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CATALOG OF NUCLEAR REACTOR CONCEPTS

Part I. Homogeneous and Quasi-Homogeneous Reactors

Section I. Particulate-Fueled Reactors

by

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

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ARGONNE NATIONAL LABORATORY
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Argonne, Illinois 60440

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TABLE OF CONTENTS

	Page
Preface	iii
General Introduction	v
SECTION I. PARTICULATE-FUELED REACTORS	
Chapter 1. Introduction	1
Chapter 2. Pebble-Bed Reactors	7
Chapter 3. Packed- (Settled-) Bed Reactors	35
Chapter 4. Fluidized-Bed Reactors	53
Chapter 5. Fluidized Reactors and Moving-Bed Reactors	81
Chapter 6. Paste-Fuel Reactors	95
Chapter 7. Reactors with Particulate Fuel Elements	107
Appendix A. Partial List of Reactor Compilations	145
Appendix B. Coding Classification System	147

PREFACE

This report represents an effort to prepare a new type of reactor catalog—one which cites the various concepts of reactors regardless of whether or not the concepts ever have materialized or will materialize as actual reactors. When the need for such a catalog confronted officials in the Division of Reactor Development, U. S. Atomic Energy Commission, they requested the Argonne National Laboratory to undertake the cataloging task. Mr. Frank Kerze, now in the Division's Office of Civilian Power, initiated the project when he was in the Evaluation and Planning Branch and has coordinated the adminstrative matters to date. He has also made significant contributions to selection and compilation of data.

The task involves finding and collecting data on the various concepts by every means possible. Except in the cases of the more familiar reactors, the search generally leads to rather obscure literature sources. Considerable correspondence is needed, but distribution of questionnaires is being deliberately avoided. Classified sources are also being searched, and the selected information that can be declassified is included.

When sufficient information was collected, a scheme for categorizing the concepts in a logical order had to be developed. The scheme finally chosen (which is explained in the General Introduction) was developed primarily by Dr. Charles E. Teeter of the AEC Chicago Operations Office. Dr. Teeter also developed the coding system for indexing the concept data on punched cards. Many other persons have assisted in compiling and reviewing the information, and we are grateful to all.

This report presents only the first segment of the catalog, i.e., Part I, Particulate-Fueled Reactors, of Section I, "Homogeneous and Quasi-Homogeneous Reactors." Other segments will be issued as additional reports as the cataloging work progresses.

J.H.M.
May 11, 1964

GENERAL INTRODUCTION

This catalog is a compilation of information on nuclear reactor concepts. "Concept," as used here, means any actual design, proposal, plan, or idea that has been recorded in a manner suitable for study apropos to further development and that includes all the fundamental features of a nuclear reactor proper, i.e., fuel, coolant, moderator, control means, and container. Unique configurations or modifications of standard components are considered as separate concepts.

The concept descriptions are organized in chapters according to their generic relationships. A dual method of presentation has been adopted. Each chapter contains a narrative description of concepts described therein, highlighting their main features and resemblances and differences. Next a series of "Reactor Concept Sheets" is presented, one for each concept in a concise, standardized format, describing briefly the main features of each concept. No attempt is made to give complete engineering data, for which the reader is referred either to the references or to one of the excellent reactor compilations that have been published by other organizations. A selected list of these compilations is given in Appendix A. At the end of each chapter is a list of references for the concepts described as well as additional selected references.

At the end of each concept sheet is a "coding" for the specific concept in terms of a coding classification system. The explanation of this classification system is given in Appendix B. From the codings a set of Royal McBee Keysort or IBM cards can be prepared and used as a comprehensive cross index for selecting reactors by moderator, coolant, fuel, or any other coded characteristic. In this way the limitations due to any arbitrariness in the cataloguing may be overcome. Some degree of arbitrariness of arrangement is inevitable. Whatever method of arranging the material is chosen, some concepts might belong equally well in one chapter as another. When a concept could be included in either of two places, the more novel feature of the concept is the basis for choice.

In this catalog, most reactor concepts are divided into two main parts: homogeneous and heterogeneous. A few concepts fall into a third, miscellaneous, part. The first part is divided according to the fuel, and the second part is divided according to the coolant. Purposes of reactors are identified, but the reactors are catalogued according to their core characteristics. The plan of the catalog is given below.

General Introduction

Part I Homogeneous and Quasi-Homogeneous Reactors

- Section I Particulate-Fueled Reactors
- Section II Reactors Fueled with Homogeneous Aqueous Solutions and Slurries
- Section III Reactors Fueled with Homogeneous Molten Salts
- Section IV Reactors Fueled with Liquid Metals
- Section V Reactors Fueled with Uranium Hexafluoride

Part II Heterogeneous Reactors

- Section I Semi-Homogeneous Reactors
- Section II Reactors Cooled with Liquid Metals
- Section III Gas-Cooled Reactors
- Section IV Organic-Cooled Reactors
- Section V Boiling Reactors
- Section VI Reactors Cooled with Supercritical Fluids
- Section VII Water-Cooled Reactors
- Section VIII Reactors Cooled with Other Liquids
- Section IX Boiling-Water Reactors
- Section X Pressurized-Water Reactors

Part III Miscellaneous Reactor Concepts

PART I HOMOGENEOUS AND QUASI-HOMOGENEOUS REACTORS

SECTION I PARTICULATE-FUELED REACTORS

Chapter 1 Introduction

In accordance with the plan outlined in the general introduction, the compilation begins with the description of reactors with particulate fuel. "Particulate" is defined as "composed of particles," but it is here used in the sense of "subdivided" as opposed to "massive." Included in this section, therefore, are reactors with fuel ranging from micron-size particles to 3-inch pebbles. The concept classification system used is summarized in Table I.

Chapter 2 covers pebble-bed reactors; Chapter 3, packed- or settled-bed reactors; Chapter 4, fluidized-bed reactors; Chapter 5, fluidized reactors and moving-bed reactors; Chapter 6, paste-fuel reactors; and Chapter 7, particulate-fuel-element reactors.

The pebble-bed reactor is defined most simply as a reactor in which fuel and moderator are in the form of small clad or unclad spheres or pebbles in a fixed bed contained or supported in the reactor vessel. Fuel and moderator may be combined in the same pebbles or may be in separate pebbles. The coolant flows through the bed; pebbles are loaded at the top and removed at the bottom.[1] Coolant flow may be either upward or downward through the bed, but if the coolant flows upward the coolant velocity must not be sufficient to raise the pebbles from their rest positions or there must be a retaining structure. Thus the pebble bed is also a "settled bed." The pebbles range from 0.4 to 3 inches in diameter. They are sometimes described as "marbles" or "balls."

Most pebble-bed reactors are designed for very high temperatures and gas cooling, but this criterion cannot be considered universal. On the other hand, most of the reactors described in Chapter 2 have been specifically named "pebble-bed reactors" by their originators. A few additional closely related concepts have been included. Other settled-bed reactors not specifically named "pebble-bed reactors" and with particles smaller than "pebble" size are described in Chapter 3 as "packed-bed reactors."

The packed-bed (settled-bed) reactors (Chapter 3) are very similar to

TABLE I Particulate-Fueled Reactors

	FIXED-BED			MOVING-BED		NO-BED
Characteristic	Pebble-bed	Packed-bed	Fluidized-Bed	Fluidized	Paste-Fueled	Particulate Fuel Element
Form of Fuel	Particles 0.4 in. or more in diameter	Particles less than 0.4 in. diameter	Particles generally less than 0.25 in. diameter	Dry powder (no coolant) or dilute fluid suspension	Fully settled suspension in coolant	Fuel in tubes, slabs, or regions; may be fluidized, suspended, or settled
Form of Coolant	Usually gas	Usually liquid	Gas or liquid	Gas or liquid	Liquid only	Gas or liquid
Disposition of Fuel or Particles During Operation	In settled bed; remains in core		In fluidized bed; remains in core	Circulates through whole system. Fuel flows downward like a liquid through the core. Pumped or fluidized by upward stream of coolant for return circuit.	Circulates through whole system. Fuel flows slowly downward as paste through core. Is diluted and fluidized by upward stream of coolant for return.	May or may not circulate
Coolant Flow	Upward or downward		Upward	Downward in core; upward in return circuit	Downward with fuel; upward in channels separate from fuel	Upward or downward
Fuel Disposition for Reprocessing	Generally discharged at bottom of core for reprocessing	May be fluidized by upward flowing coolant stream for reprocessing	Remains fluidized; can be discharged from top or bottom of core	Fluidized stream may be tapped for reprocessing		Additional coolant flow may be used for reprocessing

pebble-bed reactors except for the size of the particles or pellets, which are generally smaller in the packed-bed reactors than "pebbles." In addition, many packed-bed reactors are liquid-cooled, but a few are gas-cooled. Some of the liquid-cooled reactors are operated as settled-bed reactors while the nuclear chain reaction is occurring, but the particles can be fluidized and removed for reprocessing when the reactor is shut down. Some reactors can be operated as either fluidized- or settled-bed reactors by making small changes of geometry or loading parameter.

The fluidized-bed reactor has a core composed of fuel pellets suspended in a critical configuration in the reactor vessel by an upward-moving stream of gas or liquid.[2] The fuel pellets do not circulate outside the core; i.e., the bed is fixed, not moving. If the fluid flow stops, the pellets settle by gravity into a subcritical configuration. The distinction is explained in reference 3. The fluidized-bed reactor is similar in principle to the pebble-bed reactor except that the fuel pellets are sufficiently small and the fluid velocity is sufficiently high that the particles become suspended in the coolant, and the mixture acquires many of the properties of a liquid, like buoyancy. Sarbacher[1] states that "fluidized-bed reactors are ones in which the fuel has the properties of a quasi- or semi-fluid." Because the pellets must be readily suspended, the fluidized-bed reactor generally has smaller fuel pellets than the pebble-bed reactor; in most fluidized-bed reactors, pellets will be measured in microns, whereas the pebbles range from 0.4 to 3 inches in diameter. But, as large particles or pellets can be suspended by a sufficiently rapid coolant flow, this distinction is not absolute. Fluidized-bed reactors are described in Chapter 4.

Thus, fixed-bed reactors have been divided into three classes: (a) pebble beds, (b) packed beds, and (c) fluidized beds, in accordance with literature usage, and other secondary, but not universal, characteristics. The terms "powder bed" or "pellet bed" might have been used instead of "packed bed (settled bed)" to focus attention on the smaller particle size as compared with "pebble bed." Such terms, however, are not found in the literature. "Packed" or "settled" bed is contrasted with "fluidized" bed, as they developed together. "Pebble-bed" concepts seem to have developed separately.

Certain reactors have been described as "fluidized reactors," "fluidized-solids reactors," "suspension reactors" or "moving-bed reactors." These have the common feature of a particulate, finely powdered, or fluid-suspension fuel that flows, like a liquid, into a core vessel, where it attains criticality, then out of the core, where it becomes subcritical.[4] The fuel is then circulated by a pump or fluidized by a stream of gas or liquid through a heat exchanger to a reservoir above the core. From the reservoir the fuel flows downward by gravity into the core to complete the cycle. Although these reactors could be described as "slurry reactors," they were not so characterized by their originators, and, because of the distinctive fuel-circulation cycle, these concepts are described under fluidized and moving-bed reactors. Reactors fueled with slurries will be treated later in the catalog.

Paste-fueled reactors (Chapter 6) contain particulate fuel dispersed as a two-phase mixture in a liquid coolant--usually a liquid metal for nuclear reactor coolants--at approximately the settled density of 60 percent of solids. The paste is usually in tubes or interstices in the reactor core. This density is constant regardless of paste movement. The paste does move, though slowly, through the tubes, and the reactor may be thought of therefore as a slowly moving settled bed.

Other particulate-fueled reactors do not have the fuel disposed in a "bed" more or less co-extensive with the reactor core. Instead, the fuel, which may or may not be fluidized, is disposed in tubes, annuli, slabs, or regions, which may be described as "fuel elements." These reactors are classed as "particulate-fuel-element reactors" in Chapter 7.

References

1. R. Sarbacher, Encyclopedic Dictionary of Electronics and Nuclear Engineering, Prentice-Hall, New York, 1959.
2. V. P. Kelly, "Hydraulic Studies for the Fluid-Bed Reactor," Nuclear Science and Engineering, 10, 1961, pp. 40-44.
3. "ORNL Gas-Cooled Reactor Advanced Concepts," ORNL-2510, ORNL, Oct. 2, 1958, pp. 14·15; 14·16.
4. J. J. Went and H. de Bruyn, "Liquid Fuel Reactors with Uranium Oxides," Nuclear Engineering, Part II, Chemical Engineering Progress Symposium Series, 50, No. 12, p. 125. American Institute of Chemical Engineers, New York, 1954.

Chapter 2 Pebble-Bed Reactors

Reactors fueled with "pebbles," "marbles," or "balls" having diameters from 0.4 to 3 inches, represent an attempt to utilize in nuclear reactors the known advantages of such particles in chemical reactors. Two obvious advantages are higher surface areas than those of massive fuels and simplicity of the core. By far, most pebble-bed reactors are gas-cooled, and thus permit high temperatures. Some, however, are cooled with such liquids as liquid metals or boiling water. Some reactors that are not strictly pebble bed but are closely related are included here, as are others that have some other name than "pebble-bed reactor."

The fundamental engineering behavior of pebble beds has been investigated. For example, the advantages of regular packing of pebbles were studied by Zarić.[1] According to the author, regular packing of spheres and small cylinders with hemispherical ends makes possible the investigation of local conditions of heat transfer and fluid flow. Thus, the uncertainty associated with random packing is reduced. The free flow area between the fuel bed and moderator elements permits use of high turbulent mixing in the bed for energy transfer to the undisturbed portion of the gas stream, with a corresponding reduction in pressure drop throughout the core. The author believes that the result is optimum power distribution in the core and appropriate distribution of coolant flow.

Early History

In September 1944, Farrington Daniels described several pebble-bed reactor concepts ("Pebble Piles").[2–5] He had been studying the fixation of atmospheric nitrogen in gas-fired furnaces containing beds of quartz pebbles heated to 2000°C.[6] The transition to a pebble-bed nuclear reactor was obvious. He pointed out that the experience gained during operation of the chemical furnace indicated that there should be no serious practical difficulties in operating a similar nuclear pile at 2000°C.

Daniels described a pile charged with pebbles of uranium carbide and graphite operating at 1500°-2000°C. The pile is cooled by circulating helium passing uniformly through the whole cross section of the pile, which is kept at a steady temperature by convection and radiation.[2] Bismuth boiling within the pile is an alternate coolant.[4] In his patent filed in 1945, however, the fuel consists of roughly spherical units with a diameter of 1 to 3 inches.[3] He includes spheres, cylinders, and other shapes in his category of "pebbles," because he mentions a reactor in which moderator and uranium are in "separate unconformable units in the form of chunks, pebbles, approximate spheres, etc."[3]

Two other Daniels piles are a uranium dioxide-beryllium oxide pile cooled by air (open-cycle)[2,3] and an enriched UO_2-BeO pebble pile cooled by boiling water.

Later Concepts

Many pebble-bed concepts from various sources have been published. Only one, the Brown-Boveri-Krupp, or AVR, reactor in Germany, however, has reached the construction stage.

UKAEA

Three British patents filed in the name of the United Kingdom Atomic Energy Authority describe pebble-bed reactors.

The first of these, with an application date of May 8, 1947, refers in one alternative to a gas-cooled reactor having a core and reflector of half-inch "marbles."[7] These marbles are composed of a moderator material, or mixtures of such materials, containing dispersed fissile material in the reactor core. Thorium or a thorium compound may be included in the reflector. The vessel is built up of beryllium oxide blocks and is suspended from the steel cover plate of the cylindrical steel reactor vessel.

The other two patents, which have an application date of June 15, 1948, describe pebble-bed reactors with essentially the same elements as the previous one. In one the engineering design is carried much further.[8] The other[9] is directed specifically to the hanging reactor core vessel built up of blocks of solid moderator material, such as beryllium oxide.

Another British patent filed in the name of UKAEA, with an application date of November 16, 1950,[10] describes a pebble or marble fuel element and a method for fabricating it. The fuel element has a core of moderator material, an electrically conducting layer (copper, nickel, silver, or graphite) on the outer face, and a fissile material electrodeposited or coated on the layer.

Oak Ridge

The Oak Ridge studies on pebble-bed reactors include an ORSORT student term paper,[11] and two ORNL design studies.[12-14]

In the ORSORT reactor, unclad graphite balls one inch in diameter, impregnated with uranium-233 and thorium-232, make up the fuel. The balls are charged from a tank above the reactor and removed by rotating radial grates at the bottom of the reactor, which is a cylinder 16 feet in diameter and 24 feet high.[11]

A Pebble Bed Reactor Experiment (PBRE) was proposed to the AEC to test the feasibility of the concept as part of the Gas Cooled Reactor Project.[12,13] Fully enriched uranium is used in 1-1/2-inch balls containing graphite, uranium dioxide, and thorium dioxide, with additional reflector moderation. Control blades are placed circumferentially in the reflector so as not to interfere with the fuel balls in the core. Preventing escape of fission products by cladding the fuel was considered.

Design studies of a large pebble-bed converter were also made.[13,14] This 800-Mw(t) power reactor was carried to the conceptual design stage only, and the studies illustrated the problems involved and indicated approaches to their solution.

Brown-Boveri-Krupp

Only one design or proposal for pebble-bed reactors is known to have resulted in construction. Under the sponsorship of a group of West German utilities, a 15-Mw(e) power reactor is under construction at Jülich, West Germany. Completion is scheduled for about 1965. This reactor is usually known as the Brown-Boveri-Krupp Reactor, or AVR.[15-19] It has also been called the "potato-bed reactor." The AVR pebble-bed design uses fuel balls 6 cm (2.36 in.) in diameter, with a central cylinder containing 20 percent enriched uranium in uranium carbide dispersed in graphite, inserted into graphite balls and closed by a stopper. Balls can be charged or discharged readily, and the number of balls in the core is used as one method of control. Cooling is by a mixture of neon and helium circulated by blowers, and the entire primary system, including steam generators and blowers, is contained in a large cylindrical steel vessel.

In April 1963, it was announced that the USAEC had requested an added authorization of $5.5 million for a program in which the AEC would cooperate with the West German group.[20] The AEC would both develop and have fabricated a reactor core with coated particles, which would be irradiated in the AVR reactor. Euratom may also participate in the program. The AEC would be reimbursed for the power generated from the core it supplies.

Other Designs

A pebble-bed reactor with graphite spheres approximately three inches in diameter has been described. Spheres this large are desired to reduce pressure drop of coolant in the core.[21] These spheres are impregnated with uranium and thorium and are suspended in liquid bismuth metal as coolant. This reactor may be compared with the Brookhaven Liquid Metal Fueled Reactor, in which the uranium fuel is dissolved in the bismuth coolant.[22]

A High Operating Temperature Reactor (HOTR) was proposed in 1956.[23] This reactor was to be based on the conventional MTR design with a central high-temperature helium-cooled zone. In one alternative, the fuel is uranium-impregnated graphite pebbles. The exit temperature of the helium was to be 2500°F. It was hoped that from operation of this unit data could be obtained for designing a full-scale chemical-processing (chemo-nuclear or chemical-products) reactor.

Advanced Concept

A pebble-bed reactor has been proposed for nuclear space propulsion by Levoy and Newgard.[24-27] The design uses a hydrogen-cooled, pebble-bed reactor fueled with uranium dicarbide and graphite. The reactor is divided axially into compartments by concentric graphite cylinders to channel the flow for better distribution and better gas-temperature profile as well as to support the core. Two or more sizes of fuel-moderator pebbles are specified for the core to reduce the pressure drop, and two sizes of beryllium oxide pebbles are specified for the reflector to lower the porosity and fraction of the coolant flow through the reflector. Orificing of the concentric core channels is obtained by the use of multiple pebble diameters in the beryllium oxide reflectors.

Reactors Related to Pebble-Bed Reactors

The reactors thus far described have been fueled with "pebbles" generally spherical in shape. However, other shapes are not ruled out, for the Daniels patent noted previously includes "cylinders and other shapes" and "separate unconformable units in the form of chunks, pebbles...etc." Fuel elements in the form of Raschig rings have been suggested.[28,29] These structures are often used in packed columns for distillation or extraction. They are hollow cylinders having the outer diameter equal to the height. They offer much less resistance to coolant flow than pebbles do. Because the reactor in which this form of fuel is used corresponds in other respects to a pebble-bed reactor, it is included in this chapter.

Investigations have been carried out by Alco Products, Inc., and by Sanderson and Porter.[30-38] There have been studies for a complete power plant, and a considerable amount of experimental work on fuel development by Battelle Memorial Institute.[39-48] Most other concepts have not included cladding either the fuel particles or the pebbles to prevent emission of fission products or possible chemical reaction with the coolant, but an essential feature of the Sanderson and Porter concept of the pebble-bed reactor is the improved coated-particle fuel element.[38] A static bed of graphite spheres is heated by the fission of contained uranium and the heat generated is transferred to helium, which is circulated by forced convection through the permeable bed. According to the authors, this concept differs from other gas-cooled concepts in the spherical shape of the fuel elements and in the method of retarding the release of fission products. The fuel elements consist of fuel particles, either as oxide or carbide, coated with a ceramic such as aluminum oxide, beryllium oxide, or pyrolytically deposited carbon, dispersed in a spherical graphite matrix, which acts as the fuel carrier, moderator, and heat-transfer surface.

Various core arrangements are possible: (a) a one-region core with both fissile and fertile material in the fuel elements; (b) a blanketed core with fissile plus fertile material in the fuel elements and fertile material only in the blanket, as in the Sanderson and Porter 125-Mw(e) pebble bed;[32] or (c) fissile material only in the core and fertile material only in the blanket, which gives maximum conversion but less economical power production. A breeder would require a two-region core, but the fuel cost would be higher.

Three coolant-flow arrangements are also possible: (a) axial upflow, which was used in the Oak Ridge reactors;[11,14] (b) radial outflow, which was considered and rejected; and (c) axial downflow, which was used in the Sanderson and Porter 125-Mw(e) pebble bed,[32] in which the coolant flows downward through the reactor core and blanket in parallel. Helium coolant, graphite moderator and reflector, and uranium dioxide-thorium dioxide fuel in graphite matrix are used in the Sanderson and Porter reactor; the fuel elements have a diameter of 1.5 inches.

Evaluation and Status

The pebble-bed reactor has several advantages. They include: (a) the high temperature attainable, which presumably leads to high thermodynamic efficiency; (b) a simple core with essentially no precise machining required; (c) simple fuel-handling procedures, with fuel readily charged or discharged during operation, if desired; and (d) a minimum of fuel held outside the reactor core.[21]

Disadvantages of the reactor include high pressure drop and high thermal stresses in the fuel. Young has reviewed the data available in April 1945 on heat transfer and pressure drop in pebble piles.[49] From work of Mawrer, Bentley, and Johnson,[50] he concluded that pebble piles were likely to have poor performance on account of high pressure drop. The use of Raschig rings as fuel elements[28,29] would reduce the pressure drop but would no doubt introduce other problems.

Amorosi[51] calculated the performance of a 250-Mw(t) pile moderated with beryllium oxide and cooled by helium at 40 atmospheres. He concluded that the high heat-transfer rate obtainable in a pebble bed is of little value in a cylindrical pebble pile. "In order to capitalize on the high design temperature difference available, the pebble size comes out 4.2 inches and the stresses therein are intolerable," he says.

The problems of creating suitable fuel elements and removing fission products from the primary coolant stream, in fact, were still under research and development in December 1961.[52]

The continuance of construction on the Brown-Boveri-Krupp reactor, with the new cooperation by the USAEC, indicates that the participants believe problems with the pebble-bed reactor are solved sufficiently to warrant large-scale development.

D A T A   S H E E T S

PEBBLE-BED REACTORS

No. 1 Daniels Pebble Pile

References: N-1668 a, b, c (MUC-FD-7, MUC-FD-8, MUC-GY-31). U. S. Patent 2,809,931, Oct. 15, 1957 (filed Oct. 11, 1945).

Originator: Farrington Daniels.

Status: Conceptual design, 1944-45; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: natural uranium as uranium carbide. Moderator: graphite. Coolant: helium--100°C (inlet) to 2000°C (outlet). Fuel and moderator are roughly spherical pebbles (1 to 3 in. diameter; one fuel to four or five graphite pebbles). Fertile material: thorium oxide outside graphite reflector. Reactor vessel: cylinder, 36 ft diameter by 36 ft high. Control: Cd or B rod in water-cooled iron tube moving vertically or horizontally. Power: 250 Mw(t). Fuel and graphite pebbles randomly arranged in pebble bed. Means provided for charging at top and discharging at bottom in part or whole at intervals as desired. Internal breeding with thorium oxide or thorium carbide may be possible if "k" is high enough. Coolant passed uniformly through entire cross-section of pile, which is kept at a steady temperature by convection and radiation.

Code: 0311 12 31716 41 5242 727 81112 941 105
81212

No. 2 Daniels Pebble Pile

References: N-1668 a, b, c (MUC-FD-7, MUC-FD-8); MUC-GY-31. U. S. Patent 2,812,303.

Originator: Farrington Daniels.

Status: Conceptual design, 1944-45; no further work.

Details: Like helium-cooled Daniels Pebble Pile but uses boiling Bi (1450°C) as coolant. Above pile, Bi vapor passes through boilers, condenses in reflux condensers, and drips back into pile.

Code: 0311 12 32605 41 5242 727 81212 941 105

No. 3 Daniels Pebble Pile

References: N-1668 a, b, c (MUC-FD-7, MUC-FD-8); MUC-GY-31. U. S. Patent 2,809,931.

Originator: Farrington Daniels.

Status: Concept, 1944-45; no further work.

Details: Like helium-cooled Daniels Pebble Pile but uses natural UO_2 and BeO pebbles, with air as coolant. Uses stack and once-through system; solid fission products removed.

Code: 0311 15 31714 41 5232 727 81112 941 105

No. 4 Daniels Pebble Pile

References: CF-2860, Part 5.

Originator: Farrington Daniels.

Status: Conceptual design, 1945; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: enriched uranium in UO_2 or UO_2-BeO pebbles. Moderator and reflector: BeO pebbles. Coolant: boiling light water (inlet 355°F--water under 155 psi, or saturated steam; outlet 3630°F--superheated steam at 15 psi). Fertile material: thorium. Reactor vessel: cylinder, 6 ft diameter by 6 ft high. Power: 100 Mw(t).

Code: 0311 15 32601 44 5232 726 8XXXX 931 105

No. 5 Gas-Cooled Reactor Fueled With Marbles

UKAEA

Reference: British Patent No. 848,901.

Originator: S. G. Bauer.

Status: Conceptual design, 1947.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: half-inch marbles containing fissile material (U^{233}, U^{235}, or Pu^{239}) dispersed in BeO. Coolant: unspecified gas. Core vessel is built up of BeO blocks, has a conical top, and is suspended from the steel cover plate of the reactor vessel. Reflector: marbles, which may contain thorium, in space between core and reactor vessel. Means are provided for loading and discharging marbles. Control: rods in tubes in core-vessel walls. A 50 Mw(t) core may be 3 ft in diameter and length and may contain 13 cu ft of balls.

Code: 0311 15 317X 47 5232 726 8111X 941 105

No. 6 Gas-Cooled Reactor Fueled With Marbles

UKAEA

Reference: British Patent No. 821,607.

Originator: W. F. Wood.

Status: Conceptual design, 1949.

Details: Closely resembles No. 5, but gives more engineering design details. Core vessel is perforated top and bottom; may be suspended from top of reactor vessel or supported on bottom. Coolant: helium suggested. Control: horizontal rods.

Code: 0311 15 31716 47 5232 726 8121X 941 105

No. 7 Gas-Cooled, Large Central Station Reactor

ORSORT

Reference: CF-57-8-12, August 1957.

Originator: A. Schock *et al.*

Status: Conceptual design; term paper, 1957; no further work.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: graphite spheres, one-inch diameter, impregnated with U^{233} and thorium, unclad. Fuel balls charged from a tank directly above reactor; removed by rotating radial grates at bottom of core; 1,500,000 balls/core. Coolant: helium at 1450 psia. Control: absorber rods. Reflector: graphite, solid or pebbles. Design power: 1164 Mw(t); 400 Mw(e).

Code: 0311 12 31716 45 5242 726 81X1X 921 105

No. 8 Pebble Bed Power Reactor

ORNL

References: CF-60-12-5 (Rev); ORNL-3049.

Originator: A. P. Fraas *et al.*

Status: Conceptual design, 1960; further work pending.

Details: Thermal neutrons, steady state, converter. Fuel: slightly enriched uranium in moderator--UO_2-ThO_2-ThC_2 particles--in graphite matrix coated with Si-SiC or graphite. Fuel elements: spheres 2.5 in. diameter; 129 spheres/cu ft of core. Coolant: helium gas (700 psi) flowing upward through core. Reflector: graphite, 3 ft total thickness, one ft of graphite balls, the rest solid graphite. Control: absorber rods--B_4C in stainless steel. Power: 330 Mw(e).

Code: 0311 12 31716 42 5232 727 81X11 921 105
5242

No. 9 Pebble Bed Reactor Experiment

ORNL

References: CF-60-10-63 (Rev); ORNL-3049.

Originator: A. P. Fraas et al.

Status: Preliminary design, December 31, 1960; postponed indefinitely, 1962.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: UO_2-ThO_2 or UC_2-ThC_2 in graphite matrix coated with graphite. U^{235} atoms approximately 48.5% of total uranium plus thorium atoms initially present. Fuel elements: spheres 1.5 in. diameter--total 8500 per core. Coolant: helium gas flowing upward through core. Reflector: graphite in three sections with annuli, outer--borated graphite bricks, inner--four concentric sleeves. Control: vertically moving absorber blades (curved Inconel plates) in annulus between reflector sections. Coolant flow control also helps control reactivity. Power: 10 Mw(t). Designed to test feasibility of large pebble-bed reactor for power plant--330 Mw(e).

Code: 0311 12 31716 44 5232 726 81126 921 105
5242

No. 10 AVR Reactor

References: The Brown Boveri Review, 47, No. 12, pp. 88-96, Jan.-Feb. 1960. Proc. 2nd U. N. Int. Conf. on Peaceful Uses of Atomic Energy, 9, pp. 306-309. Journal of the Franklin Institute, Monograph No. 7, pp. 109-126, 1960.

AVR stands for "Arbeitsgemeinschaft Versuchreaktor," ("Working Group's Experimental Reactor") abbreviation for title of sponsoring group, "Arbeitsgemeinschaft Deutscher Energieversorgungsunternehmen für Vorbereitung der Errichtung eines Leistungs Versuchreaktors," ("Working Group or Working Association of German Energy Supply Enterprises for the Design and Construction of an Experimental Power Reactor").

Originator: R. Schulten.

Status: Under construction, 1960; scheduled completion, 1965.

Location: Jülich, West Germany.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: 6-cm (2.36-in.) diameter graphite balls, with inserted sintered cylinders of 20% enriched uranium in graphite-uranium carbide, closed by graphite screw plug. Coolant: pure helium if obtainable, otherwise helium-neon mixture (22% He) at about 150 psia. Core I to contain fuel and graphite spheres only; Core II fuel and fertile (thorium carbide) spheres. Charge is about 60,000 spheres (Core I) or 70,000 spheres (Core II). Reflector: graphite on all sides, 1/2 meter (about 20 in.) thick. Control: vertical motion of absorber rods; number of fuel balls charged is secondary control. Entire primary system (reactor, blowers, steam generators) in steel reactor container. Power: (Core II) 50+Mw(t)---15 Mw(e); prototype for a full-sized power reactor.

Code: 0311 12 31716 43 5241 727 8111X 921 105

No. 11 Stationary Power Reactor

Atomics International, a Division of North American Aviation, Inc.

References: NAA-SR-895.

Originator: J. R. Beeley.

Status: Concept, 1954; no further work.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: bed of graphite spheres (about 3 in. diameter) impregnated with highly enriched uranium and thorium. Coolant: Bi. Fuel is suspended in Bi, is therefore mobile and easily removed. Reflector: 2 ft graphite layer; container and piping: medium chrome steel. Control: absorber rods in closed Be thimbles extending through core.

Code: 0311 12 31105 44 5242 726 81X1X 921 105

No. 12 High Operating Temperature Reactor (HOTR)

Nuclear Development Corporation of America*

Reference: NDA-64-101.

Originator: L. Davidson, J. DeFelice, J. A. Klapper.

Status: Conceptual design of an experimental reactor with central high-temperature region, to be used to design full-scale high-temperature reactor for chemical processing (chemonuclear reactor), 1956. No further work.

Details: Thermal neutrons, steady state, burner. Fuel element: spheres with inner graphite core, fuel layer of uranium carbide, and protective outer coating of, for example, silicon carbide. Coolant: water, helium. Outer zone contains water-cooled plate fuel subassemblies similar to those used in MTR but 7 ft, 8 in. long. Water moderator is used in this region. Maximum water temperature is 170°F. Inner high-temperature zone has helium at 1000°F flowing up outer annulus and down through hot zone; exit temperature 2500°F. There are various concepts for loading--one has an impervious graphite container loaded with randomly packed fuel spheres. As with the other two conceptual loadings the spherical-fueled unit is 17 1/2 in. in diameter with a fueled length of 6 ft. Helium flows down through the unit, entering at the top drilled plate and leaving at the bottom drilled plate. Control: 7 regulator and 7 shim rods, all located in the low-temperature zone. Power: maximum of 5 Mw(t) in hot zone and 10 Mw(t) in low-temperature zone.

Code: 0313 12 31716 44 5241 711 81111 921 105

*Now United Nuclear Corporation

No. 13 Space Vehicle Propulsion Reactor

Reaction Motors Division, Thiokol Chemical Co.

References: Aero/Space Engineering, 19, No. 4, pp. 54-58, April 1960. SAE Journal, 68, No. 6, pp. 46-50, June 1960. Engineering, 189, p. 755, June 3, 1960.

Originators: M. M. Levoy and J. J. Newgard.

Status: Conceptual design, 1960.

Details: Thermal neutrons, steady state, burner. Fuel-moderator: graphite pellets impregnated with UC_2 containing highly enriched uranium. Pellet diameter varied axially to reduce pressure drop (0.7 to 3 inches). Void fraction 0.39. Reactor compartmented axially by concentric graphite cylinders for better flow characteristics and to support core. Coolant: hydrogen at 400 psia inlet pressure in downflow through core and reflector. No fertile material. Reflector: 6 in. thick, BeO pellets of mixed sizes to reduce gas flow through reflector. Core channels orificed by mixed sizes of BeO pebbles. Control: rotating drums of BeO with boron steel on half of surface.

Code: 0313 12 31715 44 5242 711 81441 921 105

No. 14 Reactor Fueled With Raschig Rings

References: French Patent No. 1,207,342. British Patent No. 894,633.

Originator: Kurt Diebner.

Status: Patents granted, 1960, 1962.

Details: Thermal neutrons, steady state, converter. Patents cover liquid and gas coolants and various types of fuel (metallic, ceramic, fuel mixed with moderator, fuel and moderator rings separate, etc.). A typical reactor with gas cooling has metallic natural uranium rings and graphite moderator rings in the ratio 1:50. Raschig rings are short hollow cylinders with the diameter equal to the length. The fuel rings may be clad. Means for charging and discharging the rings is provided.

Code: 0311 12 317X 41 5611 722 8XXXX 9XX 105

No. 15 Pebble-Bed Power Reactor

Reference: NYO-8753, May 1, 1958.

Originators: Sanderson and Porter, Alco Products, Inc.

Status: Conceptual design, 1958; further studies carried out with emphasis on fuel-element development.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: slightly enriched uranium in UO_2-ThO_2 in graphite matrix coated with graphite. Fuel particles to be coated individually to retard fission-product escape. Fuel elements: spheres 1.5 inches diameter. Coolant: helium gas, 965 psig outlet pressure. Reflector: inner section, balls of Th-containing graphite; outer reflector, solid graphite. Control: absorber rods of Haynes-25, moving vertically. Power: 337 Mw(t), 125 Mw(e). Axial-upflow, axial-downflow, and radial-flow designs. A 10-Mw(t) reactor experiment is also proposed.

Code: 0311 12 31716 42 5231 727 81116 941 105

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Chapter 3 Packed- (Settled-) Bed Reactors

A packed-bed reactor is a fixed-bed, particulate-fueled, settled-bed reactor cooled by a fluid, either in direct contact with the fuel particles or circulating through tubes immersed in the fuel-particle bed. The moderator, if present, is incorporated in the fuel particles, or it is included in or identical with the coolant: i.e., there are no moderator blocks or slabs in the core structure. The fuel particles are small--less than approximately 0.4 inch diameter--and they are usually much smaller.

Packed-bed reactors function in a manner similar to that of pebble-bed reactors.

Other names not containing the words "packed bed" have been given to reactors of this type: homogeneous reactor; sodium-cooled fast reactor with internal heat exchanger; He-UO_2 fast-reactor concept; UC-H_2 fast-reactor concept; directly-cooled reactor--sodium-cooled fast breeder, axial-flow type; and directly-cooled reactor--sodium-cooled fast breeder, radial-flow type.

Early Concepts

In 1953, W. G. Roman, C. M. Slack, et al, of Westinghouse,[1] proposed substituting fluidized or packed-bed cores for the rod, slug, or plate cores of a pressurized-water reactor. See Chapter 4, in which typical designs for fluidized-bed reactors they proposed are given. Fixed-bed designs are similar, except for modification of design parameters to compensate for greater flow resistance of the fixed beds. According to the authors, the desired coolant flow with acceptable pumping powers can be obtained by increasing the diameter of the bed. The increased diameter and the high metal-to-water ratio of fixed pellet beds result in a high fuel loading with the associated long life, reduced radiation damage, and increased conversion of uranium-238 to plutonium-239.

Using fluidizing techniques for fuel loading and handling simplifies the construction of the reactor and pressure vessel. The reactor becomes a simple cylindrical container with axial channels for the control rods. No large removable closure is needed in the pressure vessel because the fuel can be loaded and unloaded through a small pipe. If some of the fuel is removed periodically, the remaining fuel can be fluidized and thus mixed to obtain uniform burnup.

An inexpensive automatic method for fabricating pellets must be developed, and the choice of a suitable fuel also needs further study. Fuels suggested are those compatible with PWR technology, based on an approximately spherical fuel pellet (0.5 in. diameter for a typical fixed-bed PWR) with a concentric Zircaloy cladding. Uranium, uranium alloy, UO_2, and UO_2-cermet materials have been proposed for the pellet cores.

Fixed-bed reactors that could be fluidized for chemical processing were also described. The design closely resembles that of the fluidized-bed reactors except that an upper grid plate is used to keep the bed in place and such conditions as flow velocities and fuel-moderator ratios differ.

Other Westinghouse workers carried out further studies on substituting clad pellets for rod or plate fuel. In particular, Jones made heat-transfer calculations for pellet fuels in both fluidized and fixed beds.[2] For both types of beds, pellets of 0.1, 0.2, 0.4 and 0.8 inch diameter were considered. The porosity for the fluidized bed was taken to be 60 percent, corresponding to a metal-to-water ratio of 1.5; the porosity for the packed bed was taken as 37 percent.

Another early proposal (1954) which, by our definition, is a packed-bed reactor, is the "Quasi-Heterogeneous Reactor" described by de Bruyn et al.[3] This reactor is fueled with a non-circulating suspension of UO_2 incorporated in 3-mm "compound grains" of UO_2-BeO with an atomic ratio of Be/U of about 80. There is an internal heat exchanger or boiler, which consists of 1-1/2 inch graphite boiler tubes, 2-1/4 inches apart, containing D_2O. From the physics standpoint, however, the reactor may still be treated as a homogeneous reactor. Helium under pressure is circulated through the packed bed to improve heat transfer, and the hot helium (1200°C) is used to superheat the D_2O steam in an external superheater. The entire system is pressurized to about 40 kg/cm^2 (about 570 psi).

Rodin,[4] at the Argonne National Laboratory, has described a reactor that may be treated as homogeneous because of the small proportion of structural elements in the core. The core of the reactor, which is chain-reacting with fast neutrons, is made up of roughly hexagonal fuel assemblies. Each assembly consists of a stack of packed-bed fuel elements, each of which is a layer of fuel particles arranged in a holder to permit the coolant to flow radially through the bed of particles. Thin plates of porous media or wire screens may be used to support the beds. Gas coolant enters the packed bed through inlet headers, formed by grooves in the exterior wall of each hexagonal fuel element. After flowing radially through the bed the coolant exits through a central gas-outlet header in each fuel subassembly. Two fast reactors are described, a helium-cooled, UO_2-fueled reactor and a hydrogen-cooled, UC-fueled reactor.

Another reactor that can be considered in this chapter, although the core has structural features, is a fast reactor proposed by Heckman.[5] The fuel is spheres of enriched uranium carbide, contained in subassemblies of square tubes. The spheres are plated with an inner coating of tin, lead, or aluminum and an outer coating of molybdenum. At each end of the tube are blankets, spheres of fertile material. The tubes, of expanded sheet metal or wire screen, are closed at each end with screening to permit coolant flow. Liquid sodium enters the reactor at the top and flows over the core, where it is vaporized by the heat of fission. The vapor leaves the reactor, goes directly to a turbine, then to a helium-cooled condenser. The liquid sodium returns to the reactor. Helium is also used in startup and shutdown as coolant and as a gas pump to recirculate the sodium. The reactor can be loaded and unloaded by moving subassembly tubes. Control is by circulating spheres of boron carbide through a control loop in the reactor, and, for shutdown, by lowering some fuel assemblies below the position normal for criticality.

An early design by Grebe[6] was for a graphite-moderated chemonuclear reactor in which the fuel is spheres of enriched uranium carbide or a mixture of U^{235} and thorium double carbides. Hydrocarbon gases (coolant) react at very high temperatures in the reactor to form acetylene and hydrogen.

Theoretical work pertaining to heat-transfer and fluid-flow characteristics of the packed-bed fuel elements was reported by Viskanta.[7] He concluded that the highest temperature of the bed is at the exit; that instability of flow rate and bed temperature may arise from the temperature dependency of the coolant viscosity; and coolants with the highest possible heat-removal capacity should increase flow stability and power density of the reactor. Hydrogen was suggested as a coolant.

Fluidized- and settled-bed reactors have been studied at Brookhaven National Laboratory. Attention has been especially directed to liquid-metal-cooled, particulate-fueled reactors. Four settled-bed concepts have been described.[8-10] They include a sodium-cooled fast reactor, with internal heat exchanger, and three directly-cooled fast reactors: a carbide-fueled reactor with axial flow, a carbide-fueled reactor with radial flow, and an oxide-fueled reactor with radial flow. All three are cooled with sodium and would be breeders in a U^{238}/Pu^{239} cycle.

In the fast reactor with internal heat exchanger, the flow of sodium coolant is independent of the characteristics of the packed bed, but internal mechanical design is complicated.[8] A separate sodium flow is provided, when needed, to fluidize the bed for discharge or for mixing.

In the axial-flow, directly-cooled fast reactor, the sodium coolant flows downward, entering above the packed bed through a 24-inch pipe and leaving below the bed through a similar pipe.[8,9] A packed-bed blanket completely surrounds the core vessel. The core and blanket are charged with pellets in the fluidized condition. Fuel or blanket pellets are also discharged by fluidizing them. The coolant flow is reversed and the fluidized pellets are discharged through separate unloading ports for fuel and blanket.

The radial-flow directly cooled reactor differs from the axial-flow design in that the 24-inch coolant pipe runs vertically through the core vessel on its central axis.[8,9] Thus the fuel region is annular. The coolant pipe is perforated within the core vessel. The sodium coolant enters the central pipe from both the top and bottom. It flows radially outward through the core, then through perforations in the core vessel, out through the pellet blanket, which completely surrounds the core. The hydraulics of this design would need further investigation.

Evaluation and Status

Most work dealing with the advantages of packed-bed reactors has come from the Brookhaven group, who emphasize their settled-bed reactor, the bed of which can be fluidized.[8,9]

They point out that fluidization of particulate fuel in nuclear reactors gives the fuel mobility, which permits long burnup periods and simplifies the transfer of fuel to, from, and within the reactor. If fluids of relatively low conductivity, such as water and organic liquids, are the fluidizing media, fluidization greatly improves heat transfer. In the BNL reactors, however, the fluidizing agent is a liquid metal, sodium. Thus, high heat-transfer capacity is available regardless of whether the fuel is fluidized or settled. Flexibility in fundamental design studies is thus possible.

Specific advantages of the settled-bed fuel, and especially of the "fluidizable" settled bed, have been given by the Brookhaven group. Some are similar to those for pebble-bed reactors (Chapter 2) and fluidized-bed reactors (Chapter 4):

a. Distribution of the fuel-containing solids--and therefore the fuel density--is kept uniform throughout the entire core.
b. Mobility of the fuel allows the particle suspension to flow freely in tubes connecting the reactor core region with an outside vessel, for fuel makeup and reprocessing, in response to pressure adjustment in the fluidizing-liquid stream. Fuel makeup at frequent intervals is itself an important advantage because only small amounts of excess reactivity would then be required.
c. If fuel of small particle size is used, the high surface-to-mass ratio of the particles minimizes the disadvantage of the low thermal conductivity of UO_2 and other ceramic fuels. In the one design in which the larger particles are used, thermal conductivity and the resulting thermally induced internal stresses are very sensitive design considerations.
d. The high costs of making solid fuel elements under close tolerance requirements are eliminated. The cost of coating fuel particles was not taken into account, because coating must at present be considered an expensive process. Containing the fission products within the fuel particles by coatings would facilitate reactor design by minimizing problems associated with separation of fuel and coolant. The economic aspects of processes for coating particles and the over-all influence on both fuel cycle (including reprocessing) and maintenance costs are unknown. (Experience with the Martin critical experiment on fluidized beds indicates that uncoated particles are unsuited for fluidization because of erosion.)
e. The mobility of the fuel assures uniform burnup in the fuel.
f. The fuel is confined to the core of the reactor, but the other advantages of a liquid fuel are retained.

g. Particulate solid fuel can be used without the need to recirculate the fuel through pumps, valves, etc., and without problems of erosion or attrition of fuel particles. Even with fluidization of the fuel, the authors claim, almost quiescent conditions exist in the laminar flow state.

A notable advantage claimed in a later report for the Brookhaven fast breeders with settled beds is the short doubling time.[10] That of the radial-flow reactor with uranium carbide fuel is 4.1 years. Another advantage is that comparatively little sodium is needed as coolant and fluidizing agent.

Possible disadvantages of packed bed reactors have apparently not yet been evaluated completely. This situation seems to be related to the small amount of experimental work that has been carried out thus far on this type of reactor concept. However, this approach probably has few problems and is worthy of favorable consideration. Referring to the listed disadvantages of pebble-bed reactors--high thermal stresses in the fuel and high pressure drop in the bed--indicates that thermal stresses will be less for the smaller packed-bed particles. Rodin[4] has calculated that for UO_2 at 1700°C the thermal stress would be about 0.3 kg/cm^2 as compared with the tensile strength of 350 kg/cm^2. The pressure drop may be a problem, especially in gas-cooled reactors. Stable bed porosities from 0.38 to 0.42 can be achieved by normal handling, and much higher porosities are possible, although methods for attaining these have not yet been developed.[4] Pressure drop may also be lowered by careful design.

The Brookhaven group, in their plans for future development, foresee three possible difficulties that must be studied: stabilizing uranium carbide to prevent formation of free carbon, determining whether a liquid control system is possible, and preventing fuel pellets from fusing together.[9]

D A T A   S H E E T S

PACKED- (SETTLED-) BED REACTORS

No. 1 Pellet Reactor

Westinghouse

Reference: WIAP-M-32.

Originator: A. R. Jones.

Status: Calculations only, 1954.

Details: Fuel: spherical fuel element, 0.1-, 0.2-, 0.4-, and 0.8-in. diameter, of pure uranium. Moderator-coolant: H_2O at 800 psia and 400°F average temperature. Core: cylinder, 8 ft diameter and 10 ft high. Calculations made for a single-pass reactor.

Code: 0313 13 31101 44 5812 7XX 8XXXX 921 105
5212

No. 2 Packed-Bed Reactor

FOM-KEMA*

Reference: Proc. 1st U.N. Int. Conf. on Peaceful Uses of Atomic Energy, 3, pp. 121-4.

Originators: H. de Bruyn, B. L. A. v.d. Schee, J. J. Went.

Status: Concept, 1955.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: "compound grains" of 4% enriched UO_2-BeO (atomic ratio Be/U about 80) in packed bed. Grain diameter about 3 mm. Coolant: boiling D_2O in 1-1/2 in. diameter boiler tubes spaced 2-1/4 in. apart in core. Helium under pressure circulated through bed to improve heat transfer. Hot helium superheats D_2O steam in external superheater. Reflector: used but not described; presumably BeO. Control system: not described. Large--300 Mw(t)--reactor.

Code: 0311 15 32602 42 5732 723 8XXXX 921 105
31716

*FOM: Foundation for Fundamental Research on Matter; KEMA: the Electrical Equipment Testing Company.

No. 3 UO_2-He Packed-Bed Fast Reactor

ANL

Reference: ANL-6193.

Originator: M. B. Rodin.

Status: Conceptual design, 1960. Study limited to problems in materials, fluid flow, and heat transfer.

Details: Fast neutrons, steady state, converter. Fuel: highly enriched (about 90%) uranium as oxide. Fuel particles (200 μ diameter) in layers 1/2 in. deep, 18 layers per subassembly, are confined in hexagonal holders of porous media or wire screen. Coolant: helium pressurized to 40 atm (about 600 psi) inlet pressure. Helium enters packed beds through inlet headers formed by six grooves in circumference of hexagonal holders. It exits through outlet headers centrally located in each fuel subassembly. Core arrangement is based on EBR-II design. Fertile material: fuel subassemblies identical with those used in core, except that blanket subassemblies presumably contain depleted instead of enriched uranium. Control: rods moving vertically, presumably in blanket. Power: 50 Mw(t). This concept suited to use in reactors for power generation and breeding (with PuO_2 fuel).

Code: 0111 11 31716 44 5732 775 8111X 931 108

No. 4 $UC-H_2$ Packed-Bed Fast Reactor

ANL

Reference: ANL-6193.

Originator: M. B. Rodin.

Status: Conceptual design, 1960. Study limited to problems in materials, fluid flow, and heat transfer.

Details: Fast neutrons, steady state, converter. Fuel: highly enriched (about 90%) uranium as carbide. Fuel particles (200 μ in diameter) in layers 1 in. deep, 10 layers per subassembly, are confined in hexagonal holders of porous media or wire screen. Coolant: hydrogen at 60 atm (about 900 psi) inlet pressure. H_2 enters packed bed through inlet headers formed by six grooves in circumference of hexagonal holders. Gas exits through outlet headers centrally located in each fuel subassembly. Reflector used instead of blanket. Control: rods in reflector, details not given. Power: 240 Mw(t), outlet temperature 2320°C. This concept is suited for use in rocket propulsion.

Code: 0113 11 31715 44 5742 711 8111X 921 108

No. 5 Packed-Bed Fast Reactor Cooled by Sodium Vapor and Helium

USAEC-COO

Reference: T. P. Heckman, "Fast Nuclear Reactor, Metal Vapor-He Gas Cooled," Unpublished report, April 4, 1963.

Originator: T. P. Heckman.

Status: Proposal, April 1963.

Details: Fast neutrons, steady state, breeder. Fuel: UO_2, 30% U^{235}, as spheres, 0.25 in. OD, plated with inner coating of Sn, Pb, or Al and an outer coating of Mo. Spheres contained in square subassembly tubes, 4 in. by 4 in. by 48 in. Fuel spheres in center of tubes; at each end are pellets of unspecified fertile material. Tubes, of expanded sheet metal or wire screen, are closed at each end with screening to permit flow of coolant. Reactor can be loaded and unloaded by moving tube subassemblies. Coolant: liquid Na. Na flows into distributor header in downcomer annulus surrounding reactor core and down through fuel assemblies, where it vaporizes. Vapor leaves reactor at 2000°F and 75 psia, goes directly to turbine, then to condenser cooled by helium. Hot helium can be used to drive another gas turbine. Liquid Na returns to reactor. Helium also used in startup as coolant and as gas pump to recirculate Na.
Control: spheres of B_4C, 0.5 in. diameter, circulated by gas jets through closed control loop in reactor. Additional control for shutdown: some fuel subassemblies lowered below position normal for criticality. Design suggested for diverse uses.

Code:									
	0112	11	32603 31716	43	5831	7XX	81161 83159	931	109

No. 6 Pile for Chemical Products

Clinton Laboratory

Reference: J. J. Grebe, unpublished report.

Originator: J. J. Grebe.

Status: Early concept; no further development.

Details: Thermal neutrons, steady state, breeder. Fuel: spheres of enriched uranium carbide, or mixture of U^{235} and thorium double carbides. Moderator: graphite. Coolant: hydrocarbon feed gases; inlet temperature: 1830°F max; outlet: 4170°F; coolant flow rate: 75,000 lb per hr. Fertile material: U^{238} spheres. Pressure: 1 atm. Reflector: graphite. Spherical reactor. About 10% of gases react to form acetylene and hydrogen. Power: 300 Mw(t). Problems: plugging of coolant channels by free carbon formed by hydrocarbon cracking; piping materials for extremely high temperatures.

Code:	0312	12	31707	44	5842	782	8XXXX	921	105
			31708						106

No. 7 Sodium-Cooled Packed-Bed Fast Breeder Reactor

BNL

Reference: BNL-5372.

Originator: L. P. Hatch.

Status: Conceptual design for full-scale plant for cost evaluation, 1961.

Details: Fast neutrons, steady state, breeder. Fuel: UO_2-PuO_2 (75-100 μ diameter) in Na as settled bed. Coolant: Na circulating through stainless-steel heat-exchanger tubes immersed in fuel bed. Coolant tubing is 0.355 in. diameter (U-tubes) and is arranged in four quadrants individually removable. Core vessel: open stainless-steel cylinder, located centrally in main reactor vessel and surrounded by radial and axial blanket beds. Top blanket bed: 75 to 100 μ UO_2-Al_2O_3 particles hydraulically stratified because of lower density during fuel charging and resting directly on fuel bed. Radial and bottom blankets: 0.250 in. UO_2 particles cooled by Na in downflow. Fuel and blanket beds fluidized by separate Na systems for charging and discharging and redistribution. Control: rods specified but not described. Power: 815 Mw(t), 300 Mw(e). Breeding ratio: 1.33. U^{238}/Pu^{239} ratio: 8.2. Reactor core may be maintained as a fluidized bed.

Code: 0112 11 31103 46 5732 785 8111X 931 108

No. 8 Directly Cooled, Axial-Flow, Packed-Bed Carbide-Fueled Fast Breeder Reactor

BNL

Reference: BNL-5372; BNL-713

Originator: L. P. Hatch.

Status: Conceptual design for full-scale plant for cost evaluation; work continuing.

Details: Fast neutrons, steady state, breeder. Fuel: UC-PuC particles (0.225-0.265 in. diameter) in Na as settled bed. Loading: 2783 kg Pu^{239}. Composition: 60% fuel; 40% Na. Core coolant: Na flowing axially downward through bed. Coolant inlet temperature: 550°F; outlet temperature: 1200°F. Core vessel: stainless-steel tank with 2-ft diameter inlet and outlet pipes at top and bottom. Fuel bed supported on perforated plate welded into core vessel. Fertile material: spheres of UC, 0.250 in. diameter in Na. Fertile material in axial and radial blanket beds, 1.5 ft thick, surrounding core vessel. Blanket coolant: Na circulating downward through blanket, with helium in reactor head space providing additional pressure. Core and blanket beds fluidized with Na for charging and discharging. Control: mentioned, but methods not specified. Power (core and blanket): 897 Mw(t), 363 Mw(e). Breeding ratio: 1.68. Doubling time (Pu^{239} only); 15.6 years. U^{238}/Pu^{239} ratio: 12.57.

Code: 0112 11 31103 46 5842 785 8XXXX 931 108

No. 9 Directly Cooled, Radial-Flow, Packed-Bed, Carbide-Fueled Fast Breeder Reactor

BNL

Reference: BNL-5372; BNL-713.

Originator: L. P. Hatch.

Status: Conceptual design for full-scale plant for cost evaluation; work continuing.

Details: Fast neutrons, steady state, breeder. Fuel: spherical UC-PuC particles (0.122 in. diameter) in Na as settled bed; about 40% voids. Loading: 812 kg Pu^{239}. Coolant: Na. Core vessel: perforated stainless-steel tank with 2-ft diameter axial perforated stainless-steel coolant pipe; perforations about half a fuel particle diameter wide and several diameters long. Fuel bed supported on perforated stainless-steel plate. Na flows into both ends of axial coolant pipe, out of perforations, and radially through core and blanket beds. It mixes with downflowing Na in blanket beds. Fertile material: spherical UC particles, (0.125 in. diameter) in settled-bed blanket 1.5 ft thick in axial and radial blankets that support core vessel centrally. Fuel and blanket particles charged and discharged by fluidizing with Na. Control: 2-in. diameter boron steel rods in thimbles; installed either around periphery of central pipe or in fuel region. Power (core and blanket): 881 Mw(t), 359 Mw(e). Breeding ratio: 1.49. Doubling time (Pu^{239} only): 5.8 years. U^{238}/Pu^{239} ratio: 7.34.

Code: 0112 11 31103 46 5842 785 81111 931 108

No. 10 Directly Cooled, Radial-Flow, Packed-Bed, Oxide-Fueled Fast Breeder Reactor

BNL

Reference: BNL-5372; BNL-713.

Originator: L. P. Hatch.

Status: Conceptual design for full-scale plant for cost evaluation; work continuing.

Details: Similar to No. 8, but fuel particles are 0.080 in.-diameter spheres of UO_2-PuO_2, and blanket particles are 0.150-in. diameter spheres of UO_2. Power (core and blanket): 881 Mw(t), 359 Mw(e). Breeding ratio: 1.41. Doubling time (Pu^{239} only): 9.2 years. Ratio U^{238}/Pu^{239}: 7.67.

Code: 0112 11 31103 46 5832 785 8XXXX 931 108

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Chapter 4 Fluidized-Bed Reactors

Fluidized-beds, in which particles are suspended by an upward-flowing stream of fluid, are well-known in chemical engineering, but their applications to nuclear reactors have complications. Many engineering problems have to be solved to utilize such advantages as the uniformity of temperature in the bed and ease of handling.

Some fluidized-bed reactors have been given other names: fluidized suspension reactor, fluidized thermal reactor, fluidized uranium hexa-fluoride reactor, fluidized uranium oxide reactor, rabbit reactor, vibrating-bed fluidized uranium oxide reactor, and clad-pellet reactor.

A fluidized-bed reactor, in its operating condition, consists of a bed of particles (fuel, fuel-moderator, moderator, or inert material) that are individually suspended by an upward moving stream of fluid and free to move throughout the whole bed. Ideally, the bulk density is constant throughout the bed, and the volume of the bed is also constant. These criteria are important for the nuclear stability of the reactor, because variations in bulk density or volume affect the reactivity. However, if these characteristics can be purposefully changed, they offer one means of controlling the reactor. The fluidized bed is supported in a reactor tank or reactor core tank that is permeable to the fluid, usually solely on the bottom, but it may be permeable on the sides as well for better mixing and heat transfer. Sufficient volume must be provided in the reactor tank for the fluidized bed in its expanded condition, because this volume may be as much as twice the volume of the particles in a settled state. A fluidized-bed reactor is ordinarily considered fail-safe, for, if the fluidizing flow stops, the particles settle into a sub-critical configuration.

Fluidization Applied to Nuclear Reactors

Fluidization seems to differ in gas-fluidized and liquid-fluidized beds. Investigations by Rowe and Partridge[1] show that rapid mixing of particles in a gas-fluidized bed depends on passage of bubbles. Uniform bubbling gives a rapid and complex, but non-random, particle motion. In liquid-fluidized beds, on the other hand, mixing is induced by fluid turbulence and approximates a random process.

The fluidization process as a function of fluid velocity has been described by Leva.[2]

"When a fine granular material is dumped into a vessel, the resulting bed has a definite bulk density... When the wall of the vessel is tapped during dumping the bed packs somewhat more densely than under quiet conditions... If a fluid is admitted at a very low rate into the bottom of this bed, a small pressure drop will be indicated by a manometer. As the rate of flow is gradually increased, the pressure drop rises to a point of equilibrium at which the weight of the bed in the fluid stream is equal to the fluid pressure drop across the column multiplied by the cross-sectional area of the vessel...

"As the rate of fluid flow increases still further, the bed begins to expand. This expansion increases the percentage of voids in the bed sufficiently to keep the pressure drop essentially constant despite the accelerated flow rate. At a certain velocity, the bed will have expanded to such a density that the individual particles have been disengaged from each other sufficiently to permit internal motion of the particles in the bed. This internal motion is induced by the fluid moving through the interstices of the bed and indicates the beginning of fluidization...

"Additional increase in fluid rate expands the bed further and intensifies the motion of the particles... For much higher rates of fluid flow, the state of agitation increases still further, and the position of the top of the bed fluctuates considerably. For very high flow rates, large bubbles usually force their way upward through the bed..."

The equilibrium fluidized bed with particles in motion but with relatively constant bulk density and top level of bed constant is often spoken of as a "quiescent" fluidized bed. The highly agitated bed with rapidly fluctuating bulk density and bed height is called a "boiling" bed. Fluid velocities must be intermediate between the velocity that will just buoy the particle bed and the velocity that will sweep the bed out of the container.

Other excellent general references on the subject of fluidization and fluidized beds are Zenz and Othmer[3] and Leva.[4] Definitions of fluidization or fluidized beds in general, or as applied to reactors, are also given by

Squires,[5] Hatch,[6] Lane,[7] Carpenter[8] and Thewlis.[9]

Incentives for applying the fluidized-bed concept to nuclear reactors have been summarized by Slack, Roman, et al, of Westinghouse, developers of an early nuclear reactor of this type:[10]

> "All of the major reactors which have been built to date are of the type in which the fuel is contained in solid members which are fixed in position. The disadvantages of this arrangement have been recognized and this recognition has lead to serious consideration of homogeneous reactors, in which the fuel is finely divided, held in suspension or solution in the coolant-moderator, and thus can be handled in bulk as a fuel should be. In this connection, it is interesting to note an editorial by V. L. Parsegian in TID-2008, 'Reactor Science and Technology,' Vol. 3, No. 1, March 1953. Mr. Parsegian writes:
>
> > 'Fuel is ordinarily thought of as something that is shovelled or piped into a boiler, from which it is largely exhausted in the form of waste gases. The atomic reactor appears to have introduced a rather different concept of fuel element, leaning slightly in the direction of the bush which burned with fire in the presence of Moses but which surprisingly was not consumed... Our most popular reactor concepts appear to treat these slugs more as structural material than as fuel that is intended to be consumed... Under these circumstances, it is not surprising that current reactors suffer heavy compromise in low efficiency, very limited temperature, low fuel burnup, high fuel cost, and too frequent shutdowns from slug failures... The merits of continuous flowing chemical and fuel systems are too well established in modern industry not to warrant adopting them in nuclear reactor systems wherever feasible... It would be a good bet that in such improved systems the fuel will once again be piped in and once again be intended for consumption, and that there will be less dependence on the principle of the burning bush.'
>
> "The use of pellets offers a comparatively simple reactor fuel which may be produced by high speed methods and which can be applied to many types of reactors. It is subject to simple handling techniques in loading, unloading and reprocessing. The term 'Pellet' as used in this report means any unattached fuel element of small but not microscopic size. Half-inch diameter spheres are a typical example, although the spherical shape is not essential. Thus pellets represent a class of material which is intermediate between the carefully machined, rigidly supported rods or plates used in most reactors, and

a completely unfinished bulk material, such as the uranium oxide which might be used in a homogeneous slurry reactor.

"The pellets we are considering should be large enough so that they can be manufactured individually and made uniform in size, but simple enough in structure that the manufacturing processes can be performed on high speed automatic machines. As will be shown later, many other factors, some of them conflicting, govern the choice of pellet size. One factor is the effect of fuel element failures on radioactivity in the external loop. If too much fuel is contained in a single element, the failure of an element produces an intolerable high transient in the level of radioactivity. Fortunately, the pellet sizes which we are led to by heat transfer and fluid flow considerations are small enough so that individual failures do not cause high activity transients."

A comprehensive survey of the methods of application of fluidization techniques to nuclear reactors has been made by Morris et al.[11] Four types of reactors were visualized, with different combinations of solid and fluid moderator, fuel, and inert material (Table II).

TABLE II Possible Systems for Fluidized Thermal Nuclear Reactors
(M = Moderator; F = Fissile Fuel; I = Inert Material)

	Reactor Type			
	I	II	III	IV
Solids	M	F+M	F	I
Fluid	F	I	M	F+M

Several fluids were suggested (Table III). Solid materials included pure graphite, graphite impregnated with uranium dioxide, and uranium metal.

TABLE III Fluids for Use in Reactors

	Reactor Type			
	I	II	III	IV
Type of Fluid	F	I	M	F+M
Liquid	Soln U in Bi	Na,Bi,Li	H_2O,D_2O,NaOH NaOD,Dowtherm, terphenyl	Soln U in H_2O or D_2O
Gas	UF_6	CO_2,H_2O,H_2,He	CO_2^*,H_2O^*,H_2^*	No feasible gas known

*May not be feasible

Specific reactor systems of the various types were not listed. However, from the information given in the text and tables, sample systems may be theorized. For example, Reactor Type I might consist of finely divided graphite fluidized with UF_6 gas (at high temperatures); Type II might employ graphite pellets impregnated with uranium and fluidized with liquid sodium or liquid bismuth--cladding for the pellets would be required; Type III might have UO_2 pellets fluidized with molten sodium hydroxide.

For Reactor Type IV the function of the inert solid is apparently to improve heat transfer--zirconium pellets fluidized by a solution of uranyl sulfate in light or heavy water might be possible. A possible gaseous combination has been suggested by Kerze[12]--CaF_2 particles fluidized by a mixture of UF_6 and CF_4. This combination would be possible if the fluidizing mixture has sufficient moderating properties.

Application to a power-producing system involved four methods of heat removal with a gas-fluidized bed. One of these methods included circulation of the suspended solids outside the core; thus it will not be considered in this chapter. The other three differed as to whether (a) the heated gas passed directly through a turbine; (b) the heated gas transferred heat through an external heat exchanger to a second coolant, which passed through the turbine; (c) a heat exchanger and second gas coolant were used, as in (b), but the heat exchanger was located within the reactor core, i.e., within the fluidized bed.

For a liquid fluidized bed the possible methods of heat removal were limited to the double-coolant systems with internal or external heat exchangers. Additional heat-removal systems for gas fluidized beds were so-called mixed-phase systems, in which the gas was fully condensed at the low-pressure end of the turbine (single coolant) or alternatively, in an intermediate heat exchanger (double coolant). The liquid stream was then returned to the reactor and injected directly into the fluidized bed.

The general conclusion was that fluidized-bed reactors were promising but much research and development would be needed.

The nuclear stability of fluidized bed reactors as a function of changes in bed height was explored by a group at Oak Ridge National Laboratory in a preliminary study, which employed calculational methods only.[13] It was limited to reactors in which particles containing uranium-233 and thorium-232 are fluidized by liquid water. Reactors moderated with heavy water were found to be least sensitive to changes in bed height at thorium concentrations of 80-120 g/l; those moderated with light water were least sensitive in the range 1500-2400 g Th/l; and mixed H_2O-D_2O reactors at intermediate concentrations. A reactor operated at the thorium concentration at which it was least sensitive to changes in bed height was stable in response to cyclical variations of bed height.

One difficulty with fluidized-bed reactors results from the use of the same fluid for cooling the reactor and fluidizing the bed. The maximum velocity of the fluid flow may be limited because excessive rates would result in excessive bed expansion, poor distribution of the solids, attrition of the solids, and erosion of the container walls. Increasing the flow of coolant without increasing the fluidization flow would increase the power rating of a core for a given temperature rise in the coolant. Two approaches to this problem have been suggested.

Hatch <u>et al</u>, of Brookhaven, have proposed a fluidized-bed reactor in which the sodium coolant circulates through a U-tube in the bed, and another flow of sodium fluidizes the particles.[14,15] Thus the coolant flow is separated from the fluidizing flow and the rates are independent.

This type of reactor design may offer the greatest promise for a truly feasible nuclear reactor. According to Robba et al,[16] the separation of fluidized fuel from coolant results in high stability of the fluidized bed as a whole and particularly of fuel density. In addition, the almost quiescent conditions of such a fluidized bed almost eliminate attrition of particles and erosion of container walls.

A second solution was advanced by Silverstein,[17] at the Cornell Aeronautical Laboratory, who proposed substituting porous for solid reactor walls. The lower portion of the porous walls is normally bounded by solid walls, with an annular space between. The porous walls would permit part of the fluidizing liquid to leave the bed through the walls, instead of through the top surface of the bed. Thus, the average fluidizing velocity would be less for the same entrant velocity of fluid than that of a bed surrounded by solid walls. The consequent decrease in expansion of the bed was demonstrated in experiments. For example, in a solid-wall reactor, the height of a bed increased by a factor of 3 at an entrant velocity, of fluidizing water, of 0.22 feet per second. In a porous-wall reactor, at a greater entrant velocity--0.34 feet per second--the height of the bed increased by a factor of only 1.09.

The experiments showed that the behavior of the porous-wall bed was not affected appreciably by entry-velocity distribution or by restrictions at the top of the bed but was affected by flow restrictions in the annular flow passage between the porous walls and the solid walls. Fluidization in a porous-wall bed, once it begins, may be more violent than that in a solid-wall bed at the same fluid-bed fraction. The use of a porous-wall container within an outer one was tested. When an inverted cone with porous walls was placed within the outer porous container, the bed expanded in height about 30 percent, compared with a maximum of 20 percent for a cylindrical porous-wall bed.

A proposal to study the concept further was published,[18] but the status is not known.

Early Concept

Slack, Roman, et al, of Westinghouse, proposed the use of a packed or fluidized bed in a pressurized-water reactor.[10,19,20] In this converter, slightly enriched uranium, as metal, alloy, or oxide, is in the form of spherical pellets, preferably clad, about 1/4 inch in diameter. The coolant and moderator may be pressurized water, which flows upward through a perforated plate on which the pellets rest to fluidize them in a critical configuration. The authors discuss the possible application of such a reactor to a power plant. Fixed-bed reactors fluidizable for reprocessing, are also described.

Later Concepts

An Oak Ridge School of Reactor Technology (ORSORT) study by Halik, et al, described briefly four reactor concepts utilizing fluidized beds.[21] Detailed engineering and nuclear calculations were made for a fifth concept--"Fluidized-Solids Power Breeder" which is described in Chapter 5, (Fluidized and Moving-Bed Reactors). The study was chiefly directed at gas-solid systems, although one liquid-solid system was considered.

In the first reactor system, gaseous UF_6 is both fuel and fluidizing gas. There are three fluidized-bed regions--core, blanket, and heat exchanger. The core contains BeO particles suspended in UF_6 gas. Surrounding the core is a fluidized-bed blanket of ThO_2 and graphite particles. Hot BeO particles flow by gravity out of the core through a discharge pipe. A stream of argon or helium carries them through a transfer leg and discharge nozzle into the heat exchanger--the third fluidized bed. The cooled BeO particles flow from the heat exchanger by gravity through a discharge pipe, are transported by a stream of UF_6 through a transfer leg, and are charged back into the core through a distributor nozzle. The gas flows are adjusted to maintain constant-level fluidized beds in the core and heat-exchanger vessels. The blanket material is fluidized in a separate circuit. Only nuclear calculations were made for this concept, but they showed that the reactor could readily be made critical by using BeO as the moderator.

The other two ORSORT concepts employ graphite particles impregnated with uranium-233. One of the concepts (fluidized-moving-bed core and heat exchanger) uses separate heat exchanger, core, and blanket vessels, as in the UF_6-fluidized reactor. The authors, however, believe that the high velocity and large quantity of gas needed to transfer the fuel-moderator to and from the heat exchanger is likely to induce instability of the fluidized beds because of boiling, bubbling, or even slugging. Thus, the controllability of the reactor was questionable. Preliminary neutronics calculations indicated that a 4-inch drop in bed height (3 percent) increases the reactivity (δk) by 2.7 percent. There was no further development of the system beyond preparation of a schematic drawing representing the concept.

An alternative arrangement was that of a fluidized-fixed-bed core with an internal heat exchanger located near the periphery. Little consideration was given to this arrangement because of the lack of evidence of positive flow distribution of solids in gases, and because of the apparent control problem.

A liquid-solid fluidized system was examined briefly. The core is a cylinder containing graphite pebbles fluidized by an upward flowing stream of D_2O. This liquid system is more stable than the gas-solid system--reactivity changes more slowly with changes in bed height--but the system must be pressurized to obtain acceptable steam conditions. A few general calculations were made.

A second ORSORT study was carried out in 1957 by Teeter et al.[22] They discarded fast fluidized-bed reactors on account of high inventory and gas fluidized beds on account of high pumping-power requirements. Of the liquid fluidized-bed systems, both organic cooled and moderated and light water cooled and moderated reactors were judged worthy of further study. Reactors cooled and moderated with D_2O were eliminated because the moderator-to-fuel ratio was so large that the fluidized bed would be hydrodynamically unstable. The light-water system was finally chosen--although it involved high pressure--and a preliminary design calculation was made.

A review team from Foster-Wheeler Corporation and Pioneer Service and Engineering Company concluded that a thermal uranium-233 breeder with circulating fuel offered great potentialities for economic central-station power.[23] In a subsequent report[24] a group from the same two companies and the Diamond Alkali Company re-evaluated the ORSORT concepts. They rejected the boiling gas-fluidized-bed systems (with internal or external heat exchangers) because of uncontrollability. They did not consider liquid fluidized-bed reactors. They also rejected the UF_6-gas-fluidized reactor because of the corrosiveness of the gas, the low concentration of uranium atoms--which would necessitate pressurization to attain criticality in a reasonable core size, and the high pumping power required.

The system selected for further study was a uranium-233 breeder with a quiescent fluidized-bed core. Internal and external breeders were considered, as in the ORSORT study. The internal breeder is simpler, but a sphere 20 ft in diameter with a 2-ft graphite reflector would be required. This concept would call for a much larger inventory of fissionable material than that for the external breeder. To test the feasibility of a quiescent fluidized bed, preliminary experiments on fluidization, flow rate, and flow pattern were made. The group concluded that maintaining a truly quiescent gas-fluidized bed was impossible.

A group of Netherlands reactor engineers (FOM-KEMA* Reactor Development Group) studied several liquid and gaseous suspension reactors, including fluidized-bed reactors, but they, too, concluded that the fluidized-bed concepts that they investigated were not promising.[25] The authors described and rejected the boiling fluidized bed for reactor application as being uncontrollable because of density change. They described a mechanical method of fluidization by means of a vibrating cone. They mentioned a vibrating-bed reactor but did not consider it further. They stated that because of limited core size, such a reactor would require highly enriched uranium, which is undesirable for a civilian power reactor.

Astley carried out several studies at Hanford on a fluidized-bed reactor moderated with pressurized light water (Rabbit Reactor), in which the fuel is aluminum-clad uranium or uranium dioxide pellets.[26,27] The original concept was suggested by Anderson.[28] Johanson carried out some experimental studies on fluidization of 3/8-inch and 3/4-inch steel spheres in 6-inch and 9-inch columns.[29]

A fluidized bed, clad-pellet reactor was examined in a preliminary evaluation by Manowitz and Zwickler of Brookhaven.[30] A thoria-urania (uranium-233) fuel clad with nickel, molybdenum, zirconium, or stainless steel, and a moderator-coolant of light water or terphenyl were considered. Physics and heat-transfer calculations were made, and some hydraulic data were obtained with 0.1-0.15-inch lead pellets and with water at room

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*FOM: Foundation for Fundamental Research on Matter; KEMA: the Electrical Equipment Testing Company.

temperature as the fluidizing medium.

Scheve, et al, of the Martin-Company--now Martin-Marietta--have studied the fluidized-bed reactor concept.[31-35] These investigations were an extension and expansion of the work begun in the second ORSORT study.[31] In the six-month feasibility study, a series of physics calculations was given for pressurized, water-moderated, slightly enriched, thorium-uranium oxide reactors. In addition, calculations were given for diphenyl-moderated reactors with slightly enriched uranium oxide as fuel. The latter gave highest k_{eff} at high moderator volume fractions, at which the fluidized bed would be unstable. For this reason a reactor with higher enrichment and lower moderator volume fraction would have to be specified. To improve this behavior, adding BeO moderator to the UO_2 pellets was suggested. This addition would allow operation at the highest possible moderator volume fraction and at lower enrichments. Calculations involved particle sizes ranging from 0.075 to 0.275 inch. Control and hazard problems were studied, and preliminary experimental work on fabrication and testing of pellets was carried out.

The hazards report[32] describes a critical-experiment facility consisting of a fluidized-bed reactor fueled with fuel pellets of slightly enriched uranium dioxide and cooled and moderated with light water. The facility was built, but the reactor did not go critical. (See "Evaluation and Status")

The Liquid Fluidized Bed Reactor Experiment study[35] describes a reactor with aluminum-clad uranium dioxide fuel pellets 230 mils in diameter. Santowax OMP is moderator, coolant, and fluidizing medium. The enrichment is 2.5 percent.

An "Organic Moderated Fluidized-Bed Reactor" concept was described by Wright in 1958.[36] This concept employs uranium fuel in the form of spherical pellets and an organic coolant-moderator of the polyphenyl type. The power output is made essentially self-controlling by feeding back changes of average temperature to a flow-rate controller, which automatically changes the bulk density of the bed and hence the reactivity. If the coolant flow stops, the bed collapses to a subcritical condition and the reactor is therefore fail-safe. The organic fluid is considered the best choice for the fluidizing medium because:

(a) it provides lubrication between the turbulent fuel pellets; (b) its low vapor pressure allows the use of low-pressure equipment; and (c) it can be used at higher temperatures than are practical for water. The organic coolant is practically noncorrosive, and the conversion ratio attainable is high, possibly approaching unity.

A review team at Brookhaven (L. P. Hatch et al) evaluated reactors using settled-bed fuels.[14,15] One of the concepts, a sodium-cooled fast breeder reactor, has a particulate-fuel bed, with an internal heat exchanger. It is intended that the fuel will be maintained in a settled bed. As an alternative, however, if further investigation shows feasibility and desirability, the fuel may be fluidized. The particulate-fuel is composed of spherical UO_2-PuO_2 particles 75 to 100 μ in diameter. The sodium coolant circulates through stainless-steel U-tubes immersed in the bed. Additional sodium flow is provided to fluidize the core particles.

Two other concepts studied are heterogeneous reactors, with the settled or fluidized fuel occupying the space in the lattice ordinarily occupied by the fuel elements of a solid-fueled reactor.[16] These concepts will be described in the chapter on Particulate-Fuel-Element Reactors (Chapter 7).

Advanced Concept

Hatch et al have proposed a fluidized-bed nuclear reactor for rocket propulsion.[6,37] Here the designers propose to solve the problem of maintaining a quiescent fluidized bed and still keep up the required high coolant velocity by rotating the fluidized bed at high speed.

Evaluation and Status

Authorities who have evaluated concepts for fluidized-bed reactors have considered the gas and liquid versions separately.

The advantages and disadvantages of the gas-fluidized bed reactor have been summarized.[23,24]

The advantages are: high neutron economy--breeding may be possible; operability at atmospheric pressure; a minimum of corrosion problems; inexpensive structural materials; the possibility of generating high-temperature steam; no preheating of coolant prior to startup required; high specific power; negligible radiation damage to the fuel; and a simple, continuous processing system.

There are, however, two disadvantages. The stability of a gas-fluidized bed is questionable. Graphite particles averaging 60 μ in size agglomerate at about 1500°F. According to Kirkpatrick, graphite also "plates out" in the system.[38] The attrition rate of graphite in a circulating fluidized system is estimated to be about 1-2 percent per day. In a bed with circulation only in the core, the rate may be less but the fines would still have to be removed to maintain proper particle size for fluidization. Removal of fines would result in low burnup of fuel in a processing cycle, as well as loss of fuel and graphite moderator. Control is also a difficulty. The negative temperature coefficient is not adequate to assure effective self-regulation. The power increases so rapidly with increasing core density that proper control will be difficult.

The advantages of a liquid fluidized reactor have been given by Manowitz and Zwickler[30] and by Scheve.[31]

a. The fuel burnup would be uniform and the ratio of maximum to average would be essentially unity.
b. The conversion ratio should be higher and the neutron economy better than in a fixed-fuel reactor because of the absence of structural and cladding materials.
c. The fuel can be unclad pellets of uranium dioxide of simple shape, which should be relatively inexpensive the fabricate and reprocess. On the other hand, the experience of the Martin Co. with the Liquid Fluidized Bed Reactor critical experiment shows that unclad fuel pellets are not feasible, and that the erosion problem is very real.
d. Fuel may be added and removed continuously; large amounts of excess reactivity are not needed for burnup.
e. The continuous processing, the negative temperature coefficient, and variable flow and enrichment features, make it possible to control the reactivity without the use of control rods.
f. Fuel may be handled remotely.
g. Activity is contained--failure of a single pellet exposes only small fraction of total activity.
h. Construction of the reactor vessel is simple.
i. The coolant exit temperature is high and less coolant is required.
j. Down time is at a minimum.

The disadvantages are:[30] restricted fluid velocity; probably low conversion ratio; less-advanced technology; unknown factors: hydraulics, control, and cladding technology (erosion and integrity of cladding); and fouling of terphenyl at low velocities.

Apparently the Martin-Marietta Co. critical-experiment facility is the only fluidized-bed reactor that has thus far reached the construction stage. The facility was completed[39] and loading fuel for criticality began in February 1962.[40] However, criticality was not attained even after 2200 lbs of 1.6 percent enriched UO_2 pellets were loaded. Criticality had been expected at a loading of 1600 lbs of pellets. Investigation showed that abrasion of the unclad, pea-sized pellets had resulted in the loss of several hundred pounds of enriched uranium oxide. This oxide had been reduced to powder and was acting as a poison instead of as a fuel.[41] Martin proposed a new loading of uranium-molybdenum alloy pellets clad with a suitable metal to overcome the abrasion problem, but to accomplish this loading, new AEC funding was required.[42] There has been no further news of this project since October 1962.

D A T A   S H E E T S

FLUIDIZED-BED REACTORS

No. 1 Fluidized-Bed, Pressurized-Water Reactor

WAPD

Reference: U. S. Patent No. 3,058,897.

Originator: C. M. Slack and W. G. Roman.

Status: Concept in Westinghouse reports, 1953-1954. Nuclear and heat-transfer calculations. Some non-nuclear experiments on fluidized beds. No further work.

Details: Thermal neutrons, steady state, converter. Fuel: slightly enriched uranium (metal, alloy, or UO_2) preferably clad, in form of spherical pellets 0.1 in. to 0.4 in. diameter (typical size 0.25 in.). Pellets rest on perforated plate in pressurized core vessel. Hydraulic means for charging and discharging fuel. Coolant-moderator: typically H_2O, although other alternatives are possible. Coolant flow through plate fluidizes pellets and suspends them in a critical configuration. Control: by changing flow rate (changes moderator-fuel ratio). Control rods may also be used.

Code: 0311 13 31101 42 654 763 84787 921 105

No. 2 Fluidized Uranium Hexafluoride--Beryllium Oxide Reactor

ORSORT

Reference: CF-54-1-81, pp. 26-7.

Originator: R. R. Halik, L. H. Beckberger, J. M. Haibeck, J. E. Mealia, W. A. Northrop, D. R. Rees, and W. A. Robba.

Status: Concept in ORSORT term paper, 1954. Nuclear calculations and schematic drawing only; no further work.

Details: Thermal neutrons, steady state, breeder (?). Fuel: $U^{233}F_6$ gas. Moderator: BeO in form of fine particles fluidized by fuel gas. Fertile material: ThO_2 in graphite particles, fluidized in blanket. Hot moderator particles flow downward out of reactor core and are blown over and fluidized into external heat exchanger by helium or argon. Cold moderator particles flow downward out of heat exchanger and are blown over and fluidized into reactor core by UF_6 gas. These flows adjusted to maintain core and heat-exchanger beds at constant level. Circulating gas separated above fluidized beds in cyclones. Side streams of UF_6 and blanket materials reprocessed by fractional distillation.

Code: 0312 15 31710 45 662 766 8XXXX 941 104

No. 3 Fluidized Moving Bed Core and Heat Exchanger Reactor

ORSORT

Reference: CF-54-1-81, pp. 45-6.

Originator: R. R. Halik, L. H. Beckberger, J. M. Haibeck, J. E. Mealia, W. A. Northrop, D. R. Rees, and W. A. Robba.

Status: Concept in ORSORT term paper, 1954. Schematic drawing only; no further work.

Details: Thermal neutrons, steady state, breeder (?). Fuel-moderator: U^{233} impregnated graphite in form of fine particles (ca. 60 μ diameter), fluidized by coolant gas. Coolant-fluidizing agent: argon. Fertile material: ThO_2 in graphite particles, fluidized in blanket. External heat exchanger and particle transfer arrangement like ORSORT Fluidized Uranium Hexafluoride--Beryllium Oxide Reactor (No. 2). High velocity and volume of gas flow makes boiling, bubbling, or slugging in fluidized bed core likely, so that control of reactor is questionable.

Code: 0312 12 31719 45 683 766 8XXXX 941 105

No. 4 Fluidized Fixed Bed Core Reactor

ORSORT

Reference: CF-54-1-81, pp. 45, 47-8.

Originator: R. R. Halik, L. H. Beckberger, J. M. Haibeck, J. W. Mealia, W. A. Northrop, D. R. Rees, and W. A. Robba.

Status: Concept in ORSORT term paper, 1954. Schematic drawing only, no further work.

Details: Thermal neutrons, steady state, breeder (?). Fuel-moderator: U^{233} impregnated graphite in form of fine particles (ca. 60 μ diameter) fluidized by coolant gas. Coolant-fluidizing agent: argon. Fertile material: thorium metal in rods or tubes near periphery of fluidized bed. Internal heat exchanger--multiplicity of tubes (boiling-water coolant) near periphery of fluidized bed outside thorium blanket rods. Because fluidized fuel remains in core in fixed bed, boiling and slugging would be minimized, i.e., quiescent bed. No further consideration of this design by originators because of control problem and lack of evidence for positive flow distribution of solids and gases.

Code: 0312 12 31719 45 683 766 8XXXX 931 105

No. 5 Liquid-Solid Fluidized Reactor

ORSORT

Reference: CF-54-1-81, pp. 164-169.

Originator: R. R. Halik, L. H. Beckberger, J. M. Haibeck, J. W. Mealia, W. A. Northrop, D. R. Rees, and W. A. Robba.

Status: Concept in ORSORT term paper, 1954. Few calculations only, no further work.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: U^{233} impregnated graphite in 1/4 in. pebbles. Coolant-fluidizing agent: liquid D_2O. D_2O gives additional moderation. Blanket: fluidized or slurry system of ThO_2 in D_2O. Advantage over gas-fluidized reactors--all heat removed without transferring any solid material. Critical mass also less. Calculation shows reactivity changes very slowly with changes in bed height. Disadvantage--system must be pressurized to obtain acceptable steam conditions.

Code: 0311 12 31102 45 655 766 8XXXX 941 105
14

No. 6 Fluidized-Bed Reactor

ORSORT

Reference: ORNL, CF-57-8-14.

Originator: C. L. Teeter, Group Chairman, T. Ciarlariello, B. L. Hoffman, D. H. Jorgensen, F. D. Judge, L. J. King, D. A. McCune, M. R. Scheve, and H. E. Zellnik.

Status: Conceptual design in ORSORT term paper, 1957. Physics and engineering calculation. No further work, but see Martin LFBR (No. 11).

Details: Thermal neutrons, steady state, converter. Fuel: pellets of UO_2, 0.075 in. diameter, enrichment about 1.25%. Coolant-moderator-fluidizing agent: pressurized H_2O. Reflector: H_2O. Control: hollow, H_2O-filled Hf poison tubes (thimbles) that move vertically. Concept: is for a large plant--465 Mw(t).

Code: 0311 13 31101 42 654 723 81153 921 103

No. 7 Homogeneous Fluidized Uranium Oxide Reactor

FOM-KEMA

Reference: Nuclear Engineering, Part II, Chem. Eng. Progress Symposium Series, 50, No. 12 (1954).

Originator: J. Went and H. de Bruyn.

Status: Concept considered in 1954 but discarded.

Details: Thermal neutrons, steady state, burner. Fuel-moderator: mixture of moderately or highly enriched UO_2 and BeO. Fluidized by gas flow or by vibration. A vibrating bed is produced, for example, by a vibrating double cone. Authors report concept unattractive for industrial power reactor because of enrichment requirements--moderate enrichment for gas-fluidized bed, high enrichment for vibrating bed--owing to vessel-size limitation and energy requirement. No other details given.

Code: 0313 15 317XX 44 683 7XX 8XXXX 9XX 105

No. 8 Fluidized-Bed Reactor

GE-HAPO

Reference: U. S. Patent 3,046,212.

Originator: C. R. Anderson.

Status: Conceptual design, 1957. Physics and engineering calculations. Hydraulic studies with steel balls. No further work.

Details: Thermal neutrons, steady state, converter. Fuel: Al-clad pellets of slightly enriched uranium or UO_2, 3/8-3/4 in. diameter. Coolant-moderator-fluidizing agent: pressurized H_2O. Control: by controlling degree of separation of fuel pellets (moderator-fuel ratio in core) by changing coolant flow rate. Parameters for 70 Mw(t) and 650 Mw(t) reactors given.

Code: 0311 13 31101 42 654 763 84787 921 103

No. 9 Water Moderated Clad Pellet Reactor

BNL

Reference: Unpublished internal report, Brookhaven National Laboratory, "Preliminary Evaluation of a Clad Pellet Reactor," June 1958.

Originator: B. Manowitz and S. Zwickler.

Status: Conceptual design, 1958. Preliminary physics and engineering calculations. Some hydraulic experiments with lead pellets. No further work.

Details: Thermal neutrons, steady state, converter. Fuel: ThO_2-$U^{233}O_2$ pellets, 0.15-0.2 in. diameter, clad with Ni, Mo, Zr, or stainless steel. Coolant-moderator-fluidizing agent: H_2O. Fluidized bed is critical at 80% voids; is fail-safe because non-critical upon collapse of the bed or expansion above 90%. Operating pressure: 2000 psi; surface temperature: 642°F. Exit water temperature: 600°F. As compared with plate or rod system, clad-pellet bed can tolerate a temperature drop greater by a factor of four. Can therefore extract about 1.8 times more power. Alternatively, it can transport same amount of heat using one fourth of coolant required for a fixed fuel system. This advantage partly compensates for disadvantage factor of 10 in coolant velocity. Conversion ratio: 0.5

Code: 0311 13 31101 45 654 766 8XXXX 9XX 103

No. 10 Terphenyl Cooled and Moderated Clad Pellet Reactor

BNL

Reference: Unpublished internal report, Brookhaven National Laboratory, "Preliminary Evaluation of a Clad Pellet Reactor," June 1958.

Originator: B. Manowitz and S. Zwickler.

Status: Conceptual design, 1958. Preliminary physics and engineering calculations and a flow sheet. No further work.

Details: Thermal neutrons, steady state, converter. Fuel: ThO_2-$U^{233}O_2$ pellets, 0.15 in. diameter or less, clad with Ni, Mo, Zr, or stainless steel. Coolant-moderator-fluidizing agent: terphenyl. Surface temperature of 850-900°F allows exit temperature of 750°F. Working pressure: 500 psi. Provides steam at 700°F, 950 psi, and 500 Mw(t) to generate 160 Mw(e). Conversion ratio: 0.57.

Code: 0311 16 31108 45 653 766 8XXXX 9XX 103

No. 11 Pressurized Water Cooled and Moderated Fluidized Bed Reactor (LFBR)

Martin Co.*

References: MND-LFBR-1696; MND-LFBR-2179; MND-LFBR-2303; MND-LFBR-2304.

Originator: M. R. Scheve; concept related to 1957 ORSORT study.

Status: Six-months feasibility study (Ref. 31) was followed by a Hazards Summary Report for a Critical Experiment (Ref. 32), and Liquid Fluidized Bed Reactor Study Program (Ref. 33, 34). Critical experiment was loaded for criticality Feb. 1962, but criticality was not obtained because of erosion damage to unclad fuel. New core proposal was made, but probably no new work without new AEC funding, which appears problematical.

Details: Thermal neutrons, steady state, converter. Fuel: uranium, enriched about 1.5%, in UO_2. Coolant-moderator-fluidizing agent: pressurized H_2O (2000 psia). Fuel pellets are spheres, modified spheres, or cylinders with rounded ends, approximately 1/4-in. diameter, with metal or carbon coating for abrasion resistance and fission product confinement (fuel for critical experiment was unclad). Reflector: H_2O. Control: by poison rods, containing boron, moving vertically and control of water flow. Large--117 Mw(e)--reactor.

Code: 0311 13 31101 42 654 763 81111 921 103
84787

*Now Martin-Marietta Co.

No. 12 Diphenyl Cooled and BeO-Diphenyl Moderated Fluidized Bed Reactor

Martin Co.*

Reference: MND-LFBR-1696.

Originator: M. R. Scheve. Related to 1957 ORSORT study.

Status: Six-months feasibility study, 1959. No further work.

Details: Thermal neutrons, steady state, converter. Physics studies show diphenyl coolant and moderator requires adding BeO to fuel for extra moderation to allow operation with stable fluidized-bed flow characteristics at a reasonably high moderator-volume fraction and low enrichment. Fuel: slightly enriched uranium in UO_2. Fuel pellets: spheres or modified spheres approximately 1/4-in. diameter. Reflector: organic. Control: by B-containing poison rods, moving vertically in thimbles inserted in core, and flow control. Liquid poison control also considered. Large--117 Mw(e)--reactor.

Code: 0311 16 31108 42 653 763 81111 921 103

*Now Martin-Marietta Co.

No. 13 Santowax Cooled and Moderated Fluidized-Bed Reactor Experiment

Martin Co.*

Reference: MND-LFBR-2337.

Originator: M. R. Scheve.

Status: Preliminary design, 1960. Current status unknown.

Details: Thermal neutrons, steady state, converter. Fuel: 2.5% enriched uranium in 230-mil UO_2 pellets (modified spheres) clad with Al. Coolant-moderator-fluidizing agent: Santowax OMP (chiefly terphenyls). Coolant operates at 100 psig. Reflector: organic. Control: Al-clad B_4C plates inserted in rectangular thimbles in core. Small--10 Mw(t) maximum--reactor.

Code: 0311 16 31108 42 653 763 81121 921 103

*Now Martin-Marietta Co.

No. 14 Organic Moderated Fluidized-Bed Reactor (OMFBR)

WAPD

Reference: Trans. ANS, 1, No. 2, pp. 126-7, December 1958.

Originator: J. W. Wright, Westinghouse Atomic Power Department.

Status: Conceptual design; originated in 1956. Current status unknown.

Details: Thermal neutrons, steady state, converter (near breeder). Fuel: uranium (metal or alloy not specified) enriched to 2% U^{235} in spherical pellets. Coolant-moderator-fluidizing agent: polyphenyl-type organic. Fertile material: U^{238} in 2% enriched uranium. Control: control of coolant flow, which controls bulk density and thus reactivity of core. 150 Mw(t)--50 Mw(e)--plant described.

Code: 0311 16 31108 42 65X 763 84787 9XX 103

No. 15 Sodium-Cooled Fast Breeder Reactor

BNL

References: BNL-5372 (unpublished); BNL-5830

Originators: L. P. Hatch, W. H. Regan, J. R. Powell, L. Green, and W. A. Robba.

Status: Conceptual design still under consideration.

Details: Fast reactor, steady state, breeder. Fuel: UO_2-PuO_2 as 75-100 μ particles suspended in Na as settled or fluidized bed. Coolant: Na. Internal heat exchanger: multiplicity of U-tubes, through which Na circulates, in core. Fertile material: UO_2. Top blanket: UO_2-Al_2O_3 as 75-100 μ particles, blanket stays in place because its density is lower than that of the fuel. Bottom and radial blankets: UO_2 as 1/4 in. diameter spheres. Control: not discussed. Power: 815 Mw(t), 300 Mw(e).

Code: 0112 11 31103 46 656 765 8XXXX 931 108

No. 16 Fluidized-Bed Reactor for Rocket Propulsion

BNL

References: ARS Journal, April 1961, pp. 547-8; Nucleonics, **18**, pp. 102-103, December 1960.

Originators: L. P. Hatch, W. H. Regan, and J. R. Powell.

Status: Concept, 1961.

Details: Thermal (some epithermal) neutrons, steady state, burner. Fuel: U^{233} as 100 μ particles of UC-ZrC. Moderator-reflector: Be surrounding core. Coolant: hydrogen; outlet temperature, 5400°F. Gas coolant fluidizes fuel in a rapidly rotating (2000 rpm) annular bed. Control: rotating drums, containing poison, in the reflector. Power: 25,000 Mw(t).

Code: 0313 15 31715 45 683 711 8144X 921 107

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In the particulate-fueled reactors thus far considered, the fuel remains in the reactor during operation, although it may be discharged in part or *in toto* for reprocessing. However, as mentioned in the introduction to this part, some reactors employ a particulate, finely powdered, or fluid suspension fuel that flows like a liquid into a core vessel, where it attains criticality, then out of the core where it becomes subcritical.[1] These reactors have been variously described by their originators as "fluidized reactors," "fluidized-solids reactors," "suspension reactors" or "moving-bed reactors." The fuel may be recirculated by a pump or fluidized by a stream of gas or liquid to pass through a heat exchanger to a reservoir above the core, thence downward by gravity into the core to complete the cycle. We have not treated these as "slurry reactors" because they were not so treated by their originators and because they have a distinctive fuel-circulation cycle.

ORSORT Concept

In Chapter 4 three fluidized-bed reactor concepts were described.[2] The fourth concept, "Fluidized-Solids Power Breeder Reactor," is discussed in this chapter, for it has a moving-bed core and a fluidized heat exchanger. In this reactor, graphite is a moderator in the core and blanket, uranium-233 is the fuel, and thorium carbide is the fertile material. The core is operated as a moving bed, i.e., the solid particles flow into and out of the core by gravity and at nearly their settled density. The blanket is a fluidized bed of relatively low void content. The uranium-impregnated graphite particles flow downward by gravity from a reservoir into the graphite core tank and become heated by the fission process. They discharge into a plenum chamber, where they are fluidized by a stream of argon and circulated to the heat exchanger. After they lose heat to the steam coils, the gas and solids are separated in a battery of cyclones. The gas goes to a blower, and the solids discharge to the cylindrical reservoir. To conserve heat, the heat exchanger is mounted concentrically in the reservoir, so that any heat escaping serves to preheat the fuel before it enters the core.

KEMA Reactors and Related Concepts

A similar reactor concept is mentioned by Went and de Bruyn,[1] but this reference does not describe the concept further. An expanded description has been given in a later paper by de Bruyn, v. d. Schee, and Went.[3]

The reactor vessel is filled with compound grains of beryllium oxide and uranium dioxide having an atomic ratio of Be/U of about 120. The distribution of grain size is chosen to ensure a close packing (70-75% by volume). The mean grain size is about 200-250 μ. The cylindrical vessel is surrounded by a beryllium oxide reflector 70 cm thick. The grains move by gravity downward through the reactor vessel. By choosing a suitable geometric form of the bottom of the reactor vessel, a velocity distribution in the flow of grains down the reactor can be established to correspond to the buckling of the reactor.

The grains leaving the reactor vessel are transported pneumatically to a heat exchanger, where the bed of grains is fluidized by a stream of helium. The gas velocity is adjusted to ensure a moderately boiling state of the grains. Intensive boiling must be avoided to prevent too much attrition of the grains. In this boiling bed the degree of packing will be about 35 percent by volume. After passing through the heat exchanger, the grains return to the reactor vessel by overflow of the boiling bed.

Inside the heat exchanger the heat is transferred to water circulating in the boiler tubes. At 100 kg/cm^2, steam at 310°C is produced. Part of the heat exchanger may be used as a superheater to produce high-quality steam at 550°C.

The dimensions of the reactor and heat exchanger for a 300-Mw(t) power reactor were calculated, assuming a maximum temperature of 1200°C for the grains inside the reactor and 700°C in the boiling bed. The reactor vessel proper could be 1.85 meters in diameter and 1.85 meters in height when the maximum flow velocity is limited by the number of delayed neutrons necessary for smooth regulation of the reactivity. The weight of compound grains (moderator and fuel) inside the reactor is 10.2 tons beryllium oxide and 0.9 tons uranium dioxide. The holdup in the heat exchanger without superheater is 31.5 tons BeO and 2.9 tons UO_2. With superheating, it is 50.8 tons BeO and 4.7 tons UO_2 (2-in.-diameter boiler tubes, 1-1/2-in.-diameter superheater tubes, and a tube spacing of 1-1/2 times the tube diameter).

The Netherlands group has noted that nuclear superheating would probably be too expensive because of the holdup of expensive fuel. Moderately enriched (about 6%) uranium dioxide must be used. The conversion ratio is low. Attrition of the costly compound grains will probably be fairly high, and, therefore, fuel economy will be rather poor.

Another type of homogeneous reactor[4] fits the criteria for inclusion in this chapter. It is a "Homogeneous Liquid Suspension Reactor," in which the fuel is a suspension of uranium oxide in heavy water moderator. According to the authors, Went and de Bruyn, a dilute suspension should be used. Settling of the uranium oxide particles might disturb the homogeneous distribution of the uranium in the reactor. Rotating or vibrating stirrers should not be inside the reactor for homogenizing the suspension, because, inside the reactor, no moving parts that cannot be repaired easily should be used.

In the most reliable method of homogenization, the reactor is divided into two regions: (a) a thin upper compartment, in which a vibromixer or--still better--an injection system, produces a turbulent complete mixing of the suspension; and (b) the reaction chamber proper, which is separated from the upper compartment by a system of vertical partitions, to suppress all horizontal movement. Thus, in the reactor, vertical settling motion predominates. The downward movement of the water coolant assists this downward flow of the suspension.

The temperature of the reactor contents is about 250° to 300°C; the corresponding pressure is 35 to 80 atmospheres. These high pressures require that the wall thickness of the pressure tank containing the reactor be so great that neutron losses due to capture would become inadmissibly high, unless a reflector is built into the reactor vessel. To avoid contamination of the reflector by fission products, beryllium oxide is used instead of graphite.

The authors claim that, because of the ideal heat contact between the fuel and the heavy water, this type of reactor has automatic internal reactivity adjustment. The absence of internal construction parts will decrease the neutron loss; therefore the conversion factor will be high. Two important problems--the uranium concentration needed to make the reactor relatively insensitive to small fluctuations in concentration, and the dilution with thorium-232 when uranium-235* is being gradually replaced by plutonium-239--are only mentioned.

The heated suspension discharges into tubes at the bottom of the reactor and feeds by gravity into a heat exchanger. From there it enters a sump, from which it is lifted by a gas-lift pump to a gas separator above the reactor. The solid and liquid may be either separated and stored or fed back into the reactor.

A somewhat similar concept is described in a German patent application.[5] This application is chiefly concerned with the composition of the fuel particles, but the first claim suggests that the reactor operates in much the same way as the ORSORT Fluidized Power Reactor or the Homogeneous Dry Suspension Reactor.[3] In other words, the particles flow by gravity through the reaction zone and are transported to and through the heat exchanger by a gas stream (gas-lift pump). The particles, granular and preferably spherical, are between 50 and 300 μ in diameter, preferably about 175 μ. In addition to fissionable material, they contain a "heat-carrier" of low neutron-absorption cross section such as bismuth, magnesium, lead, phosphorus, lithium, zirconium, aluminum, or their compounds, especially oxides. In addition, for a homogeneous thermal reactor, the particles will contain a moderator such as beryllium oxide. A fertile material, such as uranium-238 or thorium, may also be included. Fast reactors with no moderator in the particles are also possible. Besides metallic systems, oxide or carbide systems may be used--e.g., uranium dioxide, beryllium oxide, and thorium oxide and an oxide heat carrier with a beryllium oxide reflector; or uranium carbide, beryllium carbide, thorium carbide with a carbide heat carrier and a graphite reflector. The only limitation is that the substances must not react chemically. The particles may be spongy (prepared by partial sintering) to permit easy removal of fission products.

BNL Chemonuclear Reactor

Steinberg *et al* have proposed several designs for nuclear reactors to promote chemical reactions (chemonuclear reactors). They are intended to utilize the large amounts of energy released in a reactor through fission fragments. One such reactor, which is a fluidized reactor, is used to

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*Author's statement in reference. Presumably, it should be U^{233}.

synthesize nitrogen tetroxide from nitrogen and oxygen.[6,7] The fuel is U_3O_8 as a dust, which is fluidized by the mixture of reactant gases. The gases carry the dust into the spherical reactor, which is surrounded by a reflector-moderator of graphite. After leaving the reactor the dust and gases pass through cyclones to remove the bulk of the dust, which is refluidized and returned to the reactor, and through heat exchangers. The cooled gas is also recycled to the reactor. A fraction of the gas is treated in cyclones to remove the remaining dust, and the product is separated by condensation. Some of the features that need study are: erosion by the dust, dynamic instability of circulating dust systems, possible difficulties in control, and high costs. 700 Mw(t) of by-product power is produced.

D A T A S H E E T S

FLUIDIZED REACTORS AND MOVING-BED REACTORS

No. 1 Fluidized Solids U-233 Power Breeder Reactor

ORSORT

Reference: CF-54-1-81.

Originators: R. R. Halik, L. H. Beckberger, J. M. Haibeck, J. E. Mealia, W. A. Northrop, D. R. Rees, and W. A. Robba.

Status: Conceptual design; term paper, 1957.

Details: Thermal neutrons, steady state, breeder (calculated breeding gain about 0.2). Fuel-moderator: graphite (60-μ particles) impregnated with U^{233}. About 47 kg of U^{233} are in the core and 58 kg outside. Fuel-moderator particles flow at practically settled-bed density into core, where they are heated to 2000°F by the fission reaction. In core exit plenum they are fluidized by stream of argon and lifted into the heat exchanger. Gas and solids are separated in cyclones, and solids flow into a reservoir that surrounds heat exchanger, thence into the core to complete the cycle. The solids are calculated to flow at 25 short tons/min and have a core holdup time of 30 sec. The core radius is 5.25 ft, the core vessel is graphite, and the blanket is 3.33 ft thick. The blanket contains thorium carbide-graphite as 200-μ particles; during operation the blanket contains an average of 100 kg of U^{233}. The blanket operates at 2000°F also, and has a separate circulating system and a heat exchanger that acts as a preheater for the main heat exchanger. Control: thorium plates in the blanket, U^{233} concentration in the core, blanket density (varied by varying gas velocity through fluidized bed), and blanket dumping (scram). The core can also be dumped. Design power: core, 225 Mw(t); blanket, 25 Mw(t).

Code: 0312 12 2112 45 5742 776 84779 941 101

No. 2 Homogeneous Dry Suspension Reactor

FOM-KEMA

Reference: Proc. 1st U.N. Int. Conf. on Peaceful Uses of Atomic Energy, 3, pp. 121-122.

Originators: H. de Bruyn, B. L. A. v.d. Schee, and J. J. Went.

Status: Conceptual design, 1955.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: $BeO-UO_2$ in 200-250-μ "compound grains" (Be/U ratio of about 120). About 0.9 tons UO_2 (about 6% U^{235}) are used in reactor; 2.9 tons in heat exchanger without superheater. Reflector: 70 cm BeO. Grains at a volume density of 70-75% move down by gravity through reactor vessel and are let off through holes in the bottom. Grains are transferred pneumatically to a heat exchanger in which the bed of compound grains is fluidized by a stream of helium. Gas velocity is adjusted to produce a boiling bed of volume density about 35% (attrition must be minimized). For a 300-Mw(t) power reactor operating at a maximum grain temperature of 1200°C in the core and 700°C in the heat exchanger, a vessel size of 1.85 meters diameter by 1.85 meters high was calculated.

Code: 0311 15 2112 42 5732 773 84779 921 101

No. 3 Homogeneous Liquid Medium Suspension Reactor

FOM-KEMA

Reference: Nuclear Engineering, Part II, Chemical Engineering Progress Symposium Series, 50, No. 12, AIChE, N.Y., 1954, pp. 122-123.

Originators: J. J. Went and H. de Bruyn.

Status: Conceptual design, 1954.

Details: Thermal neutrons, steady state, converter. Fuel-moderator: suspension of natural (or slightly enriched) uranium as UO_2 (10 μ particles) in D_2O. Suspension is homogenized in chamber above reactor core, separated from the latter by vertical partitions that suppress horizontal movement of the suspension. Suspension and D_2O move downward through the reactor and feed by gravity into a heat exchanger below it. Mixture discharges to a sump, whence it is raised by a gas-lift pump to a gas separator above the reactor. Solid and liquid may be separated and stored or fed back to the reactor.

Code: 0311	14	31302	41	635	752	84779	921	101
			42		753			

No. 4 Particulate Fueled Reactor with Fuel Granules Containing Heat Carrier (Homogeneous)

Stichting Reactor Center

Reference: German Patent Application No. 1033809.

Originator: W. J. D. van Dijck.

Status: German patent application, July 10, 1958.

Details: Thermal neutrons, steady state, converter--might also be used as a burner, breeder, or fast reactor. Most-distinctive feature is inclusion of a "heat carrier" in the fuel granules. This carrier may be any one of a series of metals or their compounds, particularly oxides or carbides, with a low neutron-absorption cross section. Suggested are Bi, Mg, Pb, Li, Zr, Al, or their compounds. For a homogeneous thermal reactor a moderator material is also incorporated in the particles. A fertile material may also be included. Besides metals, oxides and carbides may be used. Examples of the latter are UO_2, BeO, ThO_2 with a BeO reflector, and uranium carbide, beryllium carbide, and thorium carbide with a graphite reflector. The granular particles are preferably spherical, between 50 and 300 μ diameter (preferably about 175 μ). They may be spongy (partially sintered) to permit easy removal of fission products. In the reactor the particles move by gravity through the reaction zone and are moved to and through the heat exchanger by a gas stream (gas-lift pump).

Code:									
	0311	15	2111	47	5712	727	8XXXX	921	101
			2112		5732				
					5742				

No. 5 Dust-Fueled, Externally Moderated, Chemonuclear Reactor

BNL

Reference: BNL-602 (T-175); Meyer Steinberg, "Chemonuclear Reactors and Chemical Processing," unpublished report, BNL, Jan. 31, 1962, pp. 44-45.

Originator: Meyer Steinberg.

Status: Preliminary design, 1962.

Details: Thermal neutrons, steady-state, converter. Fuel: dust particles (5 μ) of U_3O_8 (93.5% enriched). Critical mass of fuel: 43 kg. External moderator: graphite reflector, 2-1/2 ft thick, clad with stainless steel or silicon carbide. Coolant-fluidizing agent: mixture of reactant gases, nitrogen and oxygen. Reactor: spherical stainless-steel vessel, 8 ft 10 in. diameter, within outer vessel, 14.6 ft diameter. Reactant gases carry fuel dust into reactor vessel. The dust is carried out of the reactor with the gas for heat exchange and for separating the dust and the product, N_2O_4. Gases and dust are recycled to the reactor; a portion of gases, after dust removal, is recycled to cool the walls of the reactor vessel. The bulk of the dust is separated in cyclones, fluidized, and returned to the reactor. In a second stage, the gases pass through a heat-exchange system. In the third stage, a 5% fraction of the gas is removed, the remaining dust is separated from it, and the product is condensed. Control: poison rods in moderator-reflector. Power: 700 Mw(t).

Code: 0313 11 31719 44 693 711 8121X 921 104

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3. H. de Bruyn, B. L. A. v.d. Schee, and J. J. Went, "A 'Dry' Suspension of Uranium Oxide for a Heterogeneous Power Reactor," Proc. 1st U.N. Conf. on Peaceful Uses of Atomic Energy, 3, pp. 121-122, United Nations, N.Y., 1956.
4. Ref. 1, pp. 122-123.
5. W. J. D. van Dijck, "A Nuclear Reactor and a Method for Operating Nuclear Reactors," German Patent Application No. 1033809, July 10, 1958.
6. Meyer Steinberg, J. R. Powell, and Leon Green, "A Review of the Utilization of Fission Fragment Energy for the Fixation of Nitrogen," BNL-602 (T-175), BNL, Jan. 17, 1961.
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Chapter 6 Paste-Fuel Reactors

According to the Reactor Classification System (Appendix B), a "paste" is a two-phase mixture of small, usually spherical, particles dispersed in a liquid at approximately the settled value of 60% by volume of solids. These two-phase fuel systems are thus distinguished from slurries, in which particles are dispersed in a liquid by fluid-dynamic forces. Although stiff and viscous, such a paste will flow slowly under gravitational forces. Thus, if the solid particles are fuel or fuel-moderator material and the liquid is a reactor coolant, a paste-fuel reactor can be designed. A paste-fuel reactor could also be termed a "moving-settled-bed reactor."

One reactor described in another chapter, fits this definition, although it was not designated a paste-fuel reactor by its originators. The "Heterogeneous Liquid Medium Suspension Reactor" of the Netherlands FOM-KEMA Reactor Development Group (see Chapter 7, Reference 25) uses a fully settled suspension of uranium oxide in heavy water as a fuel. This reactor, however, was treated as a reactor with particulate fuel elements because of its core design--a plurality of tubes containing the settled suspension fuel in a tank of heavy water. It will be compared with the paste-fuel reactors described in this chapter.

APDA Concepts

Atomic Power Development Associates, Inc. (APDA) has been investigating the paste-fuel concept since 1955.[1] The reactor design evolved from the interest in "a liquid-metal-cooled, fast neutron, breeder reactor, employing a high burnup fuel, with low inventory and minimum fuel and blanket fabrication" to give low-cost nuclear power. The reactor should use mobile fuels and blankets that would move continuously into and out of the reactor during full-power operation and would be reprocessed and fabricated on the site in an integrated facility. The core should be internally cooled by a separate cooling system because transporting the mobile fuel through an external heat exchanger to remove all of the reactor heat would result in prohibitively large fuel inventories. Consideration of these various requirements led to the concept of using pastes for the fuel and blanket material. Aside from the core itself, the major components of the paste-fueled reactor power plant are almost identical with the corresponding components of existing solid-fueled fast reactors, and they are arranged similarly. Thus, the major problems in development concern the core and the fuel and blanket material.

In one conceptual design of a paste-fuel reactor, the fuel and blanket consist of small spherical particles, containing fissionable or fertile material, settled in a liquid metal.[1] The concentration of solids in the paste is maintained at the settled density of approximately 60 percent by volume of solids, irrespective of paste movement. A dilute slurry of fuel particles in liquid metal is fed to a cyclone separator at the top of the core. Concentrated paste from the separator is introduced into the top of each fuel subassembly and flows slowly down through the small passages formed by the spacing between the coolant tubes. In an alternative arrangement, paste is in the tubes and coolant is in the surrounding space. The bottom portion of each subassembly is conical. Paste flows through orifices in this portion into an eductor. Carrier liquid (sodium), which is introduced into a central pipe in each subassembly connected to the eductor, dilutes the paste and fluidizes the particles, which are then carried out to the processing cell adjacent to the reactor vessel. A portion of the fuel particles is reprocessed. Oversized particles, which might result from the sintering of several particles or swelling under irradiation, are screened out. The remaining fuel particles, together with fresh particles, return in a slurry to the reactor vessel and to the cyclone separator, completing the circuit. Sodium coolant is introduced at the bottom of the core and flows upward through the coolant tubes.

This system is distinguished by several features, which, according to the originators, appear to have overcome the principal technological obstacles that have impeded the successful development of other mobile-fueled reactors. Most notable are:

a. Fuel is not used to transport heat from the reactor. Thus, small volumes of fuel can be moved external to the reactor--as well as in the reactor--at very low velocities.

b. The use of a noncorrosive liquid metal, like sodium, to transport the fuel and blanket particles largely eliminates problems of container corrosion and mass transport.

c. The low velocities of the fuel minimize the erosion of containers by the particles and breakdown of particles by attrition.

d. Loss of pumping power does not affect fuel concentration in the dynamically stable paste-fuel system, in which fuel particles are at settled density in the reactor core.

The paste-fuel system is claimed to have several advantages when compared with static bed systems, in which no throughput of fuel is involved. A paste-fuel system allows homogenized burnup and breeding by the continuous removal of fission gases. These features should allow higher mean burnups and breeding ratios than other systems. Further, clogging of the bed by fission gases should cause less difficulty in the paste-fuel system, because only the gases released in a single pass through the core are of concern.

According to the APDA workers, the paste-fuel concept retains all the advantages expected of mobile-fueled reactors over conventional solid-fuel systems. These advantages include: increased resistance of fuel to irradiation damage and dimensional change; easier fabrication of fuel and blanket; simplified loading and unloading of reactor, which can be a continuous on-site operation; and simplification and improvement in performance of some nonfuel portions of the reactor complex.

As the design of a core structure depends upon the flow characteristics of pastes under various conditions, an analytical and research program is under way.[1,2] The effect of evolution of fission gas on paste circulation may be a problem.[3]

Los Alamos Concept

The Los Alamos Scientific Laboratory has also considered paste-fuel reactors in connection with studies of mobile-fuel fast plutonium breeders.[4,5,6] The fuel-circulation cycle is very similar to that proposed by APDA,[1] but the fuel is a paste of uranium dioxide and plutonium dioxide in sodium.

KEMA Reactor

The fuel-circulation cycle of the paste-fuel reactors is very much like that of the "Heterogeneous Liquid Medium Suspension Reactor" of the Netherlands FOM-KEMA Reactor Development Group (Chapter 7). In all of these concepts a fully settled suspension of fuel particles in liquid moves slowly down the fuel passages under the force of gravity, is diluted just below the core by a stream of the pure liquid, and is raised--as a dilute suspension or slurry--by a gas lift or slurry-circulating pump to the top of the core. Here the suspension is concentrated to the fully settled condition by a cyclone or hydroclone.

However, the reactor of the Netherlands Group and the paste-fuel reactors differ significantly in two ways. First, the Netherlands reactor is a thermal reactor and uses heavy water as a moderator between the fuel tubes and as a suspension medium for the fuel. On the other hand, the paste-fuel reactors are fast reactors, use no moderator, and employ sodium as the coolant and suspension medium. Thus the reactors differ because of the difference in hydrodynamic and heat-transfer properties between heavy water and sodium. Secondly, in the Netherlands reactor the heavy water does not function as a coolant--the fuel tubes are thermally insulated from the moderator in the tank. Heat is transferred by the settled suspension, which, after dilution, flows through the heat exchanger. In the paste-fuel reactor the sodium coolant flows upward through tubes spaced throughout the paste; because of its excellent heat-transfer properties, and because of its use as the suspension medium, the temperature difference between paste and coolant is lowered. The sodium alone flows through the heat exchanger. Furthermore, the sodium coolant can circulate at a high velocity, thus increasing the rate of heat transfer, and the slow movement of the paste in the opposite direction is no disadvantage.

Evaluation and Status

A study of cost and parameter optimization on a paste-fueled reactor was carried out by Zetterbaum and Kerlin of Atomics International.[7] The reference design was an unmoderated sodium-cooled reactor with a paste fuel of uranium monocarbide in sodium. The core was surrounded by an 18-inch radial breeding blanket containing uranium monocarbide and sodium, which in turn was surrounded by an 18-inch-thick graphite reflector. The study showed that a high fuel-volume fraction was desirable because of the cost. The blanket composition affected the breeding ratio only; to increase this ratio, a high volume fraction of fertile material was desirable. Metallic fuel (uranium or uranium-plutonium) has better nuclear properties--higher density--but uranium carbide has better physical properties. Tin or lead could replace sodium with only a very slight change in the nuclear properties. A large reactor--704 Mw(t); 300 Mw(e)--was visualized.

An agreement of association has been concluded between Italy's National Committee on Nuclear Energy (CNEN) and Euratom for the preliminary development of the RAPTUS (Fast Thorium-Uranium-Sodium) fast-reactor concept. In this reactor, a paste fuel would be used. The agreement is for 3-1/2 years.[8] The fuel for the sodium-cooled reactor would be a paste of uranium-233 and thorium oxide in sodium, and the core is similar to those of APDA. It would consist of several subassemblies resembling tube-type heat exchangers. The sodium coolant flows through the tubes and the paste fuel is held in the containing shell. CNEN believes that this approach may ultimately lead to design of a practical power reactor having such advantages as very high burnup and low costs of fuel manufacture. The schedule includes solving basic questions of feasibility by 1965 and experimental testing of the design by 1967. Financing difficulties and the need for appreciable amounts of uranium-233, which is not readily available, may hinder this development program.

The few paste-fuel concepts developed to date and the present early stages of such developments show that considerably more work probably will be required before the paste-fuel concept can be considered for commercial development.

D A T A   S H E E T S

PASTE-FUEL REACTORS

No. 1 Paste-Fuel Reactor

Atomic Power Development Associates, Inc. (APDA)

Reference: APDA-143, pp. 166-178.

Originators: W. G. Blessing *et al*.

Status: Conceptual design, 1955. Research and development proceeding.

Details: Fast neutrons, steady state, breeder. Fuel: paste (fully settled suspension, 60% by volume of solids) of UO_2 in Na. Core contains tubes. Coolant: Na. Coolant flows upward through tubes at high velocity; paste fuel flows very slowly downward in spaces between tubes. At bottom of core, stream of Na dilutes paste to a slurry, which is raised by the liquid stream to top of reactor, where slurry is again concentrated to paste by hydroclone. Core is surrounded by radial blanket with tubes and paste arranged in manner similar to core.

Code: 0112 11 31413 43 646 755 8XXXX 931 108

No. 2 Paste-Fuel Reactor

LASL

Reference: Proceedings 1957 Fast Reactor Information Meeting.

Originator: R. P. Hammond.

Status: Concept, 1961. Research and development proceeding.

Details: Fast neutrons, steady state, breeder. Same fuel-circulation cycle as APDA Paste-Fuel Reactor (No. 1). Fuel: paste of UO_2 and PuO_2 in Na. Blanket is same structure as core. Coolant: Na. Coolant flow: 3000 gpm; paste-flow: 2 gpm. Core is hexagonal, surrounded by hexagonal blanket. Both core and blanket are made up of vertical tubes of elongated rectangular cross section, like thin slabs, parallel to faces of hexagon. Power: 600 Mw(t) with 3-ft core for large reactor design (ascribed to APDA).

Code: 0112 11 31413 47 646 755 8XXXX 931 108

No. 3 Paste-Fuel Reactor

Atomics International, a Division of North American Aviation, Inc.

Reference: NAA-SR-MEMO-5996.

Originators: J. M. Zetterbaum and T. W. Kerlin.

Status: Study of cost and parameter optimization, 1960.

Details: Fast neutrons, steady state, breeder. Fuel: paste of UC (50%) in Na. Coolant: Na. Core: cylinder, 5 ft diameter by 5 ft high. Core volume fractions: fuel paste, 0.4; Na coolant 0.45; structure (stainless steel) 0.15. Fertile material: 18-inch-thick radial blanket of UC, containing natural uranium (form unspecified) and Na. Radial reflector: graphite, 18 in. thick, surrounding breeding blanket. Design power: 704 Mw(t), 300 Mw(e).

Code: 0112 11 31413 44 646 7X2 8XXXX 941 108

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Chapter 7 Reactors with Particulate Fuel Elements

In the concepts described in the preceding chapters, the reactor cores are relatively homogeneous toward neutrons, i.e., they do not contain well-defined zones or regions characterized as fuel and moderator zones respectively. The fuel or fuel-moderator is particulate, of fineness from microns to more than one half an inch in diameter.

However, there are other reactors with particulate fuel disposed in a well-defined moderator structure. The fuel may be in holes or tubes in the moderator, the fuel and moderator may be in alternate slabs, or the moderator may be in shaped bodies in the fuel. In order not to subdivide our classification too far, we will include in this chapter reactors with "fuel elements" composed of packed beds, fluidized beds, or pastes, as well as those reactors, similar to fluidized or moving-bed reactors, with solid particulate fuel that circulates through tubes or between slabs of moderator material and carries the fission-generated heat to an external heat exchanger. The concepts, except for the earliest, will be discussed under these classifications. In addition, the concepts using granular coolants will be described.

Early Concepts

In the very early days of the Manhattan Project (1942), Zinn suggested cooling the pile by circulating continuous "chains" of uranium-graphite or uranium dioxide-graphite cartridges linked together so that the chains would be flexible. The units were to move at three feet per second and would be cooled outside the pile.[1]

Later in the same year, Wheeler suggested a pile cooled by circulating uranium shot (BB Shot Pile). The pile was to be a large block of graphite and the uranium shot was to be circulated by gravity, presumably from a reservoir at the top of the pile to a container at the bottom. The shot could be returned by an air blast or by buckets.[2-5]

There was some concern about erosion of the graphite by the uranium balls. Simon[4] carried out experiments in which No. 8 steel shot (about 2 mm diameter) was fed from a hopper into a hole, 1-3/8 in. diameter, in a 4 in. by 4 in. by 15 in. graphite block at a rate of about 3/4 cu ft/sq ft/sec. The only effect on the graphite was a very slight polishing effect. No further work, however, seems to have been done.

A related concept proposed by Wheeler resulted in a U. S. patent.[6] In this concept the uranium shot does not circulate, although it can be charged from above or discharged at the bottom of the piles for reprocessing. It is contained in a plurality of pipes that extend through the graphite blocks and serve to hold the blocks together. The reactor core is contained in a gas-tight pressure vessel, and the reactor is cooled with helium.

Another concept in which the reactor is fueled and cooled by particulate solid, is the UO_2 Powder Pile or Low Density UO_2 Pile proposed by Ibser in 1943.[7] In this concept, uranium dioxide powder dispersed in helium is circulated or blown through pipes in a graphite matrix. Criticality calculations were made, but no further work was done on this concept.

A pile using a flowing stream of graphite balls as a coolant was proposed by Daniels in 1947.[8] Based on the description, a patent application was filed November 15, 1950, and U. S. Patent No. 2,910,416 was issued.[9] The reactor is a four-foot cube of graphite surrounded by a one-foot graphite reflector and one foot of insulation. There are 36 channels per square foot in the core and four per square foot in the reflector. Alternate core channels are for heating and for cooling. In the heating channels, the balls are impregnated with uranium and move very slowly, only fast enough for reprocessing. As described in the patent, the fuel balls do not move continuously but are charged and discharged individually. The cooling balls, which are unimpregnated graphite, move more rapidly, being returned by an air blast or elevator buckets. The hot balls transfer their heat to gas for a gas turbine, or alternatively to a boiler and steam turbine. A 12- to 20-Mw device was visualized, with a temperature rise of 500°C across the pile and a maximum temperature of 760–2000°C.

Two modifications of this concept are described in the patent. In one, all of the refractory balls are unfueled, and the fissionable material is contained in the graphite bricks. This modification does not qualify as a particulate-fuel-element reactor and the data sheet is included in another chapter. In another modification, the fissionable material is contained in both the bricks and the fuel balls.

These concepts have a conversion zone between the reactor and the reflector. In one modification described in the patent, the fertile material is contained in balls in the conversion zone; a mechanism is provided for transferring the fertile balls to the reactor core when conversion has proceeded to a sufficient degree.

Packed-Bed Reactors

In 1953, students in the Oak Ridge School of Reactor Technology described a Uranium Pellet Power Reactor, a sodium-cooled thermal reactor.[10] The reactor core is a cylinder (radius 5.7 ft, height 10 ft) surrounded by a 9 in. reflector and a 3/4-in. steel core tank. The reactor core is made up of high-density beryllium blocks of hexagonal cross section. Each block is compound: an inner hexagonal block with a central hole is disposed within an outer hexagonal block. The inner block is approximately 3-3/4 in. across flats, the outer, 5-3/4 in. The hole in the inner block is approximately 2-3/8 in. in diameter and the inner surface has 24 narrow axial slots. In the center of this hole is a stainless-steel tube made of screening wrapped around crossed ribs for stiffening. The tube is approximately 0.8 in. in diameter, and the annulus between it and the inner surface of the block is filled with 3/16-in. pellets of uranium dioxide. Sodium flows upward through the tube, the pellet bed, and the slots, but the flow is controlled in six regions by modifying the tube and slots so as to decrease the flow rate from the center to the outside of the core. The purpose is to make the temperature drop uniform across the core. This concept was for a large reactor, 356 Mw(t), 120 Mw(e).

Glass fibers containing uranium or plutonium were suggested by Harteck, Dondes, and Michener[11] in 1956 as fuels or fertile material for reactors. Some of the advantages they listed are: better heat transfer than other fuels, stability under irradiation, greater efficiency of utilization of recoil energies than with fine powders, high tensile strength, resistance to corrosion, ease of manufacture, and simple reprocessing.

Glasses with softening points approaching 1000°C and with uranium contents up to 30 percent of fissionable material are claimed to be possible. The glass fuel can be also made into rods, tubes, batting, tape, or cloth. The authors suggested making a plate fuel element by incorporating glass fibers of high melting point (1000°C) into the interior of aluminum fuel elements. The glass fuels can be made with no special difficulties. Tests made on glass containing about 10 percent U_3O_8 demonstrated that the fibers had good stability under irradiation, high utilization of recoil energy, and good tensile strength under irradiation.

Among the general application suggested for glass fuels were reactors for chemical conversion. Some such reactors have particulate fuel elements.

A chemonuclear reactor utilizing glass fibers as fuel has been proposed by Lellouche and Steinberg at Brookhaven.[12] The fibers containing enriched U_3O_8 are held in cylindrical metal cages, which are set in vertical channels within a graphite moderator. Each channel contains 56 fuel assemblies set one above another. An annular space allows the coolant gas, air, to pass through. The process gas, also air, passes through the fuel assemblies and out of the reactor. Most of it is recycled, and the remainder is treated to remove fission products and to separate the acids formed by the chemonuclear reaction. The coolant air, after leaving the reactor, is used as a source of steam for power. The reactor produces 147 Mw(t), 40 Mw(e).

A concept for a design for a settled-bed heterogeneous reactor in which fuel pellets could be charged and discharged during operation was proposed in 1960 by Barnard.[13] Advantages of refueling under load include less weight and volume because of lower inventory of idle fuel, ease and speed of refueling, and reduction of excess reactivity. In the reactor concept described, spheres of uranium metal, 0.25–0.75 in. diameter, are held within vertically aligned tubes separated vertically into zones. Two streams of organic coolant are used. One flows downward inside the tubes in annuli between the pellets and the inner wall of the tubes. The other flows outside the tubes across the core radially from the core periphery. The use of two streams should have such advantages as more precise control and greater safety. Exhausted fuel particles are discharged from the bottom of the reactor by removing stops to allow the lowest fuel units to drop out. New pellets are added at the top. The process can be more or less continuous.

A packed-bed fuel element for a gas-cooled reactor was described by Ristić and Zarić.[14] The fuel element consists of a packed-bed core about 10 cm in diameter in the center of a cylindrical tube. The core is made up of individual ceramic spheres or pellets (of uranium oxide or carbide) each about 1 cm in diameter. The cooling gas flows mainly through the annular space between the packed-bed core and the wall and partly through the core itself. There is no partition between the annular space and the core; the stability of the central column is secured, for example, by axial fins inside the tube.

Heat-transfer calculations show that the thermal conductivity of the packed bed is several times greater than that of a solid ceramic because of the high turbulence of the gas flowing in the core. Also the heat generated in the core is transferred directly to the main body of gas in the annulus, further improving the radial heat transfer coefficient.

No complete reactor based on this fuel element was designed.

We have classified two reactors, described by a group at Brookhaven,[15-17] as particulate fuel-element reactors, although the "elements" are really regions of fuel between blocks or slabs of moderator.

The first of these is the UO_2-Sodium-Graphite Thermal Reactor. In this reactor there are hexagonal moderator logs of graphite (7 in. across flats) located in a 10 ft diameter by 10 ft high settled fuel bed of uranium dioxide in sodium. The 217 graphite moderator logs are spaced approximately 0.6 in. between flats, and have two sets of cladding, the inner cladding flat and tight against the graphite, and the outer cladding vertically corrugated. The outer cladding is spot welded to the inner cladding on vertical centers. Sodium coolant flows in the corrugated channels between the inner and outer cladding. The granular fuel, 75-100 μ particles of uranium dioxide in sodium, is charged in the fluidized condition and allowed to form a settled bed between the moderator logs. The fuel is thus a single continuous region and the structure may be described as moderator-coolant or moderator-heat-exchanger elements, so that the ordinary relation of fuel and moderator is reversed. This concept is designed as an 850 Mw(t) reactor.

The other reactor is the U^{233}-Li^7-BeO Thermal Breeder Reactor. This reactor, operated on the U^{233}-thorium cycle, is moderated by slabs of beryllium oxide and cooled by lithium-7. The 10 ft by 10 ft reactor core consists of 28 unclad beryllium oxide moderator blocks arranged to form parallel slabs. Coolant U-tubes and fuel occupy the spaces between moderator slabs. As lithium is compatible with beryllium oxide, no cladding is needed. The 100 μ granular fuel is a mixed oxide of uranium-233 and thorium. It is fluidized in lithium-7 for charging and discharging but allowed to form a settled bed during reactor operation. This concept is also designed as a 850 Mw(t) reactor.

Fluidized-Bed and Fluidized Reactors

An early concept in which a fluidized reactor is used with an internal moderator is a design by Murphree. The design was disclosed in a Canadian patent dated 1962 with a U. S. priority date of 1944.[18] The fuel, a 50-100 mesh powder, is preferably uranium metal, although UO_2 or U_3O_8 are also specified. The fuel is fluidized by helium or other gas within tubes surrounded by packed beds of graphite moderator particles. In a modification, heavy or light water surrounds the tube as moderator and is circulated for heat removal. The gaseous suspension leaves the reactor, goes to dust separator, to heat exchangers, and back to the reactor.

Workers at Brookhaven have performed studies on reactors with fluidized or fluidizable fuel elements. In the Fluidized Solids Fueled Reactor,[19] 14-ft-long blocks of zirconium-clad graphite moderator of square cross section are installed vertically in the core 1 in. apart. The fuel is uranium dioxide in particles (75 to 100 μ) fluidized with sodium in the space between the moderator blocks. Zirconium tubes for sodium coolant, between the blocks, cool the fluidized fuel.

An economic study to compare the proposed fluidized-fuel-element reactor with the Hallam Sodium Graphite Reactor was made by a group at Brookhaven.[20,21] According to the authors of the report:

> "for purposes of the evaluation study the design is based on the use of uranium dioxide as a fuel in the form of uniform, and preferably spherical, particles of UO_2, 75 to 100 microns in diameter, fluidized in liquid sodium. The fuel suspension is confined within the annular space between two concentric cylinders suitably joined to form a fuel element of which there is a multiplicity for a reactor core. The reactor is cooled with liquid Na and moderated with graphite. The design power level is 200 Mwt and 80 Mwe.
>
> "The fuel element subassembly consists of a central canned graphite moderator log within a stainless steel tube containing flowing sodium coolant. A second stainless steel tube is disposed outside the first tube, the annulus between being filled with the fluidized fuel. A third stainless steel tube is disposed outside the second tube, the annulus between containing flowing sodium coolant. The fuel element subassemblies are arranged in a

triangular pitch lattice. Spaces between the outer tubes are filled with canned triangular graphite blocks. The design core was 12 ft. diameter by 14 ft.-6 in. high, and contained 52 fuel element subassemblies. Physics and engineering calculations were made as well as technical and economic comparisons with the Hallam Title I design."

A later development of this type is the laminar fluidized-bed reactor of W. A. Robba et al.[22] In it also, the core is a continuous fluidized bed of a suspension of uranium dioxide particles in liquid sodium that fills the spaces between square moderator blocks of graphite. The coolant sodium flows through U-tubes in spaces between the moderator blocks. The laminar, or subturbulent, fluidizing flow is maintained with relatively low rates of flow; in this reactor the nominal rate is 40 gpm. The separate coolant flow permits this low rate of fluidizing flow. The power produced is 300 Mw(e).

The Brookhaven workers have continued the studies on large power reactor systems using particulate fuels. A preliminary evaluation report was written in 1961,[15] but it was not published. A status report was published in 1962.[16] One of the reactors described could be operated either as a fluidized-bed reactor (see Chapter 4) or as a settled-bed reactor (see Chapter 3).

A fluidized-bed reactor was proposed by Kim[23] for synthesizing nitric acid. The reactor vessel resembles a shell-and-tube heat exchanger. The fuel, slightly enriched uranium dioxide as 0.006 in. particles, is fluidized by the reactant gases, nitrogen and oxygen, inside the tubes. Boiling water, the coolant, is on the shell side. The gases enter the tubes, fluidize the fuel, and leave through a manifold at the top. They are processed to remove nitric acid and are recycled to the reactor.

A "Vapor-Slurry Reactor" was suggested by Crowther in 1955.[24] In this fluidized reactor, enriched particles of uranium dioxide are slurried with steam and passed through tubes in the reactor core. The tubes are surrounded by bricks of beryllium oxide moderator. The particles are heated and the steam superheated in the core. Part of the hot slurry is recycled to vaporize incoming water. The steam, after separation of particles in a cyclone, goes to turbines and then to condensers. An advantage of the reactor is that outlet temperatures of the coolant are not limited by pressure, so that turbines designed for high throttle inlet pressure and temperatures can be used.

Two related reactors suggested in the same article are the Cyclone Slurry Reactor and a reactor consisting of a heterogeneous array of screw conveyers that move fuel particles through a critical assembly. In the cyclone reactor, solid fuel particles are whirled at high velocity through the core by a tangential stream of secondary vapor. The particles are thrown to the outside of the core. There they form a rapidly moving dense layer in which fission can occur. This concept would have the advantages of simplicity and high power density. In the reactor with the screw conveyers, the solids are carried to the reactor by gas or vapor and removed from it by the gas to produce power. Thus large quantities of the gas would not flow through the reactor.

In the Heterogeneous Fluidized Uranium Oxide Reactor,[25] described by workers of the Netherlands FOM-KEMA Reactor Development Group, the dry uranium oxide particles

> "move in a vertical direction through tubes placed in a reactor tank containing heavy water. Their movement resembles that of sand in a sandglass. In this way a moving bed or liquid-expanded state is obtained...with the aid of a vibrating cone the oxide particles leaving the reactor are fluidized, and a preheated gas stream transports the particles through the heat exchanger to the cyclones in which a separation of particles and gas is executed."

The reactor tubes are made of nonporous beryllium oxide, insulated with porous BeO.

The Heterogeneous "Dry" Suspension Reactor[26] resembles the Heterogeneous Fluidized Uranium Oxide Reactor, but the engineering design is carried somewhat further, with various numerical values being given for system parameters. The reactor vessel contains graphite fuel tubes in a heavy water moderator and its core is surrounded by a graphite reflector. For a 300-Mw(t) reactor a vessel 3.4 meters by 2.5 meters high is used. The heat exchanger, which is "built around" the reactor, contains boiler and superheater sections, and when filled with uranium oxide, acts as a gamma shield. However, the holdup of uranium oxide is large.

The uranium oxide grains (250 μ in diameter) move downward through the tubes. As the heat conductivity is low, only about 2 percent of the heat is lost to the heavy water. At the bottom of the reactor the hot uranium grains are transferred to a stream of helium, which carries them to the heat exchanger. Inside the heat exchanger the bed of grains is fluidized as a boiling bed (average temperature 700°C). The steam is superheated to 550°C. About 25 tons of uranium dioxide are required inside the reactor and 150 tons in the heat exchanger and piping.

The Flowable Solids Reactor,[27,28] proposed by Oliver et al of the Fluor Corporation, Ltd., resembles the reactors designed by the FOM-KEMA group. However, this reactor uses a graphite moderator with 3-inch fuel channels that have ceramic liners. The fuel, dry crushed fused uranium dioxide in the form of a powder (average particle size 200 μ), flows by gravity down the fuel channels (orificed to control flow). It then cascades over steam generator tubes located in a chamber directly below the reactor. This heat exchanger has horizontal tubes on a triangular pitch with superheater, boiler, and preheater sections. The fuel material is recycled to the top of the reactor core by a mechanical conveyor.

A very different fuel is used in the "Armour Dust Fueled Reactor" of Krukoff et al, but we have classified it as a particulate fuel element reactor because of the core structure.[29-35] A "dust" is defined as a dispersion in a gas of solid particles ranging in size from submicroscopic to macroscopic.[36]

The Armour Dust Fueled Reactor uses an aerosol-type gas suspension of fissionable dust as a reactor fuel. There are two variants--a uranium dioxide fuel dust in carbon dioxide gas with a beryllium oxide moderator (oxide system), and a uranium carbide fuel dust in helium gas with a graphite moderator (carbide system). In both variants the dust particles are 8 to 10 μ in diameter and are blown upward through the reactor core.

In the carbide system the ducts and chambers in contact with the fuel are lined with silicon carbide; in the oxide system the lining is aluminum oxide. The gas suspension of dust circulates through a cyclone--to remove the larger abrasive particles--and a heat exchanger, and it is returned to the system by a blower. A side stream circulates through a system for fission-product cleanup.

An internally cooled core for this reactor has also been considered because the primary loop would be non-radioactive. This would give ease of maintenance and reduced fuel inventory. The core resembles a shell-and-tube heat exchanger, with the gas containing fuel on one side and pure gas on the other. The fuel is circulated at low velocity through the core and the system for fission-product cleanup. The pure gas, which serves as a coolant, is circulated at high velocity through the core and the remainder of the primary loop. The core tubes are constructed of moderator material for high neutron economy. Power density is more limited than for the externally cooled reactor, but, because of the high operating temperatures, it compares very favorably with other gas-cooled reactors.

Reactor physics and engineering calculations have been carried out, and loop experiments have been made, but the reactor concept has not been carried further.

The major potential advantages of the ADFR are stated to be:

a. High temperatures. Temperatures of 2000°-3000°F are stated to be obtainable.

b. Reduced corrosion. The carrier gas comprises more than 99.9 percent of the volume of the fuel. There is little of the dust to cause corrosion or erosion.

c. Low-cost reprocessing. The carrier gas is easily separated from the fuel. Fission gases are absorbed in a charcoal bed. Thus only the fuel and solid fission fragments need to be chemically processed.

d. High neutron economy. There are very few neutron poisons because there are no control rods, no fuel-element matrix, and no cladding or structural material. Breeding seems assured with the $Th\text{-}U^{233}$ cycle.

A dust-fueled chemonuclear reactor was proposed by Steinberg et al.[37,38] The dust consists of highly enriched U_3O_8. The reactor is internally moderated with graphite logs coated with silicon carbide. The dust is carried into the reactor by a mixture of nitrogen and oxygen, which react to form nitrogen dioxide. The gaseous suspension leaves the reactor, where the bulk of the dust is separated, the gases pass through heat exchangers, and a part of the gas is treated to recover product. Both the dust, after being refluidized, and the major portion of the gas, after heat exchange, are recycled to the reactor.

A proposal for an advanced concept was made by W. R. Corliss for a Circulating Dust-Fueled, Radiation-Cooled Space Power Reactor.[39] This scheme is

"in reality a fusion of two well-known concepts, the Armour Dust-Fueled Reactor (ADFR) and the radiation-cooled reactor allied with a shell of direct conversion elements. The resulting synthesis is a circulating dust-fueled system which radiates the energy generated in the fissionable dust to a shell of thermionic converters, where conversion to electricity takes place."

A fuel of UC_2 or PuC dust is proposed to replace the usual heat-transfer liquids and gases with a flowing solid. Moderator and reflector material is graphite, with the dust traveling in cavities or ducts in the graphite. A shell of thermionic converters makes up the walls of the ducts.

The design is stated to be suitable for power plants between 100 kw(e) and 10 Mw(e). Engineering parameters for a 1-Mw(e) design have been given. Technology as of 1980 might be required. The core radius is 3 ft and core length 10 ft. An electrostatic pump is used to circulate the dust, which is electrically charged.

A particulate fuel, one stage finer than "dust," might be called "smoke," and a "Smoke Fueled Reactor" was proposed by Aerojet General Nucleonics in 1959.[40] The reactor was entitled the "Nuclear Nitrogen Fixation Reactor" by its originators, but we have renamed it as above to describe the reactor in terms of its fuel. The reactor system is described in the Appendix to the report. The "smoke" consists of 1-2 μ particles of fully enriched oxides of uranium suspended in the process gas, a 4:1 nitrogen-oxygen mixture at 1000 psi and 200°C. Fission fragments are liberated directly in the process gas as it passes through the reactor core, causing a chemonuclear reaction, which results in the formation of nitrogen dioxide. The core of the reactor is a tank of heavy water and the gas and smoke enter a manifold from which 200 zirconium tubes exit. Each tube makes 16 passes through the reactor and connects to an outlet manifold. About 90 percent of the fuel is recovered unreacted in the separation section outside the reactor. Most of the fission heat is liberated in the heavy water moderator and dumped to a cooling tower.

Paste-Fueled Reactor

The "Heterogeneous" Suspension Reactors,[26] described by members of the Netherlands FOM-KEMA Reactor Development Group, fall within the scope of this chapter, for they have particulate fuel elements.

The Heterogeneous Liquid Medium Suspension Reactor[25] uses a fully settled suspension of uranium oxide in a plurality of tubes in a reactor tank filled with heavy water. Thus it is a type of paste-fueled reactor. The settled suspension is very viscous and moves slowly down the tubes; as it leaves the reactor, it is diluted with heavy water so that it can easily flow through the external heat exchanger just below the reactor. The suspension is lifted to the top of the reactor by a gas lift pump, and concentrated by a cyclone before it again enters the reactor tubes. It is planned to make these tubes of beryllium oxide, an inner nonporous tube surrounded by a porous outer tube for insulation.

Granular Coolants

In 1942, Lewis et al[41] discussed the use of a suspension of graphite powder as a coolant. The suspension would be circulated upward through the pile and then to a heat exchanger. The powder might be separated in a cyclone, and the gas and powder recycled.

Later, Schluderberg and others at Babcock and Wilcox also advocated the use of such suspensions as coolants.[42-44] A typical suspension consists of fine particles of graphite in such gases as nitrogen, helium, or carbon dioxide. Experiments were made in a heat-transfer loop at a fluid velocity of up to 250 ft/sec, a fluid density of up to 10 lb/cu ft, and a maximum temperature and pressure of 1100°F and 140 psig. Adding the graphite improved the heat-transfer properties of the gas. Heat-transfer coefficients of 3000 Btu/(sq ft)(°F)(hr) were obtained with helium-graphite mixtures. Turbulence promoters allowed optimum heat transfer. The increase in heat transfer over that of gases and the possibility of collecting and removing fission gases and other impurities from the coolant system are two of the advantages the authors give for advocating further development of the concept.

Another method of using granular coolants has been suggested by Henglein in a British patent.[45] A reactor and a heat exchanger are mounted within a housing. They are both surrounded by a bed of granular coolant--graphite, silicon carbide, aluminum, or zirconium--and they are separated only by the coolant. The heat exchanger is connected to an engine or turbine. The housing is rotated on its vertical axis by an electric motor to move the particles. The rotation transfers coolant material heated at the reactor to the heat exchanger and moves cooled solids from the heat exchanger to the reactor for cooling and moderating it.

D A T A   S H E E T S

REACTORS WITH PARTICULATE FUEL ELEMENTS

No. 1 Circulating Cartridge Pile

Reference: CE-106.

Originator: W. H. Zinn.

Status: Concept, 1942; no further work.

Details: Thermal neutrons, steady state, converter. Continuous "chains" of uranium-graphite or UO_2-graphite cartridges are circulated through holes in moderator, presumably graphite. Cartridges linked together so that chain is flexible. The cartridges are cooled outside the pile (method unspecified). A speed of about 3 ft/sec was suggested for the circulation.

Code: 0311 12 2112 41 5411 722 8XXXX 921 104
5431

No. 2 BB Shot Pile

References: CC-286, p. 4; CE-300, p. 2.

Originator: J. A. Wheeler.

Status: Concept, 1942; no further work.

Details: Thermal neutrons, steady state, converter. Pile: large block of graphite with vertical channels for fuel. Fuel: BB-size uranium shot, which circulates by gravity from a reservoir at the top of pile to a container at the bottom. Shot can be returned by air blast or buckets. Shot cooled outside pile by unspecified means.

Code: 0311 12 2111 41 5812 722 8XXXX 921 104

No. 3 Non-Circulating Uranium Shot Pile

Reference: U. S. Patent 2,782,158.

Originator: J. A. Wheeler.

Status: Concept, 1942; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: uranium shot (about 1/2 in. diameter). Moderator: graphite. Coolant: helium. Fuel contained in a plurality of pipes with He, which circulates through the shot, in part axially up the tubes and, in part horizontally from parallel supply channels through exhaust channels. Hot helium is pumped through a heat exchanger, and its heat is converted to useful power. Control: a central absorber tube containing variable amounts of Hg; varying inflow of the shot; scram by dumping shot. Reactor contained in a gas-tight pressure vessel. Uranium shot can be charged or discharged by mechanical means. Data given for a 100 Mw(t) reactor 28 ft in diameter by 26 ft high. Uranium carbide shot can be substituted for the uranium shot.

Code: 0311 12 31716 41 5812 722 81155 921 106
5842

No. 4 UO_2 Powder Pile

Reference: CP-445.

Originator: H. W. Ibser.

Status: Concept, 1943; physics calculations; no further work.

Details: Also known as "Low-Density UO_2 Pile." Thermal neutrons, steady state, converter. UO_2 powder dispersed in helium is circulated or blown through pipes in a graphite matrix. No further details.

Code: 0311 12 2112 41 5732 722 8XXXX 921 104

No. 5 Reactor Cooled with Graphite Balls I

References: CL-FD-42; U.S. Patent 2,910,416.

Originator: Farrington Daniels.

Status: Conceptual design, 1947; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: uranium. Moderator: graphite. Reactor is 4 ft cube of graphite, with 1 ft graphite reflector and 1 ft insulation between reflector and shield. There are 36 channels per sq ft in the core and 4 per sq ft in the reflector, or as described in the patent, in a conversion zone between the core and reflector. In the core, alternate channels contain uranium-impregnated graphite balls and unfueled balls. In the conversion zone, alternate channels contain balls impregnated with fertile material and unimpregnated balls. The unloaded graphite balls circulate rapidly by gravity and are returned by an air blast. Outside the reactor they exchange heat with a working fluid to drive a gas or steam turbine and produce power. The fueled balls are discharged one at a time for reprocessing; the fertile balls, when sufficiently converted, are charged one at a time into fuel channels.

Code: 0311 12 2112 41 5242 722 81111 941 104

No. 6 Reactor Cooled with Graphite Balls II

Reference: U. S. Patent 2,910,416.

Originator: Farrington Daniels.

Status: Conceptual design, 1947; no further work.

Details: Same as Reactor Cooled with Graphite Balls I, except that a portion only of the fuel is contained in impregnated graphite balls. A portion is also contained in the graphite moderator blocks.

Code: 0311 12 2112 41 5142 722 81111 941 105

No. 7 Uranium Pellet Power Reactor

ORSORT

Reference: CF-53-10-24 (Rev.), Sept. 1, 1953.

Originators: H. W. Graves, Jr., J. P. Burelbach, R. J. Campana, H. W. Giesler, R. J. Gimera, R. Gulino, C. S. Sorkin, and P. W. Vineberg.

Status: Reactor design and feasibility problem in ORSORT term paper, 1953.

Details: Thermal neutrons, steady state, converter. Fuel: UO_2 pellets. Moderator: BeO. Coolant: Na. Chief distinguishing feature is design of moderator-fuel block: two hollow hexagonal high-density BeO blocks, an inner block and an outer block. Inner block has central cylindrical hole surrounded by axial slots. In center of hole is tube made of stainless-steel screen. Annulus between tube and inner block is filled with 3/16-in. UO_2 pellets. Na coolant flows upward through the tube, the pellets and slots; there is also some cross-flow. Coolant flow is controlled in six regions by modifying the tubes and slots; the purpose is to equalize the temperature drop across the reactor.

Code: 0311 15 31103 42 5832 732 8111X 921 106

No. 8 Filament-Fueled Dual-Purpose Chemonuclear Reactor

BNL

References: BNL-574(T-157), pp. 12 ff.

Originators: G. Lellouche and Meyer Steinberg.

Status: Proposed design, 1962.

Details: Thermal neutrons, steady state, converter. Fuel: U_3O_8 (partially enriched) in 1 μ glass fibers containing 50 wt.% uranium. Moderator: graphite blocks. Coolant: air. Reactor contained in gas-tight shell within a biological shield. Fuel assemblies consist of fiber fuel inside cylindrical aluminum-alloy cages, 1 in. diameter, 6 in. long. Fuel assemblies are in channels in graphite moderator. Each fuel channel, which contains 56 fuel assemblies, is surrounded by an outer tube to form an annulus, through which coolant flows. Each double-tube assembly is set in a graphite block, 4 in. by 4 in. by 32 ft. Core contains 1000 such unit cells. Reflector: 2 ft of graphite surrounding core. Process gas (dried air) goes to fuel channels by subheaders connected to four main headers. Coolant gas likewise enters coolant channels from headers. Coolant enters at 779°F and leaves at 800°F. Working pressure: 1000 psi. About 90% of process gas is recycled. Remainder is treated to remove fission products and to separate acid product. Glass-fiber fuel retains many of the non-volatile fission products. Coolant air goes to heat exchangers to produce steam for turbogenerators, and the cooled air is recycled to the reactor coolant system. Steam produced at 650°F and 800 psi (design). Power: 147 Mw(t), 40 Mw(e).

Code: 0311 12 31714 43 5532 724 8XXXX 921 106

No. 9 Reactor With Dropping Fuel Balls

Naval Research Establishment, Canada

Reference: NRE Report 60/4

Originator: K. N. Barnard

Status: Preliminary study, 1960.

Details: Thermal neutrons, steady state, converter. Fuel: spheres, 0.25-0.75 in. diameter, of uranium metal of about 2% enrichment. Spheres are held within vertically aligned tubes separated vertically into zones. Smaller spheres, because of higher volume ratio of moderator to fuel, permit use of lower enrichment. Coolant-moderator: Santowax R or other organic liquid, in two streams. The main flow is downward, inside tubes, in annuli between pellets and inner walls of the tubes. The other flow is outside the tubes, across the core radially from the core periphery. Two coolant streams should give more-precise temperature control and greater safety. The external coolant could be a high-viscosity material, such as a polymer, because less of it has to be pumped. Such a polymer should have a high hydrogen content for improved moderation. Average bulk temperature of coolant in core: 380°C. Spheres were suggested as a method for refueling under load in a more or less continuous stream, with such advantages as time savings, reduced inventory of idle fuel, and decreased excess reactivity. Fuel particles are discharged from the bottom as they become depleted, by removing stops to allow the lowest fuel units to drop from the bottom. Reactor vessel: probably spherical; base plate supports tubes containing fuel; upper plate holds upper ends of tubes in place; three horizontal spacing plates; thermal shield outside core reflector space. Control: rods or spherical boron-steel units. Power: 80 Mw(t).

Code: 0311 16 31108 42 5812 723 81X11 921 103
81X61

No. 10 Packed-Bed Fuel Assembly for a Gas-Cooled Heterogeneous Reactor

Institute of Nuclear Sciences, Boris Kidrič

Reference: Proc. 2nd U. N. Int. Conf. 7, pp. 746-747.

Originators: Milorad Ristić, and Zoran Zarić.

Status: Concept, 1958.

Details: Presumably thermal reactor, steady state, converter. No complete reactor was designed but only fuel subassembly described. Fuel subassembly or element has a packed-bed core about 10 cm in diameter in center of cylindrical tube. Core made up of individual ceramic spheres or pellets of uranium oxide or carbide about 1 cm in diameter. Cooling gas flows mainly through annular space between packed bed core and wall but partly through core itself. No partition between annular space and core. Column stability obtained by mechanical means, e.g., fins inside of tube. This design greatly increases thermal conductivity of packed bed as compared with solid ceramic. Radial heat transfer coefficient also improved.

Code:	0311	1X	317XX	4X	5832	7XX	8XXXX	9XX	106
					5842				109

No. 11 Uranium Oxide-Sodium-Graphite Thermal Reactor

BNL

References: Unpublished report, BNL-5372; BNL-713; BNL-5830.

Originators: L. P. Hatch, W. H. Reagan, J. R. Powell, L. Green, and W. A. Robba. Mechanical design of the reactor by M. N. Kushner, Richard Capello and Wilson Gartland, Burns and Roe, Inc.

Status: Conceptual design, 1961.

Details: Thermal neutrons, steady state, converter. Fuel: UO_2, enriched to 3.9 or 8.3% depending on graphite cladding, as 75-100 μ particles suspended in Na. Moderator: graphite. Coolant: Na. Moderator is in form of 217 hexagonal logs (7 in. across flats) arranged in hexagonal pattern and located in settled beds of fuel-Na suspension. Logs are spaced 0.6 in. between flats and have inner and outer cladding, the inner flat and the outer corrugated. Cladding may be stainless steel or Zr. Inlet coolant Na flows from bottom upward through tubes formed by the log corrugations into outlet plenum at top. Fuel is charged or discharged in fluidized condition. Fuel phase is continuous and moderator-coolant elements may be said to be suspended in fuel, reversing the usual arrangement of heterogeneous reactors. Reflector: two ft of graphite at sides and top; BeO at bottom. Control: 25 control rods in lattice for shim and dynamic control and for scram. Power: 850 Mw(t).

Code: 0311 12 31103 42 653 723 8111X 921 106

No. 12 Uranium-233--Lithium-7--Beryllium Oxide Thermal Breeder

BNL

References: Unpublished report, BNL-5372; BNL-713; BNL-5830.

Originators: L. P. Hatch, W. H. Regan, J. R. Powell, L. Green, and W. A. Robba.

Status: Conceptual design, 1961.

Details: Thermal neutrons, steady state, breeder. Fuel: UO_2-ThO_2 mixture, as 100 μ particles suspended in Na to form settled bed that is fluidized for charging or discharging. Coolant: lithium-7. Moderator: BeO. Core structure: 28 unclad BeO slabs, 5 ft by 12 ft by 7.2 in., arranged to form 14 parallel fuel channels. 4700 zirconium-alloy U-tubes, through which Li^7 flows, between moderator slabs remove heat. Inlet lithium at 521°F; outlet at 1050°F. Fuel in 1.5-ft spaces between moderator slabs and coolant tubes. Reflector: top and bottom. Control: 14 control-rod thimbles, each in center of alternate moderator slabs. Maximum calculated breeding ratio: 1.074. Power: 850 Mw(t). Physics calculations based on three cases: (a) fuel, 70% UO_2-ThO_2, 30% BeO; (b) fuel, UO_2-ThO_2; (c) fuel, UO_2-ThO_2, fuel channel approximately twice as wide as in case (b). Case (b) gives the highest breeding ratio, but a higher percentage and inventory of fissionable material is required.

Code: 0312 15 31106 45 653 726 811XX 921 106

No. 13 Internally Moderated Fluidized Reactor

Reference: Canadian Patent 643,479.

Originator: E. V. Murphree.

Status: Design, 1944.

Details: Thermal neutrons, steady state, converter. Fuel: uranium metal (preferred), UO_2 or U_3O_8, enriched to a maximum of 50% U^{235}, as a 50-200-mesh powder suspended in helium or other gas. Moderator: graphite in packed bed, 3-10 in. thick, surrounding tubes through which the fuel flows. In an alternative, D_2O or H_2O surrounds the tubes and is circulated for heat removal. Coolant: fluidizing gas. Reactor vessel: vertical cylinder, dished at top, cone-shaped at bottom. Fuel tubes, surrounded by moderator, run vertically in reactor. Top of reactor is connected by a duct to a cyclone dust separator. In one example, the fluidized fuel enters the bottom of the reactor, passes upward through the tubes, passes from the reactor to the dust separator, to a heat exchanger and back to the reactor. Control: stopping the flow of fluidizing gas; boron-containing rods moving vertically.

Code: 0311 12 31716 43 681 764 81111 9X 106
683 83779

No. 14 Fluidized Solids Fueled Reactor

BNL

Reference: BNL-595.

Originators: L. P. Hatch, W. H. Regan, and J. R. Powell.

Status: Conceptual design, 1959.

Details: Thermal neutrons, steady state, converter. Fuel: 75-100 μ particles of UO_2 fluidized with Na. Coolant: Na. Moderator: graphite blocks of square cross section, 14 ft long, spaced 1 in. apart in core. Moderator canned with Zr. Fuel suspension in spaces between moderator blocks. Zr tubes for Na coolant are in fuel spaces.

Code: 0311 12 31103 4X 653 7XX 8XXXX 921 106

No. 15 Fluidized Fuel Element Reactor

BNL

References: Unpublished report, BNL, April 10, 1959; BNL-571.

Originators: L. P. Hatch, W. H. Regan, and J. R. Powell.

Status: Conceptual design for physics and engineering calculations and comparison with the Hallam Reactor Title I design, 1960.

Details: Thermal neutrons, steady state, converter. Fuel: 75-100 μ particles of UO_2, 4.58% enriched, fluidized by Na. Coolant: Na. Moderator: graphite. Fuel is fluidized in annular spaces between concentric stainless-steel cylinders 12-1/2 ft long, 20 in. OD. There is a central cylinder of clad graphite. Fuel annulus is cooled by inner and outer annuli containing sodium. Steel cylinders are arranged in triangular lattice in a reactor tank, and spaces between are filled with clad triangular graphite blocks. There are 50 fuel elements. Reflector: 2 ft of graphite.

Code: 0311 12 31103 42 653 763 8111X 921 106

No. 16 Laminar Fluidized Bed Reactor

BNL

Reference: Unpublished report, BNL, July 21, 1960.

Originators: W. A. Robba, L. P. Hatch, W. H. Regan, James Powell, Leon Green, Kenneth Hoffman, and James McNicholas.

Status: Conceptual design of full-scale reactor for cost evaluation, 1960; work continuing.

Details: Thermal neutrons, steady state, converter. Fuel: 75-100 μ spheres of UO_2, 2.1% enriched. Moderator: 69 vertical graphite blocks, 19.75 in. by 19.75 in. by 20 ft long, clad with 0.050 in. zirconium alloy. Blocks are in symmetrical square pattern, with each block equidistant from its neighbor. Coolant: Na. Fluidizing agent: Na. A continuous fluidized bed of fuel suspension fills the spaces between the moderator blocks. Fluidizing Na enters bottom of reactor, passes through channels between moderator blocks, and leaves from the top. Coolant: Na in a separate flow. Coolant flow through bundles of zirconium-alloy U-tubes downward between moderator blocks, upward to outlet mainfold, and then to heat exchangers. Outlet temperature: 1000°F. Reflector: canned graphite blocks, 2 in. thick, with coolant channels. Active core: 18.6 in. av. diameter, 16 ft high. Reactor vessel: stainless-steel cylinder; 22 ft int. diameter, 44 ft high; design pressure, 75 psig. Thermal shield: steel, 2 in. thick, between reflector and vessel, cooled with Na. Control: 30 vertical control rods, 2 in. diameter, 16 ft long, enclosed in zirconium alloy thimbles sealed to top of reactor vessel. Thimbles are inserted into moderator blocks. Thimbles are cooled by Na, with gas cooling inside thimbles. Conversion ratio: 0.723. Power: 850 Mw(t), 300 Mw(e).

Code: 0311 12 31103 42 653 763 8111X 921 106

No. 17 Fluidized-Bed Reactor for Nitrogen Fixation

Reference: D. S. Kim, M.S. Thesis, Ohio State University, 1960.

Originator: D. S. Kim.

Status: Design calculations, 1960; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: UO_2 particles--0.006 in. diameter--6.75% enriched. Total weight of fuel: 8800 kg. Moderator-coolant: boiling H_2O. Fuel is fluidized by gases, nitrogen and oxygen, which react to form oxides of nitrogen. Core pressure: 1000 psia. Gas temperature: 250°C. Core vessel: cylinder, 9.25 ft by 9.25 ft. Reactor shell: cylinder, 11.25 ft diameter, 14.25 ft high. Reactor resembles shell-and-tube heat exchanger. Tubes contain the fluidized fuel. Boiling water is on the shell side. Gases enter bottom of core and are distributed among tubes, where they fluidize the fuel. They leave from a manifold at the top. A portion of the gas is recycled to the reactor and the remainder is treated to remove the acids, after which it is recycled to the reactor. The coolant water enters at the bottom and leaves at the top as steam. Control: negative temperature coefficient; vertically moving control rods in core. Power: 99.3 Mw(t).

Code: 0311 13 32601 42 683 763 84687 921 103
8111X

No. 18 Vapor-Slurry Reactor

Reference: Nuclear Sci. and Technol., 1A, No. 2, pp. 335-342, August 1955, (TID-2507), (Del.).

Originator: R. L. Crowther.

Status: Preliminary design, 1955.

Details: Thermal neutrons, steady state, converter. Fuel: UO_2 particles, 16.67% enriched. Moderator: BeO in hexagonal bricks. Coolant-fluidizing agent: steam. Core: cylinder, 6.5 ft diameter, 6 ft high. Recycled fuel particles and vapor enter vaporizer, where they vaporize high-pressure H_2O entering as feed. Slurry of fuel particles in steam enters bottom of reactor core, which consists of tubes encased in the BeO moderator. The steam-fuel suspension passes through the tubes, where the steam is superheated and the fuel particles are heated. Part of the suspension is recycled, through the vaporizer, to the reactor. The remainder goes to cyclone separators, to separate solids. The separated solids are combined with the recycle slurry for return to the reactor through preheaters and the vaporizer, in which they vaporize feed water. Steam from the cyclones goes to turbines and then to condensers. Steam is produced at 1450 psi and 1000°F. Control: negative temperature coefficient; shut off flow of slurry in some tubes; vary concentration of solids in slurry. For shutdown, slurry particles are dumped. For emergencies, flow of fluid and solids is stopped and core is purged with high-pressure inert gas. Reactor may be operated as fast reactor by suspending fuel particles in Hg and eliminating moderator. Power: 488 Mw(t), 200 Mw(e).

Code:	0311	15	31701	43	684	764	84699	9X	104
	0111	11					83779		108

No. 19 Heterogeneous Fluidized Uranium Oxide Reactor

FOM-KEMA

Reference: Nuclear Engineering, Part II., Chem. Eng. Prog. Symp. Series, 50, No. 12, 1954, pp. 125, 126.

Originators: J. J. Went and H. de Bruyn.

Status: Concept, 1954; current status unknown.

Details: Thermal neutrons, steady state, converter. Fuel: dry, finely powdered UO_2 particles. Moderator: D_2O. Particles move down through BeO tubes "like sand in a sandglass." Tubes are supported in tank of D_2O. Oxide particles leaving reactor are fluidized by vibrating cone and raised through heat exchanger by gas stream. Cyclone separates gas and particles before fuel re-enters reactor. Temperature of fuel can reach 600°-700°C.

Code: 0311 14 2112 41 5732 722 8XXXX 921 104

No. 20 Heterogeneous Dry Suspension Power Reactor

FOM-KEMA

Reference: Proc. 1st. U. N. Int. Conf. on Peaceful Uses of Atomic Energy, 3, pp. 122-124.

Originators: H. de Bruyn, B. L. A. v.d. Schee and J. J. Went

Status: Concept, 1955; current status unknown.

Details: Thermal neutrons, steady state, converter. Fuel: dry, 250-μ UO_2 particles. Moderator: D_2O. Fuel moves down through graphite tubes in tank of heavy water moderator. UO_2 particles reach 1200°C at bottom of tank and are transported pneumatically to heat exchanger, where they are fluidized in a boiling bed. Heat exchanger surrounds reactor tank and has boiling and superheating sections. When filled with UO_2, heat exchanger serves as gamma shield. About 25 tons UO_2 are used in a tank 3.4 met diameter by 2.5 meters high. About 150 tons UO_2 held up in heat exchanger. Control: by moderator temperature, nominally 50°C, i.e. control by D_2O circulation rate; Cd rods or boron steel plates for shutdown. Power: 300 Mw(t).

Code: 0311 14 2112 41 5732 722 84687 921 104

No. 21 Flowable Solids Reactor

Fluor Corporation, Ltd.

Reference: Report FLR-1, The Fluor Corporation Ltd., Jan. 28, 1958.

Originators: R. C. Oliver, H. K. Orbach, M. R. Dusbabek, J. A. Porter, A. Goldstein, and R. H. Bishop.

Status: Concept, 1958; no further work.

Details: Thermal neutrons, steady state, converter. Fuel: dry, crushed fused UO_2 as flowable 200 μ powder. Moderator: graphite with ceramic-lined 3-in. fuel channels. Fuel flows by gravity down fuel channels (orificed to control flow). Fuel leaving reactor cascades over horizontal heat exchanger tubes in chamber below reactor. Fuel is returned mechanically to top of reactor.

Code: 0311 12 2112 42 5732 723 8XXXX 104

No. 22 Dust-Fueled Reactor, I

Armour Research Foundation*

Reference: AECU-3909.

Originator: D. Krucoff.

Status: Conceptual design, 1958. Physics and engineering calculations and loop tests.

Details: Thermal neutrons, steady state, burner. Fuel: 8-to-10 μ aerosol-type suspension (dust) of highly enriched uranium in CO_2 gas. Moderator: BeO. Coolant: CO_2 gas. Fuel circulates in channels in BeO moderator. Channels are lined with Al_2O_3 to minimize erosion damage. Coolant temperature reaches 2000°-3000°F. Coolant velocity 220 ft/sec. Control by negative temperature coefficient of reactivity--pressure is regulated, temperature expands carrier gas and decreases UO_2 concentration. A 500-Mw(t) reactor will have a critical mass of 17.4 kg U^{235}.

Code: 0313 15 311017 44 693 711 84699 921 104

*Now Illinois Institute of Technology Research Foundation

No. 23 Dust-Fueled Reactor, II

Armour Research Foundation*

Reference: AECU-3909.

Originator: D. Krucoff.

Details: Same as Dust Fueled Reactor I, but with graphite moderator, channels lined with silicon carbide, and the fuel a uranium carbide dust suspended in helium.

Code: 0313 12 311016 44 693 711 84699 921 104

*Now Illinois Institute of Technology Research Foundation

No. 24 Internally Cooled Dust-Fueled Reactor

Armour Research Foundation*

Reference: AECU-3909.

Originator: D. Krucoff.

Details: Thermal neutrons, steady state, burner. Uranium carbide-graphite-helium or UO_2-BeO-CO_2 systems can be used. Core resembles shell-and-tube heat exchanger, fuel-laden gas on one side, pure gas on other. This arrangement gives non-radioactive primary loop. Fuel is circulated at low velocity through core and fission-product-cleanup system. Pure gas serves as coolant and is circulated at high velocity through core and primary loop. Power more limited than for externally cooled systems.

Code: 0313 12 31716 44 693 711 84699 921 104
15 31717

*Now Illinois Institute of Technology Research Foundation

No. 25 Internally Moderated, Dust-Fueled Reactor

BNL

Reference: BNL-602 (T-175); Meyer Steinberg, unpublished report, BNL, Jan. 31, 1962.

Originators: Meyer Steinberg *et al*.

Status: Preliminary design, 1962.

Details: Thermal neutrons, steady state, burner. Fuel: dust particles (5 μ) of U_3O_8 (93.5% enriched). Critical mass of fuel: 28.7 kg. Moderator: graphite, in 16-in. diameter logs coated with silicon carbide. Coolant-fluidizing agent: mixture of reactant gases--nitrogen-oxygen. Reactor: active core--cylinder, 8 ft by 8 ft contained in cylindrical outer vessel, 14.5 ft OD by 17 ft high. Reactant gases carry dust into bottom of reactor, through core, and out. Most of the dust is separated in a cyclone, refluidized, and returned to the reactor. Gas passes through a heat exchanger, and most of it is recycled to the reactor. A portion is recycled to cool the walls of the reactor vessel. A 5% fraction of gas is treated to separate remaining dust and to remove acid by cooling. This gas is also recycled. Control: two vertically moving rods in core. Power: 112 Mw(t).

Code: 0313 12 311014 44 693 711 8111X 9X 104

No. 26 Circulating Dust-Fueled, Radiation-Cooled Space Power Reactor

Reference: *Aero/Space Engineering*, May 1960, pp. 60-61.

Originator: W. R. Corliss.

Status: Concept, 1960; physics and engineering calculations.

Details: Thermal neutrons, steady state, burner. Fuel-coolant: UC_2 or PuC dust. Moderator: graphite. Circulating dust-fueled system radiates heat to shell of thermionic converters. Dust travels in racetrack-shaped path in cavities or ducts in graphite. For a 10-Mw(t) reactor a core 3 ft in radius, 10 ft long is needed. The dust is electrically charged, and is circulated by an electrostatic pump. Technology as of about 1980 may be needed. The maximum dust temperature is 2500°K.

Code: 0313 12 341013 44 693 711 8XXXX 921 104

No. 27 Smoke-Fueled Reactor

Aerojet-General Nucleonics

Reference: AGN-3048.

Originator: F. R. Ulbrich.

Status: (1960) A miniaturized loop capsule was designed, fabricated, and operated in the Livermore Pool Type Reactor. Using the data, a conceptual design of the reactor system was made.

Details: Thermal neutrons, steady state, burner. Chemonuclear reactor. Highly enriched mixed uranium oxides as 1-2 μ particles are suspended as a smoke in process gas (4:1 nitrogen-oxygen mixture) and circulated through zirconium tubes in tank of heavy water moderator. Tubes are joined to inlet and outlet headers; there are 200 tubes, and each makes 16 passes through core. Gas conditions are 1000 psi and 200°C.

Code: 0313 14 311019 44 693 711 8111X 921 104

No. 28 Heterogeneous Liquid Medium Suspension Reactor

FOM-KEMA

Reference: Nuclear Engineering, Chem. Eng. Prog. Symp. Series, 50, No. 12, 1954. Part II, pp. 122-124.

Originators: J. J. Went and H. de Bruyn.

Status: Concept, 1954; current status unknown.

Details: Thermal neutrons, steady state, converter. Fuel-coolant: settled suspension of UO_2 in D_2O in BeO tubes in tank of D_2O. Moderator: D_2O. Suspension is very viscous and moves slowly down the tubes; as it leaves the reactor it is diluted with D_2O so that it can easily flow through the external heat exchanger located just below reactor. Suspension lifted to top of reactor by gas-lift pump and concentrated by cyclone before again entering reactor tubes. Fuel temperature is limited; that of the D_2O must not exceed 50°C.

Code: 0311 14 311402 41 643 722 8XXXX 921 104

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APPENDIX A

Partial List of Reactor Compilations

The following references contain engineering data for many nuclear reactors.

1a. Nuclear Reactor Plant Data, Volume I. Power Reactors, American Society of Mechanical Engineers, Nuclear Engineering Division, Reactor Plant Data Committee, New York, 1958.

b. Ibid., Volume II. Research and Test Reactors, 1958.

2a. Directory of Nuclear Reactors, Volume I. Power Reactors, International Atomic Energy Agency, Vienna, Austria, 1959.

b. Ibid., Volume II. Research, Test, and Experimental Reactors, 1959.

c. Ibid., Volume III. Research, Test, and Experimental Reactors (Supplement to Volume II), 1960.

d. Ibid., Volume IV. Power Reactors (Supplement to Volume I), 1959.

Other lists of nuclear reactors also give some engineering data. Perhaps the most comprehensive is:

3. "Review of Power and Heat Reactor Designs, Domestic and Foreign," HW-66666, Volumes 1 and 2, Compiled by E. R. Appleby, Hanford Atomic Products Operation, General Electric Company, Richland, Washington, March 1961. Available from Office of Technical Services, Department of Commerce, Washington 25, D. C.

Nucleonics has for the last three years published reactor tables as part of their Reference Data Manuals. These manuals are also available as reprints or microcards. The references are:

4a. "Power Reactors and Experiments the World Around," Reactor Table, Reference Data Manual, Nucleonics, 18, pp. 148 ff, November 1960, McGraw-Hill, New York.

b. Ibid., 19, pp. 122 ff, November 1961, (Revision).

c. "Research and Testing Reactors the World Around," Reactor Table, Reference Data Manual, Nucleonics, 20, pp. 116, August 1962, McGraw-Hill, New York.

d. "Power Reactors the World Around," Reactor Table, Reference Data Manual, Nucleonics, 21, pp. 112 ff, August 1963, McGraw-Hill, New York.

The U. S. Atomic Energy Commission has published a list of nuclear reactors in the United States on a semi-annual basis. The latest reference is:

5. "Nuclear Reactors Built, Being Built or Planned in the United States as of December 31, 1963," TID-8200 (7th Revision). Prepared by the Division of Reactor Development. Division of Technical Information, U. S. Atomic Energy Commission.

A useful general reference is:

6. J. F. Hogerton, The Atomic Energy Desk Book, Reinhold, New York, 1963.

APPENDIX B

Coding Classification System

Reactors can be classified in many ways, including neutron-energy level and type of coolant and moderator. A reactor catalog made up from ordinary index cards would require a separate set for each type of classification. This will be avoided if some sort of punched-card system is used, for it automatically provides a multiple cross index. The cards can be sorted, manually or by machine, into groups by characteristics, provided they are coded according to a properly designed system. Our purpose was to design a coding classification system to prepare Royal-McBee Keysort or IBM cards. Of the different reactor characteristics, eleven were chosen to describe the reactor and include neutron characteristics, coolant, and moderator. Each of the eleven main characteristics is represented, in the classification system, by a four- or five-digit number. The digits represent the main characteristic and the subcharacteristics under the main characteristic. For example, Coolant, Fluid is described by the digit 3, which is the first digit of the number describing the characteristics of the fluid coolant. Succeeding digits describe: 1--coolant mechanism, 2--coolant form, and 3--coolant material (two digits). Thus the number 31715 means: (first digit) Coolant, Fluid; (second digit) coolant mechanism, convective cooling; (third digit) coolant form, gas; (last two digits) coolant material, hydrogen. The number can then be represented by holes punched in five successive columns of an IBM card or by notches in a particular location in a Royal-McBee Keysort card.

The standard IBM card has 12 rows and 80 columns. The 10 bottom rows are numbered from 0 to 9. A number is indicated by the machine punching a rectangular hole in the row corresponding to the number, in a column corresponding to the digit. Consequently, the code for such a system must be based on digits containing numbers from 0 to 9. The system is based on digits containing numbers starting with 1, going up to 9, and in some cases up to 10 or 11. This numbering system is more readily adapted than the 0-to-9 system to the hand-punched and hand-sorted Royal-McBee Keysort cards. The code must be renumbered with 0 to 9 in each digit to adapt it to IBM cards. In addition to the 80-column machine-punched cards, IBM also makes so-called Port A-Punch Cards with 40 columns and 12 rows, the lower 10 being numbered 0 to 9. These cards are scored for punching with a hand punch, or even a pencil, and they can be sorted by hand if desired.

The Royal-McBee Keysort card has holes punched around the periphery and uses a system of representing numbers between one and 14 by combinations of notches in one, two, three, or four holes. On the "Coolant, Fluid" card, an area is laid out with a sufficient number of holes to provide for the items listed under each subcharacteristic (digit). Successive holes are numbered 7, 4, 2, 1, so that by notching combinations of two holes (2, 1), up to three items can be indicated; by notching combinations of three holes (4, 2, 1), up to seven items can be indicated; and by notching combinations of all four holes (7, 4, 2, 1), up to 14 items can be indicated. To cover Coolant, Fluid, an area of the card is marked off with enough holes to cover the anticipated number of items. The area and each of the subareas corresponding to the subcharacteristics are labeled with an abbreviation, and the required holes numbered according to the above system. In the example:

Name	Abbreviation	Holes
Coolant, Fluid	CF	
Coolant mechanism	Me	2, 1
Coolant form	F	7, 4, 2, 1
Coolant material	Ma_1	7, 4, 2, 1
	Ma_2	7, 4, 2, 1

Since there are 19 items under "Coolant material," two sets of four holes each are used. If more items must be included under any subcharacteristic than can be represented by the number of holes allowed, a new layout of the master card must be made.

Details of the system, with definitions, are given in the following pages.

Coding System

Reactor Characteristics	Abbreviation	Coding: 1st Digit N	2nd Digit T	3rd Digit CR	4th Digit U
Neutrons	N	0			
Neutron Type	T				
Fast			1		
Intermediate			2		
Thermal			3		
Mixed			4		
Neutron Chain Reaction Type	CR				
Steady State				1	
Pulsed				2	
Converging				3	
Diverging				4	
Neutron Utilization	U				
Converter					1
Breeder					2
Burner					3

Definitions* Neutrons refers to the Neutron Type, Chain Reaction Type and Utilization of the neutrons in a reactor. Neutron Type refers to the energy of the majority of the fission-producing neutrons in a reactor. Fast neutrons--energy greater than about 100 kev. Thermal neutrons--energy equivalent to average moderator temperature. Intermediate neutrons--energy between thermal and fast ranges. Mixed--different neutron energies in different regions of reactor. Neutron-Chain-Reaction Type refers to the character of the chain reaction (as defined by the reactivity, k_{eff}) and its variation with time. In a steady-state chain reaction k_{eff} equals 1 and

*In devising these definitions, liberal use was made of information contained in a letter from W. A. Robba, formerly of BNL, now of Space Age Materials Corporation, to Frank Kerze, USAEC, December 28, 1960.

remains constant. In a <u>pulsed</u> chain reaction k_{eff} varies with time, from less than 1 to greater than 1 and back to less than 1. We intend to include so-called burst or excursion reactors like KEWB, BORAX, or Godiva (single pulse reactors), as well as some reactors that have been designed to give neutron bursts or pulses with a regular repetition rate. In a <u>converging</u> chain reaction k_{eff} is less than one (exponential pile or Pickle Barrel). In a <u>diverging</u> chain reaction k_{eff} is greater than 1, and the chain reaction is uncontrolled (not a reactor in the usual sense). <u>Neutron Utilization</u> refers to production and consumption of neutrons (neutron economy). A <u>converter</u>** is a reactor that produces less fissionable material than it consumes: i.e., the conversion ratio is less than 1. A <u>breeder</u>** is a reactor that produces more fissionable material than it consumes: i.e., the conversion ratio is greater than 1. A <u>burner</u> is a reactor in which conversion is negligible, usually because no fertile material is present.

** American Standards Association definition.

Reactor Characteristics	Abbreviation	Coding 1st Digit M	2nd Digit Ma
Moderator	M		
Moderator Material	Ma		
No moderator			1
Graphite			2
H_2O			3
D_2O			4
Be or compound			5
Organic			6
Inorganic			7
Fluorocarbon			8
Other			9
More than one moderator			10

Reactor Characteristics	Abbre-viation	Coding 1st Digit CS	2nd Digit Me	3rd Digit F	4th Digit Ma
Coolant, Solid	CS	2			
Coolant Mechanism	Me				
Conduction			1		
Radiation			2		
Melting			3		
Coolant Form	F				
Moving solid				1	
Fixed solid				2	
Coolant Material	Ma				
Metal					1
Nonmetal					2

Definitions   A solid coolant ordinarily transfers heat by conduction, but at high temperatures heat transfer by radiation becomes important. Heat transfer can also be brought about by latent heat, i.e., melting the solid.

The solid coolant may be a finely dispersed moving solid (example, a reactor cooled by blowing graphite powder through it) or it may be a system of rotating blades or vanes that are heated as they move through the chain-reacting part of the system and are cooled as they pass through a heat exchanger. The coolant may also be a fixed solid, for example, bars of a good heat conductor. Another example is a completely solid reactor, like CP-1, in which heat was conducted to the outside and radiated to the environment. Such a reactor has to run at low power, as heat dissipation is small.

Reactor Characteristics	Abbre-viation	Coding: 1st Digit CF	2nd Digit Me	3rd Digit F	4th Digit Ma_1	5th Digit Ma_2
Coolant, Fluid	CF	3				
Coolant Mechanism	Me					
Convection			1			
Boiling			2			
Dissociation			3			
Radiation			4			
Coolant Form	F					
Liquid (one component)				1		
Solution				2		
Slurry				3		
Paste				4		
Fluidized solid (liquid carrier)				5		
Two-phase fluid (non-dispersed) or boiling liquid				6		
Gas or vapor				7		
Fog				8		
Fluidized solid (gas carrier)				9		
Dust or smoke				10		
Plasma				11		
Coolant Material	Ma					
H_2O or H_2O solution or suspension					01	
D_2O or D_2O solution or suspension					02	
Na					03	
NaK					04	
Bi					05	
Metal (other)					06	
Organic (aliphatic)					07	
Organic (aromatic)					08	
Fluorocarbon					09	

Reactor Characteristics	Abbreviation	Coding 1st Digit CF	2nd Digit Me	3rd Digit F	4th Digit Ma_1	5th Digit Ma_2
Coolant, Fluid (cont.)						
Coolant Material (cont.)						
Hex (UF_6)					10	
Salt (molten)						11
Hydroxide (molten)						12
Compound, inorganic, other, or nonmetal						13
Air						14
Hydrogen						15
Helium						16
Carbon Dioxide						17
Nitrogen						18
Gas, other						19

Definitions Fluid coolants include liquids, boiling liquids, various fluid solid-liquid and solid-gas mixtures, vapors (gases below critical temperature), and gases. Liquid (one component) means a pure liquid (one chemical substance). A liquid solution is a molecular dispersion, kept homogeneous by diffusion, that can only be separated by changes of state (boiling off or freezing out the solvent). A slurry is a two-phase, solid-liquid system, a fine suspension. Although such a suspension can settle, a fine suspension settles only slowly, and settling can be retarded by a moderate amount of fluid flow or agitation. Ultrasonic vibration has been suggested as one method of keeping slurries suspended. Another source* defines a slurry as a "two-phase system in which the particles are dispersed in the liquid by fluid-dynamic forces." To be useful as a reactor coolant, a slurry must be capable of circulation through the core and the heat exchanger without settling out or depositing in low-flow parts of the system. A paste is a two-phase mixture of small spherical particles dispersed in a liquid (usually a liquid

*W. G. Blessing, et al, "Summary of the APDA Fuel Development Program," Atomic Power Development Associates, Inc., APDA-143, April 1961, page 166.

metal for nuclear reactor coolants) at approximately the settled value of 60 percent of solids. The density is constant irrespective of paste movement. A fluidized bed is a two-phase system of solid particles maintained in a dispersed or suspended state by an upward flow of fluid at a velocity below the particle transport value. Fluidized beds are divided, in the classification scheme, into fluidized solid (liquid carrier), 5, and fluidized solid (gas carrier), 9. If the fluid flow stops, the particles settle rapidly. Gases include vapors, which are gases below the critical temperature. A fog is a dispersion of liquid droplets in a gas (a colloidal dispersion, droplets electrically charged). A dust or smoke is a dispersion of solid particles in a gas (a colloidal dispersion, particles electrically charged). A plasma is an electrically neutral ionized gas, i.e., a gas containing equal numbers of positive and negative ions.

Reactor Characteristics	Abbreviation	Coding: 1st Digit	2nd Digit	3rd Digit	4th Digit
		Fu	T		
Fuels	Fu	4			
Fuel Type	T				
Natural uranium			1		
Slightly enriched U (0.8-10%)			2		
Moderately enriched U (10-70%)			3		
Highly enriched U (above 70%)			4		
Uranium-233			5		
Plutonium-239			6		
More than one fuel (or mixed fuels)			7		
		FuS	F	Ma	C
Fuel, Solid	FuS	5			
Fuel Form	F				
Block			1		
Lumps (pebbles)			2		
Plates			3		
Rods, slugs, pins			4		
Wires			5		
Tubes			6		
Powder (fine)			7		
Pellets			8		
Dispersion (cermet)			9		
Fuel Material	Ma				
Pure metal				1	
Alloy				2	
Oxide				3	
Carbide				4	
Phosphide				5	
Silicide				6	
Sulfide				7	

Reactor Characteristics	Abbre-viation	Coding 1st Digit FuS	2nd Digit F	3rd Digit Ma	4th Digit C
Fuel, Solid (cont.)					
Fuel Material (cont.)					
Compound, other				8	
Fuel Cladding	C				
Clad					1
Unclad					2

Definitions Lumps (pebbles)--this form of fuel may vary from large, irregular (though generally spherical) lumps, 3-5 inches in diameter down to small pebbles or marbles. Generally pebbles are no smaller than 0.4 to 0.5 inch in diameter; we have called smaller particles pellets or powder. Rods are generally considered solid cylinders of full core length; short rods are called slugs. The term "rodlets" has also been used. Pins are fine rods, usually of less than full core length. Wires are continuous fine rods, in some sort of bent or woven structure. Powder refers to loose powder only, not powder-metallurgy solid material. Pebbles, pellets and powder are loosely defined terms for three degrees of subdivision. Dispersion fuel is a particular type (cermet) with ceramic fuel particles, such as UO_2, surrounded by metal, such as stainless steel. Dispersion fuel is usually made by powder-metallurgy methods.

Reactor Characteristics	Abbreviation	Coding 1st Digit FuF	Coding 2nd Digit F	Coding 3rd Digit Ma
Fuel, Fluid	FuF	6		
Fuel Form	F			
Liquid (one component)			1	
Solution			2	
Slurry			3	
Paste			4	
Fluidized solid (liquid carrier)			5	
Gas or vapor			6	
Fog			7	
Fluidized solid (gas carrier)			8	
Dust or smoke			9	
Two-phase fluid (nondispersed) or boiling liquid			10	
Fuel Material	Ma			
Metal (liquid)				1
Hex (UF_6)				2
Other compound				3
H_2O mixture				4
D_2O mixture				5
Liquid metal mixture				6
Molten salt mixture				7

Definitions Liquid (one component) refers to a pure liquid containing a single chemical compound as opposed to a solution. The terms solution, slurry, paste, fluidized solid, gas or vapor, and dust or smoke have been defined under Coolant, Fluid above. Under fuel material, the terms H_2O mixture, D_2O mixture, etc., are combined with the terms under fuel form to give such composites as "solution, H_2O mixture" (water solution); "slurry, molten salt mixture" (molten salt slurry); "fluidized solid, liquid carrier, liquid metal mixture" (solid pellets fluidized with liquid metal).

Reactor Characteristics	Abbreviation	Coding 1st Digit Fe	Coding 2nd Digit F	Coding 3rd Digit Ma
Fertile Material	Fe	7		
Fertile Material Form	F			
No fertile material			1	
Solid			2	
Liquid			3	
Solution			4	
Slurry			5	
Fluidized solid			6	
Powder			7	
Pellets			8	
Pebbles			9	
Fertile Material Type	Ma			
None				1
Natural U				2
Slightly enriched U (0.8-10%)				3
Moderately enriched U (10-70%)				4
Depleted U				5
Thorium				6
More than one fertile material				7
Lithium				8

Reactor Characteristics	Abbreviation	Coding 1st Digit C	2nd Digit Me	3rd Digit Mo	4th Digit F	5th Digit Ma
Control	C	8				
Control Method	Me					
Poison introduction or removal			1			
Reflector movement			2			
Fuel addition or removal			3			
Other changes in material buckling (e.g., moderator density) also changes in diffusion length and Fermi age due to temperature changes.			4			
Configuration change (change in geometric buckling)			5			
Control Element or Material Movement	Mo					
Vertical				1		
Horizontal				2		
Angular (swinging)				3		
Rotating				4		
Infiltration (gas or liquid throughout reactor core)				5		
Volume change of moderator or coolant (expansion or contraction)				6		
Concentration change (liquid or gas)				7		
Temperature change of moderator or coolant--see Volume change						
Control Element or Material Form	F					
Rods					1	
Plates, blades, leaves					2	
Crosses, tees, wyes					3	
Cylinders (hollow) or segments					4	

Reactor Characteristics	Abbre-viation	Coding 1st Digit C	2nd Digit Me	3rd Digit Mo	4th Digit F	5th Digit Ma
Control (cont.)						
Control Element or Material Form (cont.)						
Tubes					5	
Other solid shapes					6	
Dispersion or solution in fuel or coolant					7	
Liquid					8	
Gas					9	
Control Material	Ma					
Boron or boron compound						1
Cadmium						2
Hafnium						3
Rare earth						4
Mercury						5
Other poison						6
Moderator material						7
Reflector or blanket material						8
Fuel material						9

Reactor Characteristics	Abbreviation	Coding 1st Digit Re	2nd Digit ReT	3rd Digit ReL
Reflector	Re	9		
Reflector Type	ReT			
No reflector			1	
Scattering material			2	
Fertile material			3	
Both scattering and fertile material			4	
Reflector Location	ReL			
External				1
Internal				2
Both external and internal				3

Reactor Characteristics	Abbre-viation	Coding 1st Digit Co	2nd Digit CoA
Core	Co	10	
Core Arrangement	CoA		
Fuel, coolant, moderator one phase (homogeneous) or fuel fine suspension in coolant-moderator; "soup" circulates			1
Fuel, coolant, moderator two or more immiscible liquids			2
Coolant, moderator continuous (single phase) or the same substance; fuel suspended in coolant-moderator			3
Fuel, coolant continuous (single phase) or identical, or fuel fine suspension in coolant; fluid mixture or coolant circulates through moderator			4
Fuel, moderator continuous (single phase) or fuel suspension or dispersion in moderator; coolant circulates through or around fuel-moderator			5
Moderator continuous or in large blocks; fuel suspended in moderator or in channels in moderator; coolant circulates through or around fuel			6

Reactor Characteristics	Abbre-viation	Coding 1st Digit Co	Coding 2nd Digit CoA
Core (cont.)			
Core Arrangement (cont.)			
Reflector moderated; coolant circulates through or around fuel			7
No moderator; fuel suspended in coolant			8
Other arrangement			9

Definitions The single-phase fuel, coolant, moderator refers to the homogeneous solution reactor. The fine suspension fuel is the slurry reactor, which is usually also termed homogeneous. The fuel solution or slurry has been termed "soup" by Oak Ridge National Laboratory reactor engineers. (Coded as 1)

Because some liquids are mutually insoluble or nearly so (immiscible liquids), several reactors have been proposed with two or more liquid layers with some means of transferring heat between them. Thus in the rotating-plate reactor a chain-reacting mass of molten moderator-fuel, such as a molten salt containing beryllium and uranium fluorides, is surmounted by a layer of molten sodium. Many refractory metal plates on a rotating shaft transfer heat from the chain-reacting mass to the sodium, which is circulated to an external heat exchanger. (Coding 2)

In a light-water-cooled and -moderated reactor, the coolant and moderator are the same substance; in most such reactors the solid fuel elements are suspended or supported in the coolant-moderator (example, Pressurized Water Reactor). (Coding 3)

In some reactors the moderator is separate from the coolant, and the fuel is dissolved or suspended in the coolant. A "heterogeneous" solution or slurry reactor would have this core arrangement. For example, a reactor might be made up of graphite blocks (moderator) with holes through which a fuel-coolant solution or slurry circulates. The fuel may also be fluidized in the coolant, in which case the coolant alone circulates. (Coding 4)

In other reactors, the moderator and coolant are separated, as above, but the fuel is suspended or dispersed in the moderator instead of the coolant.

Two quite different examples may be given. A chain-reacting heavy-water solution or slurry contained in a tank may be cooled by light water contained in tubes or pipes immersed in the solution or slurry. Another example is a pebble-bed reactor. The pebbles contain fuel and moderator, and a gas coolant circulates around the pebbles. (Coding 5)

In some reactors the coolant, moderator, and fuel are all separate. The moderator is penetrated by fuel channels or tubes, in which the fuel is suspended or supported, and the coolant flows around the fuel. The Chalk River reactor has this arrangement--the heavy-water moderator is contained in a tank (calandria) penetrated by fuel tubes. The fuel rods are suspended in the tubes; light-water coolant flows around them. The X-10 Graphite Reactor also uses this arrangement although the materials are different: clad uranium slugs are supported in fuel tubes in a graphite moderator; air coolant circulates around fuel. (Coding 6)

Codings 7, 8, and 9 are believed to be clear without further explanation.

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