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CATALOG OF NUCLEAR REACTOR CONCEPTS

Part I. Homogeneous and Quasi-homogeneous Reactors

Section V. Reactors Fueled with Uranium Hexafluoride, Gases, or Plasmas

by

Charles E. Teeter, James A. Lecky,
and John H. Martens

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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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Technical Publications Department

March 1966

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PREFACE

This report is an additional section in the Catalog of Nuclear Reactor Concepts that was begun with ANL-6892 and continued in ANL-6909, ANL-7092, and ANL-7138. As in the previous reports, the material is divided into chapters, each with text and references, plus data sheets that cover the individual concepts. The plan of the catalog, with the report numbers for the sections already issued, is given on the next page, which is followed by pages listing the concepts included in this section.

Dr. Charles E. Teeter, formerly employed by the Chicago Operations Office at Argonne, Illinois, is now affiliated with the Southeastern Massachusetts Technological Institute, New Bedford, Mass. Through a consultantship arrangement with Argonne National Laboratory, he is continuing to help guide the organization and compilation of this catalog.

We wish to acknowledge the assistance of Miss Ellen Thro in the preparation of this section.

J.H.M.
March, 1966

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PART I. HOMOGENEOUS AND QUASI-HOMOGENEOUS REACTORS

SECTION V. REACTORS FUELED WITH URANIUM HEXAFLUORIDE, GASES, OR PLASMAS

Chapter 1. Introduction

This section covers reactors fueled with uranium hexafluoride, either as a gas or a liquid, and those fueled with other gases (such as vaporized fissile metals) or with plasmas (ionized gases). Although uranium hexafluoride is normally a solid or a gas (it sublimes at 56.4°C under atmospheric pressure[1]) its use as a liquid by keeping the system under pressure has been proposed. The liquid phase appears above the triple point of 147.3°F and 22 psia. The critical point is at P_c, 45.5 atm; and T_c, 446°F.[2] The reactors fueled with UF_6 are included in Chapter 2. Reactors fueled with other gases or with plasmas are in Chapter 3; in some of these, uranium hexafluoride is the original form of the fuel.

The UF_6-fueled reactors might be considered fairly conventional, in that the liquid or gaseous fuel is in a reactor system resembling those previously described for reactors fueled with molten salts or metals. The fuel may either circulate for cooling or be cooled by another material. In the reactors fueled with gaseous metals or with plasmas, on the other hand, the gaseous fuel, at extremely high temperatures, mixes with a gas that is both a rocket propellant and the reactor coolant. Sophisticated means are needed both to contain and later to separate the two gases. Most of the concepts in this section are for thermal reactors. Another moderator is therefore needed because with fluorine alone as a moderator the critical mass would be excessive.

The advantages of UF_6 as reactor fuels were recognized early in the wartime atomic energy program. It has a low cross section for parasitic neutron capture. Like other fluid fuels, UF_6 can be used in simple reactor systems and can be circulated to give heat to a boiler or other heat outlet. Fuel fabrication is not necessary, and both fission products and bred fissile material can be removed by simple means. The gaseous fuels have the added advantage that they are not limited by structural properties to any minimum temperature. There are, however, difficulties with the systems described in this section. Such problems as possible instability, corrosiveness, and fission-product deposition with UF_6 and the need for special containment methods for gases and plasmas at extremely high temperatures will be covered in Chapters 2 and 3. Two difficulties common to both types of gaseous reactors are that gases are poor conductors of heat and extremely large volumes are needed to obtain a critical mass because of the low density of gases.

An early suggestion for the use of uranium hexafluoride as a reactor fuel was in the concept by Anderson and Brown in 1942.[3] They proposed using liquid UF_6. Several other concepts were advanced during World War II and shortly thereafter. Concepts have been published intermittently since then, although no practical development has occured in the United States. Some of the suggestions published are too incomplete for data sheets to be made. In Russia, a low-power experimental reactor fueled with gaseous UF_6 began operation in 1957.[4]

The reactors fueled with high-temperature gases, such as the vortex and the plasma reactors, first received attention shortly after the war, especially for rocket propulsion. Several concepts have been published; much of this work deals with the problem of separating the gaseous fuel and the propellant gas. Work is continuing in this field, but details of some developments are not available.[5]

References

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2. J.W. Arendt, E.W. Powell, and H.W. Saylor, comps. and eds., A Brief Guide to UF_6 Handling, K-1323, Union Carbide Nuclear Co., Feb. 18, 1957.
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4. I.K. Kikoin, V.A. Dmitrievsky, Y.T. Glazkov, I.S. Grigoriev, B.G. Bubovsky, and S.V. Kersnovsky, Experimental Reactor with Gaseous Fissionable Substance (UF_6), Proc. 2nd U. N. Int. Conf. on Peaceful Uses of Atomic Energy, 9, pp. 528-534, United Nations, N.Y., 1958.
5. R.S. Cooper, Advanced Nuclear Propulsion, Nuclear News, 7, No. 11, pp. 40-41, Nov. 1964.

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Chapter 2. Reactors Fueled With Uranium Hexafluoride

Most of the concepts in this chapter are for thermal reactors. Use of uranium hexafluoride alone is not practical, and a moderator must be used with it. Gaseous (helium), liquid (heavy water or fluorocarbons), and solid (beryllium or graphite) moderators have been suggested.

The early concepts for UF_6 as a fuel employed either liquid or gaseous forms. Later, use of the gaseous fuel predominated. The advantages of a gas as fuel have been given in Chapter 1.

Some problems appear to need further investigation: stability of the compound under irradiation; corrosion of containment materials, especially under irradiation; settling out in the reactor of solid UF_6, fission products, or corrosion products; and the use of a moderator for which a reactor of reasonable size is possible: for example, if heavy water were to be used as has been suggested, a very large amount would be needed.

The only reactor reported to have actually operated with UF_6 as fuel was a Russian reactor that operated at low temperature (90°C) and low power (1.5 kW).[1] The Russian investigators, Kikoin et al., found that the decomposition of the UF_6 could be hindered by adding chlorine trifluoride. No experience on the stability under radiation at temperatures usual in power reactors has been reported.

The corrosivity of UF_6 toward metals has been investigated, but apparently not under conditions of irradiation. Heymann and Kelling[2] found that the corrosion rates at 80°C are low for nickel, copper, Monel, aluminum, alloy steels, and titanium alloys. For use at high temperatures, high-purity nickel and Monel appear to be best. Langlois[3] studied corrosion by UF_6 at high temperatures. High-purity nickel has the lowest corrosion rates above 800°C, and these rates are compatible with industrial uses. Between 550° and 700°C, however, corrosion of nickel and Monel by penetration along crystalline boundaries prohibits the use of these metals in this temperature range. Nickel of the highest purity, in which impurities responsible for intergranular attack are eliminated, should have greatly improved corrosion resistance. Dry UF_6 is normally contained in nickel or Monel. Lane[4] points out that the stability under irradiation of the protective film on these metals has not been investigated.

In 1947, Hull[5] described several concepts and discussed different aspects of using UF_6 as fuel. He listed many advantages, most of which have been given here already. Others he noted are: remote operation permits low-decontamination separation, with consequent simplified processing; and elimination of cooling permits a low inventory. He suggested hydrogen fluoride (b.p., 19.4°C), deuterium fluoride, and fluorocarbons as liquid solvent-moderators for homogeneous reactors. Helium or fluorocarbons would be coolants; water or liquid metals would have to be kept separate from the UF_6 because of the vigorous reactions that would occur on contact between them and the fuel. Graphite reacts so vigorously with UF_6 that it also would have to be separated. For containment materials, he suggested beryllium or nickel; aluminum or magnesium could be used if the problem of attack by UF_6 could be solved. Areas in which he thought investigation was needed are: corrosion of metals by uranium hexafluoride and fluorine; decomposition of UF_6 by fission-product fluorides, with or without solvents; and heat transfer by radiation and conduction through gaseous UF_6. A possible problem with liquid UF_6 is formation of gas bubbles that might cause instability.

In 1962, Wethington[6] proposed that research be carried out on a reactor fueled with a solution of uranium hexafluoride in a fluorocarbon. He cited the Russian experience and the work of others to show that although there would be some decomposition of UF_6 under radiation it could be controlled and it would be no worse than that of other compounds used in reactor technology. The fluorocarbons were suggested as promising moderators because published information indicates that they have good radiation stability. More investigation, however, would be needed on the concept.

As mentioned in Part I, Section I, of this catalog, Kerze has suggested that CaF_2 particles might be fluidized with a mixture of uranium hexafluoride and tetrafluoromethane (CF_4) to give a gaseous suspension. The feasibility of such a system would depend upon the mixture having sufficient moderating properties.

Another concept with uranium hexafluoride as a gaseous fuel has been discussed in Part I, Section I. Halik et al. proposed fluidizing fine particles of beryllium oxide moderator by the fuel gas.

Reactors Fueled With Liquid Uranium Hexafluoride

In 1942, Anderson and Brown,[7,8] of the Metallurgical Laboratory of the University of Chicago, suggested a reactor fueled with liquid uranium hexafluoride, as well as two variants of the original design. The reactor would be a breeder for producing plutonium. In the original design, the fuel-coolant-fertile material is natural or enriched liquid UF_6. The fuel circulates through tubes in a moderator of graphite or heavy water and goes to an external heat exchanger. The tubes are of uranium lined with nickel or other corrosion-resistant metal of low neutron-absorption cross section. A power of more than 100 MW(t) was expected. In the first variant, the central portion of the graphite matrix contains uranium rods, which are cooled by helium passing between the rods. At the periphery of the matrix are aluminum tubes containing liquid UF_6, which passes to an external heat exchanger. Breeding occurs in this outer region, which also serves as a reflector for the inner section of rods. In the second variant, there is a central spherical void, filled with heavy water, in the graphite matrix. The UF_6 circulates through tubes that are imbedded in the graphite and pass through the heavy water. A power of more than 100 MW(t) was expected.

Two 1943 concepts from the Metallurgical Laboratory, University of Chicago, are a Liquid Hexafluoride Pile and the Proposed Hanford Circulated-Hexafluoride, Thermal Pile.[9] Both are rated at 390 MW(t). In the first, the liquid UF_6 circulates through tubes of aluminum in a graphite moderator and out to a heat exchanger. This concept is a burner. In the second concept, the fuel circulates through tubes, immersed in 25 tons of heavy water surrounded by a graphite reflector, to an external heat exchanger. It is a breeder, with the fuel and fertile material being natural uranium moderated by heavy water.

In the U^{233} Hexafluoride Breeder,[10] suggested by Metallurgical Laboratory staff members in 1944, a fluorocarbon is utilized to dissolve $U^{233}F_6$, and thorium is the reflector-breeding blanket. The fuel circulates in tubes through the cylindrical core. The power is 100 to 200 MW(t).

A 1944 concept by Anderson is the Hex P-9 Pile (UF_6-D_2O pile).[8,11,12] This would require 686 tons of liquid UF_6("Hex"), probably highly enriched for a burner and natural uranium for a breeder, with 63 tons of heavy water ("P-9") as moderator. The fuel circulates through tubes in the moderator and out the top to a heat exchanger. Temperature limits to prevent both solidification and vaporization of the UF_6 are 75°C minimum and 150°C maximum.

Among the concepts described by Hull in 1947[5] were two for liquid UF_6 fuel. In one, the fuel is liquid UF_6 dissolved in either a liquid fluorocarbon or deuterium fluoride. The fuel circulates for heat exchange and removal of fission products. It has thorium tetrafluoride as fertile material. In the second concept, the fertile material, thorium tetrafluoride, is present as a fine powder within beryllium cylinders in a graphite bed.

Reactors Fueled With Gaseous Uranium Hexafluoride

In 1947, Hull[5] described the use of gaseous uranium hexafluoride, pointing out the advantages of the fluid fuel, and he described concepts originated by staff members of the Clinton Laboratories (now Oak Ridge National Laboratory). A preliminary study on such piles had been published earlier in the same year by Hull and Miles.[13]

In one design, the fuel, U^{233} or U^{235} in UF_6, is contained in porous beryllium tubes surrounded by impervious beryllium tubes. The pores are for trapping fission products. The tubes are within a graphite moderator core that is either in the form of rods in the center of a triangular lattice of fuel tubes or as annular tubes around them. The coolant, helium, circulates through the spaces in the core and out to a heat exchanger. A blanket of thorium powder in beryllium tubes within a graphite bed is the fertile material. Bred fissile material is leached out of the fuel by slowly circulating fluorine through the bed. The porous design of the fuel tubes, intended to facilitate trapping of fission products, allows the products to be removed from the UF_6 without chemical processing. This design was for a power of 96 MW(t).

In a modification of this design, the fuel circulates slowly through aluminum tubes outside the reactor. These tubes have large pores that do not trap the fission products. Thus removal of fission products is continuous, permitting better neutron economy. Because of their low cost, these aluminum tubes can be discarded instead of being reprocessed, but their use results in lower power potential. The power is 50 MW(t).

In a high-flux pile, the water coolant flows in an annulus between porous aluminum rods and beryllium cylinders. The rods contain U^{233} or U^{235} as gaseous uranium hexafluoride. Water cooling of the rods, according to the author, gives a high power output--32 MW(t)--but at a temperature too low for economic value in generation of electrical power. The moderator would be either water or beryllium. A reflector-blanket, like that in the previous design, permits breeding.

The originators believed that the uranium bred in the reactor could be removed fairly simply from the blanket of the finely powdered thorium fluoride contained in beryllium tubes. A hot mixture of helium and fluorine flowing through the powder would convert the products to fluorides. If the powder were fine enough and the temperature high enough, the PaF_5 and UF_6 could diffuse through the beryllium, be volatilized at the surface, and be carried away by circulating gas. The UF_6 could be separated in a fractionating column continuously as soon as the proactinium decays to U^{233}.

Two other concepts described were for reactors in which gaseous UF_6 circulates outside the reactor for removal of fission products and, presumably, for heat exchange. Both would operate at 230°C or higher. This temperature would avoid the need for excessive pressure. In one design, the fuel circulates through holes in a cylinder of beryllium moderator. The authors stated that fission products would settle out of the gas onto surfaces within the reactor, but using the gaseous form of UF_6 avoids the problem of gas bubbles that would occur with liquid UF_6. In the other design, the reactor is homogeneous, with the moderator being a gas, helium or carbon tetrafluoride (tetrafluoromethane). The operating pressure is 100 atm. The authors specify a spherical reactor with a diameter of 17 meters, but they stated that it was too large to be considered at that time. Breeding with a blanket would be possible, but the blanket would have to be extremely large.

A 1947 suggestion by Goodman[14] for a reactor fueled with gaseous UF_6 included the use of fluorine to stabilize the UF_6 and to act as additional moderator. The fuel either circulates to an external heat exchanger or remains fixed and is cooled by a coolant such as liquid metal passing through coils.

In 1953 Kerner proposed the use of the direct expansion of UF_6 in an internal-combustion engine, a turbine, or a reciprocator.[15] The gas is briefly compressed to supercriticality with a piston; it heats up and pushes back the piston. The gas returns to the core through a heat exchanger and a pump.

Reactor concepts in which this direct expansion were utilized were advanced in 1953 by Fortescue[16] and in 1957 by Clasen.[17] In the 1953 concept, the moderator is molten beryllium fluoride surrounding fuel tubes in a cylindrical nickel calandria. The reactor is under a pressure of 20 atm. Cadium absorbers in the heat exchangers were suggested for control of criticality outside the core. In the 1957 concept, the fuel is within a beryllium core; the turbine also is to be made of beryllium as much as possible. A graphite reflector surrounds core and turbine. A blanket of $U^{238}F_6$ is suggested if breeding is desired. A fast reactor is suggested as an alternative, but no details are given.

The expansion of gaseous $U^{235}F_6$ is the basis for another reactor, for which few details are given, in which a piston compresses the gas fuel in each end of a cylinder.[18-20] The compression causes criticality, and the gas expands to drive the piston to the opposite end, where the gas at that end expands. Thus a reciprocating action of the piston results. Each end of the cylinder is surrounded by a moderator and reflector. Direct conversion of the piston motion into electrical action by use of electromagnetic induction was proposed. The application of the concept to locomotives has been suggested, and in 1955 the USAEC awarded a contract for the study of a nuclear-powered reciprocating engine for locomotive propulsion to the Baldwin-Lima-Hamilton Corporation and the Denver & Rio Grande Railroad.[20] The chief problems visualized were in startup and in handling UF_6.

The only UF_6-fueled reactor to be built and operated is the Russian low-power [1.5 kW(t)] experimental reactor, fueled with gaseous UF_6. It went critical in 1957.[1,21] Russian investigators reported that the reactor operated satisfactorily. There was a pressure drop and a decrease in reactivity at a higher power level, which was attributed to dissociation of the UF_6 under irradiation. Adding chlorine trifluoride permitted stable operation. The fuel is highly enriched uranium hexafluoride, the moderator is beryllium, and the reflector is graphite. The fuel is within channels formed from aluminum tubes. Criticality is achieved by increasing the pressure. Control rods are provided. The authors suggest that improved methods of plutonium breeding might be possible with the UF_6 reactor. Some plutonium fluorides are not volatile, and plutonium hexafluoride, which has a high vapor pressure, is unstable. Thus special traps in the fuel-coolant system might be used to collect plutonium fluorides.

A 1958 concept by Baron[22] was for a circulating-fuel converter utilizing slightly enriched uranium in the gaseous fuel as both fuel and fertile material. The fuel flows by natural circulation through double-wall aluminum tubes set within graphite blocks in the core; helium, the intermediate coolant, is in the annulus between the tube walls and in an external heat exchanger to which the fuel circulates. The fuel leaves the core at 900°F. To maintain sufficient fuel circulation, a core height of 25 feet is specified. The power is 35 MW(e).

Hammitt,[23] in 1960, described a concept for a fast breeder reactor in which the UF_6 fuel and the sodium coolant flow through parallel tubes made from a nickel alloy. A blanket of fertile material surrounds the core. The power given is 300 MW(t).

Status

There appear to have been no sustained developmental programs leading to reactor experiments for reactors fueled with uranium hexafluoride. The early interest in uranium hexafluoride as a reactor fuel has resulted in comparatively few concepts and, aside from the low-power Russian reactor, apparently no practical development. Recent concepts have been few. Questions of practical reactor operation, such as stability and corrosivity of UF_6 under operating conditions of a power reactor, are not yet clarified.

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DATA SHEETS

REACTORS FUELED WITH URANIUM HEXAFLUORIDE

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No. 1 Hexafluoride Thermal Pile

Metallurgical Laboratory, University of Chicago

References: CN-362; U.S. Patent 2,990,354.

Originators: H.L. Anderson and H.S. Brown.

Status: Proposal, November 1942; patent issued, 1961.

Details: Thermal neutrons, steady state, breeder, for production of Pu. Fuel-coolant-fertile material: natural or enriched U in liquid UF_6. Moderator: graphite or D_2O. Core arrangement: liquid UF_6 circulates through tubes in moderator matrix to external heat exchanger. If moderator is graphite blocks, tubes are of U lined with Ni or other corrosion-resistant metal of low neutron-absorption cross section. If moderator is D_2O, tubes are of U lined with alloys of metals of low neutron-absorption cross section, such as Ni, Be, or Mg. With D_2O, 223 tubes, 8 cm ID, in cylindrical core 3.31 m long, 3.6 m diameter; 1.082 reproduction factor. With graphite, 1700 tubes, 4 cm ID, 8.30 cm long. Bred Pu can be recycled as fuel or separated chemically. Control: Cd or boron steel rods. Power: probably more than 100 MW(t). Breeding ratio: 1.029.

Code:	0312	12	31110	41	612	732	81X11	941	104
		14		42		733	81X12		

No. 2 Uranium Hexafluoride Thermal Pile

Metallurgical Laboratory, University of Chicago

References: CN-362; U.S. Patent 2,990,354.

Originators: H.L. Anderson and H.S. Brown.

Status: Proposal, November 1942; patent issued, 1961.

Details: Variant of concept in Data Sheet No. 1. Central portion of graphite matrix contains U rods cooled by helium, which passes through spaces between rods. At periphery of matrix, Al tubes contain circulating liquid UF_6, which passes to external heat exchanger. Outer graphite-UF_6 system acts as reflector to U-rod section and also serves as breeding section, from which Pu can be extracted.

Code:	0312	12	31110	41	612	732	81X11	941	109
			31716	42		733	81X12		

No. 3 Uranium Hexafluoride Thermal Pile

Metallurgical Laboratory, University of Chicago

References: CN-362; U.S. Patent 2,990,354.

Originators: H.L. Anderson and H.S. Brown.

Status: Proposal, November 1942; patent issued, 1961.

Details: Variant of concept in Data Sheet No. 1. Graphite matrix has central spherical void filled with D_2O. Al or U tubes imbedded in graphite pass through D_2O. UF_6 circulates through tubes.

Code:	0312	12	31110	41	612	732	81X11	941	109
		14		42		733	81X12		

No. 4 Liquid Hexafluoride Pile

Metallurgical Laboratory, University of Chicago

Reference: Unpublished report, 1943.

Originators: Staff members.

Status: Preliminary proposal, 1943.

Details: Thermal neutrons, steady state, burner. Fuel-coolant: liquid UF_6. Moderator-reflector: graphite. Fuel circulates through 170 Al tubes surrounded by graphite to external heat exchanger. Secondary coolant: H_2O. Moderator would probably have to be cooled by subsidiary water cycle. Fraction of fuel continuously withdrawn and put through evaporator for removing fission products. Core requires 15 tons of UF_6 and 25 tons of graphite. Fuel temperature in core: 194°F; temperature rise in center tube: 108°F. Power: 390 MW(t).

Code:	0313	12	31110	44	612	711	8XXXX	921	104

No. 5 Proposed Hanford Circulated-Hexafluoride Thermal Pile

Metallurgical Laboratory, University of Chicago

Reference: Unpublished report, 1943.

Originators: Staff members.

Status: Proposal, 1943.

Details: Thermal neutrons, steady state, breeder. Fuel-coolant-fertile material: natural U in liquid UF_6, which circulates to external heat exchanger. Pu^{239} bred from U^{238}. Moderator: D_2O. Reactor: vertical cylinder. Fuel circulates through core in tubes of Al, Be, Mg, or U. Tubes immersed in 25 tons of D_2O surrounded by graphite reflector. UF_6 enters at 176°F and leaves at 248°F. Operating pressure: 250 psia. Power: 390 MW(t).

Code: 0312 14 31110 41 612 732 8XXXX 921 104

No. 6 U^{233} Hexafluoride Breeder

Metallurgical Laboratory, University of Chicago

Reference: Unpublished report, 1944.

Originators: Staff members.

Status: Proposal, 1944.

Details: Thermal neutrons, steady state, breeder. Fuel-coolant-moderator: U^{233} in UF_6 dissolved in fluorocarbon; circulates to external heat exchanger. Fertile material: Th reflector-breeding blanket. Fuel circulates through tubes in cylindrical reactor. Temperature rise, fuel inlet to outlet: 90°F. Power: 100 to 200 MW(t).

Code: 0312 18 31209 45 622 7X6 8XXXX 931 101

No. 7 Hex P-9 Pile (UF_6-D_2O Pile)

Metallurgical Laboratory, University of Chicago

References: CE-1150; CE-1074; U.S. Patent 2,990,354, June 27, 1961.

Originator: H.L. Anderson.

Status: Preliminary design, 1944.

Details: Thermal neutrons, steady state, burner or breeder. Fuel-coolant: 686 tons liquid UF_6 (465 tons U). U, probably highly enriched in U^{235} for burner, probably natural for breeder. Bred Pu could be recycled as fuel. Moderator: 63 tons D_2O. Fertile material: U^{238} in UF_6. Core arrangement: fuel circulated by thermal syphon into reactor at bottom, through pipes in core, and out at top to external heat exchanger. Cold fluid returned to bottom of core. Maximum temperature: 150°C, to avoid need for high pressure to keep UF_6 liquid; minimum temperature: 75°C, to prevent solidification. Pressure: 150 psi, to prevent vaporization. Control: control rod and safety rod of Cd or boron steel; high rate of change of density and high temperature coefficient of expansion of UF_6. Power: 600 MW(t). Specific power: 1300-1600 kW/ton UF_6 at ΔT of 75-130°C; 550-650 kW/ton UF_6 at ΔT of 75-105°C.

Code:	0312	14	31110	41	612	711	81X11	9XX	104
	0313			44		732	81X12		
				46			84689		

No. 8 Homogeneous, Circulating Liquid UF_6 Fueled Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Preliminary proposal, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or producing high flux. Fuel-coolant-moderator: U^{235} in liquid UF_6 dissolved in either liquid fluorocarbon or DF. Fertile material: ThF_4. Fuel solution circulates for continuous removal of fission products and for heat exchange. Reactor would operate at 100°C and, with DF moderator, 15 atm. Containment material would probably be Ni rather than Al or Mg, despite the loss in breeding gain.

Code:	0311	17	31209	44	622	7X6	8XXXX	9XX	101
	0312	18	31213						

No. 9 Circulating Liquid UF_6 Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Preliminary concept, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or production of high flux. Fuel-coolant: U^{235} in liquid UF_6; could circulate to external heat exchanger. Moderator: Be. Reflector-breeding blanket: ThF_4 as fine powder in Be cylinders in graphite bed. Containment materials: Be, Al, or Mg. Pressure: 4 atm. Specific power: about 1 kW/kg UF_6.

Code: 0311 15 31110 44 612 776 8XXXX 941 104
0312

No. 10 Gaseous UF_6 Fueled, Gas Cooled Power Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Preliminary design, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or production of high flux. Fuel: U^{233} or U^{235} in gaseous UF_6. Coolant: helium. Moderator: graphite. Reflector-breeding blanket: fine powder of ThF_4 in Be cylinders in graphite bed. Bred fuel removed by slow leaching out of PaF_6 and UF_6 by slow circulation of F_2 through the bed. Core structure: cylinder, 99 cm radius and 192 cm high. Fuel vol: 5900 liters, with 15.8 kg U^{235}. Fuel contained in porous Be fuel tubes, 1 cm diam., providing 75% voids; each porous element core enclosed in solid Be shell, 1.1 mm thick, which closes pores on outside. Total fuel tubes: 5151; each contain 3.07 g U^{235}. Graphite moderator either of rods at the center of triangular lattice of fuel tubes or annular tubes around them. Helium circulates through voids in core with ΔT of 750°F and an outlet temperature of 1250°F. Reactor designed to operate at 800°C and 10 atm. Since fission products become trapped in fuel-element pores, they are removed from UF_6 without chemical processing. Control: rods. Breeding ratio: slightly less than 1 with U^{235}, slightly more with U^{233}. Specific power: 6000 kW/kg U^{235}. Power: 96 MW(t).

Code:	0311	12	31716	44	662	776	81X1X	941	106
	0312			45					

No. 11 Gaseous UF_6 Fueled, Gas Cooled Power Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Preliminary concept, 1947.

Details: Variant of concept in Data Sheet No. 10. Gas fuel circulates slowly through porous Al fuel tubes (90% voids) outside reactor for continuous fission-product removal that makes possible better neutron economy. Fuel tubes have large pores that do not trap fission products as small pores in Be tube do. Use of Al, which allows tubes to be discarded rather than reprocessed, causes lower power potential from reactor. Pressure: 10 atm. Specific power: 2500 kW/kg U^{235}. Power: 50 MW(t).

Code: 0311 12 31716 44 662 776 81X1X 941 106
0312 45

No. 12 Water-cooled, High Flux, UF_6 Fueled Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Conceptual design, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or production of high flux. Fuel: U^{233} or U^{235} as UF_6. Coolant: H_2O. Moderator: H_2O or Be. Reflector-breeding blanket: ThF_4 in blanket similar to that in the concept in Data Sheet No. 10. Core structure: 240 liters of fuel, containing 3.25 kg U^{235}, within porous Al rods encased in Be tubes. Fuel elements mounted in hexagonal pattern; interstices filled with solid Be, leaving 3-mm annulus around each fuel element for H_2O flow at 17 ft/sec. Containment: Be, Al, or Mg. Temperature: 260°C. Pressure: 50 atm. Specific power: 10 MW/kg U^{235}. Power 32 MW(t).

Code: 0311 13 31101 44 662 776 8XXXX 941 106
0312 15 45

No. 13 Circulating Gaseous UF_6 Fueled Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Preliminary design, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or production of high flux. Fuel-coolant: U^{235} in gaseous UF_6. Moderator: Be. Reflector-breeding blanket: ThF_4 in blanket similar to that in concept in Data Sheet No. 10. Core structure: Be cylinder with longitudinal holes through which fuel circulates. Containment: Be, Al, or Mg. Pressure: 20 atm.

Code: 0311 15 31710 44 662 776 8XXXX 941 104
0312

No. 14 Homogeneous, Circulating Gaseous UF_6 Fueled Pile

Clinton Laboratories

Reference: MonN-336.

Originators: Staff members.

Status: Proposal, 1947.

Details: Thermal neutrons, steady state, could be used for power production, breeding, or production of high flux. Fuel-coolant-moderator: U^{235} in gaseous UF_6 mixed with helium or CF_4 (moderating gas). Reflector-breeding blanket: ThF_4 in blanket similar to that in the concept in Data Sheet No. 10. Fuel circulates outside reactor for removal of fission products and heat exchange. Reactor vessel: sphere, 17 m in diameter. Pressure: 100 atm. Containment: Be, Al, or Mg.

Code: 0311 18 31710 44 662 776 8XXXX 941 101
0312 19

No. 15. Gaseous UF_6-Fueled Reactor

Reference: The Science and Engineering of Nuclear Power, I, pp. 303-6.

Originator: Clark Goodman.

Status: Proposal, 1947.

Details: Thermal neutrons, steady state, burner. Fuel-coolant-moderator: enriched UF_6 with F_2 added to stabilize molecular UF_6 and to act as additional moderator. Gas either circulates to external heat exchanger or remains within reactor and is cooled by a coolant, such as liquid metal, passing through coils.

Code:	0313	1X	31710	44	662	711	8XXXX	9XX	101
		17	31106						105

No. 16. Direct Expansion UF_6-Fueled Reactor

UKAEA

References: British Patent 799,575.

Originator: Peter Fortescue.

Status: Conceptual design, 1953; patent issued, 1958.

Details: Thermal neutrons, steady state, burner or breeder, with direct expansion of fuel to turbine. Fuel-coolant: U^{235} in gaseous UF_6. Moderator: Be as molten BeF_2. Core structure: moderator in cylindrical Ni calandria substantially filling Ni-lined cylindrical pressure vessel about 3 feet long. Fuel flows through calandria tubes. Heat produced by critical mass causes fuel to expand directly to turbine. Fuel then goes to external heat exchanger and is recycled to core. Pressure: 20 atm. Control: as gas expands, reactivity and heat decrease; Cd absorbers can be included in heat exchangers to prevent criticality outside of core.

Code:	0312	15	31710	44	662	711	84699	9XX	104
	0313						81XX2		

No. 17 Direct Expansion UF_6-Fueled Reactor

Metallgesellschaft Aktiengesellschaft

References: United Kingdom Patent 855,155; French Patent 778,697; German Patent 1,110,334.

Originator: Hermann Clasen.

Status: Conceptual design, 1957; United Kingdom patent issued, 1960.

Details: Thermal or fast neutrons, steady state, breeder or burner with direct expansion of fuel to turbine. Fuel-coolant: U^{235} or U^{233} in gaseous UF_6. Moderator: Be; reactor core and turbine to be made of Be as far as possible. Reflector: graphite around core and turbine. Fuel contained in conical core, which serves as turbine housing. Fission of U, initiated by Ra-Be source, expands UF_6 directly to rotor. Vapor is then recompressed and recycled to core. If breeding is desired, $U^{238}F_6$ would surround turbine. Pressure: 35 atm., high enough to begin chain reaction. Containment: for thermal reactor, pure Be core surrounded by shielding of Monel alloy. For fast reactor, core and turbine of Ni-Cu alloy. Control: decrease in pressure from expansion of UF_6.

Code:	0112	15	31710	44	662	711	84699	921	104
	0113			45		7X5			
	0312								
	0313								

No. 18 UF_6-Fueled Reactor for Locomotive Propulsion

Baldwin-Lima-Hamilton Corp. and Denver & Rio Grande Western Railroad

References: Soviet J. At. Energy (English Transl.), 2, No. 5, p. 587 (1957); Railway Age, 138, No. 14, p. 7; 141, No. 16, pp. 20-21.

Originators: Staff members.

Status: Proposal, 1955.

Details: Thermal neutrons, pulsed, burner. Fuel: U^{235} in gaseous UF_6. Fuel contained in two ends of cylinder having a piston. Reciprocating action by piston compresses gas in each end alternately, causing criticality; piston pushed to opposite end of cylinder by expansion of fissioning fuel. Each end of cylinder surrounded by moderator and reflector.

Code:	0323	1X	3XXXX	44	662	711	8XXXX	921	109

No. 19 Gaseous UF_6 Reactor

Institute of Atomic Energy, Academy of Sciences, USSR

References: Proc. 2nd U.N. Int. Conf., 9, pp. 528-534; AECL-1011.

Originators: I.K. Kikoin et al.

Status: Experimental operation, 1957.

Details: Thermal neutrons, steady state, burner. Fuel-coolant: 90%-enriched U in gaseous UF_6. ClF_3 could be added to make UF_6 stable under irradiation. Moderator: Be. Reflector: graphite. Core structure: fuel in cylindrical core with 148 square Al channels, 40 x 40 cm, in square lattice under 1.3 atm. Channels divided into sections connected to main header coupled to gas-pumping system, allowing simultaneous filling of channels. Total vol: 314.liters. Graphite reflector surrounding core is 50 cm thick on sides and 60 cm on top and bottom. Criticality reached by heating fuel to 80-90°C, to cause a progressive increase in pressure. Containment: sealed protective vessel. Asbestos in space between reflector and this vessel to prevent heat loss. Control: one horizontal and 4 vertical channels for control and safety rods--steel tubes filled with B_4C. Manual control: 2 tubular steel rods filled with B_4C. Power: about 1.5 kW(t).

Code: 0313 15 31110 44 662 711 81111 921 104
81211

No. 20 UF_6 Gas Phase Reactor

Burns and Roe, Inc.

Reference: Nucleonics, 16, No. 8, pp. 128-133, Aug. 1958.

Originator: S Baron.

Status: Conceptual design, Aug. 1958.

Details: Thermal neutrons, steady state, converter. Fuel-coolant-fertile material: 8%-enriched uranium in gaseous UF_6 with BrF_3 added. Moderator: graphite. Reflector: graphite. Core structure: core diameter 7.5 ft; height 25 ft. Fuel flows inside Al double-tube-wall channels; intermediate coolant (helium) in annulus between tube walls and in external heat exchanger. Tubes set within graphite moderator blocks. Fuel, under 30 atm max. pressure, enters core at 450°F and leaves at 900°F. Fuel flows by natural circulation; core height of 25 ft necessary for maintenance of sufficient fuel velocity. Since fuel is 8% enriched, some Pu forms, but only as incidental product. Control: negative temperature coefficient. Power: 35 MW(e).

Code: 0311 12 31710 42 662 7X3 84699 921 104

No. 21 Gaseous-Fuel Fast Breeder Reactor

Worthington Corp.

Reference: Nucl. Power, 5, No. 47, pp. 125-126, March 1960.

Originators: F.G. Hammitt and David Aronson.

Status: Conceptual design, March 1960.

Details: Fast neutrons, steady state, breeder. Fuel: U^{235} in gaseous UF_6. Coolant: Na. Fuel and coolant flow through parallel tubes made of Ni alloy, such as Inconel X. Containment: Inconel X. Radial breeding blanket surrounds core. Control: negative temperature coefficient; pressure of UF_6 in tubes controlled. Power: 300 MW(t).

Code: 0112 11 31103 44 662 7XX 83699 9XX 109
84699

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Chapter 3. Reactors Fueled With Gases or Plasmas

Concepts in this chapter included those in which the fuel is a nonionized gas or an ionized gas (plasma) at extremely high temperatures. Before operating conditions are reached, the fuel may be a solid or liquid. A concept for such reactors was described by Shepherd and Cleaver in 1949.[1] The advantage of a gaseous fuel, its capability for attaining temperatures too high for liquids or solids, is the basis for the suggested use of most of these concepts for rocket propulsion. In rocket propulsion, the propellant gas would act as coolant for the reactor. For interplanetary flights, the nuclear reaction would have to raise the propellant temperature by regenerative heating to about 10,000°R. The name "cavity reactor" was suggested by Safonov[2] for those reactors in which a core of uniformly distributed gaseous fuel is surrounded by a moderator-reflector of uniform density. They were so named because the flux distributions of dilute fuels approach the flat distribution of an empty cavity and because of the gaseous fuel is at near-vacuum as it is used in the system.

General

In the simplest kind of a cavity reactor, the fuel and coolant are fed separately into the core region, where they mix intimately, and are expelled from the core. Separation is done externally. Because cost and weight must be minimized in a rocket system, the fissionable material must be separated from the coolant and conserved; yet, the coolant, which is also the rocket propellant, must be able to pick up energy efficiently from the fuel for the system as a whole to operate effectively. For this reason, several sophisticated methods of achieving fuel-coolant separation have been considered. In some, the two fluids are separated after mixing; in others, they are kept separated in the core.

Configurations to keep the fuel and coolant separated while they both are in the core region include (1) coaxial flow, (2) magnetohydrodynamic means, and (3) magnetic fields. These methods of separation are discussed under the concepts taken up in this chapter.

In many concepts, the fuel is a plasma, which raises problems of containment.

There are two ways of restricting the interaction between high-temperature gases and adjacent solid materials: (1) limit the interaction in time; or (2) limit the interaction in space by eliminating all solid material in the vicinity of the hot gas and replacing it with an electromagnetic field.

Nelson[3] has suggested that, despite these problems, plasmas should be considered because of their advantages. A plasma can be confined electromagnetically, separating it from the surrounding solid materials with which it would otherwise react; it can be accelerated by electromagnetic means to greater supersonic velocities than are obtainable with a nonionized gas accelerated by means of fluid jets; and it can be separated from the nonionized propellant. The simplicity of the system relies on the fact that the ionized fuel is confined by a field barrier, whereas the nonionized hydrogen propellant diffuses through the field. Limitations on the principal system variables in plasma systems are given in Table 1.[3]

Table 1. Limitations on Principal System Variables

Variable	Lower Limit	Upper Limit
Size	Criticality	Wt of moderator-reflector Excessive fuel inventory Excessive magnetic field vol Fabrication difficulties
Temperature	Fuel ionization temperature	Radiative heat transfer to walls Propellant ionization
Magnetic field strength	Plasma confinement Cost of maximum tolerable fuel loss by diffusion	Electric power requirements Coil wt.
Electrical field strength	Rotation of plasma too slow; thus instability and intolerable axial diffusions	Supersonic-flow problems Excessive voltage drop across plasma
Propellant flow rate	Flow channel across section excessive (moderator too heavy)	Excessive pressure Helmholtz waves (propellant swept through nozzle)
Plasma rotational velocity (homopolar configuration)*	Plasma instability (maximum permissible propellant flow rate too slow) Approaches diffusion properties of simple magnetic bottle	Shock waves and boundary-layer turbulence Rotational kinetic energy wasted in spinning propellant

Nelson suggested confining plasma by either a simple magnetic bottle with mirrors at each end or a homopolar device, which provides more reactor control.

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*Fissioning plasma rotates by being electromagnetically pumped by crossed electric and magnetic fields. Centrifugal force associated with the rotation tends to keep the plasma away from regions where leakage would most likely occur.

In reactors such as the vortex reactors, in which the propellant and fuel mix intimately, the cooling mechanism is either regenerative heating or the direct heating of the gaseous propellant by the slowing down of fission fragments. In systems where the fuel and propellant do not mix, such as in the magnetic containment of ionized fuel or coaxial flow, heat transfer from the fuel to the propellant is principally by thermal radiation.

In those systems in which the primary energy-transfer mechanism is thermal radiation, the radiation must be attenuated by the propellant gas before it can reach the cavity walls. Also, at certain temperatures, the gases become transparent to radiation. Hydrogen gas is transparent between 5000°R and 12,000°R. Graphite dust can be used to "seed" hydrogen for radiation absorption but it sublimes at 6800°R.

Concepts

In Shepherd and Cleaver's 1949 concept for rocket propulsion,[1] the fuel and coolant are fed into a core area formed by the moderator-reflector. Here they mix and the critical mass is reached. The propellant-coolant must be heated to 3000-5000°K. The fuel material and moderator material are not specified, but the original form of fuel might be a powder, a liquid suspension of a powder, a wire (extruded into the chamber) or a liquid compound of fissile material. The coolant could be hydrogen, deuterium, helium, ammonia, or steam. Control might be possible by varying the amount of fuel fed to core. A specific power of 100 MW per metric ton was sought.

In 1955 Safonov[2] advanced a design for a cavity reactor, with different arrangements to fit different purposes. The gaseous fuel, of low density at the high operating temperature of the reactor, could be U^{233} or U^{235}, as well as plutonium. The fuel is in a region surrounded by a moderator-reflector of heavy water, beryllium, or graphite. This moderator-reflector region could contain fertile material for breeding and a thermal-absorbing material for control. The coolant, an unspecified gas, is pumped around or through the fuel. An inherent safety factor is stated to be the prompt neutron regeneration time, which is as long or longer than that for solid-fuel thermal reactors. The high neutron flux produced might make the reactor suitable for engineering testing. Other modifications are: a gas- or air-cooled power reactor; zirconium tubes carrying liquid-metal coolant in the center and fissile material at or near the outer surfaces; liquid metal to carry the fissile material; or uranium hexafluoride fuel. The gas- or air-cooled and the UF_6-fueled reactors could be used to operate a turbine; the UF_6-fueled reactor would operate by direct expansion. In all, the fuel would be gaseous in reactor operation.

The direct conversion of mechanical energy produced in a pulsing plasma to electrical energy is proposed in a 1957 concept by Colgate and Aamodt.[4] The gaseous fuel, plutonium or uranium, is partially ionized at the temperature of operation. A magnetic field compresses the gas at one end of a cylindrical graphite fuel container, which is blanketed by heavy water (the coolant-moderator-reflector). The blanket is contained in aluminum or zirconium. As the gas is compressed, criticality occurs to release fission energy, which drives the gas to the other end of the container. Here it is again compressed and driven back by the fission energy. The oscillation of the gas between the two ends causes the portion of the gas directly behind the shock front to become highly ionized. As this plasma, acting as a conductor, moves through the magnetic field it induces an electrical current in an external electrical circuit. The power is 500 MW(e).

A high-temperature (15,000°K) reactor with electromagnetic confinement of fuel was described by Taylor in 1957.[5] The fuel, a plasma of U^{233}, U^{235}, or Pu^{239}, is in a core surrounded by the moderator-reflector, heavy water or beryllium. The coolant-propellant, hydrogen, passes through the core, where it gains energy, and leaves the reactor. The fuel is retained in the core by externally applied electromagnetic fields, which do not retain the nonionized propellant.

A preliminary design for a reactor of high power, called a "fizzler", was published by Bussard and DeLauer in 1958.[6] Designed to produce 5000 MW(t), this reactor was intended for rocket propulsion. Fuel (U^{233}, U^{235}, or Pu^{239}) and coolant (rocket propellant) mix in a core region formed by the unspecified moderator-reflector. Here criticality heats the fuel to above its vaporization temperature. The authors conclude that at the operating pressure considered reasonable (1000 psi), greatly excessive amounts of fuel would be lost.

Two 1959 concepts by Grey[7] were for rocket propulsion; few details were given. In one, the "fizzler" reactor, the fuel is mixed in a solid with the propellant, which is also the moderator. Removal of a portion of a cadmium control rod causes criticality, which vaporizes the fuel. The other concept is for a series of subcritical solid-fueled reactors. They are made temporarily highly supercritical when propellant gas containing fissile material is passed through them. The gas increases in temperature as it passes through the series of reactors until it comes out of the nozzle at a very high temperature.

Meghreblian described two cavity reactors of similar design that were intended for rocket propulsion. In both, two fuel zones were used, one of solid fuel and one of gaseous. In one,[8,9] a central moderator matrix contains the gaseous fuel and is surrounded by a solid fuel zone. In the other,[10] the solid is in the central portion and the gaseous fuel in the moderator matrix surrounds it. A reflector-moderator surrounds the core in both. The coolant, which is the rocket propellant, passes into the core, and picks up heat, first from the solid-fuel region and then from the gaseous fuel. No details of materials were specified.

The concept for a vortex reactor,[11-17] proposed by Kerrebrock and Meghreblian,[11,12] emphasized the separation of fuel and propellant, after mixing, by the formation of a vortex. The fuel (gaseous uranium, plutonium, or their compounds, in hydrogen) is contained as a jet-driven vortex in many long thin tubes imbedded in moderator material (beryllium oxide or graphite). After the fuel and coolant mix, the mixture spirals into the center of core, is drawn off axially, and is discharged. Because of the radial pressure gradient within the vortex, the heavier fuel molecules would be contained in a steady-state concentration distribution in the vortex, while the lighter propellant gas would diffuse through it.[16] A core temperature of 10,000°R and a power of 500 MW(t) were sought. In addition to the method described for attaining a vortex, magnetic fields, magnetic mirrors, or magnetohydrodynamics (externally imposed electrical and magnetic fields) might be used.

Certain variables--tube diameter, mass flow rate per unit tube length, jet injection velocity, and wall pressure--affect vortex strength.[15] The strength increases as tube diameter decreases and as mass flow rate increases, and it increases with subsonic rather than supersonic injection. Because vortices develop turbulent instabilities, particularly at the periphery, several configurations designed to produce a laminar flow by stabilizing the shear boundary layer on a concave wall have been considered. They are: (1) bleed-off of the boundary layer through a uniformly porous wall, (2) injection of heavy gas uniformly through a porous wall, (3) wall cooling, and (4) bleeding off some of the total flow axially at radial positions between the tube center and the wall so that the exit radial flow is held to an allowable rate, based on diffusion considerations (bled-off flow would be recirculated).[15]

Three variants have been explored in somewhat more detail.

One variant includes a rotating porous wall through which the propellant is introduced.[15] Turbulence is reduced because the boundary layer on the outer wall is effectively eliminated. However, to produce significant thrust levels, many small tubes would still be required because mass flow per unit of vortex tube length remains limited by the diffusion process. There is a severe mechanical problem in combining high temperature, high speed, and many tubes.

In another variant, excess mass flow, which has been jet-injected into the system and which causes the vortex instabilities, is bled off and recirculated. The heavy mass could be helium + C_8F_{16} or Freon-12 (CCL_2F_2).[15]

The third variant[17] is based on the same principle as the vortex reactor except that, to reduce turbulence and to dissipate instabilities, several vortices are generated in a single container in square array, by means of fluid injection from tubes located in the container. The injection and exit pattern is designed so that adjacent vortices roll on one another, producing zero shear at the interfaces. This eliminates a major source of instability, turbulence at the periphery of the vortices that are located in the interior of the matrix. Also, since wall area per vortex decreases as the number of vortices increases, the wall area per vortex approaches the area of a single injection tube as the number of vortices becomes infinite. This greatly reduces the momentum removed from the system by the action of shear forces, which is proportional to the wall area involved.

In the Coaxial Flow Reactor of Weinstein and Ragsdale,[18,19] the fuel, fully ionized gaseous Pu^{239}, and the hydrogen coolant are fed into the core, which is surrounded by a moderator of graphite, heavy water, or both. Here criticality occurs. The fuel is fed into the center of the core, and the hydrogen enters around the periphery at a flow rate different from that of the fuel. Because of the differing axial velocities, the two streams do not mix. They are exhausted from the core through a nozzle. The average reactor temperature is about 10,000°R. Heat transfer from the fuel at this temperature is primarily by radiation. The thermal energy must be attenuated by the propellant to avoid overheating the walls (maximum temperature 5000°R). Because hydrogen is transparent to radiation between 5000° and 12,000°R, "seeding" with an absorber is necessary for radiative heat transfer. Solid particles, such as graphite dust, might be adequate up to the sublimation point of graphite (6800°R).

A recent design by staff members at the Hanford Atomic Products Operation is for a system to produce electrical power by a magnetohydrodynamic generator and a secondary heat exchanger.[20] Both would derive their power from a reactor fueled with fissionable gas such as uranium hexafluoride. The gas flows in a toroidal container at a density below that of criticality, except in the core region. Here it is compressed to give criticality, and the gaseous fuel is ionized. The plasma flows through a magnetohydrodynamic channel, which consists of rails carrying current, and two large cryogenic magnets, which supply the cross-current field. The plasma stream provides an emf to generate current flow between the rails. The gas flows to a turbine and then to a heat exchanger to produce steam from the remaining usable heat. After purification, the gas is returned to the system.

Status

A brief summary of a conference held at the Los Alamos Scientific Laboratory in April 1964 indicates recent work on some gas- and plasma-fueled reactors, although few details are given.[21]

Ragsdale reported further work on the coaxial-flow reactor described earlier in this chapter. Research was reported in heat transfer, hydrodynamics, and nucleonics. Larger flow area, plus higher propellant velocity, is thought to give an economic ratio of propellant to fuel in the exhaust gas. The ratio would be about 50.

In the "Glo-Plug" reactor, the gaseous fuel is contained within a double-walled transparent tube. Hydrogen flowing between the walls cools the tube. Heat transfer is by radiation through the tubes and coolant. The propellant, seeded with material to make it absorbent, absorbs the radiation. Quartz was being considered as material for the tubes.

Stumpf and Rosenweig, in reporting experiments on vortices, discussed the possibility of combining vortex containment with other methods. For example, fuel might be contained in some cells of a matrix of vortices and propellant could flow through others.

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DATA SHEET

REACTORS FUELED WITH GASES OR PLASMAS

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No. 1 Gaseous Reactor for Rocket Propulsion

Reference: J. Brit. Interplanet. Soc., 8, No. 1, pp. 23-37, Jan. 1949.

Originators: L.R. Shepherd and A.V. Cleaver.

Status: Preliminary concepts, 1949.

Details: Thermal neutrons, steady state, burner, for rocket propulsion. Fuel: material not specified, but could be in initial form of: (1) powder; (2) powder suspension in liquid; (3) wire extruded into chamber; or (4) liquid compound of fissile material. Authors favor the last. Fuel would vaporize at reactor operating temperatures. Coolant: H_2 or D_2; helium; ammonia, either NH_3 or $N^{15}D_3$; or steam, either H_2O or D_2O. Moderator-reflector: external, material unspecified. Fuel and coolant each fed into core area formed by moderator-reflector, where they mix intimately and where critical mass is formed. Reaction must heat coolant, which is rocket propellant, to 3000-5000°K. Heated coolant is exhausted through nozzle. Control: varying amount of fuel fed into the core. Specific power: 100 MW/metric ton.

Code:	0313	1X	31701	4X	66X	711	83799	921	107
			31702						
			31713						
			31715						
			31716						

No. 2 Cavity Reactor

Rand Corporation

Reference: RM-1520.

Originator: George Safonov.

Status: Preliminary concept, 1955.

Details: Thermal, possibly epithermal neutrons, steady state, burner or breeder. Fuel: U^{233} or U^{235} possibly in UF_6; Pu^{239}. Coolant: unspecified gas. Moderator-reflector: D_2O, Be, or graphite. Fertile material could be contained in moderator-reflector without affecting criticality of core region. Core structure: low-density fuel contained in region surrounded by moderator-reflector. Coolant pumped through or around fuel. Fuel density (presumably at operating conditions) between 0.05 and 0.10 lb/cu ft--less than ¼ molecular density of gases under standard conditions. Control: thermal-absorbing material in moderator-reflector. Inherent safety factor is the prompt neutron regeneration time, which is as long as or longer than that in solid-fuel thermal reactors. A 6-ft diameter core in Be or graphite would require 12-14 kg U^{235} for criticality; the same size in D_2O would require 2 kg U^{235}. Smaller amounts of Pu^{239} or U^{233} would be required. If neutrons in the epithermal range were used, smaller core might be possible. The high neutron flux that would be produced might make the reactor suitable for use in engineering testing. Author suggests the following possibilities for reactor configurations, with initial form of fuel (in operation, the fuel would be gaseous):

1. Gas- or air-cooled reactor operating at "respectable specific power", perhaps on a once-through basis for running a gas turbine.

Code:	0312	12	31714	44	662	7XX	81XX8	921	107
	0313	14	31719	45	66X			941	
	0212	15		46					
	0213								

2. Zirconium tubes carrying fissile material on or near their outer surfaces. Liquid-metal coolant would run through the center of the tube.

Code:	0312	12	31106	44	66X	7XX	81XX8	921	107
	0313	14		45				941	
	0212	15		46					
	0213								

3. Fissile material carried by a circulating liquid metal. This would have self-stabilizing features of liquid-metal fuel.

Code:	0312	12	31106	44	66X	7XX	81XX8	921	107
	0313	14		45			84689	941	
	0212	15		46					
	0213								

4. Fuel might be $U^{235}F_6$, which could expand directly for running a turbine or a reciprocating engine.

Code:	0312	12	31710	44	662	7XX	81XX8	921	107
	0313	14						941	
	0212	15							
	0213								

No. 3 Fission-Plasma Reactor

Radiation Laboratory, University of California, Livermore, and LASL

Reference: Nucleonics, 15, No. 8, pp. 50-55, Aug. 1957.

Originators: S.A. Colgate and R.L. Aamodt.

Status: Preliminary concept, Aug. 1957.

Details: Thermal neutrons, pulsing, burner, with direct conversion to electrical energy for power production. Fuel: U^{235} or Pu^{239} in gaseous form, or gaseous UF_6. Coolant-moderator-reflector: D_2O, which blankets graphite fuel container, to cool graphite and act as neutron moderator-reflector. Gaseous fuel is uniformly contained in graphite and Al or Zr, which is surrounded by D_2O blanket, also contained in Al or Zr, and concrete shielding. Magnetic field produced by Cu coils located in D_2O blanket section compresses fuel at one end of the container, causing criticality. Direct conversion is accomplished by having ionized gas do work against the magnetic field. The released fission energy creates a shock wave which drives the gas towards the other end of the container. As the gas oscillates, the portion directly behind the shock front becomes highly ionized. This plasma acts as a conductor moving in a magnetic field. The plasma, as it moves through the magnetic field, induces a current in an external electrical circuit. This conversion of mechanical energy to electrical is the basis for the generation of electrical power--500 MW(e).

Code: 0323	14	31102	44	662	711	8XXXX	921	109
			46	66X				

No. 4 Plasma Core Reactor

Reference: Aerojet-General Corp., unpublished report, 1957.

Originator: Lawnie Taylor.

Status: Preliminary concept, 1957.

Details: Thermal neutrons, steady state, burner for interplanetary rocket propulsion. Fuel: U^{233}, U^{235}, or Pu^{239} plasma. Coolant: H_2. Moderator-reflector: D_2O or Be. Core structure: plasma-fuel core is surrounded by moderator-reflector. H_2 coolant, which is rocket propellant, gains energy by moving through core. Moderator-reflector material is core wall. Wall temperature is calculated to be 15,000°K or higher. Containment: fuel confined within core region by externally applied electromagnetic fields, by either (1) simple magnetic bottle with mirrors at each end or (2) homopolar device providing a strong electrostatic field for which moderator-reflector is outer electrode and plasma is inner electrode. Magnetic field contains ionized fuel but does not contain the nonionized coolant. Control: addition of poison to coolant; variation of fuel and coolant consistency and injection rates; variation of moderator consistency; variation of mirror separation and ratio; variation of field intensity. Power density: 12-27 kW/cm^3.

Code:	0313	14	34715	44	661	711	8159X	921	107
		15		45			83699		
				46			83799		
							84667		
							84767		

No. 5 Fizzler Reactor

Reference: Nuclear Rocket Propulsion, pp. 322-327.

Originators: Bussard and DeLauer (based on calculations of Safonov).

Status: Preliminary concept, 1958.

Details: Thermal neutrons, steady state, burner, for rocket propulsion. Fuel: U^{233}, U^{235}, or Pu^{239} initially in solid, liquid, or gaseous form but ultimately in gaseous form. Coolant: gas, not specified. Moderator-reflector: not specified. Fuel and coolant, which is rocket propellant, mix in core region formed by moderator-reflector. Criticality raises fuel above vaporization temperature. Fuel density needs to be about 0.10 lb/cu ft. Power: 5000 MW(t). Power density: 100 MW/cu ft. Drawback: at operating pressure of 1000 psi, which authors consider reasonable, 20,000 lb of fuel would be lost. To lose only 300 lb, which is calculated to be a maximum amount, pressure of 67,000 psi would be needed; this is impractical.

Code:	0313	1X	3X7XX	44	661	711	8XXXX	921	107
				45					
				46					

No. 6 Fizzler Reactor for Rocket Propulsion

Reference: Astronautics, 4, pp. 23-25, 111-112, Oct. 1959.

Originator: Jerry Grey.

Status: Preliminary concept, 1959.

Details: Thermal neutrons, steady state, burner. Fissile material mixed in a solid "grain" with moderating propellant. Control: Cd rod. Removal of a portion of control rod causes criticality in fuel immediately adjacent, which heats the fuel to vaporization temperature. Heat from this vaporization travels up the fuel axis, reducing the neutron-absorption cross section of the control rod enough to allow criticality, temperature rise, and vaporization of all of the fuel.

Code:	0313	1X	3X7XX	4X	66X	711	81212	9XX	109

No. 7 Gas-Solid Fueled Reactors, Series for Rocket Propulsion

Reference: Astronautics, 4, pp. 23-25, 111-112, Oct. 1959.

Originator: Jerry Grey.

Status: Preliminary concept, 1959.

Details: Pulsed burner. A series of subcritical "conventional" (solid-fueled) reactors are temporarily rendered highly supercritical when a slug of propellant gas containing some gaseous fissionable material passes through them. Gas is heated to increasingly high temperatures as it passes through each succeeding reactor, finally coming out of nozzle at very high temperature.

Code: 0X23 1X 3XXXX 4X 66X 711 8XXXX 9XX 109

No. 8 Cavity Reactor

Jet Propulsion Laboratory

References: JPL-TR 32-42; JPL-TR 32-94.

Originator: R.V. Meghreblian.

Status: Preliminary concept, 1961; work continuing.

Details: Thermal neutrons, steady state, burner, for rocket propulsion. Central moderator matrix contains gaseous fuel. This is surrounded by solid-fuel region. Reflector-moderator surrounds core. Coolant, which is rocket propellant, is fed into core tangentially, first picking up heat (regenerative cooling) from temperature-limited solid-fuel region, then from gaseous-fuel region, which is not temperature-limited. Coolant mixes with gaseous fuel and then is exhausted from reactor. No details of materials given.

Code: 0313 1X 317XX 4X 5XXX 66X 711 8XXXX 921 109

No. 9 Gaseous Propulsion Reactor

Jet Propulsion Laboratory

Reference: Nucleonics, 19, No. 4, pp. 95-99, (Apr. 1961).

Originator: R.V. Meghreblian.

Status: Preliminary concept, 1961.

Details: Similar to reactor described in Data Sheet No. 8. However, solid fuel is located in the center of the core and is surrounded by a moderator matrix, which contains gaseous fuel. This, in turn, is surrounded by the moderator-reflector. The coolant, fed in tangentially, first picks up heat from the solid-fuel region, then from the gaseous-fuel region. No materials indicated.

Code:	0313	1X	317XX	4X	5XXX	66X	711	8XXXX	921	109

No. 10 Vortex Reactor

References: AD-265961; CF-57-11-3; J. Aerospace Sci., 28, No. 9, pp. 710-724, (Sept. 1961); NASA-TN-D-288; ORNL-2837; N-2865a; NP-10270.

Originators: J.L. Kerrebrock and R.V. Meghreblian.

Status: Concept, 1958; work continuing.

Details: Thermal neutrons, steady state, burner, for rocket propulsion. Fuel: U, Pu, or their compounds, in H_2. Fuel either gas or a gas-carrying solid. Coolant: CH_4, NH_3, or H_2. Moderator: BeO or graphite. Reflector: Be or D_2O. Fuel contained as a jet-driven vortex in many long, thin, discrete tubes imbedded in moderator material. Vortex can also be generated by: (1) externally imposed electrical and magnetic fields; (2) rotating magnetic field--a radial electric field between a pair of cylindrical electrodes combined with an axial magnetic field; or (3) magnetic mirror in a cylindrical configuration. Fuel and coolant, which is also rocket propellant, mix. As mixture spirals into center it is drawn off axially and discharged through one end. In the vortex, a strong radial pressure gradient exists. With such a gradient, the heavy fissionable gas is contained in a steady-state concentration distribution in the vortex and the lighter propellant gas diffuses through it. Reactor is right cylinder of equal height and diameter. Gas exit pressure might be 100 atm., core temperature 10,000°R. Power: 500 MW(t).

Code:	0313	12	3X707	44	661	711	8XXXX	921	104
		15	3X715	46	663				107
			3X713						

No. 11 Coaxial Flow Reactor

National Aeronautics and Space Administration

References: TID-7653 (Pt.1), pp. 110-114; ARS Paper No. 1518-60, 1960.

Originators: H. Weinstein and R.G. Ragsdale.

Status: Concept, 1960; work continuing.

Details: Thermal neutrons, steady state, burner, for rocket propulsion. Fuel: fully ionized gaseous Pu^{239}. Coolant: H_2 seeded with something like graphite dust. Moderator-reflector: graphite or D_2O as external reflector-moderator, or a two-region moderator with graphite inside and D_2O outside. Core structure: criticality takes place in cavity (10 ft long, 10 ft diam.) formed by external moderator-reflector. Fuel is fed into center of core; fuel region about 10 ft diam. Coolant, which is rocket propellant, is fed into core around periphery at flow rate different from flow rate of fuel. Differing axial velocities prevent two fluids from mixing. Coolant and a small portion of the fuel are exhausted from core region through nozzle. Control: rotating-drum control rods. One study using both graphite and D_2O as moderator-reflector has been based on the following parameters: reactor overall is 16.6 ft long and 16.6 ft in diameter, cavity: 10 ft long, 10 ft in diameter; moderator-reflector: 3.3 ft thick. Fuel velocity: 0.2 ft/sec. Coolant velocity: 17 ft/sec. Temperatures: fuel, 20,000°R; hydrogen, 10,000°R; graphite, 5,000°R; D_2O, 70°R. Since hydrogen at these temperatures is transparent to radiation, it must be "seeded" with absorbing material for heat transfer. Graphite dust might be satisfactory up to its sublimation point (6800°R). Pressure: 2200 psia with fully ionized fuel.

Code:	0313	12 14	34715	46	661	711	8144X	921	107 109

No. 12 Homogeneous Gas Phase Magnetohydrodynamic Nuclear Reactor

General Electric Co., Hanford

Reference: Unpublished report, 1965.

Originators: Staff members.

Status: Concept, 1965.

Details: Steady state, burner. Fuel: gas, e.g. UF_6. Gaseous fuel flows in toroidal container in subcritical density except in core region, where it is compressed to criticality. Nuclear reactions and heat cause ionization of fuel. Ionized stream passes through magnetohydrodynamic channel composed of current-carrying rails and 2 cryogenic magnets that provide a cross-current field. Ionized gas stream provides the electromotive force to generate the current flow between the rails. The gas could then expand directly to a turbine. Gas then proceeds through heat exchanger for steam production and to unit for gas separation and purification. Fission products and wastes are discarded, and purified gas plus enough new fuel to keep consistent level circulates again to compressor.

Code: 0X13 1X 3X710 4X 662 711 84699 921 109

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