Review of Fission Engine Concepts

KARLHEINZ THOM*
Space Nuclear Systems Office, USAEC/NASA, Washington, D.C.

Karlheinz Thom has studied physics and philosophy at the Universities of Berlin, Göttingen and Bonn. After receiving his Ph.D., he worked for the Dielektra AG, a high voltage component firm in West Germany. He joined the NACA Langley Research Center, Hampton, Va., in 1958, where he became involved in research on electromagnetic plasma acceleration. In 1962 he became program manager for plasma physics research at NASA Headquarters. He was transferred to the NASA Headquarters Space Nuclear Systems Division in in 1970. In the years 1968–70, Dr. Thom served on the AIAA Plasmadynamics Technical Committee; he is a Member of AIAA. In the summer of 1971 he was a Visiting Professor of Nuclear Engineering Sciences at the University of Florida. In the NASA Space Nuclear Systems Division he is responsible for plasmadynamics research and for research on plasma core reactor systems.

Introduction

IDEAS for the use of nuclear fuel in the plasma state for high specific-impulse (I_{sp}) propulsion in space date back to the fifties.[1–7] In chemical combustion, the energy release per reaction limits the I_{sp} to about 500 sec, whereas, the energy of nuclear fissions is sufficient for a specific impulse of any desirable magnitude. However, in solid-core nuclear reactors, the energy of fission fragments is rapidly thermalized by heating the fuel rods to temperatures compatible with structural requirements. For example, in the NERVA nuclear rocket engine system this limitation leads to a specific impulse not greater than 850 sec, at a core temperature of about 2500°K.

At much higher temperatures, the nuclear fuel would exist in a gaseous, partially ionized state. The need to heat a propellant to similarly high temperatures, to contain the costly uranium fuel, and to isolate it thermally from confining structures has led to various "concepts" of gaseous-core nuclear reactors, and to a large number of analytical and experimental investigations.[8–10] Specialized literature dealing with the neutronics and the fluid mechanics of gaseous-core nuclear reactors is available, such as Ref. 11–13.

It appears that the enthusiasm and confidence in the feasibility of nuclear gaseous-core schemes has been fluctuating, in part because of questions regarding the need of their particular propulsion capabilities, and in part because of apparent great technical difficulties. A particular problem in evaluating the plasma core reactor concepts derives from the fact that a small-scale prototype test reactor cannot easily be built because of critical mass requirements. A full-scale engine would produce power equivalent to the consumption of large cities, in a volume in the order of a cubic meter, with temperatures up to 100,000°K and at a pressure of up to a thousand atmospheres.

NASA research,[14] consisting of analytical investigations and of testing simulated functional gaseous core reactor details, has recently led to increased optimism. Mission analyses have now more clearly defined the categories of space flight for which propulsion by means of plasma-core reactors offers unique advantages. For example, Fishbach et al.[15] have analyzed a fast manned mission to Mars with plasma core rocket propulsion which can be accomplished within 60 days, possible landing operations excluded.

Beyond high specific impulse propulsion, fissioning plasma research may result in other technological innovations. Most significant are the coupled plasma-core reactor-MHD system for terrestrial power generation at high efficiency and low thermal pollution,[10] and the nuclear pumped laser.[16]

Major Plasma-Core Nuclear Rocket Concepts

Figure 1 shows the major concepts of plasma-core nuclear rocket systems motivating current research: the coaxial-flow gas-core nuclear rocket and the nuclear light-bulb engine.[17–18] The complete nuclear light-bulb engine consists of seven modules such as shown in the figure. They are each surrounded by BeO, and all are contained in a pressure vessel,

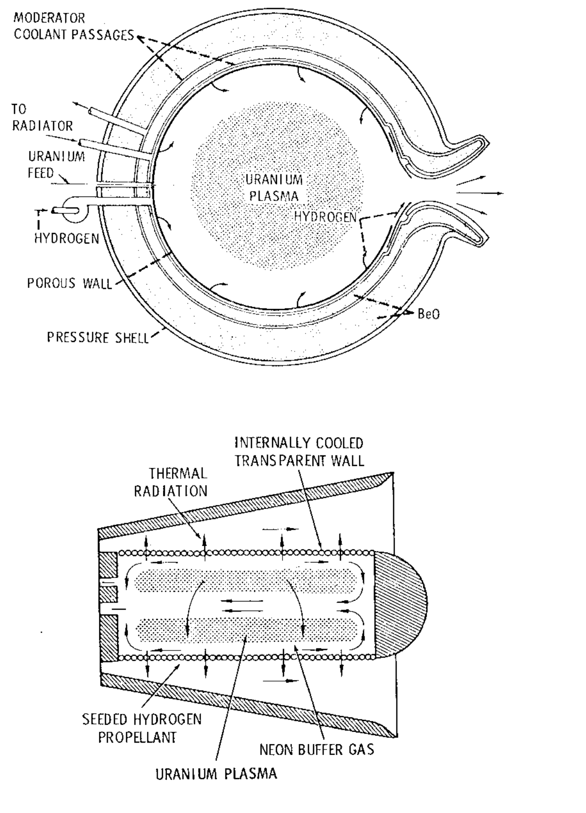

Fig. 1 Coaxial flow system, top; nuclear light bulb engine, bottom.

Presented at the 2nd Symposium on Uranium Plasmas: Research and Application, Atlanta, Ga., November 15–17, 1971; submitted December 23, 1971; revision received May 8, 1972.
Index category: Nuclear Propulsion.

* Program Manager, Nuclear Plasma Research. Member AIAA.

which opens down-stream to an exhaust nozzle. It should be noted that these two schemes have evolved from a variety of plasma core reactor concepts which have been conceived and investigated in the past. Therefore, they should be considered matured[19] in the sense of an intensive analytical and experimental probing, short mainly of fission power tests.

The need to thermally isolate the fissioning hot plasma from structures is, in both concepts, met by fluid mechanical means. One sees that in the coaxial flow system, wall jet injection of the propellant keeps the U^{235} plasma in the central region of a cavity surrounded by a moderator-reflector shell and a high-pressure container. In the nuclear light-bulb engine the fissioning plasma is confined within a transparent cell and in similar fashion kept away from the walls of that cell by a swirl-flow of tangentially injected buffer gas. The transfer of power from the fissioning fuel to the propellant proceeds in both cases by radiative heat transfer. Obviously, in the coaxial flow system such heat transfer can go unimpeded whereas, in the light bulb engine, limited transparency of the confining quartz structure restricts radiative energy fluxes to a certain wavelength region. On the other hand, the concept of the light-bulb engine offers complete fuel confinement, while in the coaxial flow system, flow mixing can lead to fuel losses which raises questions not only of technological feasibility but also of economical practicality. Both concepts have in common the problem of propellant heating by radiation, such that not only the propellant reaches temperatures high enough for achieving the desired specific impulse, but also that radiation is absorbed in the propellant to a degree that the cavity walls will not be destroyed.

With the principal problem areas so defined, research should be focussed on the following specific areas: 1) demonstration of criticality of gaseous UF_6 fuel in a cold static configuration, 2) investigations of the stability of fissioning plasmas, and of the spectral distribution of radiated power, 3) the confinement of a gaseous-fuel by fluid mechanics means in cold-flow tests, 4) demonstration of criticality of gaseous UF_6 confined in a cold-flow configuration, 5) propellant heating by radiation from an electrically or fission heated gas, 6) the confinement of a hot gaseous fuel by fluid mechanic means, and finally, 7) a prototype test configuration, which incorporates all the previous detailed functional elements.

Current NASA plasma core reactor research is listed in Table 1. The A's in this chart stand for analytical work, the E's indicate experimental investigations. For example, at the NASA Lewis Research Center and at the United Aircraft Research Laboratory the nucleonics of coaxial flow systems and of light-bulb engines, respectively, are being investigated to determine critical mass, pressure and volume requirements as they relate to performance characteristics. At the Idaho Reactor Test Site the criticality of $U^{235}F_6$ was demonstrated at zero power, in cylindrical and spherical geometries, and the effect of void fractions was determined.[20] The stability of a fissioning plasma with respect to heat flux and density fluctuations, coupled with alterations of fission rates, are the subject of analyses at Versar Inc.

The category "Radative Heat Transfer" deals predominantly with experimentation with r-f and inductively-heated gases at high pressure for the simulation of a fissioning plasma, considering the fact that radiation from an optically thick gas is independent of the kind of radiating gas. Research at the University of Florida is aimed at determining whether a fissioning plasma, indeed, is optically thick and, if so, over what ranges of pressures and temperatures. At the University of Maryland experiments are being conducted with a shock-heated mixture of helium and UF_6 to obtain information about the emission spectra of uranium and ionized uranium. In the plasma focus facility at the NASA Langley Research Center research is being conducted to investigate the radiation from highly ionized uranium atoms, as must be expected to exist in a fissioning plasma. Research on radiative heating of propellant also is underway at the NASA Lewis Research Center, at the United Aircraft Research Laboratories, and at the Georgia Institute of Technology. This research involves, as an integral part, investigations of techniques to seed hydrogen propellant with μ-sized particles, because at temperatures less than 10,000°K this gas is transparent.

Nuclear fuel confinement research is predominantly concerned with two-flow problems relevant to the schemes shown in Fig. 1. In addition, wall jet boundary-layer research is being carried out at the NASA Lewis Research Center and at the University of Arizona to examine various ways and means for making a nozzle for a plasma core rocket; such a nozzle would have to survive very hot exhaust temperatures. At the NASA Ames Research Center, an experiment has been conducted for confining a fissioning plasma by magnetohydrodynamic means[21]; this experiment differed from some of the previous concepts for MHD confinement examined in

Table 1 NASA uranium plasma research[a]

Criticality of Gaseous Fuel	Radiative heat Transfer	Nuclear fuel confinement	Systems study
NASA Lewis (A)	NASA Lewis (A/E)	NASA Lewis (A)	NASA Lewis (A)
Aerojet Nuclear (E)	TAFA Division Humphreys Corp. (E)	Ill. Inst. of Technology (A/E)	United Aircraft Research Labs. (A)
United Aircraft Research Labs. (A)	Ga. Inst. of Technology (E)	Cornell Univ. (A/E)	Ga. Inst. of Technology (A)
Versar Inc. (A)	AEDC (E)	United Aircraft Research Labs. (A/E)	Univ. of Florida (A)
	United Aircraft Research Labs. (A/E)	Aerojet Nuclear (E)	Computer and Applied Sciences (A)
	Univ. of Florida (E)	Univ. of Arizona (E)	
	Univ. of Maryland (E)	NASA Ames (E)	
	NASA Langley (E)		

[a] A = analysis; E = experimental.

that the electric and magnetic fields were arranged to establish a plasma flow like a solid body rotation.

Research on the coaxial flow system is predominantly carried out at the NASA Lewis Research Center, whereas the nuclear light bulb scheme is under investigation at the United Aircraft Research Laboratory. Consequently, at each of these laboratories relevant system studies are underway, including the examination of performance characteristics, engine dynamics and more detailed subjects such as radiation hazards to the crew of a plasma core rocket propelled space ship due to fission fragment radiation in the exhaust plume. The application of fissioning plasmas for magnetohydrodynamic power generation is being investigated at the Georgia Institute of Technology and the Computer and Applied Sciences Inc. Also, at the Georgia Institute of Technology, research has been initiated on the methods of using a plasma core reactor as a fast breeder. At the University of Florida some analysis is underway on a fissioning UF_6 engine, resembling a 4-cycle Otto engine.

It appears that at the present no integrated plasma core reactor research effort is underway comparable to the NASA program. Numerous independent studies on related subjects, such as nuclear pumped lasers, pulsed plasma-core reactors, radio-frequency induction heating, uranium emission spectra, and coupled fluid and neutronic oscillations, are contained in Ref. 8. The United States Air Force supports research on plasma core reactor-MHD power generation, and on colloid core reactor concepts,[22–24] on a small basis. Recent research results on plasma core reactor concepts are summarized by Ragsdale[25] and Latham,[26] expressing increased confidence in feasibility and high performance in rocket application. 5000 sec specific impulse is now envisioned for the coaxial flow system, and 3000 sec for the nuclear light bulb engine.[27] Based on results from reactor neutronics studies, cold-flow experiment results, and hot flow experimentation, Ragsdale[28] concludes: 1) no reason has been found indicating the plasma core reactor is not feasible; 2) specific impulses of 5000 sec appear feasible; 3) a complete test is required to demonstrate feasibility.

Fissioning Plasma

A complete test, as Ragsdale suggests, would involve a fissioning plasma confined in a flow configuration. An intermediate step toward Ragsdale's complete test may be possible in form of short time fissioning plasma experiments, which would relax the requirement of fluid mechanical confinement. Samples of fissioning plasmas must now be produced and be analyzed, particularly in regard to their radiative properties and in regard to their neutronics and plasma-dynamics stability, for nuclear plasma core research.

Research at the University of Florida is concerned with these particular problems. A fissioning plasma does not necessarily have to be critical by itself. If a sufficiently large external neutron flux is available, and if a fissionable gaseous fuel can be made dense enough, such that the fission fragment stopping distance becomes comparable or smaller than the dimension of the fuel volume, fissioning plasma samples can be produced with relative ease. Plans are to employ a ballistic piston compressor to compress $U^{235}F_6$, for a short time, to a density greater than 10^{19} particles/cm^3, and to expose the compressed plasma to the neutron flux of a research reactor.[29] The University of Florida research reactor, with a neutron flux density of 10^{12} n/cm^2-sec, is not powerful enough to heat $U^{235}F_6$ to high temperature. However, sufficient interaction between fission fragments and the plasma is expected to make spectroscopic studies possible. Substantial fission heating should be obtained if the experiment is conducted in a high flux reactor with a neutron flux density greater than 10^{15} n/cm^2-sec. Basic research on fissioning plasma properties is possible by this method. One can envision a gradual expansion of this technique to eventually incorporate short time flow-confinement and flow-heating experiments. However, such experiments may become as complicated as trying to achieve a steady-state fissioning plasma configuration, which in a similar fashion cannot achieve criticality unless its neutron flux is boosted by an external source.

For example, the United Aircraft Research Laboratory has forwarded suggestions[30] for in-reactor tests of a small scale nuclear light-bulb element, such as depicted in Fig. 1. Obviously, the steady-state testing of fissioning plasmas must involve mechanisms for heat removal; for the very high plasma temperatures such mechanisms are in principle readily at hand from the study of plasma core reactor concepts. Yet, cost and the need to test components dictate a step by step approach. Consequently, the United Aircraft Laboratory proposes that first a static fissioning plasma cell be tested, in which the heat is removed by a noble gas flow around that cell. The plasma must be kept away from the walls of that cell by an internal vortex flow of buffer gas, as in the case in the light bulb engine concept. In addition, the walls of the cell must be made of a highly reflecting aluminum, such that most of the radiation is reflected back to the plasma and its temperature is raised. In a next step, a sleeve of transparent wall material is to be inserted inside the aluminum vessel, to test its transmission of radiative power in a nuclear environment. In a final configuration, the heating of a propellant flow is to be attempted. Such tests may be conducted in the Los Alamos Nuclear Furnace, which in a test section can provide a neutron flux density of 10^{15} n/cm^2-sec. To offset the physical size of the test cell which is appreciably smaller than desired, the pressure and temperature of the fissioning plasma must be of the order of that envisioned for the conceptual light bulb engine, in order to obtain the substantial fission heating and a spectral distribution of radiative power needed for good engine performance. Data comparing the test cell and full-scale engine module are presented in Table 2. The numbers are based on a specific fission power of 31 kw/g U^{235}. Figure 2 shows how the plasma temperature and the power of radiation can be raised by increasing the specific power and pressure. The dashed lines, T_6, indicate the internal plasma temperature; the solid lines show the temperature of the radiating plasma surface. The pressure appears as a parameter.

At a fuel loading of 6.2 g and a specific power of 31 kw/g, the fractional power of the test cell is less than a half of a percent of the total reactor power. Therefore, the proposed test cell can be used only for investigation purposes.

Hyland[31] has conceived and analyzed a system in which the fractional power of a fissioning plasma within a reactor configuration could range from 14% to 25%. In this way, the fissioning plasma can be employed to do work, in particular, to produce thrust at high specific impulse. Obviously, this Mini-Cavity Probe Reactor comes close to Ragsdale's complete test. The Mini-Cavity Probe Reactor is not a full-scale gaseous core reactor assembly. Its power is only about one-thousandth of that envisioned for a full-scale

Table 2 In-reactor test of light bulb cell (Los Alamos Scientific Laboratory Nuclear Furnace)

	Full scale	Test cell
Length, cm	200	17.5
i.d., cm	40	6.5
Fuel loading (grams Uranium)	2,100	6.2
Power, kw	7,000,000	190
Plasma surface radiating temperature, °K	8,333	5940
Pressure, 10^5 N/m^2	500	500

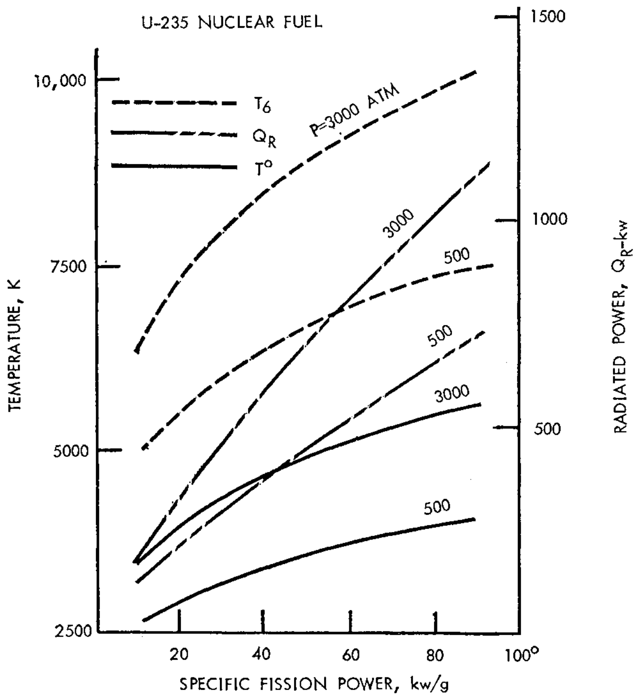

Fig. 2 Radiating temperatures and power levels for in-reactor test of nuclear light bulb unit cell.

gaseous-core reactor, and it is surrounded by a mantle of driving solid fuel elements for criticality. The scheme is shown in Fig. 3. In the center is a coaxial flow nuclear reactor configuration, embedded in a BeO moderator shell. Between this and another BeO moderator-reflector shell are located the solid driver fuel elements, similar to those used in the NERVA engine, but cooled by an inert gas instead of hydrogen. The whole assembly is contained in a pressure shell which can withstand a pressure of up to 1000 atm. Hyland's computations specify 121 cm for the diameter of the entire reactor and 60 cm for the plasma cavity. The power of the driver section would be 50 Mw and the cavity 10 Mw; this would provide specific impulse values of up to 2000 sec and thrust values of up to 900 N. One disadvantage of the system would be a low thrust-to-engine weight ratio; however, Hyland envisions the system as being useful for space propulsion for unmanned planetary missions. Another use could be for testing a small magnetohydrodynamic power conversion device. The Mini-Cavity Probe Reactor's exhaust temperatures, at 4000–5000°K are extremely interesting for MHD power conversion work because: 1) at such temperatures, a working fluid can become sufficiently ionized in equilibrium; and 2) methods appear to be at hand to control heat transfer for the survival of MHD generator wall structures.

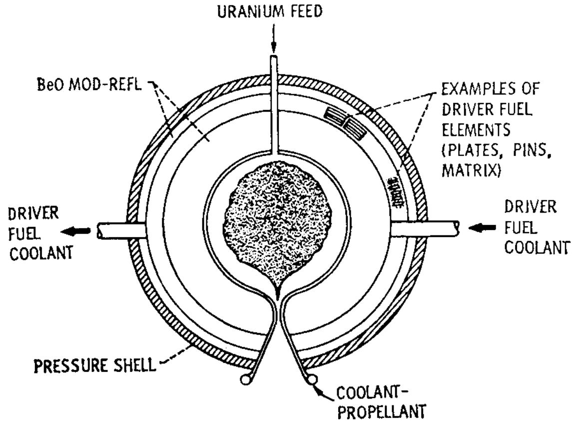

Fig. 3 Mini-cavity reactor.

In the course of plasma core nuclear reactor research and development, the Mini-Cavity Probe Reactor appears most significantly to be a stepping stone to a full scale gas core engine. Its feasibility has been theoretically demonstrated; however, questions relating to the radiative properties of fissioning uranium plasmas, confinement and fuel-propellant separation in a coaxial flow configuration remain to be resolved.

For research purposes, a test bed reactor, in which various fissioning plasma engine concepts could be investigated, would be most desirable. Such a test bed was recently proposed by Rom and Ragsdale.[32] The basic scheme would be similar to Hyland's Mini-Cavity Probe Reactor, however, with a differently shaped solid fuel driver section. Conventional fuel elements are to be used in order to avoid technology development, unessential for the test bed purpose. The solid fuel driver section is cylindrical for an easy insertion and removal of various plasma core engine configurations. The reactor is heavy water and beryllium moderated and housed in a pressure shell. Provisions are made for the through-flow of propellants and the feeding of nuclear fuel into the test section. A scrubber system for the handling of gaseous effluents is under examination. Partitioning of power of driver and test section is similar to that of Hyland's Mini-Cavity Probe Reactor. In the test section a neutron flux density of several times 10^{14} n/cm^2-sec up to 10^{15} n/cm^2-sec is achievable, sufficiently high to test coaxial flow configurations, nuclear light bulb elements, nuclear pumped lasers, and other advanced reactor concepts. Provisions can be made to conduct experiments on coupled plasma core reactor-MHD power generation.

Colloid Core Nuclear Reactor Concepts

Colloid core or fluidized bed nuclear reactors have a logical place in the description of gaseous core reactor development. They provide an intermediate step from the solid core reactor to the plasma core reactor. In the colloid reactor the nuclear fuel exists in a solid or liquid phase, in contrast to a gaseous phase which makes possible smaller reactor sizes than those of plasma core reactors. Colloid fuel particles, 10–100 μ in size, have a surface to volume ratio more than ten times that of solid fuel rods, resulting in a drastic increase of heat transfer rate. Colloid core reactors can therefore be compact at high power densities. In rocket application a thrust to weight ratio can be achieved surpassing that of any other nuclear propulsion scheme. Because there are no structural requirements for the colloidal fuel, it can be operated at higher temperatures than solid fuel rods, leading to a higher specific impulse than that of NERVA type engines. It is conceivable that colloid core reactors may also find application in terrestrial power networks for peak power demands. The high-temperature particulate fuel must be kept off the cavity walls by fluid mechanical means, similarly as in the plasma core concepts. In contrast to plasma core reactor schemes, heat transfer from the fuel to the propellant is not radiative but predominantly by convection. Separation of fuel from propellant is provided by centrifugal forces, which are generated either by a vortex flow within a cavity, or by fast rotation of a drum containing the colloidal fuel. When the propellant is injected tangentially, as in the case of the vortex flow scheme, or through the porous walls of the rotating drum, a state can be established in which the radial pressure drop due to the effluent propellant balances the centrifugal forces exerted on the fuel particles. It has been demonstrated that fuel containment and detachment from the walls can be achieved in this fashion.

The rotating fluidized bed reactor is schematically shown in Fig. 4. It has been studied at the Los Alamos Scientific

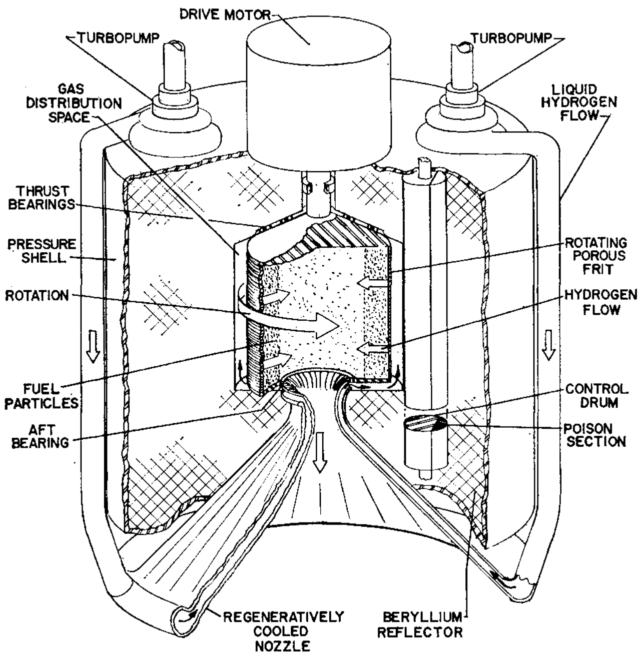

Fig. 4 Rotating fluidized bed reactor.

Laboratory[33] and the Brookhaven National Laboratory.[34] A rotational speed of less than 3000 RPM is required. The diameter of the drum is about 60 cm. The temperature of the exit gas would be 2700°K, as predicted from preliminary experimental results of research on uranium vaporization. The specific impulse would, as a consequence, be larger than that of the NERVA engine, namely, 970 sec. A summary of rotating fluidized bed engine characteristics is provided in Table 3.

The vortex driven colloid core reactor concept[35–36] is shown in Fig. 5. In contrast to the rotating fluidized bed reactor concept, this scheme does not require rotating machinery which in a nuclear environment could impose technological difficulties. It is also claimed that a more complete detachment of the particulate fuel from the walls can be achieved and, with a vaporization and condensation cycle of the submicron size fuel particles, temperatures up to 3500°K may be possible.

Such advantages over the rotating fluidized bed engine appear to be attainable by means of a quite complicated flow system produced by an array of tangential and peripheral wall jets. The requirement of boundary-layer control for preventing radial motion of fuel and subsequent fuel losses and for separating the fuel from the walls, dictate a dome-shaped cavity structure. Analysis shows that this shape of the cavity has adverse effects on the criticality, but not to the extent that the diameter of the vortex chamber needs to exceed one meter. Thus, the vortex-driven colloid-core reactor would have in common with the rotating fluidized bed reactor the advantage of compactness. After extensive testing of cold flow fluid mechanics,[37] sufficient knowledge has been gained to warrant a full fledged feasibility study of this

Table 3 Summary of rotating fluidized bed reactor characteristics[a]

Drum rpm	Core length, *m*	Engine weight, kg	Power, mw	Thrust, kp
1200	0.6	12,500	1400	27,000
2400	0.6	12,500	2800	58,000
1200	1.2	13,250	2800	58,000
2400	1.2	13,250	5600	116,000

[a] Core diameter = 0.6 m; [b] I_{sp} = 970 sec.

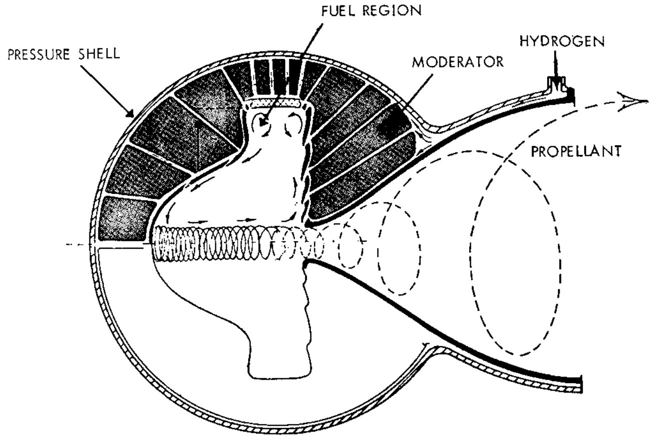

Fig. 5 Colloid core reactor.

concept. A first step might be to construct a full-scale, noncritical vortex chamber. In such a scheme, the vortex chamber could be exposed to neutron fluxes from external sources, such as in the previously described test bed reactor. In a gradual fashion, the vortex chamber could be loaded with an increasing amount of colloidal nuclear fuel, thereby permitting testing of various uranium-alloy powders, hot flow characteristics, reactivity, and possible instabilities of the coupled neutronics and fluid mechanics system.

It is projected that a colloid-core nuclear rocket could produce specific impulse values up to 1600 sec, a thrust to engine weight ratio of 5, and a thrust of 5000 kp.

Nuclear Piston Engine

Fission is an exothermic process. When it occurs in a gaseous nuclear fuel, thermodynamic cycles can be envisioned to use it for power generation in a similar way as in internal combustion engines. From plasma core reactor research, it is known that steady state configurations with appreciable void fractions for propellant flow and very high temperatures for high specific impulse, require large reactor dimensions and large critical masses. However, if enriched UF_6 is compressed in a transient fashion and, if the expansion of the fission heated uranium gas is employed for heat removal and power generation, reactor size and critical mass can be made much smaller. Of course, the advantages of very high temperatures are lost, and such schemes would not be directly applicable to advanced space propulsion. However, in comparison with plasma core driven MHD devices for power generation, as described for example by Clement et al.,[10] such "internal nuclear fission engine concepts" could circumvent many of the difficult problems of the plasma core reactor concept and in particular those connected with radiative energy transfer from the fissioning plasma to a working fluid. Power, for example, would be obtained mechanically as in a turbojet or in an Otto engine.

A turbojet scheme is suggested by Deresh,[38] in which gaseous enriched UF_6 is passed through a moderator-reflector region, where it is compressed and becomes critical, and then is expanded to drive a turbine for power generation. After this, it is recirculated to the reactor station.

A nuclear Otto engine is proposed by Schneider and Ohanian[39] as shown in Fig. 6. The engine has an intake stroke for drawing enriched UF_6 into a cylinder which is surrounded by a moderator-reflector. An exhaust stroke ejects the UF_6 plus fission products. Chain reaction is initiated by the neutron flux from an auxiliary source. An auxiliary precompression piston follows the working piston at high compression to provide time for the chain reaction

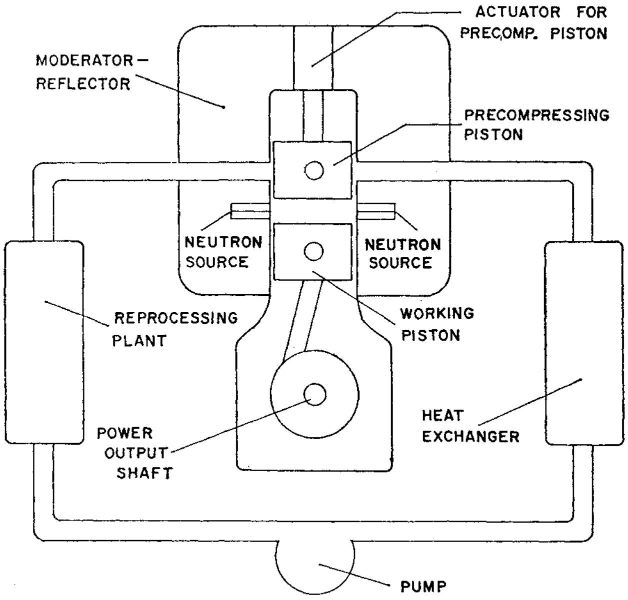

Fig. 6 Nuclear piston engine.

to build up and to assure that maximum power is released as the working piston passes top dead center. Thereafter, the reactor must be shut down rapidly to avoid release of fission heat after the working piston is already well in the next stroke. This is accomplished by retracting the precompression piston abruptly, causing a sudden high neutron leakage. External equipment removes fission products, cools the gas, and recycles it back to the engine. Thermodynamic efficiency can be improved with a UF_6-He mixture as a combined fuel-working fluid, because of increased average specific heat.

The cylinder has a minimum volume of 0.24 m^3 and a compression ratio of 10. The speed of the crankshaft is 100 rpm, and the critical mass is figured to be 2.1–2.9 k U^{235}. Performance calculations indicate power up to several megawatts per cylinder at an efficiency up to 60%.

Kylstra et al.[40] consider the requirement to rapidly initiate and to stop the neutron fluxes to be the most difficult problem. Another problem is to find suitable materials to handle the chemically aggressive UF_6.

Conclusions

For rapid missions to the nearby planets, plasma core rockets offer a propulsion potential unmatched by any other advanced propulsion scheme. Because of the criticality to be achieved in high temperature gaseous uranium fuel, plasma core reactors would operate at very high pressures, up to 1000 atm, and their power would range from 5000 to 50,000 Mw.

Apart from obvious technological difficulties, basic physics problems have to be solved before the feasibility of plasma core reactors can be demonstrated. It appears that the most critical question is that of the radiative power spectrum of fissioning plasmas. Research on fluid mechanical confinement of the gaseous uranium fuel and on fuel-propellant separation has yielded encouraging results. So have criticality investigations of stationary gaseous UF_6 at zero power. Fissioning plasmas have not yet been produced in the laboratory. Trends in forthcoming research indicate emphasis on in-core testing of uranium plasmas. In case of nonequilibrium radiation, modifications of present plasma core reactor schemes may be in order. In another respect, nonequilibrium radiation may be advantageous for nuclear radiation pumped lasers.

If temperature is decreased, appreciable reductions of pressure and power can result. Low-temperature plasma core reactors do not offer the same propulsion capabilities as high-temperature reactors, but are more amenable to technological realization. At 4000°K exhaust temperature, they appear to be ideal energy sources for MHD power converters. Operated in a repetitive, pulsed fashion, they could drive a piston and crankshaft, similar to an internal combustion engine. In this case, power transfer would be mechanical, rather than radiative, and the aforementioned radiative heat transfer problems would be circumvented.

At even lower temperatures, the uranium fuel becomes a solid and can exist in a colloidal form. Suspended by a radial propellant inflow, such fuel dust could be maintained within a rotating drum, or in a vortex chamber away from walls, and still yield higher propellant temperatures than a solid-core reactor, such as the NERVA.

In summary, there appears to be numerous ways to exploit fission energy for special applications in more beneficial ways than can be achieved in conventional reactor technology. For space propulsion, the high temperature plasma core reactor is most desirable. But fissioning plasmas may find important technological applications other than in space propulsion.

References

[1] Bussard, R. W. and DeLauer, E. D., *Nuclear Rocket Propulsion*, McGraw-Hill, New York, 1958.

[2] Meghreblian, R. V. and Stumpf, H. J., "Gaseous Core Reactors," Third Symposium on Advanced Propulsion Concepts, U.S. Air Force Office of Scientific Research and Flight Propulsion Div., General Electric Co., Cincinnati, Ohio, 1962.

[3] Bussard, R. W., *Proceedings of Nuclear Propulsion Conference*, United States Atomic Energy Commission, 1962, pp. 82–114.

[4] Rom, F. E. and Ragsdale, R. G., "Advanced Concepts for Nuclear Rocket Propulsion," *Nuclear Rocket Propulsion*, NASA SP-20, Dec. 1969.

[5] Cooper, R. S., "Proceedings of an Advanced Nuclear Propulsion Symposium," AEC Contract W-7405-Eng 36, 1965, Los Alamos Scientific Lab., Los Alamos, N.Mex.

[6] Rosa, R. J., "A Discussion of Nuclear Propulsion Using MHD Conversion Techniques," Rept. AMP 153, 1965, Avco Everett Research Lab., Everett, Mass.

[7] Maxwell, W. H., *Thrust into Space*, Holt, Rinehart, and Winston, New York, 1966, pp. 154–163.

[8] Thom, K. and Schneider, R. T., "Research on Uranium Plasmas and Their Technological Applications," *Proceedings of a Symposium*, NASA SP-236, 1971.

[9] Rom, F. E., "Comments on the Feasibility of Developing Gas Core Nuclear Reactors," TMX-52644, Oct. 1969, NASA.

[10] Clement, J. D. and Williams, J. R., "Gas Core Reactor Technology," *Reactor Technology*, Vol. 13, No. 3, Summer 1970, pp. 226–251.

[11] Oblow, E., "Neutron Thermalization in High Temperature Gaseous Media," Ph.D. thesis, 1970, Columbia Univ., New York.

[12] Eno, B. E., "Stability of Plane Vortex Sheet Between Gases Exchanging Heat by Radiation," Contract Rept. NGL 33-010-042, 1971, NASA.

[13] Lewellen, W. S., "A Review of Confined Vortex Flows," CR-1772, 1971, NASA.

[14] Ragsdale, R. G., "To Mars in 30 Days by Gas-Core Nuclear Rocket," *Astronautics and Aeronautics*, Vol. 10, No. 1, Jan. 1972, pp. 65–71.

[15] Fishbach, L. H. and Willis, E. A., "Performance Potential of Gas Core and Fusion Rockets: A Mission Applications Survey," *Second Symposium on Uranium Plasmas: Research and Applications*, AIAA, New York, 1971.

[16] Thom, K. and Schneider, R. T., "Nuclear Pumped Gas Lasers," *AIAA Journal*, Vol. 10, No. 4, April 1972, pp. 400–407.

[17] Schwenk, F. C. and Franklin, C. E., "Comparison of Closed- and Open-Cycle Systems," *Research on Uranium Plasmas and Their Technological Applications*, NASA SP-236, 1971, pp. 3–13.

[18] Ragsdale, R. G., "Are Gas-Core Nuclear Rockets Available?," TMX-52-435, 1968, NASA.

[19] K. Thom, "Review," *Research on Uranium Plasmas and Their Technological Applications*, NASA SP-263, 1971, pp. XI–XV.

[20] Lofthouse, J. H. and Kunze, J. F., "Spherical Gas Core Reactor Critical Experiments," CR-72781, 1971, NASA.

[21] Park, C. and Love, W. L., "Gas Core Nuclear Rocket with Fuel Separation by MHD Driven Rotation," *Research on Uranium Plasmas and Their Technological Applications*, NASA SP-236, 1971, pp. 139–148.

[22] Gritton, E. C. and Pinkel, B., "The Feasibility of the Gaseous-Core Nuclear Reactor for Electric Power Generation," RM-5721-PR, U.S. Air Force Contract F 44620-67-C-0045, 1969, Rand Corp. Santa Barbara, Calif.

[23] Tang, Y. S., Stefanko, J. S., and Dickson, P. W., "An Engineering Study of the Colloid Fueled Reactor Concept," *Journal of Spacecraft and Rockets*, Vol. 8, No. 2, Feb. 1971, pp. 129–133.

[24] Anderson, L. A., Hasinger, S., and Turman, B. N., "Two Component Vortex Flow Studies, with Implications for the Colloid Core Nuclear Rocket Concept," *Journal of Spacecraft and Rockets*, Vol. 9, No. 5, May 1972, pp. 311–317.

[25] Ragsdale, R. G. and Willis, E. A., "Gas Core Rocket Reactors —A New Look," TMX-67823, 1971, NASA.

[26] Latham, T. S., "Summary of the Performance Characteristics of the Nuclear Light-Bulb Engine," AIAA Paper 71-642, Salt Lake City, Utah, 1971.

[27] Ragsdale, R. G., "Second Symposium on Uranium Plasmas: Research and Applications," AIAA, New York, 1971.

[28] Ragsdale, R., private communication, April 1971, NASA Lewis Research Center, Cleveland, Ohio.

[29] Miller, E. B., Schneider, R. T., Thom, K., and Lalos, G. T., "Ballistic Piston Fissioning Plasma Experiment," *Second Symposium on Uranium Plasmas: Research and Applications*, AIAA, New York, 1971.

[30] Latham, T., private communication, April 1971, United Aircraft Corp., Hartford, Conn.

[31] Hyland, R. E., "A Mini Cavity Probe Reactor," *Second Symposium on Uranium Plasmas: Research and Applications*, AIAA, New York, 1971.

[32] Ragsdale, R., private communication, April 1971, NASA Lewis Research Center, Cleveland, Ohio.

[33] Grey, J., "The Liquid Core Nuclear Rocket," *Proceedings of an Advanced Nuclear Propulsion Symposium*, USAEC Contract W-7405-Eng 35, Los Alamos, N.Mex., 1965.

[34] Lindauer, G. C., Tichler, P., and Hatch, L. P., "Experimental Studies on High Gravity Rotating Fluidized Beds," Rept. 50013 (T-435), 1966, Brookhaven National Lab., Upton, N.Y.

[35] Tang, Y. S., Stefanko, J. S., and Dickson, P. W., "The Colloid-Core Concept—A Possible Forerunner of the Gaseous Core," *Research on Uranium Plasmas and Their Technological Applications*, NASA SP-236, 1971, pp. 29–34.

[36] Jackomis, W. and von Ohain, H., "Comments on the Colloid-Core Reactor," *Research on Uranium Plasmas and Their Technological Applications*, NASA SP-236, 1971, pp. 415–417.

[37] Jackomis, W. and Turman, B. N., "The Colloid Core Nuclear Reactor Concept," ARL-70-0167, 1970, Aeronautical Research Lab., Wright-Patterson Air Force Base, Ohio.

[38] Deresh, B. A., "The Physics of a Circulating Critical Gas," Ph.D. thesis, 1971, Univ. of California, Los Angeles, Calif.

[39] Schneider, R. T. and Ohanian, M. J., patent disclosure to NASA, 1970.

[40] Kylstra, C. D., Cooper, J. L., and Miller, B. E., "UF_6 Plasma Engine," *Second Symposium on Uranium Plasmas: Research and Applications*, AIAA, New York, 1971.