200
Transparent-wall models	Wall thickness, in.	0.005	0.005
	Heat deposition rate, kw/in.^{2}	1.6	2.2
Radiant energy source	Radiant flux, kw/in.^{2}	178	47.9
Two-component vortex tests	Simulated-fuel partial pressure fraction	0.25	0.1 (rf tests) 0.4 (constant-temperature tests)

ductivity, the transparent walls must be thin,[13] on the order of 0.005 in. in the representative engine of Ref. 7.

A substantial effort has been devoted to the development of techniques for fabricating models from thin-wall fused silica tubes.[11] A photograph of a model having 0.005-in.-thick transparent walls developed under this program is given in Fig. 11.

A comparison of the results of fluid mechanics research with the requirements of the full scale reference nuclear light bulb engine is given in Table 1.

Other Areas of GNR Research

Heat Transfer

The problems of radiant heat transfer for the coaxial-flow reactor and the nuclear light bulb reactor are similar in many respects. In both engines, the opacity of the gaseous nuclear fuel is so high that the centerline temperatures are much greater than the blackbody radiating temperatures (a centerline temperature of ~100,000°R for the reference coaxial-flow reactor, and a centerline temperature of ~60,000°R for the nuclear light bulb reactor).[14,15]

Both engines also require that the hydrogen propellant be seeded with a material which enhances its absorption characteristics at low temperature. This material is usually assumed to be tungsten in the form of small-diameter particles whose total mass is several per cent of the mass of the hydrogen propellant. A summary of the latest information available on the spectral absorption coefficients of all the gases and particles which might be employed in gaseous nuclear rockets is given in Ref. 3.

Nuclear-Induced Coloration of Transparent Wall

The transparent wall material dividing the propellant and fuel regions of a nuclear light bulb engine must be transparent to the wavelengths of the radiant energy emitted from the fuel region. This energy is mostly contained in the wavelength region between 0.1 and 4.0 μ. Results from Ref. 16 of measurements of the transmission characteristics of fused silica indicate that exposure of the specimen to neutron and gamma irradiation resulted in an increase in the absorption coefficient in the ultraviolet, primarily centered at a wavelength of ~0.21 μ. However, heating of the specimen to ~800°C resulted in annealing of this radiation-induced coloration back to its preradiation value. Therefore, the transparent wall must be operated at ~800°C. If the absorption spectrum of the transparent wall at 800°C is used with the blackbody radiation spectrum for a temperature of 15,000°R (the radiating temperature in the representative nuclear light bulb engine of Ref. 7), then it is calculated that ~1% of the incident energy is absorbed. Recent studies of the actual spectrum emitted from the fuel region, which is different from the blackbody spectrum because of the spectral variation of fuel absorption coefficient, indicate that a greater percentage of the energy is contained in the ultraviolet than is indicated by the blackbody spectrum. Studies of the possibility of employing needs to alter this spectrum are now being conducted.

Tests have also been conducted to determine the equilibrium absorption coefficient during simultaneous irradiation and thermal annealing.[17] One problem in such investigations is that it is extremely difficult to simulate the neutron and gamma flux which is present in a full-scale engine; therefore, some tests have been conducted at the full-scale ionizing dose rate by the use of a Dynamitron electron accelerator located at the NASA Langley Research Center. Results from these tests yield an equilibrium absorption coefficient which is approximately one order of magnitude less than is indicated by extrapolation of reactor irradiation data obtained at lower fluxes. (The reaction irradiation data were obtained at the Air Force Institute of Technology Reactor.) This result is not believed to be due to the absence of fast neutrons in the Dynamitron tests, since the rate of coloration due to neutrons plus gamma rays is approximately equal to that due to gamma rays alone. Additional information is obviously required in this problem area. However, even if the equilibrium absorption coefficient in the full-scale engine is 6 cm^{-1}, as is indicated by extrapolation of the reactor data, it is necessary only to decrease the wall thickness from 0.005 to 0.003 in. In addition, preliminary tests also indicate that the photon flux in a full-scale engine may bleach out nuclear-radiation-induced color.

Nuclear Criticality

Two experimental programs have been conducted to measure the critical mass of cavity reactors to obtain data for comparison with theoretical calculations. The first of these was conducted at the Los Alamos Scientific Laboratory.[18] In this program, the cavity length and cavity diameter were both equal to 40 in., the moderator was composed of a 20-in.-thick layer of heavy water, and a $\frac{3}{16}$-in.-thick aluminum liner was employed between the cavity and the heavy water. It was determined that the critical mass of uranium-235 in the form of foils was equal to 6.0 kg. Two-dimensional transport calculations[19] to determine the multiplication factor for this configuration yielded a value of 1.01. (A value of 1.00 would have provided perfect agreement with the experiment.)

The second experimental program was conducted at GE-Idaho.[20] In this experiment, the cavity length and the diameter of the fuel containment region were both equal to 121.9 cm; however, the internal diameter of the 127-cm-thick aluminum liner separating the cavity from the moderator was 182.9 cm. The moderator reflector material was heavy water and was 88.9 cm thick, and a simulated exhaust nozzle was incorporated into this experiment. The critical mass of uranium-235 in the form of uranium hexafluoride was 17.27 kg. The calculated multiplication factor using two-dimensional transport theory was within 1% of that indicated by experiment, and the power density distribution was within 5% of that measured in the experiment.

It can be concluded from these two experiments that the critical mass of cavity reactors can be calculated to good accuracy using conventional techniques, at least for simple configurations. However, it is not possible to simulate all of the conditions in an experiment that will exist in a full-scale engine. For instance, calculations indicate that the hot hydrogen located between the fuel and the reflector should have a substantial effect on the neutron energy spectrum and hence on critical mass. Since this effect would be very difficult to simulate in a critical experiment, reliance must be placed on theory for determining the influence of such effects.

The critical mass of a multiple-cavity configuration (such as is envisioned for the nuclear light bulb) should be easier to calculate than for a single-cavity configuration. The effective internal moderation resulting from the moderator walls located between the individual cavities results in a configuration which is closer to a homogeneous reactor; the characteristics of such configurations are well known.

Controllability

Gaseous nuclear rocket engines are different from most other types of nuclear reactors in that the amount of nuclear fuel contained in the engine can be varied. Because of this, it appears that the power produced in a gaseous nuclear rocket can be changed by adjusting the fuel injection rate. Analytical studies to investigate this possibility are reported in Ref. 21. It is assumed in this study that the fuel injection rate is proportional to the product of the fuel injection area and the square root of the difference between the fuel duct pressure and the cavity pressure. One set of results obtained indicated that an instantaneous 10% increase in fuel injection area results in approximately a 2% increase in power, with a highly damped transition between the two power levels. These studies were made for the nuclear light bulb engine, but should apply equally well to the coaxial-flow reactor. Additional studies are now under way to determine the pressure difference across the transparent wall of a nuclear light bulb reactor during such transients.

Concluding Remarks

The relative performance advantages foreseen for GNRs in comparison to solid-core nuclear rockets (SCNRs) for manned Mars missions remain as attractive as forecast in 1967 and presented in Fig. 14 of Ref. 1. Required initial masses in earth orbit for 13- to 18-month missions should be reduced by factors of 2 to 6 by use of GNRs instead of SCNRs. (Hybrid SCNR-electric rocket systems would give intermediate performance.) The GNR also would be a desirable device to employ for missions with lower velocity increment requirements than a manned Mars mission, particularly if its reusability feature develops as expected. Thus, development of a GNR would offer many advantages, assuming that all the technical problems can be overcome. Let us now review a program which will lead to the development of such an engine.

Phase I in the development of GNRs was essentially completed in 1967. Sufficient progress had been made in cold-flow aerodynamics, radiant heat transfer calculations, and engine calculations to indicate that either a coaxial-flow engine or a nuclear light bulb engine probably could be developed if the problems encountered with high-temperature engine operation could be solved. Phase II began with tests at a number of agencies using rf and arc heaters in model-scale investigations to determine the characteristics of the various concepts during operation at the temperatures expected in a full-scale engine. Information from these rf tests has been discussed in preceding sections. We are now midway through phase II; additional tests in rf and arc-heated gases at small scale will result in additional information on fuel containment and should provide results showing that gases can be heated by thermal radiation to high temperatures. Successful completion of phase II will lead to the desirability of conducting tests with small-scale models in which the power is created by nuclear fuel which is fissioned as a result of the neutrons emanating from a surrounding "driver" reactor. Various estimates indicate that such tests could be initiated in two to six years, assuming successful completion of phase II. Following the small-scale nuclear tests in phase III, the path would be open for tests of a full-scale nuclear engine in phase IV.

It is obvious that solutions to many problems must be demonstrated before full-scale engine development should be initiated. However, this program can proceed through a series of logical steps as each problem is solved. The rate at which this program is pursued must obviously be related to the technical progress achieved and to the needs of the nation for a high-performance space propulsion system.

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