ANL-7092

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# Argonne National Laboratory

## CATALOG OF NUCLEAR REACTOR CONCEPTS

## Part I. Homogeneous and Quasi-homogeneous Reactors

## Section III. Reactors Fueled with Molten-salt Solutions

by

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

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ANL-7092
Reactor Technology
(TID-4500, 46th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

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Technical Publications Department

September 1965

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

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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. 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 following page.

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.

J.H.M.
September, 1965

# PLAN OF CATALOG OF REACTOR CONCEPTS

# PART I. HOMOGENEOUS AND QUASI-HOMOGENEOUS REACTORS

## SECTION III. REACTORS FUELED WITH MOLTEN-SALT SOLUTIONS

### Chapter 1. Introduction

The reactor concepts described in this section utilize a fluid fuel consisting of a fissionable material dissolved in a carrier of molten salt. Some such concepts also call for a molten salt as a primary coolant.

H. G. MacPherson has reviewed the technology of molten-salt reactors.[1,2]

The fissionable compound usually chosen is uranium tetrafluoride.[2] Uranium fluorides other than the tetrafluoride have the disadvantages of higher volatility, instability, or corrosivity. Chlorides or fluorides as solvents have been given the most consideration because of the need for radiation stability and high solubility. The chlorides are used for fast reactors, and the fluorides, because of their low cross sections for thermal neutrons, are best for thermal and epithermal reactors.

Compounds other than fluorides and chlorides have been suggested, including phosphates,[3] sulfates,[4] sulfides,[4] hydrosulfides,[4] and hydroxides.[5,6] Molten fluoride mixtures, e.g. LiF-NaF, have the most desirable properties: they dissolve adequate amounts of fuel; they have satisfactory heat transfer properties; they resist radiation; they can tolerate an accumulation of fission products; the melting points are low enough that corrosion problems of excessively high temperatures are avoided; and the vapor pressures are low enough to permit low-pressure operation.[4,7,8] Although fluorine itself has some moderating properties, a better moderator must be present, either in the molten-salt mixture or as a separate structure, to obtain a thermal reactor of reasonable size. The alkali metal fluorides have been especially considered as solvents because they have low melting points. Beryllium fluoride may be added to the mixture as a moderator, and thorium tetrafluoride can be added for conversion.

Graphite and beryllium are commonly used as structured moderators. Discussion of structured-moderated reactors in this section may appear anomalous, in that most reactors in this first part of the catalog have completely homogeneous cores. The fuel itself, however, is a homogeneous solution, and such structure-moderated reactors are otherwise closely related to the more homogeneous ones.

Molten-salt reactors can be classified in several ways--by the purpose of the reactor, by the use or nonuse of a separate moderator, by the cooling method (internal or external), or by the core arrangement

(one- or two-region). For this catalog, the classification will be by one- and two-region reactors. Chapter 2 will cover the first and Chapter 3 the second. According to MacPherson,[7] the most attractive types are the one-region, graphite-moderated reactor, and the two-region reactor. The one-region reactor is simpler, and it is cheaper to construct and operate for small power stations. Most of the one-region reactors discussed in Chapter 2 are burners. The two-region reactor has better neutron economy, is better for breeding, and, in larger installations, gives higher conversion ratio and lower fuel-cycle costs.

The origin of the molten-salt concept is not clear. Early in the 1950's, however, molten salts were considered as reactor fuels to satisfy the need for high temperature and extremely high power densities needed for reactors intended for nuclear aircraft propulsion. Development work, particularly at Oak Ridge National Laboratory, resulted in several concepts, and in 1954 the Aircraft Reactor Experiment (ARE), part of the Aircraft Nuclear Propulsion Project (ANP), was operated. Since the cancellation, as of October 1957, of work on circulating-fuel reactors for aircraft,[9] work has continued aimed at developing power and breeder reactors that utilize molten salts.

Molten-salt reactors are attractive concepts for several reasons.[1,2,7] They provide high temperatures in a low-pressure system to produce steam at temperatures high enough to give high thermal-cycle efficiencies. They are versatile because of the range of solubilities of different compounds of fissionable elements in salts. The simple ionic salts are stable under irradiation. Such reactors also have the advantages of other fluid-fueled reactors; for example, they have high negative temperature coefficients of reactivity, fission products can be removed continuously, fuel elements need not be fabricated, and make-up fuel may be added as needed. According to Weinberg,[10] a great advantage is that the fissionable materials can be consumed at very high thermal efficiencies and with extremely high burnup. The major problem with a salt-fueled reactor is that all the salt in the system must be kept molten at all times.

In 1959, the Fluid Fuel Reactor Task Force compared the aqueous homogeneous, molten-salt, and liquid-metal fueled reactors.[11] The principal conclusions were: the molten-salt reactor had the best chance of achieving technical feasibility; only with the homogeneous aqueous reactor was there a possibility of achieving a reasonably short doubling time; and the total power costs for the MSR were between those for the aqueous reactor and the liquid-metal-fueled reactor.

Salt-fueled reactors are advanced concepts, and there is as yet no adequate experience for building large-scale power plants, although many concepts have been developed for such plants.[7] Current development is represented by the Molten Salt Reactor Experiment, which achieved criticality at ORNL in mid 1965.

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10. A. M. Weinberg, Advanced Systems--A Personal Appraisal, Nuclear Eng. 5, No. 53, pp. 463-465, October 1960.
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# Chapter 2. One-region Reactors

Most of the one-region reactors discussed in this chapter are burners, with highly enriched uranium in the molten fuel and no external blanket. The converters have either partially enriched uranium or thorium salts as fertile material in the fuel-salt mixture. One-region reactors have been considered both for aircraft propulsion and for the generation of heat and electrical power. The ANP (Aircraft Nuclear Propulsion) Project led to many concepts, and one reactor experiment, ARE (Aircraft Reactor Experiment), was operated for a short time. As part of the Aircraft Nuclear Propulsion Project, several designs for molten-salt-fueled aircraft reactors were proposed both before and after the operation of the Aircraft Reactor Experiment. In addition to the studies at ORNL, work was carried out by such contractors as the H. K. Ferguson Company and the Pratt & Whitney Aircraft Company. In 1957, however, work on circulating-fuel reactors for aircraft was discontinued. The MSRE (Molten Salt Reactor Experiment) is the current major effort on this type of reactor, with criticality achieved in mid 1965.

## Reactors for Propulsion

### Early Concepts

Concepts reported by H. K. Ferguson in 1950 and 1951 included both reactors fueled with molten fluorides and a few fueled with suspensions of uranium oxide in molten sodium hydroxide. The suspensions were used because of the difficulty of dissolving uranium compounds in NaOH. These suspensions are included here, although they cannot be defined as molten-salt solutions.

In the Homogeneous Circulating Suspension Reactor, the fuel is a suspension of 2.2 wt.% uranium oxide in sodium hydroxide, which acts as moderator.[1] The fuel enters the top of the reactor, where a whirling motion is imparted to it by vanes, and leaves through the bottom to a heat exchanger.

In a similar concept,[1] the fuel is a coarse suspension of the oxide in sodium hydroxide, which circulates through a spherical reactor. The oxide is removed in a cyclone separator; the liquid passes through a heat exchanger, and then picks up the oxide before returning to the core.

The Circulating-fluoride Reactor concept includes beryllium rods as moderator and a molten fluoride fuel, which circulates to a wraparound heat exchanger.[2] This concept was studied as a variation of a reactor fueled with molten metal.

In another concept,[1] the beryllium moderator is in different forms. In one, it is distributed throughout the core; in the other, it is a reflector layer.

The Circulating Moderator-coolant Reactor utilized uranium tetrafluoride dissolved in a molten mixture of sodium and beryllium fluorides.[3] Instead of a solid moderator, molten sodium hydroxide is used as moderator, coolant, and reflector. The sodium hydroxide flows downward through tubes in the core to cool the quiescent fuel salt. Secondary cooling is by exchange with sodium in a heat exchanger. The reflector is a jacket of the hydroxide around the core. The design power for this reactor is 140 MW(t). A very similar reactor is the Circulating-moderator ARE.[3]

In 1952, Dayton and Chastain made calculations for the design of one- and two-region circulating reactors using hydroxides as moderator-coolants.[4] The compounds studied were sodium hydroxide, lithium-7 hydroxide, and lithium-7 deuteroxide. Uranium-233 oxide, suspended in the hydroxide within the spherical reactor, was the fuel specified. For the one-region reactors, thorium oxide was added to the fuel for breeding. The conversion ratios were so low that the authors concluded that internal breeding would not be feasible if a small critical mass were required. If, however, cost and size are not considered, $Li^7OD$ appears to be the most attractive of the compounds.

Two ORNL designs were for a 200-MW(t) Aircraft Reactor (1951)[5] and a Circulating-fuel Reactor for Direct Heat Transfer to Engines (1953).[6]

In the first reactor, the fuel--a molten mixture of beryllium, sodium, and uranium fluorides--does not circulate. It is contained in U-tubes, which are within coolant tubes through which sodium circulates. Beryllium oxide is the moderator and reflector in the cylindrical reactor. This was intended to be a full-scale reactor, and the ARE was to duplicate it as far as possible in materials, temperature pattern, and kinetics, but not in fuel circulation or power. In the second reactor, hot fuel circulates from the core directly to the aircraft engine; otherwise this reactor is similar in many respects to the first.

## The Aircraft Reactor Experiment

The ARE was built at Oak Ridge National Laboratory as a circulating-fuel reactor of low power and high temperature, but materials suitable for use in a reactor of high power were employed.[7-9] According to Weinberg, "The purpose of this reactor experiment was simply to gain experience in handling salts in a reactor at very high temperatures, to see whether one could in fact contain the intensely radioactive circulating fuel, and to study the kinetic behavior of the reactor."[10]

Before the circulating fuel was decided upon, solid fuel pins and stagnant fluoride fuels were considered.[11]

Stagnant fluoride fuel was used in the first design.[11] The core would have a cylindrical moderator matrix, containing vertical holes into which small fuel tubes would be placed. This assembly would be within a cylindrical pressure shell, through which sodium would be passed. A slab of boron carbide would be placed at the top of the lattice, and the fuel tubes would extend through the slab, which would act as a "neutron curtain" for control. Severe problems, however, made this concept less attractive than a circulating-fuel reactor. The molten salts have poor thermal conductivity. The extremely large thermal gradiant at reasonably high power levels would make the temperature of the fuel near the center of the tube prohibitively high. There would be difficulties in loading the reactor. Also, during loading, large control rods would be needed, and the heat cycling and draining of coolant between fuel additions would pose many problems. Expansion during melting might be a problem relative to possible deformation (expansion) or rupture.

The final fuel was uranium tetrafluoride dissolved in a mixture of sodium and zirconium fluorides. Beryllium oxide was the moderator and reflector; blocks of it were stacked around the fuel tubes, tubes for reflector cooling, and control assemblies that passed vertically through the core. The fuel took a serpentine path through parallel circuits to the outside of the core, finally leaving at the bottom. It circulated to an external heat exchanger then back to the core. Sodium passing through tubes in the moderator cooled it. Barren fuel salt also had been suggested as coolant. The maximum design power was 2.5 MW(t).[12,13] The reactor became critical on November 11, 1954, and it was shut down the following evening. It had demonstrated the feasibility of using a high-temperature fluoride fuel in a circulating-fuel reactor.[14]

A reactor with a tandem heat exchanger was suggested as a modification of the ARE.[15] The moderator-reflector is water or sodium hydroxide, with the core and the tandem heat exchanger being surrounded by a layer of water at 300-350 psi. The fuel enters the reactor at the top, makes a loop through fuel tubes in the reactor, and exits to heat exchangers. The moderator enters the lattice around the periphery at the rear of the reactor and flows to an outlet at the forward end.

In another modification, the fuel-coolant salt circulated through the coolant tubes in the BeO reflector of the ARE.[16] In this modification, there would be a larger leakage of high-energy neutrons and of gamma radiation than with barren fuel salt as moderator coolant.

## The Fireball and Related Concepts

A concept that originated before the operation of the ARE and was scheduled for use in later developments was a circulating-fuel, reflector-moderated reactor, known originally as the Fireball.[17,18] In this reactor there are no fuel tubes. The fuel circulates in an annulus between a central island of beryllium moderator and an outer shell of moderator and reflector. In the earliest design the central island was spherical, but later development resulted in a vase-shaped island.[18] This shape, according to Fraas, reduces the critical mass, improves power distribution, and hydrodynamically gives the best passage for fuel.[18] Cooling is by circulating the fluid salt to a circumferential wraparound heat exchanger between the moderator shell and the pressure shell. There heat transfer to sodium or sodium-potassium takes place. The fuel passes downward in the annulus, then outward. The moderator is cooled by sodium flowing downward between the beryllium and the enclosing shell.

Fraas and Savolainen have discussed eight core designs for the spherical reflector-moderated reactor, with a wraparound heat exchanger, that are related to the Fireball.[19]

The simplest design is the core in which a thick spherical moderator shell surrounds a spherical chamber for liquid fuel. The shell has top and bottom ducts for fuel to pass in and out of the core. Because of absorption of neutrons near the fuel-reflector interface, power density decreases to a comparatively low value near the center. Also, the flow pattern is indeterminate. Vanes or screens at the inlet might improve the flow.

Adding a central island reduces critical mass and gives a more uniform power distribution. The moderator, however, must be cooled in this design. Liquid bismuth or lead could be circulated between the fuel and moderator regions to remove the heat.

Graphite was suggested in two other modifications. A block of graphite containing parallel passages for fuel flow is placed in the central zone to give a nearly homogeneous mixture of fuel and graphite in the core. Concentric shells of graphite could be used as moderator and as guides for the fuel flow. The authors concluded that these designs were little better, from the nuclear standpoint, than the simple core with no moderator structure.

Three designs were for the use of molten sodium hydroxide as a liquid moderator. In one, the moderator passes through coiled tubes in the core. The tubes would both serve as moderator in the core and improve distribution of fuel velocity. It would, however, be difficult to avoid local hot spots, and the structural material would capture a high

percentage of neutrons, so that the critical mass would be increased. In two other modifications, fuel passes through tubes and the hydroxide moderator circulates through spaces between fuel passages. In one design, the tubes are straight. In the other, they are curved to fit the shell contours, in order to reduce the volume of header regions and to give a more nearly spherical core shape, with lower shield weight.

Some concepts that have employed the Fireball design with little change are the Aircraft Reactor Test,[20] The Circulating Fluoride-fuel High Flux Reactor,[21] and a modified Fireball concept of General Electric.[22] In the High-flux Reactor, which includes a central island of graphite, use of a layer of bismuth between the central island and the fuel layer was suggested by the author to resist flow of thermal neutrons from the central island, where they are created, to the shell, where they are absorbed. It would also protect the internal island from gamma radiation.

Pratt & Whitney concepts were originally variations and developments of the Fireball design, with changes in the dimensions and other factors to give reactors of different power levels.[23,24] In two simplified versions[25] the annulus of the Fireball is replaced by five tubes in the center of the core. In one, the core is a graphite cylinder and in the other it is a beryllium sphere. The design was intended to give more structural stability and to alleviate problems of flow separation. Graphite was used to obtain more favorable critical mass and power distribution. The beryllium-moderated concept was developed into a more complete design.[26] In another modification, the island is cylindrical, rather than vase shaped as in the original Fireball.[27] Other variations considered briefly were the use of beryllium, beryllium oxide, or graphite for the island and for the reflector, and using and not using a reflector. Alternative fuels considered were lithium or beryllium fluorides as bases for fuels, and slurries of uranium dioxides in alkali metals.[24] Lithium-7 was considered as a coolant,[24] and zirconium hydride as a moderator.

The use of zirconium hydride as a moderator was incorporated in one concept.[28] The core consists of fuel tubes and zirconium hydride rods, with lithium-7 flowing parallel to the tubes. Two arrangements of fuel tubes were studied. In one, a multitube arrangement, the fuel flows down through the inner tubes then returns through the outer tubes. In the other, a thimble-tube design, the fuel flows through an inner tube and returns through the annulus between this tube and an enclosing outer tube. Lithium-7 could circulate directly to the engine radiator. The hydride moderator, which would be clad with molybdenum, is claimed to permit high temperature without the need for excessive cooling or structural support.

In 1955, staff members at the Walter Kidde Nuclear Laboratories, Inc., published designs for reactors for aircraft propulsion.[29]

One reactor was similar to an earlier concept of H. K. Ferguson Co. The fuel is stationary, within tubes. A great many tubes are required because they must be small to avoid excessive internal temperatures. Heat removal would be difficult because of the poor conductivity of the molten salts.

Three were circulating-molten-salt reactors, two closely resembling earlier concepts. They included a reactor having the Fireball structure, with a modification in which the core is cylindrical rather than spherical; a circulating-fluoride reactor with rods of beryllium moderator in the core; and a circulating-fluoride reactor with molten sodium hydroxide as moderator and reflector.

An ORSORT concept, the Screwball (1953), differed from the Fireball chiefly in that helical fuel tubes replaced the annular passage between the central island, which was eliminated, and the moderator shell.[30] Thus it somewhat resembles the Pratt & Whitney concept described in Ref. 26. The moderator is circulating NaOD. According to the authors, problems with the Fireball design indicated need for changes. The Screwball design is claimed to eliminate or alleviate all but one, namely, pressure surges. Use of fuel tubes reduces uncertainty of sustained instabilities in fuel region. "Self-shielding" should be less with the tubes than with the spherical fuel annulus of the Fireball. Lower power density (2.5 $kW/cm^3$) was chosen to aid problems of questionable fuel density. Removal of the solid island eliminates the need to cool it. The pressure-surge problem was not alleviated. Surges may be larger with Screwball because of the tortuous expansion path out of the core, but pressure is not expected to be great enough to cause difficulty. Substitution of circulating NaOD leads to problems with corrosion; stagnant or low-velocity layers of NaOD next to hot fuel tubes or containing shell, therefore, must not occur.

## Reactor for Ship Propulsion

ORSORT students designed a molten-salt reactor for ship propulsion, which contained many of the features of the aircraft reactor concepts.[31] A compact, high-performance reactor was sought in order to reduce weight. In the cylindrical reactor core, the moderator is an array of Inconel-clad beryllium oxide rods tipped with poison material to reduce end leakage and fissioning in the entrance and exit plenums for the fuel. The fuel flows up through the central core region, then down through an annular downcomer at the core periphery. There it enters a wraparound heat exchanger, which is cooled by molten salt. This 125-MW(t) reactor has a nickel reflector, as well as extensive shielding.

An advanced design of this type of reactor was conceived by the same group to improve reactor performance and reduce weight. To improve moderation in the core, the designers substituted zirconium hydride

for beryllium oxide as moderator and used a beryllium-containing fuel. Nickel-molybdenum cladding was substituted for Inconel cladding in the core because thinner cladding could be used to reduce the amount of poison in the core. In the resulting design, dimensions and power level were reduced.

## Reactors for Electrical Power and Heat

Even before the Aircraft Reactor Experiment was carried out, some one-region reactors had been proposed for purposes other than aircraft propulsion. Development of such reactors has continued. They include some designs that generally resemble the ARE in core structure.

### Early Concepts

An early concept, on which little has been published, is for a thorium converter for electrical power production, which was developed by Davidson and Robb.[32] In this converter, the fuel is a solution of 93 percent enriched $U^{235}F_4$ in molten fluorides containing thorium fluoride for conversion.

Four concepts, by students at the Oak Ridge School of Reactor Technology, are intended for power and heat, and one is a breeder.

The Fused Salt Reactor for Power and Heat, proposed in 1953, could be either a burner or converter, with thorium fluoride added to the molten salt if conversion is desired.[33] The core is a graphite sphere, through which fuel circulates from the bottom through channels cut into the graphite. The graphite is clad with an Inconel shell and is contained in an Inconel pressure vessel. The reactor is designed for installation at remote locations to produce power--about 5 MW(t)--and heat. The heat is produced by water heated by low-pressure waste gas from the turbine.

In the Fused Salt Breeder Reactor (FSBR),[34] the fuel is a solution of uranium-233 fluoride and thorium fluoride in fused lithium-7 fluoride and beryllium fluoride. Stacked graphite blocks form the core, which has a spherical top, a flat bottom, and cylindrical sides. The fuel passes through passages in the graphite and through heat exchangers in the graphite surrounding the core. The fuel passes to intermediate heat exchangers cooled by sodium. Two sizes were considered, one for 125 MW(e) and one for 250 MW(e).

The 600-MW Fused Salt Homogeneous Reactor Power Plant[35] utilizes a fuel salt of fluorides of uranium-235, zirconium, and sodium. The reactor is stated to be self-moderating because of the fluorine.

The reactor vessel is a vertical cylinder, with a dished bottom, of stainless steel. The fuel circulates through the multipass vessel upward to a sodium loop within the vessel, to an annular U-tube heat exchanger, and to a secondary heat exchanger. The design of this burner could be altered so as to breed uranium-235.

The Fused Salt Reactor for Process Heat (1956)[36] has two features that differ somewhat from previous designs. The aim was to generate as much heat as possible in the regions of the reactor not bearing fuel and to use a ceramic as both moderator and heat-exchange medium for high-temperature heat exchangers. Magnesium oxide was chosen as the best available material to meet both requirements, even though it is not a very good moderator. The reactor consists of a cylindrical matrix of hexagonal magnesium oxide blocks penetrated by Inconel tubes in a triangular array. Fuel circulates through these tubes. Beryllium oxide reflector surrounds the core, and a steel pressure vessel is the container. Of the 400 MW(t) produced by the reactor, 35 Mw is generated in the MgO moderator and is used to heat steam from heat exchangers. The moderator is perforated to allow passage of steam. The remaining heat is removed by the fuel circulating to external heat exchangers. The design is for four reactors to be used in conjunction with a coal-hydrogenation plant. The high-temperature steam from the moderator would be used to gasify coal to produce hydrogen for the hydrogenation. The remaining steam, at a lower temperature, would be used to drive turbines.

The use of natural convection has been suggested to eliminate the problem of providing reliable, long-lived pumps for fuel circulation.[37,38] This advantage is at the cost of a greater fuel volume. The fuel circulates by natural convection through the core, vertical convection risers, and primary heat exchangers. In the design suggested, the core is spherical, with the primary heat exchanger above the core. The heat-exchange medium may be either molten salt or helium. Either would give a power of 22 MW(e). This system may be attractive for some applications because of easy maintenance and good reliability.

Molten lead is suggested as coolant in an ORNL concept of 1958.[39] The only moderator is the fluorine in the fuel salt--$NaF-ZrF_4-UF_4$. The molten lead circulates the fuel salt by direct mixing with a jet pump. Heat exchange is rapid and no primary exchanger is needed. The lead is separated from the salt downstream by a pipeline separator; the fuel goes to the core, the lead to a heat exchanger. The design power is 194 MW(e).

## The MSRE and Related Concepts

Before the design of the MSRE was decided upon, other concepts originated from the Molten Salt Reactor Project at Oak Ridge National

Laboratory. Two that were developed furthest were the Slightly Enriched, Fused-Salt-Fueled Reactor and the Experimental Molten-Salt-Fueled 30 MW(t) Power Reactor.

## Predecessors to MSRE

The Slightly Enriched, Fused-Salt-Fueled Reactor[40-42] is a converter fueled with slightly enriched uranium tetrafluoride dissolved in molten lithium fluoride and beryllium fluoride. It was proposed in 1958, and a preliminary design was published in 1959. The cylindrical core is of unclad graphite, which serves as moderator. The fuel flows upward through holes in the graphite. Highly enriched uranium is added as makeup fuel. The reactor produces 315 MW(e).

The Experimental Molten-Salt-Fueled 30-MW(t) Power Reactor[42,43] is a burner fueled with highly enriched uranium tetrafluoride dissolved in molten lithium fluoride and beryllium fluoride. There is no other moderator. The core is a sphere of INOR-8. The fuel circulates to a heat exchanger. Barren molten salt--lithium fluoride-beryllium fluoride--is the secondary coolant.

## MSRE

The Molten Salt Reactor Experiment[44-46] is the first of the three stages in the development of molten-salt reactors discussed by MacPherson in 1960.[47] After this one-region reactor, a two-region reactor experiment was planned, and a high-power prototype of a molten-salt reactor would follow.

The MSRE has the objectives of showing that a circulating molten-salt-fuel system will operate successfully and demonstrating a reactor type that can be developed into an advanced converter or thermal breeder. It also is intended to demonstrate that unclad graphite is a satisfactory moderator that can be used in contact with molten salts for extended periods and that on-site hydrofluorination processing can clean up contaminated fuel.

The MSRE is a converter, with the possibility of internal breeding. In structure it resembles the Aircraft Reactor Experiment more closely than such later aircraft reactor developments as the Fireball. The moderator consists of vertical stringers of graphite, which form a cylindrical core within a reactor vessel. The fuel passes downward in an annulus between the graphite cylinder and the containing vessel. It then flows upward in channels formed between the stringers, out the top to a heat exchanger (in which the intermediate coolant is $LiF-BeF_2$), and back to the core.

## Advanced Concept

The use of molten fluorides as fuel in a 10-MW(e) fast reactor for spacecraft was considered by Allen.[48] Calculations were made to estimate the size and weight of such a reactor and to compare them with those of a reactor fueled with uranium carbide. Highly enriched (93.5 percent) uranium tetrafluoride was the fuel, with fluorides of sodium, beryllium, lithium, and zirconium considered as solvents. The fuel mixture for which calculations were made is 70 percent $UF_4$, 30 percent NaF. Lithium is the coolant, and the reactor is unmoderated, with an inner reflector of zirconium and an outer reflector of beryllium. The author concluded that uranium fluoride does not have an apparent advantage over uranium carbide; it does not achieve the full potential of liquid fuels for the purpose; and other liquid fuels, such as liquid metals, should be studied.

## Status

The Molten Salt Reactor Experiment apparently is the only current active program for developing molten-salt reactors. Construction is in progress, and criticality was achieved in 1965.[49] The one-region reactor is meant as an intermediate step in developing a large two-region breeder, but one-region reactors have also been suggested for uses in their own right, especially in smaller power stations.[47]

# DATA SHEETS

## ONE-REGION REACTORS

## No. 1 Homogeneous Circulating Suspension Reactor

H. K. Ferguson Co.

Reference: Unpublished report, H. K. Ferguson Co., Dec. 12, 1950.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Design, 1950.
Details: Thermal neutrons, steady state, burner. Fuel-coolant: suspension of 2.2 wt % $U^{235}O_2$ in NaOH. Moderator: NaOH. Fuel suspension circulates to external heat exchanger; secondary coolant: Na. Reflector: 6 in. Inconel in 3 laminated shells around core. Core: cylinder, within spherical pressure vessel. Fuel suspension enters top of reactor, where whirling motion is imparted to it, and leaves through opening in bottom of core, to shell-and-tube heat exchanger. Shielding: tank of borated $H_2O$; Pb; plastic. Control: negative temperature coefficient; shim rod--3 concentric cylinders of boron steel, $H_2O$ filled, located in nickel-plated Zr thimble through vertical axis of core. Power: 270 MW(t). Problems: high freezing point of NaOH delays startup and shutdown; NaOH corrosive; stability of slurry under irradiation questionable.
Code: 0313 17 31312 44 637 711 84677 921 101
81111

## No. 2 Homogeneous Circulating Fuel-moderator Slurry Reactor

H. K. Ferguson Co.

Reference: Unpublished report, H. K. Ferguson Co., 1950.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Preliminary study 1950; abandoned.
Details: Similar to concept in Data Sheet No. 1. Coarse suspension of $UO_2$ in molten NaOH circulates through spherical reactor. Fuel is removed in cyclone separator. Liquid goes through heat exchanger, then picks up fuel and returns to core. Secondary coolant: Na, NaK, or NaOH.
Code: 0313 17 31312 44 637 711 84677 921 101
81111

## No. 3 Circulating-fluoride Reactor

H. K. Ferguson Co.

Reference: Unpublished report, June 1, 1951.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Design, 1951.
Details: Thermal neutrons, steady state, burner. Fuel-coolant: $UF_4$ dissolved in molten NaF-BeF, 3.4 wt % U. Moderator: Be rods, 2 in. diameter, clad with stainless steel. Fuel circulates to wrap around heat exchanger. Core: cylinder, 42 by 42 in. Reflector: 2 in. of moderator rods. Control: negative temperature coefficient, vertically moving control rods; each rod filled with molten Pb-Cd alloy; rods in thimbles. Power (max.): 152 MW(t).
Code: 0313 15 31211 44 627 711 81112 921 104
84679

## No. 4 Circulating-fuel, Dispersed-moderator Reactor

H. K. Ferguson Co.

Reference: Unpublished report, H. K. Ferguson Co., 1950.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Preliminary study, 1950; abandoned.
Details: Thermal neutrons, steady state, burner. Variation of a liquid-metal-fueled reactor. Fuel-coolant: molten mixture of U, Na, and Be fluorides. Moderator: Be or BeO distributed throughout core. Fuel circulates through reactor to heat exchanger cooled by Na, K, or Li. Power (for liquid-metal fuel): 200 MW(t).
Code: 0313 15 31211 4X 627 7XX 84679 9X 104

## No. 5 Circulating-fuel, Reflector-moderator Reactor

H. K. Ferguson Co.

Reference: Unpublished report, H. K. Ferguson Co., 1950.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Preliminary study, 1950; abandoned.
Details: Same as concept in Data Sheet No. 4 except that Be or BeO moderator is reflector layer in the spherical reactor.
Code: 0313 15 31211 4X 627 7XX 84679 921 104

## No. 6 Circulating Moderator-coolant Reactor

H. K. Ferguson Co.

Reference: HKF-112.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Design, August 1951.
Details: Thermal neutrons, steady state, burner. Fuel: $UF_4$ (18 wt % $U^{235}$) dissolved in molten salt--40 mol % NaF-60 mol % $BeF_2$. Moderator-coolant: molten NaOH. Reactor: vertical cylinder, 32 in. diameter, 32 in. high, with small, closely spaced Inconel tubes in triangular-pitch lattice. Fuel-expansion chamber connected to top and bottom of core. Reflector: 4-in. jacket of NaOH around core; 10 in. NaOH in top and bottom headers. NaOH coolant flows downward through tubes in core. Fuel is in space between tubes. NaOH goes to heat exchanger for heat exchange with Na. Control: shim control--negative temperature coefficient; fine control--single rod, along axis of core, consisting of vertical annular rod filled with molten Pb-Cd. Power: 140 MW(t).
Code: 0313 17 31112 44 627 711 84677 921 106
81112

## No. 7 Circulating-moderator ARE

H. K. Ferguson Co.

Reference: HKF-112.
Originators: Staff of Atomic Energy Division, Karl Cohen, Director.
Status: Design, August 1951.
Details: Closely resembles "Circulating Moderator-coolant Reactor," Data Sheet No. 6. Thermal neutrons, steady state, burner. Fuel: molten $UF_4$-NaF-$BeF_2$ containing 3.40% uranium. Moderator-coolant: circulating molten NaOH. Reflector: NaOH, 8 in. thick top and bottom, 4 in. thick at circumference. Reactor: cylinder, 32 by 32 in. Quiescent fuel is on shell side of coolant tubes, through which NaOH flows at 890 gpm. Inlet temperature: 1409°F; outlet: 1419°F (average). NaOH goes to heat exchangers. Control: shim--negative temperature coefficient, varying level of fuel; fine--axial control rod. Power: 1 MW(e).
Code: 0313 17 31112 44 627 711 84677 921 106
8111X

## No. 8 Unreflected Homogeneous Reactor Moderated by Sodium Hydroxide

Battelle Memorial Institute

Reference: BMI-746.
Originators: R. W. Dayton and J. W. Chastain.
Status: Design calculations, 1952.
Details: Steady state, thermal neutrons, converter. Fuel-moderator-coolant: homogeneous mixture of $U^{233}O_2$, NaOH, and $ThO_2$. Mixture presumably circulates to external heat exchanger. Core container: zirconium sphere. Core temperature: 1100°F. No reflector. Calculations indicated that internal breeding not feasible if small critical mass is required.
Code: 0311 17 31312 45 637 756 84677 91 101

## No. 9 Unreflected Homogeneous Reactor Moderated by Lithium-7 Hydroxide

Battelle Memorial Institute

Reference: BMI-746.
Originators: R. W. Dayton and J. W. Chastain.
Status: Design calculations, 1952.
Details: Same as concept in Data Sheet No. 8, except that $Li^7OH$ is used instead of NaOH.
Code: 0312 17 31312 45 637 756 84677 91 101

## No. 10 Unreflected Homogeneous Reactor Moderated by Lithium-7 Deuteroxide

Battelle Memorial Institute

Reference: BMI-746.
Originators: R. W. Dayton and J. W. Chastain.
Status: Design calculations, 1952.
Details: Same as concept in Data Sheet No. 8, except that $Li^7OD$ is used instead of NaOH.
Code: 0312 17 31312 45 637 756 84677 91 101

## No. 11 200-MW(t) Aircraft Reactor

ORNL

Reference: Unpublished report, ORNL, 1951.
Originators: Staff of ORNL ANP Project.
Status: Preliminary design, 1951. Project cancelled, 1957.
Details: Intermediate neutrons, steady state, burner. Fuel: molten $BeF_2$-$NaF$-$UF_4$. Moderator and reflector: BeO. Coolant: Na, primary and secondary. Core: 3 ft square cylinder with ellipsoidal ends. Inconel pressure shell. 2268 parallel coolant tubes, spaced by perforated and dimpled disks, run along long axis of core. In each coolant tube are 3 U-tubes (0.100 in. diameter) containing fuel. Legs of each U-tube connected to separate inlet and outlet headers. Fuel does not circulate. Control: negative temperature coefficient; shim control by varying volume of fuel. Power: 200 MW(t). This reactor intended to be full-scale reactor for which the ARE was to duplicate, as far as possible, materials, temperature pattern, and kinetics.
Code: 0213 15 31103 44 627 711 84679 921 106
83189

## No. 12 Circulating-fuel Reactor for Direct Heat Transfer to Engine

ORNL

Reference: Unpublished report, 1953.
Originators: R. W. Schroeder and B. Lubarsky.
Status: Preliminary design, 1953. Project cancelled, 1957.
Details: Intermediate neutrons, steady state, burner. Fuel-coolant: molten fluorides containing $UF_4$. Moderator: BeO. Reflector: BeO, cooled by circulating barren molten fluorides. Core: parallel tubes arranged in concentric circles within a cylinder, 40.4 in. diameter, with conical and truncated ends. Each core tube is surrounded by hot-pressed BeO. Around core is BeO reflector. Core has two manifolds to allow two-pass flow of fuel. Inconel structural material for all metallic parts in contact with fuel or with moderator coolant. Fuel flows in through center of inlet, passes through tubes, and leaves through annuli between fuel inlet and wall. Control: negative temperature coefficient; power demand; fuel drainage for shutdown. Shielding: Pb, plastic, $H_2O$. Power: 640 MW(t). Direct flow of hot fuel to engine eliminates liquid-liquid heat exchanger but makes problems in shielding.
Code: 0213 15 31211 44 627 711 84679 921 104

## No. 13 Aircraft Reactor Experiment with Stagnant Fuel

ORNL

Reference: Nuclear Sci. and Eng. 2, No. 6, pp. 804-825, Nov. 1957.
Originators: E. S. Bettis, R. W. Schroeder, G. A. Christy, H. W. Savage, R. G. Affel, and L. F. Hemphill.
Status: Design; abandoned for circulating-fuel reactor.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel: molten-salt mixture containing $UF_4$. Moderator: BeO. Coolant: Na. Core: cylindrical matrix of BeO with small vertical holes for fuel tubes. Core within pressure shell. Fuel remains within tubes. Na pumped through pressure shell. Control: poison rods within matrix; slab of $B_4C$ at top of lattice. Fuel tubes are not completely filled at design pressure and zero power, but fuel level extends above $B_4C$. Increase in temperature expands more fuel above $B_4C$ for fast control. Difficulties: at reasonably high power, high thermal gradient in molten salt causes fuel in center of tubes to reach prohibitively high temperatures; difficulties in loading fuel at room temperature--phase changes of fuel during heating might rupture fuel tubes, large control rods would be needed, and heat cycling and draining of coolant between fuel additions would pose many problems.
Code: 0413 15 31103 44 627 711 8111X 921 106
83189

## No. 14 Aircraft Reactor Experiment (ARE)

ORNL

References: ORNL-1845, Del.; Nuclear Sci. and Eng. 2, No. 1, Feb. 1957, pp. 797-853; CF-53-12-9.
Originators: First suggested by R. C. Briant. Project directed by him until his death, and subsequently directed by W. H. Jordon and S. J. Cromer.
Status: Critical, October 1954. Final shutdown, November 1954.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: circulating mixture of 93.4% enriched $U^{235}$ as $UF_4$ in NaF and $ZrF_4$. Moderator and reflector: BeO blocks stacked around fuel tubes, reflector cooling tubes, and control assemblies. Innermost section: about 3 ft diameter x 3 ft high cylindrical core. BeO in form of small hexagonally machined blocks, split axially. Fuel circulated in closed loop through 6 parallel circuits at inlet fuel header at top of reactor core; each circuit makes 11 series of passes through core, starting at core axis and progressing in serpentine fashion to periphery of core, finally leaving at the bottom of the core. Fuel circulated to external heat exchanger and back to core. Reflector coolant: Na, passed up through reflector tubes, cooling reflector and Inconel pressure shell and filling moderator interstices before leaving core. Na also helps transfer heat readily from moderator to fuel stream. Control: one regulating and 3 vertical shim rods of slugs of hot-pressed $B_4C$ clad in stainless steel; negative temperature coefficient. Maximum power: 2.5 MW(t).
Code: 0413 15 31211 44 627 711 81161 921 104
84679

## No. 15 Aircraft Reactor with Tandem Heat Exchanger

ORNL

Reference: ORNL-1227.
Originators: ANP staff.
Status: Preliminary design, 1952; discontinued.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel: molten fluorides. Moderator-reflector: $H_2O$ or NaOH. Cooling: circulation of fuel to heat exchanger. Reactor and heat exchanger in tandem. Reactor horizontal cylinder. Core and heat exchanger surrounded by 1/2-in. layer of $H_2O$ at 300-350 psi. Fuel enters reactor at top rear, makes a complete loop through fuel tubes in core, and discharges to heat exchanger. Fuel tubes: stainless steel, $1\frac{1}{2}$ in. ID, 0.015 in. wall thickness. Moderator enters active lattice around periphery at rear of reactor and flows toward outlet at forward end. If $H_2O$ is moderator, double-wall construction is used. Reactor vessel surrounded by about 4 ft $H_2O$. Control: 2 curtains of 50 Cd rods mounted on two endless tracks; curtains move from reflector into active lattice; each rod is cylinder, 12 in. long, 1/2 in. OD, 1/4 in. ID. Power: 400 MW(t).
Code: 0413 13 31211 44 627 711 84677 921 104
17 81212

## No. 16 Fireball, Early Design

ORNL

Reference: Y-F10-104.
Originators: Suggested by R. C. Briant to A. P. Fraas, who worked out details.
Status: Preliminary design calculations; project cancelled 1957.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: molten fluorides containing uranium. Moderator-reflector: BeO, graphite, or circulating moderator of NaOD. Fuel circulates to external heat exchanger. Structure: 3 concentric spheres of BeO or graphite. BeO: (90% BeO, 10% Na) central sphere, 14 in. diameter; fuel-coolant shell, 4 in. thick, 22 in. OD. Reflector: 1 ft thick, 46 in. OD. Graphite: central sphere 18 in. diameter; fuel-coolant shell: 6 in. diameter. Reflector: 12 in. diameter. Graphite reduces moderating power, with more leakage of fast neutrons. Deuterium-bearing compound could be added to graphite to make it equivalent to BeO, or circulating reflector of NaOD might be used. Island decreases critical mass and increases uniformity of fissioning density.
Control: negative temperature coefficient.
Code: 0413 12 31211 44 627 711 84677 923 104
15
17

## No. 17 Reflector-moderated Circulating-fuel Reactor (Fireball)

ORNL

References: Y-F10-104; ORNL-1515.
Originators: Suggested by R. C. Briant to A. P. Fraas, who worked out details.
Status: Design incorporated in Aircraft Reactor Test; project cancelled 1957.
Details: Thermal and intermediate neutrons, steady state, one-region burner. Fuel-coolant: molten fluorides containing about 2 mol % uranium. Moderator: Be shell. Fuel circulates to heat exchanger; secondary coolant: NaK; moderator cooled by Na. Reflector: Be moderator shell, 12 in. thick. Around reflector is 1 in. boron carbide. Reactor vessel: four concentric shells. Two inner shells surround core region and separate it from vase-shaped island of Be in center of reactor. Outer Be moderator-reflector shell surrounded by main pressure shell. Fuel-region diameter: 21 in. for 200 MW(t) reactor. Primary construction material: Inconel. Fuel circulates downward through annulus between two innermost shells, where fission occurs, then downward and outward to circumferential spherical heat exchanger that is between moderator shell and pressure shell. Fuel flows upward in heat exchanger to top, where it enters the top of the annular passage leading back to the core. Moderator cooled by Na flowing downward in annulus be-between Be and enclosing shells and back upward through passages in the Be to external heat exchangers. Vase-shaped island used because it reduces critical mass, improves power distribution in fuel region, and hydrodynamically gives best passage for fuel. Shielding: pressure shell, Pb shielding, thermal insulation, and borated water in self-sealing rubber tank. Control (suggested): fine--one or two rods in central region or in reflector; coarse shim--negative temperature coefficient. Power: 200 MW(t).
Code: 0413 15 31211 44 627 711 8111X 923 104
84679

## No. 18 Fireball without Central Island

ORNL

Reference: Unpublished report, ORNL, Dec. 3, 1954.
Originators: A. P. Fraas and A. W. Savolainen.
Status: Part of general design survey; project discontinued, 1957.
Details: Same as Fireball, but without central island.
Code: 0413 15 31211 44 627 711 8111X 921 104
84679

## No. 19 Fireball Cooled by Lead or Bismuth

ORNL

Reference: Unpublished report, ORNL, Dec. 3, 1954.
Originators: A. P. Fraas and A. W. Savolainen.
Status: Part of general design survey; project discontinued, 1957.
Details: Same as Fireball, except that liquid Pb or Bi coolant circulates between fuel and moderator regions.

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| | | 31106 | | | | | | |

## No. 20 Graphite-moderated Fireball

ORNL

Reference: Unpublished report, ORNL, Dec. 3, 1954.
Originators: A. P. Fraas and A. W. Savolainen.
Status: Part of general design survey; project discontinued, 1957.
Details: Same as Fireball, except that graphite is moderator, either as block in central zone with holes for fuel passage, or as concentric shell.

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| | | | | | | 84679 | | |

## No. 21 Fireball Moderated with Sodium Hydroxide

ORNL

Reference: Unpublished report, ORNL, Dec. 3, 1954.
Originators: A. P. Fraas and A. W. Savolainen.
Status: Part of general design survey; project discontinued, 1957.
Details: Same as Fireball, except that molten NaOH is moderator. NaOH either circulates through coiled tubes in core or through spaces between fuel passages. Tubes are either straight or curved to fit shell contours.

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| | | | | | | 84679 | | |

## No. 22 Aircraft Reactor Test

ORNL

Reference: ORNL-1835.
Originators: R. C. Briant, A. P. Fraas, et al.
Status: Design, 1953; project cancelled 1957.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: molten $NaF-ZrF-UF_4$ (50-46-4 mol %) or $NaF-KF-LiF-UF_4$ (11-42-44-3 mol %); enrichment: 93.5% $U^{235}$. Secondary coolant: NaK. Moderator-reflector: Be, 12 in. thick. Reflector coolant: Na. Structure of reactor same as for Fireball, with spherical central island of Be and outer Be reflector, and out of core. Fuel circulates downward between inner Be island and outer Be reflector, and out of core. Then fuel flows upward through heat exchanger region, which is around spherical core. Fuel is discharged downward into core. Heat is transferred in heat exchangers to the secondary coolant. Reflector cooled by Na flowing downward through passages in Be andupward through annular space between Be and enclosing shells. Central Be island cooled similarly except that the Na enters through bottom of island and returns to top of reactor through cooling passages in main pressure shell. Core diameter: 21 in.; island diameter: 11 in. Fuel-region thickness: 4.5 in. Reflector thickness: 72 in. Shielding: 7 in. borated $H_2O$; 31 in. $H_2O$. Control: negative temperature coefficient; shim control: one rod, 5% $\Delta k/k$. Power: 60 MW(t).
Code: 0413 15 31211 44 627 711 84679 923 104
81X1X

## No. 23 Circulating Fluoride-fuel High-flux Reactor

ORNL

Reference: CF-56-6-9 Rev. 2.
Originator: W. K. Ergen.
Status: Preliminary design data, 1956.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel: solution of 0.167 mol % $U^{235}F_4$ in $NaZrF_5$. Moderator-reflector: graphite. Coolant: presumably, circulation of fuel solution to external heat exchanger. Core: spherical shell embedded in infinite moderator. Central island of graphite. Core radius: 50 cm. Flux at center of sphere: $3 \times 10^{-4}$ neutrons/$cm^2$. Control: negative temperature coefficient; prepoisoning or control rods to control excess reactivity. Layer of Bi between central island and fuel layer suggested to resist flow of neutrons from central island, where they are created, to shell, where they are absorbed. It would also serve as a gamma shield for protecting the internal column. Power: 444 MW(t).
Code: 0413 12 31211 44 627 711 84679 923 104
815XX
81X1X

## No. 24 Reflector-moderated LF-1 through LF-6

General Electric Company

Reference: APEX-135.
Originators: W. C. Cooley and C. Hussey, ANP Project.
Status: Design study, 1953.
Details: Fireball modification. Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: mixture of fluorides, either "Fulinak" (Li, Na, K, and U fluorides) or "Fubeli" (Be, Li, and U fluorides) containing 93.4% enriched $U^{235}$ as $UF_4$. Moderator-reflector: Be. Annular core region between 9-in. OD internal Be moderator island and 18-in. ID external Be reflector. Reflector: 12-in. thick, with 48 in. diameter spherical contour, around which intermediate heat exchanger is located. Secondary coolant: Na or NaK. Structural material: Inconel. Fuel flows downward through annular core passage and returns upward outside the NaK tubes in the intermediate heat exchanger to the pump section. Fuel inlet temperature: 1000°F; outlet: 1500°F. Reflector and moderator cooled by Na. Control: negative temperature coefficient; control rod in the central Be island for fine control; an additional rod may be installed. Concept is identical for LF-1, -2, -3, -4, -5, and -6, except for power produced: LF-1, 76 MW; LF-2, 101 MW; LF-3, 115 MW; LF-4, 135 MW; LF-5, 180 MW; and LF-6, 232 MW.
Code: 0413 15 31211 44 627 711 81111 923 104
84679

## No. 25 300-MW Circulating-fuel Reactor

Pratt & Whitney Aircraft Division, United Aircraft Corp.

References: Unpublished reports, 1953-54.
Originators: Staff members.
Status: Design calculations; work discontinued 1957.
Details: Modification of Fireball. Intermediate neutrons, steady state, burner. Fuel-coolant: molten $NaUF_5 \cdot NaZrF_3$ (3.26 mol % $UF_4$). Moderator: Be. Fuel circulates to circumferential heat exchanger. Fireball structure with internal island of Be and Be moderator-reflector. Core volume: 127 liters. Be island: 6.69 in. OD. Inconel-clad pressure shell: 34.3 in. OD. Shield: Inconel, with boron thermal shield. Control: probably negative coefficient of reactivity and probably vertically moving control rod in moderator, as with Fireball. Power: 300 MW(t).
Code: 0213 15 31211 44 627 711 84679 923 104
81X1X

## No. 26 Core-moderated Reactor (PWAR-7)

Pratt & Whitney Aircraft Division, United Aircraft Corp.

Reference: Unpublished report, 1957.
Originators: Staff members.
Status: Preliminary design, 1956; work discontinued, 1957.
Details: Fireball type. Intermediate neutrons, steady state, burner. Fuel-coolant: $NaF-ZrF-UF_4$, containing 3 mol % $UF_4$. Moderator: Be. Fuel circulates to circumferential NaK heat exchanger. Be island. Reflector: 7 in. Be. Core diameter: 29 in.; length: 37 in. Pressure shell: overall height, 5 ft; OD, 62 in. Inconel structure. Max. fuel temperature: 1600°F. Control: presumably negative temperature coefficient. Power: 190 MW(t). Design for twin reactors. Suggestions to increase power and decrease weight. Fuels: LiF- or $BeF_2$-based fluorides, or slurries of uranium oxide in alkaline-earth metals. Coolant: $Li^7$. Structural materials: Mo; Mo-0.45% Ti; Nb-0.65% Zr; FP-16 (23% Ni, 14% Mo, 8% Cr, 1% Al, 2.5% Ti).
Code: 0213 15 31211 44 627 711 84679 923 104

## No. 27 Modified Fireball (Early Concept for Core-moderated Reactor)

Pratt & Whitney Aircraft Division, United Aircraft Corp.

References: Unpublished reports, 1954.
Originators: Staff members.
Status: Design calculations, 1954; project discontinued, 1957.
Details: Same as Fireball, except that fuel annulus is replaced by five tubes with end diffusers, in a circular pattern, which pass through the core. In one, the tubes pass through a graphite cylinder within a Be core. Graphite is believed to give better critical mass and power distribution. In the other design, the fuel passages are through the spherical Be core, which is within an Inconel pressure vessel. This modification of the fuel passage is believed to reduce flow-separation problems and to give more structural stability.
Code: 0213 15 31211 44 627 711 81X1X 84679 923 104

## No. 28 Circulating Fuel Core-moderated Reactor (CMR)

Pratt & Whitney Aircraft Division, United Aircraft Corp.

Reference: PWAC-186.
Originators: Staff members.
Status: Design, 1956; project discontinued, 1957.
Details: Intermediate neutrons, steady state, burner. Fuel-coolant: enriched $UF_4$ in molten $NaF-ZrF_4$. Moderator: Be. Fuel circulates to wraparound NaK heat exchanger between reflector and pressure shell. Reflector: Be. Core: essentially cylinder of Be (29.1 in. diameter, 37 in. high) through which 30 straight parallel tubes (3 in. ID) pass. Fuel enters core from plenum chamber above, passes downward through fuel tubes, enters plenum at bottom, and flows on shell side of heat exchanger. Fuel enters core at 1200°F; leaves at 1600°F. Core and reflector cooled by Na flow. Internal shield: cermet of $B_4^{10}C$ and Cu, clad with Inconel, between reflector shell and reflector support shell. Control: central vertical rod, in thimble, for reactor shim and control--rod is clad cermet of $B_4^{10}C$ and Cu cooled with He; negative temperature coefficient. Power: 190 MW(t). Two reactors to be used in tandem. Use of moderator in core expected to lower fuel requirements. Using tubes instead of annulus for fuel expected to eliminate unpredictable and possibly unfavorable flow and heat-transfer characteristics of the original Fireball core. A cylindrical rather than spherical core should simplify structural and fabrication problems.
Code: 0213 15 31211 44 627 711 81111 923 104
84679

## No. 29 Circulating Fuel, Reflector-moderated, Epithermal, Aircraft Reactor

Pratt & Whitney Aircraft Division, United Aircraft Corp.

Reference: PWAC-189.
Originators: Staff members.
Status: Design, 1956; discontinued, 1957.
Details: Fireball structure. Intermediate neutrons, steady state, burner. Fuel-coolant: $NaF-ZrF_4-UF_4$ (56.3, 37.2, 6.5%); uranium 93.5% enriched. Moderator: Be. Core components cooled by Na. Reflector: Be, 48 in. OD. Fuel annulus: 6 in. thick. Inner island is cylindrical, 8 in. diameter. Pressure shell: sphere, 70 in. diameter. Fuel enters core at 1200°F, circulates downward then outward and upward and leaves at 1600°F to NaK wraparound heat exchanger. Internal shielding: shells containing $B^{10}$. Control: central vertical rod, cooled by He, consisting of rare earth oxides in Ni matrix, clad with Hastelloy-X; negative temperature coefficient. Power: 194 MW(t). Two reactors to be used in tandem for aircraft propulsion.
Code: 0213 15 31211 44 627 711 81114 923 104
84679

## No. 30 Direct-circulating, Zirconium Hydride-moderated Reactor

Pratt & Whitney Aircraft Division, United Aircraft Corp.

Reference: Unpublished report, 1956.
Originators: Staff members.
Status: Design, 1956; project discontinued, 1957.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel: uranium salt in molten fluorides, possibly LiF- or BeF-based. Moderator: $ZrH_X$. Coolant: $Li^7$. Core: fuel tubes and ZrH rods, clad with Mo. Coolant flows parallel to tubes. In one design, the fuel flows down through tubes in center, goes to a header, and returns through outer tubes. In alternative, fuel flows down through inner tube and up through annulus formed by enclosing inner tube with an outer one. $Li^7$ coolant could flow directly to an engine radiator. Use of $ZrH_X$ permits high temperature without need for excessive cooling or structural support.
Code: 0413 17 31106 44 627 711 84679 9XX 106

## No. 31 Stationary Fluoride Fuel, Sodium Cooled, Reflector-moderated Reactor

Walter Kidde Nuclear Laboratories, Inc.

Reference: WKNL-42.
Originators: Staff members.
Status: Design for evaluation, 1955. Project discontinued, 1957.
Details: Similar to H. K. Ferguson concept in Data Sheet No. 6. Thermal neutrons, steady state, burner. Fuel: either $U^{235}$ or $U^{233}$ in molten KF-NaF-$ZrF_4$-$UF_4$ mixture (4 mol % $UF_4$). Stationary fuel is in tubes. Using $U^{233}$ instead of $U^{235}$ increases coolant volume and reduces fuel required, but increases average heat flux excessively. Increasing $U^{235}$ concentration to 27.5 mol % also would increase fuel volume, but because of decreased thermal conductivity would require more than three times as many fuel elements, 68,400 instead of 20,400. Supporting so many with parallel flow of coolant would be very difficult. Coolant: Na. Difficulties: difficult heat removal because of poor thermal conductivity of the molten salts; because tubes must be small to avoid excessive internal temperatures, many tubes are required.
Code: 0313 1X 31103 44 627 711 8XXXX 9XX 106

## No. 32 Beryllium Core Moderated, Circulating Fluoride-fuel Reactor

Walter Kidde Nuclear Laboratories, Inc.

Reference: WKNL-42.
Originators: Staff members.
Status: Design for evaluation, 1955. Project discontinued.
Details: Thermal neutrons, steady state, burner. Fuel-coolant: molten fluorides--50.8 mol % NaF, 46.8 mol % $ZrF_4$, 2.4 mol % $UF_4$. Moderator: 1630 Inconel-clad Be rods, 0.88 in. OD, 42 in. long, in core. Annular heat exchanger. Reactor container: 64-in. ID multiwall Inconel shell with dished bottom; cooling channels in wall. Core: circular cylinder, 72 in. by 72 in. Fuel flows downward parallel to rods, upward through Na-cooled heat exchanger, and back to core through pumps. Reflector: 4-in. blanket of 885 Be rods cooled by fuel. Fuel inlet temperature: 1500°F, outlet (max), 1150°F. Control: negative temperature coefficient; 13 borated steel control rods in Inconel thimbles extending from top of reactor shell into core, replacing like number of moderator rods. Power: 300 MW(t).
Code: 0313 15 31211 44 627 711 81111 921 104
84679

## No. 33 Beryllium Reflector Moderated, Circulating Fluoride-fuel Reactor

Walter Kidde Nuclear Laboratories, Inc.

Reference: WKNL-42.
Originators: Staff members.
Status: Design for evaluation, 1955; project discontinued.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: molten fluorides--50 mol % NaF, 46.2 mol % $ZrF_4$, 3.8 mol % $UF_4$. Moderator-reflector: clad Be. Fireball structure. Island: 12 in. OD; Reflector: 24.4 in. ID, 48.4 in. OD; Inconel pressure shell: 69 in. OD. Fuel circulates from core annulus, up through wraparound Na-cooled heat exchanger, and back to top of core. Island and reflector cooled by separate Na system. Control: negative temperature coefficient; vertical rod through center of island. Power: 300 MW(t). Alternative design: cylindrical reflector to avoid difficulties of fabricating spherical reflector. Moderator shell, island, and fuel annulus as in spherical design.
Code: 0413 15 31211 44 627 711 8111X 923 104
84679

## No. 34 Sodium Hydroxide Core Moderated, Circulating Fluoride-fuel Reactor

Walter Kidde Nuclear Laboratories, Inc.

Reference: WKNL-42.
Originators: Staff members.
Status: Design for evaluation, 1955. Project discontinued.
Details: Thermal neutrons, steady state, burner. Fuel-coolant: molten fluorides--51.1 mol % NaF, 47.0 mol % $ZrF_4$, 1.0 mol % $UF_4$. Fuel circulates to Na-cooled heat exchanger. Moderator: molten NaOH in 98 Inconel U-tubes, 2 in. OD, 42 in. long. Moderator circulated to external Na-cooled heat exchanger. Reflector: 4 in. thick annulus containing NaOH. Core: circular cylinder, 42 by 42 in. Pressure shell: 70 in. OD. Fuel inlet temperature: 1150°F; outlet (max) 1765°F. Control: negative temperature coefficient; 4 vertical borated steel control rods. Power: 300 MW(t).
Code: 0313 17 31211 44 627 711 81111 921 104
84677

No. 35 Reflector-moderated, Circulating-fuel Aircraft Reactor (Screwball)

ORSORT

Reference: CF-53-9-84.
Originators: J. H. MacMillan et al.
Status: Preliminary design study for feasibility; ORSORT term paper, 1953.
Details: Modification of Fireball. Thermal and intermediate neutrons, steady state, burner. Fuel: molten mixture of 50 mol % NaF, 47 mol % $ZrF_4$, and 3 mol % enriched $UF_4$. Moderator: circulating molten NaOD. Coolant: NaK. Reflector: spherical Be shell, 11 in. thick, 2 in. OD. Structure: spherical, with Be shell, pressure shell, and helical fuel tubes in annular form. Inconel structural material; clad with nickel where in contact with NaOD. Helical tubes used to reduce uncertainties of unstable flow in reactors of high power density. Fuel enters core at north pole and flows downward through six 3.5 in. ID Inconel tubes. Five tubes are wrapped in a variable-pitch helix to form a spherical annulus of fuel. Sixth passes through center of sphere, forming smaller-diameter helix. In returning, fuel flows over primary NaK-cooled heat exchanger. NaK coolant in circumferential heat exchanger, spherical shell. Fuel and coolant flow countercurrently. NaOD, which cools reflector, flows downward through spherical cavity in reflector and surrounds fuel tubes; acts as moderator "island." Returns to top through holes in reflector, through spherical cavity outside reflector, through a shell-and-tube heat exchanger and back to core. NaOD cooled in exchanger by exchange with NaK that is returning to reactor. NaK then goes to primary heat exchanger to cool fuel. Control system needed to keep temperature of returning NaOD constant to prevent corrosion from over-heating or freezing from cooling. Heat-exchange system uses only one intermediate heat-transfer medium and eliminates need for additional radiators to cool part of NaK, as proposed for Fireball. Control: negative temperature coefficient; shim control--adding enriched fuel; variable by-pass in xenon separator would add xenon to provide fine adjustment in reactivity between additions of enriched fuel. No rods. Basically, power extracted is determined solely by demand of propulsion system. Power: 200 MW(t).
Code: 0413 17 31204 44 627 711 84677 923 107
83789
81596

## No. 36 High-performance Marine Reactor

### ORSORT

Reference: Unpublished ORSORT term paper, August 1957.
Originators: K. H. Dufrane, T. G. Barnes, C. Eicheldinger, W. D. Lee, N. P. Otto, C. P. Patterson, T. G. Proctor, R. W. Thorpe, and R. A. Watson.
Status: Design and feasibility study, 1957.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: $U^{235}$ in molten-salt mixture containing 49 mol % NaF, 45% $ZrF_4$, 6% $UF_4$. Moderator: cylindrical Be rods, clad with Inconel, equally spaced throughout core region in triangular pitch array and extending length of core. Rods tipped with poison material (BeO plus $B^{10}$) to reduce end leakage, as well as to reduce fissioning in exit and entrance plenums for fuel. Fuel circulates to secondary heat exchanger. Reflector: Ni blanket, 6 in. thick, around core. It is surrounded by $5\frac{1}{2}$-in. thick region of cylindrical rods, 3/4-in. thick, containing mixture of BeO and $B^{10}$. Boron-bearing Inconel rods in interstices of cylinders. Reactor vessel: cylinder, 80 by 80 in., containing expansion tank for fuel and coolant coils in head for removing internally generated heat by flow of portion of fuel. Shielding: primary--structural steel plus 5 in. Pb plus 39 in. $H_2O$; secondary--4-$6\frac{1}{2}$ in. Pb; thin slab of $B_4C$ in Cu matrix surrounds this region. Primary construction material: Inconel. Fuel flows up through central core region (75 cm diameter, 80 cm high) and down through annular downcomer at periphery containing primary (fuel-to-secondary fluid) wraparound heat exchanger cooled by molten salt (30 mol % NaF, 20% LiF, 50% $BeF_2$). Heat exchanger of once-through, shell-and-tube, counterflow design; fuel goes to shell side, coolant to tube side. Fuel returns to core, coolant to steam-generating equipment. In a modification, an intermediate heat exchange with a tertiary fluid suggested to reduce shielding weight. Control: negative temperature coefficient; varying coolant flow; single vertical control rod (Inconel-BeO-Ni-1 vol. % $B^{10}$) in thimble extending length of core at core centerline for reactor shutdown, change in mean temperature, and fuel burnup; rod thimble about 4 in. diameter, with gap for cooling by molten salt or metal; provision for emergency fuel dumping. Power: 125 MW(t).

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| | | | | | | | 84679 | | |

## No. 37 Modified High-performance Marine Reactor

ORSORT

Reference: Unpublished ORSORT term paper, August 1957.
Originators: K. H. Dufrane, T. G. Barnes, C. Eicheldinger, W. D. Lee, N. P. Otto, C. P. Patterson, T. G. Proctor, R. W. Thorpe, and R. A. Watson.
Status: Preliminary study, 1957.
Details: Modification of design in Data Sheet No. 36 to give advanced design that would reduce weight and improve performance. Fuel-coolant: molten salt, 42 wt % BeF-38% NaF-20% $UF_4$; Be salt to increase moderation in core. Moderator: ZrHX rods, 0.5 in. diameter, instead of BeO to increase moderation. Ni-Mo cladding (0.01 in.) used on rods instead of Inconel. Ni-Mo corrosion resistance permits thinner cladding on moderator and thus less poison in core. Core: 40 cm diameter by 78 cm high. Fuel circulates to Na-cooled U-tube heat exchanger. Fuel enters core at 1100°F, leaves at 1300°F. Intermediate heat exchanger used to reduce amount of shielding necessary. Shielding: primary--1 in. structural steel just outside insulation of core vessel; next 15.7 in. $H_2O$ and 6 in. Pb; finally 70 in. $H_2O$ in 1/2-in. thick steel vessel. Power: 100 MW(t). Other details same as original design.
Code: 0413 17 31211 44 627 711 81111 921 104
83789
84679

## No. 38 Molten-salt Thorium Converter for Electrical Power Production

Knolls Atomic Power Laboratory

Reference: KAPL-M-JKD-10.
Originators: J. K. Davidson, W. L. Robb, L. Bernath, W. H. Horton, R. P. Schuman, R. H. Simon, and A. D. Tevebaugh.
Status: Informal reactor evaluation, 1952-53; no further work.
Details: Thermal and intermediate neutrons, steady state, converter. Fuel: solution of 93% $U^{235}F_3$ or $UF_4$ in $LiF-BeF_2-ThF_4$. Core: Inconel, 5.77 ft radius. Up to 85% average conversion of $Th^{232}$ to $U^{233}$ is possible; conversion ratio would be 0.73 to 0.905. Fuel would have to be added periodically.
Code: 0411 1X 31211 44 627 746 84679 9XX 104

## No. 39 Fused Salt Reactor for Power and Heat

ORSORT

Reference: CF-53-10-26
Originators: Theodore Jarvis et al.
Status: Conceptual design, 1953; ORSORT term paper.
Details: Thermal and mixed neutrons, steady state, burner or converter. Fuel: $U^{235}F_4$ (0.3 mol %); thorium fluoride might be added for conversion. Critical mass $U^{235}$: 2.7 kg. Moderator: graphite, of high density to avoid penetration of fuel. Reflector: graphite sphere. Containment: graphite sphere in Inconel shell, surrounded by Inconel pressure vessel. Fluoride fuel circulates from bottom through many parallel channels cut directly into the graphite moderator out the top of the reactor to external heat exchangers, in which nitrogen is the heat-exchange medium. Channels of different length so that core approaches shape of sphere. No provisions for cooling channels in graphite moderator because its temperature will not exceed 2000°F at maximum power level and with surface cooling. Reactor pressure shell, heat exchanger, and piping are Inconel. Control: negative temperature coefficient; dumping as additional emergency control; no control rods. Power: 5.3 MW(t). Reactor designed for installation at remote location to produce electrical power, as well as power for station heating. Heat provided by water heated by low-pressure waste gas from the turbine exhaust.

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| | 0413 | | | | | 746 | 83189 | | |

## No. 40 Fused Salt Breeder Reactor (FSBR)

ORSORT

Reference: CF-53-10-25.
Originators: D. B. Wehmeyer et al.
Status: Design study, 1953; ORSORT term paper.
Details: Thermal and intermediate neutrons, steady state, breeder. Fuel-coolant-fertile material: solution of $U^{233}F_4$ and $ThF_4$ in molten $Li^7F$ and $BeF_2$. Intermediate coolant: Na. Moderator-reflector: stacked graphite blocks, which contain the salt. Fuel is pumped through graphite passages and through heat exchangers located in the graphite mass surrounding core. Critical radius of core: 160 cm. Core has spherical top, flat bottom, and cylindrical sides. Average operating temperature: 1400°F. Control: negative temperature coefficient; control of fuel concentration. Breeding ratio: 1.0. Two sizes of reactors: 310 MW(t), 125 MW(e); 616 MW(t), 250 MW(e).

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| | | | | | | | 84679 | | |

## No. 41 600-MW Fused Salt Homogeneous Reactor Power Plant

ORSORT

Reference: CF-56-8-208, Del.
Originators: R. W. Davies et al.
Status: Design and feasibility study, 1956; ORSORT term paper.
Details: Intermediate neutrons, steady state, burner. Fuel-coolant: solution of highly enriched $U^{235}F_4$ in molten NaF and ZrF. No moderator other than fluorine in solution. Reflector: core vessel. Core: cylinder, 2 ft diameter by 10 ft high, surrounded by tube bundles of primary heat exchanger. Reactor vessel: multipass cylindrical container. Fuel flows up through core and U-tube heat exchangers and through annular downcomer at periphery of the vessel. Eight pumps circulate the fuel. Inlet temperature: 1050°F; outlet: 1200°F. Control: negative temperature coefficient. Intermediate coolant: Na. Ni-Mo alloys for construction materials. Reactor designed to burn $U^{235}$, but design could be altered to breed $U^{233}$. Power: 600 MW(t).
Code: 0213 17 31211 44 627 711 84677 921 101

## No. 42 Fused Salt Reactor for Process Heat

ORSORT

Reference: CF-56-8-211.
Originators: J. T. Roberts et al.
Status: Conceptual design, 1956; ORSORT term paper.
Details: Thermal and intermediate neutrons, steady state, burner. Fuel-coolant: 93% enriched $UF_4$ in $NaF-ZrF_4$. Moderator: MgO ceramic. Reflector: BeO. Fuel circulated at 17.4 ft/sec through 90 2-in. ID Inconel tubes in triangular array on 12-in. centers. Tubes are in a 10-ft-diameter by 12-ft-high cylindrical matrix of hexagonally shaped blocks of MgO. Moderator perforated to allow passage of steam through tubes inserted in holes. 35 MW(t) is generated in the MgO and used to heat steam from 2040°F to 3000°F. Annulus between tubes and walls of MgO may be filled with aluminum silicate "wool" as a thermal barrier. Fuel heated from 1050°F to 1200°F in a single pass upward through the core by internal heat generation; delivers the heat to Na in an external heat exchanger. Core reflected on sides with 8-in. BeO and contained in a 12-ft-diameter by 18-ft-long steel pressure vessel. Control: rods included, but no details given; presumably also negative temperature coefficient. Design includes 4 such reactors for an integrated coal-hydrogenation plant. Each produces 400 MW(t); 123 MW(e).
Code: 0413 17 31211 44 627 711 81XXX 921 104
84679

## No. 43 Molten Salt Natural Convection Reactor

American Standard and ORNL

References: CF-58-2-46; Trans. ANS, 1, No. 1, p. 64.
Originators: F. E. Romie (American Standard) and B. W. Kinyon (ORNL).
Status: Proposal, 1958.
Details: Intermediate neutrons, steady state, presumably burner. Fuel-moderator-coolant: solution of $UF_4$ in $LiF-BeF_2$. Core vessel: sphere, 8 ft diameter. Fuel solution circulates by natural convection through the core from the bottom, through vertical convection risers, to primary heat exchangers above the core. Maximum fuel temperature: 1225°F; minimum: 975-1025°F. Primary heat exchanger may be cooled by either molten salt or helium. Control: presumably negative temperature coefficient. Power: 60 MW(t); 22 MW(e).
Code: 0213 17 31211 44 627 711 84677 9X 101

## No. 44 Homogeneous Fused Salt Power Reactor

ORNL

Reference: Trans. ANS, 1, No. 1, pp. 63-64.
Originators: W. A. Box *et al*.
Status: Feasibility study, 1958.
Details: Intermediate neutrons, steady state, burner. Fuel-moderator: highly enriched $UF_4$ dissolved in molten $NaF-ZrF_4$ (57 mol %-43 mol %). Coolant: molten Pb. Core: cylinder, 10 ft diameter, 10 ft high. Pb circulates molten salt by direct mixing by means of jet pump. Heat exchange is very rapid; no primary heat exchanger needed. Fuel and coolant separated downstream from the jet pump by pipeline separator. Fuel goes to core, Pb to steam generator. Heat extracted from Pb by six heat-transfer loops that supply turbine generators. Pressure: 140 psi. Control: negative temperature coefficient. Power: 600 MW(t); 194 MW(e).
Code: 0213 17 31106 44 711 84677 9X 105

## No. 45 Slightly Enriched, Fused-salt-fueled Reactor

ORNL

References: ORNL-2684, pp. 18-22; CF-58-10-60; CF-59-1-26.
Originators: H. G. MacPherson and C. E. Guthrie.
Status: Proposal, 1958; preliminary design, 1959.
Details: Near-thermal neutrons, steady state, converter. Fuel-coolant: slightly-enriched 1.3-1.8% $U^{235}F_4$ in molten $LiF-BeF_2$. Moderator: graphite. Unclad graphite moderator core, $12\frac{1}{4}$ ft in diameter and height, is contained in a cylindrical INOR-8 vessel. Fuel flows at 35,470 gpm from bottom to top of core through 3.6 in. holes on 8-in. centers in the graphite. Highly enriched uranium added as make-up fuel. Control: controlling temperature and fuel concentration. Initial conversion ratio of U to Pu: about 0.79. Power: about 775 MW(t); 315 MW(e).
Code: 0311 12 31211 42 627 743 84679 922 104
83789

## No. 46 Experimental Molten-salt-fueled 30 MW(t) Power Reactor

ORNL

References: ORNL-2796; ORNL-2684, pp. 3-17.
Originators: L. G. Alexander *et al.*
Status: Preliminary design, 1960.
Details: Intermediate neutrons, steady state, burner. Fuel-moderator-coolant: solution of 90% enriched $U^{235}F_4$ in molten $LiF-BeF_2$. Core: sphere, 6 ft diameter. Secondary coolant: molten $LiF-BeF_2$. Single structure contains core, heat exchanger, expansion tank, and fuel pump volute. Fuel circulates at 1480 gpm through bottom of core, flows upward at walls of core to heat exchanger and back to core, where it flows down. Steam produced at 1000°F and 1450 psi. Exit temperature of fuel: 1235°F. Structural material: INOR-8. Control: negative temperature coefficient; control of fuel concentration. Power: 30 MW(t); 10 MW(e).
Code: 0213 17 31211 44 627 711 84677 9XX 101
83789

## No. 47 Molten Salt Reactor Experiment (MSRE)

ORNL

References: Proc. Symp. Power Reactor Experiments 1, IAEA, Vienna, 1962, pp. 247-92; Nucleonics 22, No. 1, pp. 67-70, January 1964.
Originators: MSR project, ORNL.
Status: Conceptual design, 1960. Criticality achieved in 1965.
Details: Thermal neutrons, steady state, converter (possibly with internal breeding). Fuel-coolant: solution of 93.5% enriched $U^{235}F_4$ in $LiF-BeF_2-ZrF_4-ThF_4$. Intermediate coolant: $Li^7F-BeF_2$. Moderator: unclad graphite, 1064 stringers (2 x 2 x 63 in. long) loosely pinned to restraining beams at core bottom; form cylindrical core (about 5 ft diameter by 7.5 ft high) contained in a reactor vessel. Annulus between this inner cylinder and outer shell provides cooling for the shell. Flow is laminar at 1200 gpm; fuel, blanketed by helium gas, enters top of core at 635°C, flows in a spiral path downward in annulus along the wall to the bottom where a dished head reverses the flow. It then flows up through channels in the graphite core matrix formed by machining the faces of the stringers. All components in contact with the fuel are of INOR-8. Exiting at 663°C the fuel enters the sump-type pump from which it is discharged through the shell side of the heat exchanger back to the core inlet. Control: negative temperature coefficient; 3 shim control rods--thin-walled cylinders of $B_4C$ made of stacked short sections clad in INOR-8. Power: 10 MW(t).
Code: 0311 12 31211 44 627 746 84679 923 104
0312 81111

## No. 48 Uranium Fluoride-fueled Fast Reactor for Spacecraft

Jet Propulsion Laboratory, Calif. Inst. Tech.

Reference: JPL-TR-32-198.
Originator: L. S. Allen.
Status: Calculations, 1962.
Details: Fast neutrons, steady state, burner. Fuel: uranium as 93.5% enriched $UF_4$ dissolved in molten-salt mixture--70% $UF_4$, 30% NaF. No moderator. Coolant: Li, which flows to engine. Core: sphere, 21 in. diameter, 40 liters vol. Core composition: 42% $UF_4$, 18% NaF, and 10% Zr by volume. Reflector: internal, Zr; external, 3 in. Be. Control: presumably negative temperature coefficient. Power: 10 MW(t).
Code: 0113 11 31106 44 627 711 84679 923 109

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# Chapter 3. Two-region Reactors

In the development of practical molten-salt-fueled reactors, two-region reactors represent a more advanced stage of development than one-region reactors. A two-region power breeder is the goal. Work on two-region MSR's has been nearly all concentrated at Oak Ridge National Laboratory. Most reactors described in this chapter have graphite-moderated cores and fluoride fuels, although two concepts utilize chloride fuels and no moderator.

In 1960, MacPherson described three possible types of reactor construction for breeding.[1]

The first, the unit fuel tube, was believed to be the most practical. The fuel passes through the reactor in graphite tubes, which are enclosed by graphite moderator. The blanket, which contains a thorium salt, surrounds the core. The blanket salt also passes through small passages in the graphite as a coolant.

The graphite core shell consists of three blocks of graphite--a top header, a center section, and a bottom header. The blocks should be of graphite that is nearly impervious to the fuel solution. The three blocks are either clamped, cemented, or held together by posts.

In the internally cooled reactor, the fuel is in graphite tubes extending through the moderator into the blanket. The tubes are connected at each end to a header system, so that the fuel can be slowly circulated to keep it uniform, to remove gaseous fission products, and to allow for the fuel concentration to be adjusted for burnup. The heat is transferred through the tube wall to the blanket salt, which thus acts as a coolant. Graphite inserts in the tubes force the fuel to the outer portion of tubes to increase heat transfer. A problem with this structure is that it is unlikely that all of the 10,000 tubes needed for a 200 MW(e) reactor would keep their integrity for a long reactor lifetime.

## Hydroxide-moderated Reactor

In considering hydroxide-moderated two-region reactors, Dayton and Chastain emphasized lithium-7 hydroxide and lithium-7 deuteroxide.[2] The spherical reactor, consisting of concentric shells of zirconium, has an outer annulus, which contains a suspension of thorium oxide in heavy water. This suspension serves both as a breeding blanket and as a reflector. The specified core temperature of 1100°F was assumed to be high enough for efficient power production but low enough to avoid excessive corrosion. Breeding gains greater than 0.2 were postulated for reactors with either lithium compound. The authors concluded that the reactor moderated with

$Li^7OD$ would be preferable. The reactor moderated with $Li^7OH$ has a lower-cost moderator, smaller core radius, and smaller fuel requirements. These advantages, however, are more than offset by those of the reactor moderated with $Li^7OD$. This reactor, because of its larger core radius, would offer a larger breeding gain and would have improved heat-removal properties. Also, although more fuel is required, it is a much smaller percentage of the total mass than is required with the reactor moderated with $Li^7OH$.

## MIT Fast Reactor

A reactor designed in early 1952 that differed from most two-region reactors was the MIT Fluid Fuel Fused-salt Reactor reported by Goodman *et al.*[3,4] Instead of fluorides, the fuel is uranium tetrachloride, which is dissolved in a molten mixture of lead chloride and sodium chloride. The higher thermal neutron-absorption cross section of the chlorides requires this to be designed as a fast reactor. The blanket consists of uranium tetrachloride containing depleted uranium. A lead reflector around the semispherical core is used for shim control.

## ORSORT Fast Breeder

A similar design for a fast reactor was employed by Bulmer *et al.*, students at the Oak Ridge School of Reactor Technology, in 1956.[5] Again the fuel salt was a chloride instead of a fluoride, with both plutonium and depleted uranium chlorides dissolved in sodium and magnesium chlorides. The depleted uranium permits internal breeding. The blanket, a paste of depleted uranium oxide powder in sodium, is divided into two regions by a graphite moderator, which makes possible a smaller blanket. A molten-lead reflector is between the core and the blanket. A graphite reflector surrounds the second blanket region. A power of 260 MW(e) was given.

## Internally Cooled Molten-salt Reactor

Lackey calculated the nuclear characteristics for this reactor, which uses molten fluorides of uranium, thorium, lithium, and beryllium as fuel. The blanket and coolant are the molten-salt solutions without uranium.[6] Graphite is the moderator. Cylindrical passages for coolant are in a triangular lattice within the graphite, with the fuel in the annular space between the coolant tube and the graphite. The fertile salt is in a blanket around the graphite. A different core arrangement, to reduce doubling time, would use two concentric tubes with fuel in the annulus and coolant flowing through the inner tube and outside the outer tube. This design was for a reactor of high power--1563 MW(t).

## Thermal Convection Reactor

Zasler has proposed a reactor,[7,8] for which few details are given, in which circulation of fuel could be either by natural convection for a 5-MW experimental reactor, or by fuel pumps for a 50-MW(t) pilot plant. In the spherical reactor, which is surrounded by a blanket, fuel flows from the reactor to a shell-and-tube heat exchanger.

## Molten Salt Reactor (MSR)

This ORNL concept[9-11] has been given many names: MSR; Interim Design Reactor; Molten Fluoride Converter; Molten Fluoride Power Reactor; Reference Design Reactor; RDR; MSR Reference Design; and Homogeneous, Two-region, Molten-fluoride-salt Reactor. It underwent several modifications, particularly in the core design. The fuel is highly enriched uranium tetrafluoride in a eutectic of lithium, beryllium, and thorium fluorides. Plutonium-239 has been suggested as an alternative fuel.[12] A fertile blanket of the same composition as the fuel salt but without the uranium surrounds the fuel region. The core has the shape of an inverted pear. The fuel enters the bottom of the reactor, passes to the top, goes to the primary heat exchangers, and returns to the reactor. The reactor, designed for central-station power, would produce 260 MW(e).

## Two-region, Graphite-moderated, Molten-salt Breeder Reactor

Members of the MSR Project staff selected a typical design for calculation of reactor performance.[13] The core is a graphite shell structure with a single cylinder of graphite as the main part and two graphite end pieces. The three pieces are held together by rods of INOR-8 or other alloy. The fuel, uranium-233 in a molten fluoride carrier containing thorium, passes downward through channels in the core then back upward to an external heat exchanger. The blanket, which contains thorium in molten salt, is kept at a slightly higher pressure than the core. The power would be 125 MW(t).

## Molten Salt Breeder Reactor (MSBR)

A reactor considered in 1961 in a comparison of homogeneous reactors for thorium breeding was the MSBR,[14,15] which was based on a design by MacPherson in 1959.[1] In both the 1959 and 1961 designs, the fuel is a solution of enriched uranium tetrafluoride in $LiF-BeF_2$, the blanket surrounding the core is molten salt containing thorium, and the fuel passes through tubes in the graphite moderator. In the 1959 design, the core is of the unit-fuel-tube construction, in which one-pass graphite tubes go through the graphite moderator. In the 1961 design, the core is constructed of graphite prisms, machined at the corners to form vertical

passages, into which two-pass bayonet graphite tubes for fuel flow are inserted. Both designs are for use in groups of reactors for power production. The 1959 concept is for three reactors producing 333 MW(e) each, the 1961 concept for two reactors producing 500 MW(e) each.

# DATA SHEETS

# TWO-REGION REACTORS

## No. 1 Reflected Homogeneous Reactor Moderated by Lithium-7 Hydroxide

Battelle Memorial Institute

Reference: BMI-746.
Originators: R. W. Dayton and J. W. Chastain.
Status: Design calculations, 1952.
Details: Thermal neutrons, steady state, converter. Fuel-moderator-coolant: Homogeneous suspension of $U^{233}O_2$ in LiOH. Minimum fuel for criticality: about 2.5 kg $U^{233}$. Reflector-breeding blanket: circulating suspension of $ThO_2$ in $D_2O$, about 1 g/cm$^3$, in spherical annulus. Blanket thickness: 60 cm. Core contained by 2 concentric Zr shells, 0.5 cm thick. Shells separated by air space 1 cm thick, which is thermal barrier. Zr foil in air space to improve thermal barrier. Core temperature: 1100°F. Blanket temperature: 250°F. Breeding gain: more than 0.2.
Code: 0311 17 31312 45 637 756 84677 941 101

## No. 2 Reflected Homogeneous Reactor Moderated by Lithium-7 Deuteroxide

Battelle Memorial Institute

Reference: BMI-746.
Originators: R. W. Dayton and J. W. Chastain.
Status: Design calculations, 1952.
Details: Same as Data Sheet No. 1, except that $Li^7OD$ is used instead of $Li^7OH$.
Code: 0311 17 31312 45 637 756 84677 941 101

## No. 3 MIT Fluid Fuel Fused-salt Reactor

MIT

References: MIT-5000, pp. 12-19, 25-150; MIT-5001, pp. 11-37.
Originators: Clark Goodman *et al.*
Status: Design adopted for study of nuclear problems of nonaqueous fluid-fuel reactors, 1952.
Details: Fast neutrons, steady state, converter. Fuel-coolant: mixture of molten $UCl_4$ (22% $U^{235}$), $PbCl_2$, and NaCl. No moderator. Reflector: Pb, immediately surrounding semispherical core. Fertile material: blanket of depleted U (containing 0.3% $U^{235}$) as $UCl_4$, around reflector. Fuel-coolant is circulated to external heat exchangers. Structural materials: Ni or Fe. Control: reflector for shim control; negative temperature coefficient. Conversion ratio of $U^{238}$ to $Pu^{239}$: about 1.15. No power given.
Code: 0111 11 31211 43 627 735 84679 941 108
82X88

## No. 4 Fused Salt Fast Breeder Reactor

### ORSORT

Reference: CF-56-8-204, Del.
Originators: J. J. Bulmer et al.
Status: Design and feasibility study, 1956. ORSORT term paper.
Details: Fast neutrons, steady state, breeder. Fuel coolant: circulating mixture of molten NaCl, $MgCl_2$, $PuCl_3$, and $U^{238}Cl_3$; $PuCl_3$ is assumed to be in solution with $UCl_3$; depleted U is for internal breeding. Fertile material: blanket of paste of depleted $UO_2$ powder in Na. Fuel contained in a 72.5 in. ID, nearly spherical, vessel, tapered at the top and bottom to 24 in. for pipe connections. Vessel is of Ni-Mo alloy-clad stainless steel. Reflector: 1 in. liquid Pb immediately surrounding core. Around reflector is blanket, under 100 psi pressure. Stationary blanket is divided into 2 regions by a $5\frac{1}{8}$-in. stainless steel-clad graphite moderator. An 8 in. graphite reflector surrounds second blanket region. Use of graphite moderator in middle of blanket reduces size of blanket necessary. Blanket cooled by Na flowing through tubes. Fuel enters reactor core at bottom at 1050°F and leaves through the top at 1350°F, then is pumped through an external loop and tube side of Na heat exchanger. Control: mainly through negative temperature coefficient. Shim control by changing level of Pb reflector. Estimated breeding ratio: 1.09. Power: 700 MW(t), 260 MW(e).
Code: 0112 11 31211 46 627 755 84679 941 108
82188

## No. 5 Internally Cooled Molten-salt Reactor

### ORNL

Reference: CF-59-6-89.
Originator: M. E. Lackey.
Status: Calculations of nuclear characteristics, 1959.
Details: Thermal neutrons, steady state, breeder. Fuel: $U^{233}F_4$ in molten mixture--$ThF_4$-LiF-$BeF_2$. Two compositions: $ThF_4$--7, 13%; LiF--67.25, 71%; $BeF_2$--25.75, 16%. Coolant: molten fuel carrier. Moderator: graphite. Fertile material: blanket, 2.5 ft thick, of molten fuel carrier. Core: cylinder, 19.15 ft diameter, 19.15 ft high, surrounded by blanket, in INOR-8 pressure shell, 1.5 in. thick. Cylindrical passages for fuel and coolant in moderator, parallel to core axis, in triangular lattice. Coolant tube in each passage. Fuel in annular space between coolant tube and moderator. No reflector. Control: negative temperature coefficient. Power: 1563 MW(t). Doubling times: with 7 mol % $Th^{232}$, 27.5 years; with 13 mol %, 22.5 years. The $Pa^{233}$ formed could be diluted by mixing the fuel-carrier salt with the blanket and coolant salts. This should reduce doubling times. Further reduction possible by different core arrangement: 2 concentric tubes, with fuel in the annulus and coolant flowing through the inner tube and on outside of outer tube.
Code: 0312 12 31211 44 627 746 84679 931 106

## No. 6 5 MW(50 MW) Thermal-convection Molten Salt Reactor

ORNL

References: ORNL-2551, pp. 49-51; ORNL-2626, p. 48.
Originator: J. Zasler.
Status: Proposal for preliminary design, 1958.
Details: Thermal neutrons, steady state, breeder. Spherical core, 5 ft diameter, surrounded by 0.5 ft blanket. Fuel-coolant: flows at 158 gpm through reactor and shell-and-tube heat exchanger, cooled by Na, entering the heat exchanger at 1210°F and leaving at 1010°F. 5-MW(t) experimental reactor could be converted to 50-MW(t) pilot plant by adding fuel pumps (to increase flow to 1515 gpm) and increasing capacity of the fuel pumps.
Code: 0312 1X 31211 4X 627 7XX 84679 9XX 106

## No. 7 Molten Salt Reactor (MSR; Interim Design Reactor; Molten Fluoride Converter; Molten Fluoride Power Reactor; Reference Design Reactor, RDR; MSR Reference Design; Homogeneous, Two-region Molten-fluoride-salt Reactor)

ORNL

References: ORNL-2751; Proc. 2nd U.N. Int. Conf. 9, 1958, pp. 188-201; Lane et al., Fluid Fuel Reactors, pp. 657, 681-696.
Originators: H. G. MacPherson et al.
Status: Conceptual design, 1959; work continuing.
Details: Intermediate neutrons, steady state, converter. Fuel-coolant-moderator: mixture of 90% enriched $U^{235}F_4$ with $LiF-BeF_2-ThF_4$; alternate fuel: $Pu^{239}$ instead of $U^{235}$. Neutrons with this fuel are thermal.
Fertile material: 2-ft-thick blanket, of $ThF_4$ as eutectic of $LiF-BeF_2-ThF_4$, completely surrounding fuel region. Both fluids circulated to external shell-and-tube heat exchangers, where heat is transferred to Na. Several core configurations considered: 1) straight-through flow, 2) concentric inlet (inner pipe)-outlet (outer annulus) flow, 3) concentric inlet (outer annulus)-outlet (inner pipe) flow. Core: inverted-pear-shaped, Ni-Mo alloy, 8-ft in diameter (6-ft in early designs), surmounted by expansion chamber containing fuel pump. Fuel temperature: approximately 1200°F. Control: negative temperature coefficient. Blanket produces $U^{233}$ at conversion ratio of 0.6 to 0.8, depending upon processing. Reactor designed as central-station power plant to produce 600 MW(t), 260 MW(e).
Code: 0211 17 312 44 627 746 84677 931 101
0311 46

## No. 8 Two-region, Graphite-moderated Molten-salt Breeder Reactor

ORNL

Reference: ORNL-2799.
Originators: MSR project staff.
Status: Typical design for calculation of performance, 1959.
Details: Thermal neutrons, steady state, breeder. Fuel-coolant: $U^{233}$, presumably as $UF_4$, dissolved in molten $LiF-BeF_2-ThF_4$. Moderator: graphite. Reflector: graphite. Fertile material: 30-in. blanket of 13 mol % Th in molten $LiF-BeF_2-ThF_4$. Core: main part made from single cylinder of graphite, about 5 ft diameter, 5 ft long, and two end pieces. Three pieces held together by rods of INOR-8 or other alloy. Parallel vertical channels for fuel flow, 1/2 in. max. radius. Molten fuel salt passes downward through core then back upward to external heat exchanger. Blanket, which surrounds core, is kept at slightly higher pressure. Pressure: 1000 psi max. Control: presumably negative temperature coefficient. Power: 125 MW(t).
Code: 0312 12 31211 45 627 746 84679 941 104

## No. 9 Molten Salt Breeder Reactor (MSBR)

ORNL

References: CF-61-3-9, pp. 68-81; CF-61-8-86.
Originators: H. G. MacPherson, L. G. Alexander, et al.
Status: Reference design for evaluation of thorium breeder reactors, 1961.
Details: Near-thermal neutrons, steady state, breeder. Fuel-coolant: $UF_4$ in LiF and $BeF_2$. Moderator: graphite. Fertile material: blanket of $ThF_4$ in LiF and $BeF_2$. Reflector: graphite. Core cylinder $7\frac{2}{3}$-ft x $7\frac{2}{3}$-ft. of graphite moderator prisms, 7.5 in. square by approx. 7 ft long. Corners machined to form vertical passages of about 5 in. diameter circular cross-section. Fuel flows through 90 2-pass bayonet graphite tubes inserted into these vertical passages. Core surrounded on all sides by 3-ft blanket, which is then surrounded by the 1-ft graphite reflector. Heat exchanger and fuel pump mounted directly above the reactor. Maximum fuel temperature: 1300°F; minimum 1125°F. Operating pressure: 100 psi. Control: through negative temperature coefficient. Power station would include 2 such reactors to produce 2364 MW(t) or 1000 MW(e)--1182 MW(t) and 500 MW(e) each.
Code: 0312 12 31211 44 627 746 84679 941 104

## No. 10 Graphite-moderated, Circulating Fuel, Molten Salt Reactor Plant

ORNL

Reference: CF-59-12-64 Rev.
Originator: H. G. MacPherson.
Status: Reference design, 1959.
Details: Thermal neutrons, steady state, breeder. Fuel-coolant: $U^{235}F_4$ in $LiF-BeF_2$, at minimum temperature of 975°F and maximum of 1300°F, circulating at 20 fps. Moderator: graphite. Fertile material: blanket of Th, presumably as $ThF_4$, in $LiF-BeF_2$. Core: 5.3 ft in diameter; blanket: 2.5 ft thick. Graphite moderator core contains graphite tubes through which fuel passes (unit fuel tube construction). Blanket salt also passes through small passages in moderator for cooling. Fuel inlet and outlet at bottom of core, although straight-through flow is possible. Control: presumably by negative temperature coefficient. Possible breeding ratio: 1.06. Each of 3 reactors in plant produces 815 MW(t), 333 MW(e).
Code: 0312 12 31211 44 627 746 84679 931 104

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