ANL-6148
Reactors - General
(TID-4500, 15th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

A PRELIMINARY DESIGN STUDY OF A
BOILING SLURRY REACTOR EXPERIMENT

by

M. Petrick and J. F. Marchaterre

April, 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	5
I. INTRODUCTION.	5
II. STATE OF THE "ART"	10
III. NEED FOR REACTOR EXPERIMENT	12
IV. PURPOSE OF THE EXPERIMENT.	12
V. PRELIMINARY PLANT DESIGN	14
VI. REACTOR CONTROL	23
VII. REACTOR STARTUP	24
VIII. REACTOR INSTRUMENTATION	24
IX. PLANT INSTRUMENTATION	25
APPENDICES	27
APPENDIX A - Probable Performance Parameters	27
APPENDIX B - Reactor Physics	33

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Preliminary Boiling Slurry Reactor Experiment Facility Layout	15
2.	Slurry Plant Pictorial	16
3.	Simplified BSRE Flow Diagram.	16
4.	Reactor and Auxiliary Component Elevation	17
5.	Reactor Vessel Assembly	19
6.	Schematic Diagrams of Reactor Systems	30
7.	Core Steam Volume Fraction as a Function of Reactor Power	30
8.	Core Recirculation Velocity as a Function of Core Steam Volume Fraction	31

A PRELIMINARY DESIGN STUDY OF A BOILING SLURRY REACTOR EXPERIMENT

M. Petrick and J. F. Marchaterre

ABSTRACT

An experiment is described which would test the feasibility of the boiling slurry reactor concept and investigate its potential as a practical nuclear power reactor. The experiment would yield data and information on reactor stability and safety characteristics, performance parameters, feasible slurry concentration limits, behavior of slurries under actual reactor operations, rates of radiolytic gas evolution, rates of fission gas release, etc.

I. INTRODUCTION

A boiling water reactor concept which is potentially very attractive, but is as yet unproven, is the homogeneous boiling slurry reactor. The evolution of slurry reactors and their present technological status has been amply documented, first by Lane⁽¹⁾ for the 1958 Geneva Conference, and then by Oak Ridge National Laboratory⁽²⁾ for the AEC's review of the Civilian Power Reactor Program.⁽³⁾ The AEC's homogeneous reactor program as a whole has been the subject of a detailed evaluation performed at the AEC's request by the Fluid Fuel Reactor Task Force.⁽⁴⁾ This review included an examination of American slurry technology and evaluation of two-region, circulating homogeneous reactors with a thorium slurry blanket and a solution or slurry core. The following survey has therefore been restricted to boiling homogeneous reactors, with emphasis on boiling slurry reactors, and to activities in the slurry field in other countries.

In May 1951, following operation of HRE-I, one group at ORNL focused attention on boiling homogeneous reactors. To answer questions regarding nuclear stability and maximum permissible power density, design of a boiling reactor experiment (BRE) called TEAPOT was initiated. To obtain preliminary information, ORNL and LASL jointly operated SUPO at solution power densities up to 0.5 kw/l. A proposal was made to the AEC to build BRE, and a more detailed study was undertaken. The project was abandoned in late 1953, partly because "it became evident from HRE-I and the associated development program that construction of a second homogeneous reactor experiment would be a more suitable course of action. The main reason for this decision was that the HRE-I did not demonstrate all the engineering features required for continuous operation of a nuclear power plant."⁽¹⁾ In regards to a boiling solution, experiments

"indicated that at oxygen concentrations likely to be encountered in a boiling reactor (6 to 7 ppm) reduction of the uranium would occur in solutions in contact with stainless steel." (1)

Experiments and theoretical calculations of the power removal from boiling homogeneous reactors, (5,6,7) were continued. These "provide a basis for estimating the obtainable power density of such reactors under varying core heights, operating pressures and moderator density decreases. Values range from 10 to 40 kw/liter with an average of 18.5 kw/liter for a 15-ft-high core, operating at 2000 psi, and a density decrease due to steam of 0.4. Although the effect of such void fraction on nuclear stability is not known, boiling reactors may be able to achieve average power densities comparable or larger than those estimated for large scale non-boiling circulating-fuel reactors operating under a similar pressure. (8) In this latter case, the holdup of solution in the external circulating system lowers the power density based on total system volume to an average of about 10 to 20 kw/liter." (1)

The values in the above quotation refer to designs involving natural circulation of the liquid through steam separators, greatly increasing the system pressure drop and reducing the recirculation velocity and attainable power density. There is no clear-cut experimental evidence that this is required to get adequate steam separation. Therefore, considerably higher power densities may be attainable.

Three design studies of full-scale boiling homogeneous reactors have been performed at ORSORT. The first of these, by Widdoes et al. (9) was for a direct cycle, boiling pot with no internal recirculation. This limited power density to 4.03 kw/l at an average of 10% voids. The reactor was designed to produce 280 Mw(e) with plutonium as a byproduct from the fuel material of UO_3 in heavy water.

The other two studies were carried out simultaneously by Karmack et al. (10) for a converter using uranyl sulfate or UO_3 slurry in heavy water and by Zeitlin et al. (11) for a breeder using UO_2 - ThO_2 in heavy water. In the converter, the preference was for uranyl sulfate because of presumably fewer unknowns, although it was admitted that there was no information on corrosiveness of the fuel solution at the proposed operating conditions. At the operating pressure of 1500 psi, a concentration of 0.25 M sulfuric acid was required to prevent reduction and precipitation of uranium from the uranyl sulfate; and the corrosion resistance of the proposed titanium liner material to the solution was unknown. The hydraulic design involved natural circulation of the liquid through steam separators and through an internal downcomer in the pressure vessel. The resistance of the separators and the lines leading to them from the pressure vessel is sufficient to reduce the recirculation ratio to 21 for a total system pressure drop of 3.90 psi. This produces a power density of only 5.3 kw/liter for an optimistic

61% maximum and 45.4% average steam void fraction. The design also required a 25-ft titanium-lined pressure vessel for 1500-psi operation. Despite this and the unknown corrosion problem, an obviously optimistic power cost of 6.9 mill/kw-hr was evolved.

The breeder design also involved liquid circulation through steam separators, this time internal to the pressure vessel. The design is somewhat more conservative, producing 4.15 kw/liter in a 1000-psi system with 32% average void fraction. The design power level is 500 Mw(t) producing 150 Mw(e) from a 20.5-ft pressure vessel. The breeding ratio was arbitrarily chosen as 1.

A fourth ORSORT design study⁽¹²⁾ involved a 10-Mw Homogeneous Boiling Reactor suitable for remote operation. This is a solution-type boiling pot with no internal recirculation, producing 5-10 kw/liter.

Some studies were carried out on the use of a boiling slurry blanket for the large-scale thermal breeder reactor design being evolved at ORNL. These studies indicated the following:

1. Greater reliability and more favorable cost could probably be achieved with a boiling blanket. Consideration was given to modifying the HRT for a boiling blanket. This was not recommended because of added complication at the point in the design.^(13,14)
2. The thermal breeder plant efficiency was improved from 26 to 29% by the use of a boiling blanket with a reheat cycle.⁽¹⁵⁾
3. Essentially the same amount of power can be extracted from a boiling blanket as from a circulating one for the specific design examined.⁽¹⁶⁾
4. "The apparent advantages are that no circulating pump would be required to handle slurry, containment of the highly active slurry in the reactor vessel, and the possibility of operating the blanket at the core pressure and using the blanket power for heating the secondary steam. One major problem is that of keeping the slurry suspended during startup."⁽¹⁾

Foreign interest in boiling homogeneous reactors was expressed at both Geneva Conferences. In 1955, the Russians⁽¹⁷⁾ reported on a preliminary parametric study, indicating power densities up to 50 kw/liter could be attained, but insufficient design detail or assumptions were given to permit verification of their results.

In 1958, the French⁽¹⁸⁾ reported on the first phase of a novel boiling slurry concept. The slurry is accelerated centrifugally and the resulting vortex in the middle is used to collect steam and noncondensable gases. Calculations of performance were based on one-group physics analyses.

Parametric studies show influence of height, void fraction and vortex diameter. The vortex diameter cannot conveniently exceed one-tenth the core radius, a condition which may imply hydraulic problems. Power densities were low. Breeding potential was not evaluated.

The next step they proposed was construction of an atmospheric pressure reactor experiment called Phoebus which was to produce 500-1000 kw in a 35-cm radius core. This corresponds to a power density of 2-4 kw/liter. The fuel for this is to be small marbles of $\text{ZrO}_2\text{-UO}_2$ (3-60 microns dia). These have adequate corrosion resistance at 100°C, but thus far not at higher temperatures.

At the 1958 Geneva Conference, work on nonboiling slurry reactors by two other countries was reported. Czechoslovakia presented a very preliminary design study with little detail suitable for evaluation.⁽¹⁹⁾ The Dutch reported⁽²⁰⁾ continuation of work earlier documented at the 1955 conference,⁽²¹⁾ leading to construction of a 250-kw experimental reactor unit operating on 20% enriched UO_2 . Uranium was to be maintained in the plus four state by a 300-psi partial pressure of hydrogen. Particle size was selected as between 4 and 13 microns, the upper limit being set by desiring a 90% escape probability for fission fragments. They proposed to circulate activated charcoal with the slurry to remove fission products continuously.

The boiling slurry reactor may be regarded as a crossbreed of the heterogeneous boiling reactor and the homogeneous reactor concepts, retaining much of the simplicity of the former and the promising fuel cycle of the latter. The reactor basically consists of a vessel in which the slurry is circulated by means of natural convection and from which steam is withdrawn directly, providing evaporative cooling. The natural convection of the slurry is maintained by the boiling process. The boiling slurry reactor can be a burner-converter or possibly a breeder. As a burner-converter, it would operate on the $\text{U-H}_2\text{O-Th}$ or $\text{U-H}_2\text{O-Pu}$ fuel cycles, depending on the development and advancement of slurry technology. The breeder would operate on the $\text{U-D}_2\text{O-Th}$ cycle.

More specifically, the boiling slurry reactor concept is attractive for the following reasons:

1. Offers Promise of High Specific Power and High Power Density Operation. The fuel inventory in a boiling slurry reactor can be kept at very low levels, since the slurry remains essentially in the "pot" and is not circulated through external loops containing pumps, heat exchangers, etc. In addition, the elimination of core structure, fuel cladding, and other neutron poison material in the system can increase the neutron economy substantially and reduce the fuel requirements even further. With the absence of a high-resistance core, the reactor system is "hydrodynamically

clean," and as a result high recirculation rates, and hence high power density operation, can also be achieved. The high power density operation coupled with the low fuel inventory satisfies the requirements of a high specific power system.

2. Has a Potentially Attractive Fuel Cycle. The boiling slurry reactor possesses all the well-known advantages of the fluid fuel reactor system. Briefly, they are (1) high neutron economy resulting from the removal of fission product poisons and core structure; (2) elimination of costly fuel element fabrication; (3) breeding potential; and (4) the possibility of continuous fuel processing.

3. Possesses Excellent Heat Transfer Characteristics. The problem of fuel element "burnout" normally associated with heterogeneous boiling reactors is removed as such, since the fuel is dispersed as minute particles which are in intimate contact with the coolant. Therefore, heat transfer aspects will not be a major limiting criterion for determining power density limitations.

4. Steam Is Withdrawn Directly from the Reactor Vessel. The simplification in the reactor system and the advantages derived from the direct removal of steam from the reactor vessel are considerable. Since the highly radioactive slurry remains in the reactor vessel, the number of components in the external system is reduced and equipment such as circulating pumps, pressurizers, gas separator, etc., is no longer required. As a result, the remote-maintenance problem is significantly lessened. This is due not only to the reduction in components requiring maintenance, but also to the lower activity levels in the external loops.

5. Has Excellent Safety Characteristics Because of the intimate contact between the fuel and coolant, the self-regulating power response characteristics of the boiling slurry reactor should be excellent. It appears that the negative void coefficient will be exceptionally strong, since as steam voids are formed in the core, fuel is also expelled. Another important safety aspect is the use of the metal oxides as fuel, which eliminates the fear of fuel cladding meltdown and the associated metal-water reactions.

6. Simplicity of Operation and Control. The reactor can be controlled effectively without the use of mechanical control rods, since there is a unique set of reactor parameters of pressure, core steam volume fraction, slurry concentration and enrichment which can exist at any time to maintain a just critical system. Reactor control can be achieved by either varying the recirculation velocity or adjusting the slurry concentration.

7. Primary Circulation Is Achieved by Natural Convection.

Allowing the slurry to boil in the core creates sufficient density differentials so that recirculation of the slurry can be accomplished by natural convection. As a result, the recirculating pumps, valves and associated hardware, and the very formidable problem of remote pump maintenance are eliminated. Another beneficial aspect of the natural convection system is the "self agitation" which is characteristic of the boiling process. Such agitation should aid in maintaining a uniform distribution of particles and in reducing segregation and settling of the particulate material.

II. STATE OF THE "ART"

An evaluation of the Boiling Slurry Reactor Concept must depend at present on the technology that has been developed in the Heterogeneous Boiling Reactor and Fluid Fueled Reactor programs. A brief discussion of the technology that is pertinent to the Boiling Slurry Reactor and of the major areas of uncertainty that remain follows.

A. Slurry Technology.

The two types of slurry fuels for which any technology has been developed are the $\text{UO}_3 \cdot \text{H}_2\text{O}$ and $\text{UO}_3\text{-ThO}_2$ slurries. The major amount of development has been for the latter. Preliminary studies of $\text{UO}_3 \cdot \text{H}_2\text{O}$ as a slurry fuel have been made, but the technology has not been developed to the point of the ThO_2 slurries.^(1,22)

The stable form of uranium oxide in a hydrogen and oxygen atmosphere is $\text{UO}_3 \cdot \text{H}_2\text{O}$. The rodlet or platelet form of $\text{UO}_3 \cdot \text{H}_2\text{O}$ is easily suspended and redispersed by mild agitation. The solubility of $\text{UO}_3 \cdot \text{H}_2\text{O}$ in water is very low, even at high temperatures, so that the slurry may be regarded as practically neutral. Corrosion and erosion rates of a $\text{UO}_3 \cdot \text{H}_2\text{O}$ slurry in a stainless steel system are practically nil. Corrosion rates in a carbon steel system are not expected to be excessive.

The slurry concentrations that appear desirable from both a hydrodynamic and physics viewpoint (see Appendices A and B) lie in a range of 400-600 gm $\text{UO}_3 \cdot \text{H}_2\text{O}$ /liter. The fluidity of such a slurry should be reasonably good.

Slurries of $\text{UO}_3 \cdot \text{H}_2\text{O}$ have been circulated successfully at temperatures less than $\sim 400^\circ\text{F}$. Above 400°F , deposition of the slurry in soft cakes on the piping was observed. Sufficient development work to find whether this could be overcome was not done. The $\text{UO}_3 \cdot \text{H}_2\text{O}$ slurries at the present stage of development appear limited to operation at lower temperatures.

A major amount of development work has been done on the $\text{UO}_3\text{-ThO}_2$ slurries.⁽²²⁾ This would be the fuel of interest for a large breeder or converter. Thorium oxide prepared by the thermal decomposition of thorium oxalate appears suitable for a reactor slurry at concentrations up to 1500 gm Th/kg H_2O . Study of the various variables involved in the preparation of the slurry indicates that considerable control can be exercised over the properties of the slurry oxide.

Slurries of $\text{UO}_3\text{-ThO}_2$ have been circulated successfully at temperatures up to 500°F. The caking problems have been solved by preparation of the oxide. One of the advantages of $\text{UO}_3\text{-ThO}_2$ is that more highly concentrated slurries can be handled successfully; however, they are not as easily redispersed as are the $\text{UO}_3 \cdot \text{H}_2\text{O}$ slurries. Their rheological properties can also be changed easily by additives.

Studies of corrosion and erosion rates of $\text{UO}_3\text{-ThO}_2$ oxide slurry systems at high temperatures indicate that the problem may be successfully controlled. The corrosion rates of the carbon steels, while higher, may be acceptable for a short-term experiment. A carbon steel system has the additional advantage of not being susceptible to stress corrosion.

Experiments have been carried out which show that treatment with high-temperature water has practically no effect on the characteristic properties of ThO_2 . Also, experiments using simulated fission product addition have been run without significantly affecting slurry properties.

B. Boiling Water Reactor Technology.

Stable high-power density operation in natural convection boiling systems has been demonstrated both in laboratory loops as well as in existing heterogeneous boiling reactors, such as EBWR. Laboratory studies have demonstrated that high recirculation flow rates can be achieved by means of natural convection in a properly designed system. Calculation procedures have been developed for boiling systems so that reliable analyses can now be made.

The stability of boiling reactors has proved to be considerably better than initially anticipated. The stability problem has been subjected to a concentrated study and, as a result, an understanding of the pertinent factors is being acquired. The information derived from the existing heterogeneous boiling reactors, such as EBWR and BORAX, has contributed greatly toward clarifying the boiling reactor stability problem.

C. Areas of Uncertainty.

Although slurry technology has progressed rapidly during the past few years, major gaps remain where there is a complete lack of data. Perhaps the most important of these is the behavior of slurries under actual reactor conditions. The effects of the radiation and fission products on the rheological properties of the slurries has not been established. Additional problems, such as rate of radiolytic gas evolution, caking tendencies of slurries under irradiation, rate of gaseous fission product release, etc., which are affected by the nuclear environment must be studied and resolved.

Another major uncertainty is the stability of a critical boiling slurry system. Although the stability problem of the boiling slurry reactor is related to the heterogeneous boiling reactor, several basic differences exist which could cause the stability characteristics of the boiling slurry reactor to differ considerably. The vapor formation time constant of the boiling slurry reactor should be smaller, since heat does not pass through a fuel element and cladding; in fact, a substantial fraction of the heat could be released directly in the coolant. Also, the vapor residence time could be expected to differ since less resistance to vapor removal is present with the absence of core structure. Finally, the unique geometry of the boiling slurry reactor could conceivably affect the overall stability problem.

There are also very limited data available on boiling slurry systems. The effect, if any, of boiling on the physical properties of the slurry, corrosion, slurry separation and caking, etc., remains to be evaluated.

III. NEED FOR REACTOR EXPERIMENT

Although laboratory tests can supply valuable information and data, so that some of the uncertainties may be resolved, these experiments can supply only partial answers, since the nuclear effects cannot be duplicated. Because the major uncertainties of the boiling slurry reactor are primarily nuclear in nature, as discussed above, the final answers can be obtained only through an actual reactor experiment. In-pile tests could be run, but they are of necessity very limited in scope, since there are numerous restrictions regarding material of construction, size, etc., which are designed to safeguard the reactor in which they are placed. Because of these restrictions, in-pile loops have proven to be extremely costly.

IV. PURPOSE OF THE EXPERIMENT

The experiment described is of the "go-no-go" type. It is not intended to be a sophisticated experiment and as a result would not supply all of the answers. The primary purposes of the experiments will be to determine

whether the predicted high specific powers can be achieved under stable conditions and to explore the safety characteristics of the reactor concept. If the experiment is successful, sufficient data and information could be obtained so that the merits of the boiling slurry concept as a practical nuclear power reactor can be evaluated, and a decision to proceed with a development program could be made. With this in mind, sufficient flexibility has been incorporated into the preliminary design so that not only the feasibility of the concept can be established, but also limited engineering and nuclear tests could be run. Some of the studies that could be made are as follows:

1. A parametric-type study to investigate the relationship between reactor power, fuel concentration, recirculation flow rate, pressure and other system parameters. Such a study is needed to obtain a better understanding of the behavior of boiling slurry reactors over a range of conditions and to explore limits of operation.
2. Investigation of the rate of radioactive gas evolution and associated activity levels as a function of reactor power. The activity levels will also be measured in all parts of the external system and the reactor proper to study the deposition of activity.
3. Studies on the behavior of the slurry during reactor operation. Information on the behavior and chemical stability of the slurry under boiling conditions and on possible problems of precipitation and adhesion to structural components is needed.
4. A study of the overall stability problem and an evaluation of the reactor safety features. The effect of sudden reactivity addition must be observed in small-scale experiments at steady-state conditions. Also, the effect of fuel concentration gradients or fluctuations that could occur under certain conditions must be studied.
5. Investigation of the rates of decomposition of water inside the reactor. The decomposition should be less than that observed for the homogeneous solution reactor since the fission fragments are traveling only a portion of their mean stopping path in the water. It is difficult to predict the amount of decomposition from studies performed outside the reactor. Also, various catalysts would be added to the slurry to attempt to recombine the gases internally.
6. Physics tests on criticality, void coefficients, temperature coefficients, conversion ratio, etc.
7. Study of the vapor transport and separation problems associated with boiling reactors under high power density operation in a slurry.

8. Investigation of system hydrodynamics so that a sound calculation procedure can be developed for predicting the performance of a slurry reactor.

9. Investigation of the response and control characteristics of the boiling slurry reactor.

10. Obtain information on the erosion and corrosion rates in the reactor and associated structural components under sustained operation.

V. PRELIMINARY PLANT DESIGN

A. General

A system pressure of 150 psi was chosen for the experimental reactor. Although a higher pressure would have been desirable, that selected was deemed sufficient for the purpose of the experiment. Carbon steel was chosen for a structural material in keeping with the philosophy of the experiments.

The plant is designed for operation at a maximum power level of 5 Mw. This gives sufficient flexibility in the design so that if the initial low-power experiments are successful, high-power experiments can be run to obtain reactor design data.

The plant layout is shown in Figs. 1, 2, 3, and 4. Basically, the plant consists of two tanks, one 15 by 25 ft and the other 15 by 17 ft, which house the reactor and major components; and two Armco buildings, one of which houses the slurry preparation unit, make-up water system, motor starters, and instrument substation, and one which protects the top of the tanks and permits working on the reactor in inclement weather.

The placing of the components in the tank is twofold. By flooding the tanks, shielding is provided during operation and for remote maintenance of components. Also, the tanks will contain the activity in case of a spill. The two tanks are also surrounded by a mound of dirt to provide additional shielding and protection from freezing for external piping entering and leaving. Reactor operation will be conducted remotely from a control trailer located a safe distance from the reactor.

B. Description of Plant Components

The major components of the boiling slurry reactor experiment are the reactor vessel, heat-dissipation system, and the high-pressure off-gas system which is used for reactor operation and control.

FIG. 1
PRELIMINARY BOILING SLURRY REACTOR EXPERIMENT FACILITY LAYOUT

FIG 2
SLURRY PLANT PICTORIAL

FIG. 3
SIMPLIFIED BSRE FLOW DIAGRAM

FIG 4
BSRE REACTOR & AUXILIARY
COMPONENT ELEVATION

The flow diagram of the plant is shown in Fig. 3. The steam generated in the reactor flows to the condenser-boiler, where most of the steam is condensed and gas diluent is added. The remaining steam, fission gases, diluent gas and radiolytic hydrogen and oxygen flow to the recombiner, where the hydrogen and oxygen are recombined. The exit gases from the recombiner pass to the after-cooler where they are condensed. The noncondensable gases which contain the radioactive fission gases are recycled into the high-pressure gas stream.

The feasibility of installing the recombiner directly after the steam-throttling valve is being investigated. This would eliminate several pieces of equipment and simplify the plant considerably.

The reactor and slurry storage and handling units are placed in one tank and the remaining components are located in the second tank. The purpose of such a layout is to isolate the fuel-bearing slurry system from the non-nuclear plant. A brief description of the major plant components is given below.

C. Reactor Vessel

The BSRE reactor vessel is shown in Fig. 5. It consists of a 2-ft cylindrical core, a riser, a steam slurry separator, and two downcomers. Sections of the vessel other than the core where there is a chance of achieving criticality are heavily poisoned to prevent such an occurrence. Recirculation of the slurry through the core is by natural convection. The probable performance characteristics of the reactor system are discussed in Appendix A.

This particular design was selected over the standard pressure vessel for several reasons:

(1) The problem of vapor separation and removal from a high power density, small compact system is reduced. If a 2-ft pressure vessel were used, the superficial steam velocities in the disengaging section would be excessive and the steam-slurry separation problem would be acute.

(2) The reactor vessel is made from standard piping and fittings; therefore replacement of any portion could readily be made.

(3) The system shown is much more flexible than that which could be obtained from a standard pressure vessel and, as a result, is more desirable for an experiment of this type.

FIG 5
BSRE REACTOR
VESSEL ASSEMBLY

(4) The cost of fabrication is lower or at least equal to a standard vessel.

(5) The experimental data can be taken more readily from the proposed reactor than from a pressure vessel type.

(6) The vessel is of a type which can be readily adapted to a heterogeneous boiling reactor; therefore any information derived from such a system would be very useful in itself.

The riser is a 12-in. diameter pipe extending into the separator. The separator is constructed from 36-in. IPS schedule 80 ASTM-A106 Grade A pipe, with standard caps for end closure. Internal plates of neutron absorber are placed through the separator to prevent criticality, and are also used for steam and slurry guidance. The two downcomers are 8-in. pipes of the same grade pipe. Ring joint flanges provide ready disassembly for removal or replacement if desired.

The core is constructed from a 24-in. IPS schedule 50 ASTM-A106 Grade A seamless pipe, with 24 by 8-in. and 24 by 12-in. standard concentric reducers attached to give a 24-in. active core section. Preliminary analysis indicates that a thermal shield will not be necessary, but an alternate design including a thermal shield that utilizes the make-up water for cooling can be used if necessary. The core section is easily removed for inspection and replacement.

D. Fuel Slurry System

Two types of slurry fuels could be considered: $\text{UO}_3 \cdot \text{H}_2\text{O}$ or $\text{UO}_3\text{-ThO}_2$ in light water.

Initial fuel loadings of $\text{UO}_3\text{-ThO}_2$ would be approximately 500 gm/liter with 8% fully enriched uranium. The fuel loadings in the case of $\text{UO}_3 \cdot \text{H}_2\text{O}$ would be approximately 5% enriched with concentrations ranging from 400-600 gm/liter.

Detailed physics calculations giving core loadings, enrichments, etc., are discussed in Appendix B.

E. Slurry Preparation

The slurry preparation system is located in the Armco Building adjacent to the reactor plant. It consists of an 8-in. diameter tank, 10 ft long, in which the fuel is mixed with water. The slurry is dispersed and suspended by the mixer located at the top of the tank. The mixing tank is equipped with hi-low level indicators and a D-P cell. The slurry concentration can be calculated from the static pressure

reading obtained from the D-P cell. After each batch of slurry has been prepared, it is pumped to the slurry storage system. The slurry preparation area is accessible when the reactor is not running.

F. Slurry Storage

The slurry storage system is composed of tanks located at the periphery of the water tank housing of the reactor. The geometry of the slurry storage tank is set so that a noncritical system exists under all contemplated operating conditions of concentration, enrichment, temperature, etc., during the course of the experiment. Suspension of the slurry is maintained by a mixer located at the top of the tank. The mixing shaft will be encased in a nuclear poison, such as cadmium or boron steel, to aid in maintaining noncritical conditions. Because of the high power requirements in mixing highly concentrated non-Newtonian slurries with power-driven agitators and the problem of seal leakage, a gas-agitation system should be considered, as well as methods for reducing the number of tanks by poisoning. The slurry concentration is obtained from the static pressure difference over a fixed height which is measured by a D-P cell unit. The levels in the tanks are controlled by high-low level indicators in conjunction with the D-P cells.

Three of the slurry storage tanks may be used as slurry concentrators. Concentration of the slurry is required when reactor operating ranges are changed. The concentrators have several additional D-P cells so that the slurry concentration levels and gradients within the tank can be followed more readily. To concentrate, agitation within the tank is stopped and the slurry is allowed to settle. After the desired concentrations have been obtained, as indicated by the D-P cell readings, the concentrated slurry is removed from the bottom of the tank.

The slurry will be transferred to and from the slurry tanks by gas pressurization. The operation of the slurry system must, of necessity, be entirely by remote control.

G. Gas-handling System

The problem of direct disposal of the noncondensable radioactive fission gases is circumvented by recycling them through the high-pressure gas system. Gas is required for reactor control, pumping of slurry by pressurization, and for line sparging. The gas system consists of a two-stage water-cooled compressor coupled with three storage tanks of 35 ft³ capacity. Either He or O₂ will be used in the gas system, depending on the type of slurry being used and conditions desired in the reactor.

Initially one of the tanks is filled with gas at approximately 250 psi for use in reactor startup and operation. A second tank is maintained as a low-pressure bleed tank which collects the gases from the cold trap and slurry-handling system during reactor operation. The diluent radioactive fission gases are pumped directly back into the high-pressure storage tank by the compressor. Thus, the radioactive fission gases are continuously recycled in the closed high-pressure gas system. Because of the activity levels anticipated, the entire gas system will be welded shut to minimize gas leakage.

The third storage tank is used for secondary storage in the event of reactor shutdown. The radioactive gases are held up until the short-lived activity decays to a sufficiently low level. The gas will then be gradually discharged up the stack without exceeding accepted rates of activity release. While this process is proceeding slowly, the high-pressure storage tank can be refilled with gas and reactor operation resumed.

H. Heat-dissipation System

The heat-dissipation system consists of: (1) an atmospheric boiler-condenser; (2) recombiner and aftercooler; and (3) cold trap. A brief description of each is as follows.

1. Atmospheric Boiler-Condenser. The reactor steam is dumped directly to the boiler-condenser unit through a 4-in. pipe. The steam discharge is controlled by a throttling valve and measured by an orifice. The steam condenses within the tubes and the water drains to the condensate tank. On the shell side, cooling is provided by boiling water at atmospheric pressure. The steam from the boiler is discharged directly to the atmosphere. The boiler-condenser unit is a modified evaporator unit with $\frac{3}{4}$ -in. nickel tubes. The unit is designed to take full reactor pressure. Feed water for the shell side cooling is provided from a deionized water supply tank of 15,000-gal capacity located at the site.

2. Recombiner and Aftercooler. The oxygen and hydrogen will be recombined by passing the diluted gas stream over platinized nickel screening in a catalytic recombiner. Exhaust gases from the recombiner ($\sim 500^{\circ}\text{F}$) are condensed and cooled in the aftercooler. Recombiner pressure is controlled by an exit throttling valve and the amount of gas passing into the recombiner is metered. An alternate design for the experimental system would put the recombiner directly after the steam-throttling valve. This would eliminate the need for a diluent and aftercooler. Internal recombination catalysts could also be tried as part of the experimental program.

3. Cold Trap. Final traces of moisture will be removed in the cold trap which is maintained just above freezing. The condensate will be returned to the condensate tank and the noncondensable gases will be discharged to the bleed tank of the air and gas-handling system.

I. Water Supply System

Water for the reactor system is brought to the site and stored in the raw-water storage tank. The raw water is pumped through a 10-gpm mixed-bed deionizer and the deionized water is stored in a 15,000-gal capacity treated water supply tank. Water from this tank will be used for makeup to the condensate tank, makeup to the slurry system, and feed water for the condenser unit.

J. Electrical System

Three 75-kva transformers will be located at the site to provide the electrical requirements for the tank heater and various equipment. The electricity will be brought in by a 12,500-volt transmission line.

A motor-control center located in the Butler Building at the site will distribute 480-volt leads to the various loads. It will consist of the following units: one main breaker, one starter for the 7.5-hp condensate makeup pump, three starters for the water handling pumps, one starter for the air compressor, and breakers for the four tank heaters. An additional panel will supply the lighting needs and control instrumentation power.

VI. REACTOR CONTROL

For a boiling slurry reactor there is a unique set of reactor conditions of pressure, core steam volume fraction, slurry concentration, and slurry enrichment which can exist at any time to maintain a just critical system ($k_{eff} = 1$). As a result, the reactor can be controlled effectively without the use of mechanical control rods. Reactor control can be achieved by either adjusting slurry concentration or by varying the recirculation velocity.

Adjusting the recirculation velocity would cause the reactor power level to respond very quickly, since the reactor power will adjust to maintain the same amount of reactivity tied up in voids. A sudden increase in the recirculation velocity would produce a supercritical condition ($k_{eff} > 1$), since the core mean steam volume fraction would be lowered. The reactor power would therefore increase to again re-establish a just-critical system ($k_{eff} = 1$). A sudden drop in recirculation flow rate would automatically drop the reactor power level, since a subcritical system would tend to exist. The reactor can be controlled by velocity adjustment very quickly over wide ranges of power levels.

The recirculation velocity is most conveniently varied by adjusting the "net driving head" of the natural circulation system. This is accomplished by the injection of gas (voids) into the downcomer. The gas injection is made at points near the top and bottom of each downcomer to assure quick production of gas voids in the downcomer regardless of the downcomer velocity.

Variation of reactor power by adjusting slurry concentration is a more gradual type of secondary control. The slurry concentration can be changed by either of several methods. Other means of varying concentration by the use of centrifugal devices, such as hydroclones, are possible.

The slurry concentration can be varied by a batchwise procedure by using the slurry-storage and handling system. Concentration of the slurry in a critical system can be accomplished by first reducing the make-up water flow and allowing the excess water in the reactor to boil off until the flow level alarm is tripped and then injecting additional concentrated slurry from the storage tanks to re-establish the proper levels. To concentrate under noncritical conditions the circulation would be stopped and the slurry allowed to settle in the reactor. The excess water is bled from the upper region of the reactor into the slurry storage tank. Additional concentrated slurry is then pumped into the reactor until criticality is achieved. The water which was removed is fed back into the reactor as make-up water to vacate the slurry-handling tanks. The slurry concentration is lowered by the process of dilution. The slurry is transferred from the reactor to the slurry-storage tank and simultaneously the proper excess of make-up is injected.

Further study of the control problem may indicate that other control schemes which would tend to expedite and perhaps simplify the reactor operational procedure could be incorporated into a final design.

VII. REACTOR STARTUP

The reactor would initially be started up with a natural uranium slurry and the off-gas system to completely check out the system under noncritical conditions. These preliminary shakedown runs would establish the operability of the system. Should inadequacies in the design become apparent or malfunctions develop in the system, they may readily be corrected. Following the shakedown period, initial criticality experiments and low-power runs would be made.

VIII. REACTOR INSTRUMENTATION

The following instrumentation is required for control purposes and for acquisition of data:

(1) D-P cell on the downcomer legs to record the static pressure difference across a fixed height. From this measurement, the circulating slurry concentration can be calculated. The gas void fraction can also be obtained when gas is injected into the downcomer for velocity regulation. This will also aid in reactor control.

(2) D-P cell on the riser. This measurement will yield the mean steam void fraction which is necessary for evaluation of the reactor performance characteristics.

(3) Thermopiles in the downcomer legs for measuring the recirculation velocity by a heat-balance method. The thermopiles will measure the subcooling resulting from make-up water injection. Knowing the flow rate of make-up water and the subcooling, the recirculation flow rate of the slurry can be calculated.

(4) High-low indicator alarms in the separator drum to aid in slurry-level control during reactor operation.

(5) A D-P cell across the demister pad at the steam exit from the separator drum. This measurement will reveal the degree of slurry carry-over, if any, since any slurry carried in the steam would tend to cake in the pad and increase the pressure drop.

(6) Nuclear instrumentation for reactor startup. This will include a miniature ion chamber inside the core for dynamic flux measurements and, located on the outside periphery of the core, two BF_3 counters for the slow-neutron range, two compensated ion chambers for the log range, and three uncompensated ion chambers for the power range.

IX. PLANT INSTRUMENTATION

A. Introduction

Instrumentation is proposed only for measurement of those parameters needed for satisfactory control of the reactor, slurry and air systems. The measurement concepts are based on the necessity for an entirely remote and spatially distant operation. Transmission of measurements to and control signals from the remote control center will be electrical.

B. Process Instruments

Process instruments cover measurements of all variables except those in the nuclear and electrical systems.

Level-density measurements are provided for the slurry make-up tank, all the slurry-storage tanks, the reactor, heat exchanger, and condensate tank. High and low-level alarms are also provided in most cases. Use of a diaphragm-type sensing element is assumed for all slurry applications. It should be noted that this type of unit as supplied by the known manufacturers will require a change in the filling medium because of the polymerizing effect of gamma radiation on silicone oils.

Orifice plates are used for flow measurements except for that of the slurry, for which a flow tube is proposed. This latter unit should probably use a strain gage sensor in place of the usual D-P cell to permit flush installation and thus to avoid clogging of meter lines with slurry. Water purging is a complicated alternative.

Pressure is measured on all the slurry tanks, the air system, the steam system, the reactor vessel and in the discharge of all pumps. Where slurry pressure is measured directly, chemical seals will be required to prevent clogging of the impulse lines. High and low-pressure alarms are provided as required.

Temperature is measured with thermocouples in the make-up tank, all the slurry tanks, the reactor, the steam and condensate systems, the recombiner and the air system. Thermocouple leads are taken to a reference junction station from which copper wire is used to the remote-control station.

At the remote-control center, multi-point strip chart recorders are used to read out all variables except those which are used for control. These control signals are read out on individual recording controllers.

C. Nuclear Instruments

The nuclear instrumentation system is designed to provide adequate coverage of the reactor at all operating levels from sources to full power. Two channels each are provided in the source and intermediate ranges and three channels in coincidence in the power range. A single wide-range channel with remote switching is provided to cover the overall power operation. Because of the distance between the reactor and the control center, additional amplification is provided as required. The amplifiers together with the preamplifiers will be located in the reactor area, probably in the water treatment building. A recorder is provided for the log counting rate channels, another for the log N channels, another for the wide-range channel, and three miniature recorders for the power channels. Period and level-indicating meters and scalars are also included.

APPENDIX A

PROBABLE PERFORMANCE PARAMETERS

Hydrodynamic Considerations

The performance of boiling reactors are to a large extent dependent on the hydrodynamic characteristics of the reactor system; that is, for a given amount of reactivity tied up in the core steam voids, the reactor power is almost directly proportional to the recirculation velocity.

The recirculation velocity for a natural circulation system can be calculated by the following equation, which is derived from a static pressure balance on the flow system:

$$\frac{V_0^2}{2g} = \frac{a + b + c}{n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7 + n_8 + n_9 + n_{10} + n_{11}}, \quad (1)$$

where the individual terms are classified in the following manner.

Hydrostatic Heads

$a = (\bar{\rho}_D - \bar{\rho}_{NB}) L_{NB}$	Net driving head in nonboiling section.
$b = (\bar{\rho}_D - \bar{\rho}_B) L_B$	Net driving head due to steam voids in boiling section.
$c = (\bar{\rho}_D - \bar{\rho}_R) L_R$	Net driving head due to steam voids in the riser section.

Pressure Drop due to Frictional Losses

$n_1 = f_D \left(\frac{L_T}{D_D} \right) \left(\frac{\rho f^2}{\bar{\rho}_D} \right) \left(\frac{A_C}{A_D} \right)$	Frictional resistance in downcomer.
$n_2 = f_C \left(\frac{L_{NB}}{D_C} \right) \left(\frac{\rho f^2}{\bar{\rho}_{NB}} \right)$	Frictional resistance in nonboiling region of core.
$n_3 = f_C \bar{R} \left(\frac{L_B}{D_C} \right) \rho_f$	Frictional resistance in boiling region of core.
$n_4 = f_R R_R \left(\frac{L_R}{D_R} \right) \left(\frac{A_C}{A_R} \right)^2 \rho_f$	Resistance in adiabatic risers due to steam voids.
$n_5 = H \rho_f$	Frictional losses due to expansions and contractions in external circuit; H represents a summation of the loss coefficients.

Pressure Drop due to Acceleration of Fluid

$$n_6 = \left(\frac{A_C}{A_D} \right)^2 \rho_f$$

Acceleration of liquid due to flow area reduction from upper plenum to downcomer (neglecting velocity of liquid in upper plenum).

$$n_7 = \frac{\rho_f^2}{\rho_D}$$

Acceleration of liquid due to flow area reduction from lower plenum to core (neglecting velocity of liquid in lower plenum).

$$n_8 = 2 \rho_f \left(\frac{\rho_0 - \rho_f}{\rho_D} \right)$$

Acceleration due to density change in nonboiling section of core.

$$n_9 = r \rho_r^2$$

Acceleration of fluid due to formation of steam voids in the boiling section of core.

$$\text{For } \frac{A_R}{A_C} < 1$$

$$n_{10} = \rho_f \left[\left(\frac{A_C}{A_R} \right)^2 \left(\frac{1}{(1 - \alpha_R)^2} + \frac{K_C}{(1 - \alpha_R)^2} - \frac{1}{(1 - \alpha)^2_C} \right) \right]$$

Acceleration of fluid due to area reduction from core to riser (based on actual liquid flow area).

Recoverable Acceleration Pressure Drop

$$\text{For } \left(\frac{A_R}{A_C} \right) > 1$$

$$n_{10} = -2 \rho_f \left[\left(\frac{A_C}{A_R} \right) \frac{1}{(1 - \alpha_R)(1 - \alpha_C)} - \left(\frac{A_C}{A_R} \right)^2 \left(\frac{1}{1 - \alpha_R} \right) \right]^2$$

Deceleration of fluid due to area expansion from core to riser (based on actual liquid flow area).

$$n_{11} = -E \rho_f \left(\frac{A_C}{A_D} \right)^2 \left[1 - \left(\frac{A_D}{A_C} \right)^2 \right]$$

Deceleration of fluid due to area expansion from downcomer to lower plenum.

E = diffuser efficiency

The boiling slurry reactors possess a rather unique flow geometry. Inasmuch as there is no core structure, the frictional losses in the core are nil, since the equivalent diameter of the flow path is very large. The same is true for the riser and downcomers, which also have small frictional pressure drops. As a result, the principal losses in the system are the irrecoverable acceleration pressure drops.

The acceleration pressure drops are a function of the relative flow areas existing in various regions in the reactor system. More specifically, the losses are very sensitive to the ratio of downcomer flow area to core flow area A_D/A_C , and to the ratio of riser flow area to core flow area A_R/A_C ; see equation (1). For the case of $A_D/A_C < 1$ approximately 80% of the pressure drop occurring at the contraction from the upper plenum or drum to the downcomer is irrecoverable unless a high-efficiency diffuser is used for the expansion into the lower plenum or core. With the use of a high-efficiency diffuser, upwards of 75% of the pressure drop can be recovered. On the other hand, the acceleration pressure drop occurring in the core and in the riser ($A_R/A_C < 1$) are treated as completely irrecoverable at the expansion into the upper drum or plenum. This assumption is borne out by laboratory tests which have shown the pressure drop across an abrupt expansion of large area change is practically zero or very slightly positive for a two-phase mixture.

Reactor System

The acceleration pressure drops can be virtually eliminated by designing a system in which area ratios A_D/A_C and $A_R/A_C \geq 1$. Such a system would be hydrodynamically clean and as a result high recirculation velocities could be obtained with nominal riser heights. The simplest such system would be a pressure vessel with an internal guide structure (see Fig. 6A). The guide structure would be placed so that boiling would take place only in the upcomer. The positioning of the guide structure will depend upon the pressure, power distribution, desired downcomer-upcomer area ratios, etc. Such a system would be ideal for a breeder reactor operating on the U^{233} - D_2O - ThO_2 cycle, since both the fuel and D_2O inventory can be kept at a minimum. The specific power of such a system would be determined primarily by limitations of natural vapor separation.

An alternate system, shown in Fig. 6B, is composed of a core with multiple risers and downcomers connected to drums in which vapor separation is obtained. Such an arrangement would probably be required for a high-power density, large total power reactor, since the vapor separation problem becomes acute.

In designing the reactor experiment, the latter type system was chosen for reasons discussed in the section on Reactor Vessel. The

FIG. 6
SCHEMATIC DIAGRAMS OF REACTOR SYSTEMS

objective of obtaining a hydrodynamically clean, high-performance system was sacrificed to an extent in the interest of obtaining a simple low-cost system which would satisfy the requirements of the experiment.

Reactor Performance

The estimated reactor performance characteristics of a $\text{UO}_3 \cdot \text{H}_2\text{O}$ slurry are given in Figs. 7 and 8, which show the relationship between the core velocity, mean core steam volume fraction, power density, riser steam volume fraction, and total reactor power. The core velocity shown is the superficial velocity at the maximum core diameter. Although the recirculation velocities do not appear very large, it should be borne in mind that as boiling commences the actual slurry velocity increases as it

FIG. 7
CORE STEAM VOLUME FRACTION AS A FUNCTION OF REACTOR POWER

FIG. 8
CORE RECIRCULATION VELOCITY AS A FUNCTION
OF CORE STEAM VOLUME FRACTION

flows through the core. This results from the creation of steam voids which reduce the actual fluid flow area.

The actual slurry velocity will therefore be considerably greater than the superficial velocities indicated. Another factor that could be very beneficial for maintaining a dispersed slurry is the "self agitation" resulting from the boiling process.

The low superficial core velocity is due to the irrecoverable acceleration pressure drop in the reactor system resulting from the constricted downcomer and riser. As a result the power densities are not exceptionally high

but are equal to or greater than the power density that could be obtained from a heterogeneous boiling reactor of comparable geometry.

The performance estimates are based on data obtained from a steam-water system and the assumption was made that the slurry was Newtonian in nature.

NOMENCLATURE

Primary Letter Symbols

A	total flow area, sq ft
D	equivalent hydraulic diameter, defined as $4(\text{flow area}/\text{wetted perimeter})$.
f	Fanning friction factor
g_c	conversion factor, $(\text{lb}_m)(\text{ft})/(\text{lb}_f)(\text{sec}^2)$
H	miscellaneous velocity head losses due to restrictions in downcomer, turning losses, etc., based on the velocity at the inception of boiling.
L	length, ft
r	acceleration pressure drop multiplier, ft^3/lb
R	local two-phase friction factor multiplier

$\bar{R}$	average two-phase friction factor multiplier
v	specific volume
V	velocity, ft/sec
X	quality, ratio of vapor flow rate to total mixture flow rate.

Primary Greek Symbols

α	volume fraction, ratio of vapor phase flow area to total flow area.
ρ	density, lb/ft ³

Subscripts

B	boiling
C	core
D	downcomer
e	refers to exit of the core
f	saturated liquid
NB	nonboiling
o	point in core where mixture reaches saturated conditions
R	riser
T	total

APPENDIX B

REACTOR PHYSICS

Part I. UO₃·H₂O-H₂O Slurry System - J. A. Thie

Criticality

The boiling slurry reactor has three degrees of freedom:

1. Enrichment (χ = atoms of U²³⁵/total uranium atoms)
2. Concentration ($C = \frac{1}{6}$ kg of UO₃·H₂O per liter of slurry),
3. Voids (α = fraction of volume occupied by voids).

Thus, the material buckling of this system can be evaluated as a function of these three variables. This has been done using a modified three-group diffusion theory that allows resonance fission.

As a critical equation for the bare reactor (ignoring delayed neutron transport), one has

$$\frac{1 - \delta}{p_e} = \frac{k}{(1 + L^2 B^2) (1 + \tau_1 B^2) (1 + \tau_2 B^2)} ,$$

where τ_1 and τ_2 have been given by Deutsch,⁽²³⁾ p_e is the escape probability from $1/v$ capture and U²³⁵ resonance capture in the epithermal region, and δ is the ratio of epithermal fissions to total fissions. The latter is

$$\delta = \frac{\eta_e f_e p (1 - p_e)}{(1 + \tau_1 B^2) (1 + \tau_2 B^2)} .$$

A simplified treatment⁽²⁴⁾ of the thermal group's constants has been adopted.

Table 1 shows the buckling as function χ , C , and α . The simple dependence on the latter is due to the fact that only τ_1 , and τ_2 , and L^2 are dependent on α , which is taken as position independent. A more detailed breakdown of the physics is given for a particular case in Table 2, which might be representative of operating conditions.

The geometric buckling of a 2-ft cylinder reflected by water and 1-ft cylinder can be computed by two-dimensional diffusion theory, but simple one-dimensional theory can be used to bracket this quantity. The latter result is $B_g^2 = 0.00495 \begin{smallmatrix} +0.0006 \\ -0.0010 \end{smallmatrix} \text{ cm}^{-2}$.

Table 1
 k_{∞}
 MATERIAL BUCKLINGS/ $(1 - \alpha)^2$ OF VARIOUS CONCENTRATIONS AND ENRICHMENTS

χ C	0.035	0.04	0.045	0.0525	0.06	0.08	0.12	0.20	0.93
0.0333							$\frac{1.213}{0.004454}$	$\frac{1.445}{0.00916}$	$\frac{1.908}{0.01773}$
0.05					$\frac{1.050}{0.001073}$	$\frac{1.191}{0.004020}$	$\frac{1.377}{0.00781}$	$\frac{1.575}{0.01179}$	$\frac{1.948}{0.01774}$
0.0667			$\frac{1.032}{0.000689}$	$\frac{1.108}{0.002285}$	$\frac{1.172}{0.003627}$	$\frac{1.305}{0.00636}$	$\frac{1.472}{0.00976}$	$\frac{1.644}{0.01317}$	$\frac{1.963}{0.01703}$
0.0833		$\frac{1.066}{0.001422}$	$\frac{1.123}{0.002618}$	$\frac{1.196}{0.004135}$	$\frac{1.257}{0.00540}$	$\frac{1.381}{0.00793}$	$\frac{1.533}{0.01100}$	$\frac{1.684}{0.01395}$	$\frac{1.965}{0.01592}$
0.1	$\frac{1.073}{0.001576}$	$\frac{1.137}{0.002913}$	$\frac{1.192}{0.004057}$	$\frac{1.261}{0.00550}$	$\frac{1.319}{0.00668}$	$\frac{1.435}{0.00903}$	$\frac{1.574}{0.01182}$	$\frac{1.709}{0.01440}$	$\frac{1.958}{0.01448}$
0.1667	$\frac{1.244}{0.00516}$	$\frac{1.299}{0.00630}$	$\frac{1.346}{0.00726}$		$\frac{1.450}{0.00938}$		$\frac{1.644}{0.01314}$		

Table 2
 LATTICE CONSTANTS FOR $\chi = 0.09$, $C = 0.0667$, $\alpha = 0.2$

Neutron Temperature	490°K	$\tau_1 = \frac{1}{3}\bar{\Sigma}_{a1}\bar{\Sigma}_{tr1}$	47.18 cm ²
$\bar{\Sigma}_{tr3}$	1.41 cm ⁻¹	η_{25}	2.085
$\bar{\Sigma}_{a3}$	0.03685 cm ⁻¹	p	0.9437
$L^2 = \frac{1}{3}\bar{\Sigma}_{a3}\bar{\Sigma}_{tr3}$	6.42 cm ²	$k_{\infty} = \eta^{25}Fp$	1.357
$\bar{\Sigma}_{tr2}$	0.390 cm ⁻¹	η_e^{25}	1.763
$\bar{\Sigma}_{a2}$	0.0546 cm ⁻¹	p _e	0.9649
$\tau_2 = \frac{1}{3}\bar{\Sigma}_{a2}\bar{\Sigma}_{tr2}$	15.65 cm ²	$k_{\infty e}$	1.247
$\bar{\Sigma}_{tr1}$	0.1453 cm ⁻¹	B ²	0.00473 cm ⁻²
$\bar{\Sigma}_{a1}$	0.04865 cm ⁻¹		

In regard to the accuracy of low-group diffusion theory, it has been pointed out⁽²⁵⁾ that ages about 15% lower than those typically used in water systems must be used to reconcile theory and experiment for small homogeneous systems. If this result is applied to the above calculations, the material bucklings will be about 15% higher.

Reactivity Coefficients

It will suffice for current purposes to estimate the void coefficient from

$$\frac{d\rho}{d\alpha} = -\frac{d}{d\alpha} \left[\frac{1 + \frac{M_0^2 B^2}{(1-\alpha)^2}}{k_\infty} - 1 \right] = 2 \frac{1 - k_\infty}{k_\infty(1-\alpha)}$$

For the case of Table 1, this is -0.9, which is substantially more negative than that of heterogeneous boiling reactors.

Since enrichment affects principally thermal utilization, F , its effect on reactivity is essentially

$$\chi \frac{d\rho}{d\chi} \cong \frac{\chi}{F} \frac{dF}{d\chi} \cong \frac{1}{F} - 1$$

which would be 0.45 for Table 1.

From Table 1 and the relation

$$\rho = M^2(B^2 - B_g^2)/k \quad ,$$

the effect of changing concentration at constant χ and α is readily obtained.

Power Distribution

A precise distribution of power in the slurry is a complex multi-dimensional physics and hydraulics problem. However, doing simple one-dimensional calculations for the case of Table 1 gives for the axial power distribution:

TYPICAL ESTIMATED POWER DISTRIBUTION

	<u>Per Cent of Total Power</u>
8-in. pipe below core	8%
Core	91%
1-ft pipe core	1%

Kinetics

The kinetic behavior of a boiling slurry might be comparable with that of other homogeneous systems. Of two sources of reactivity disturbances during operation, local concentration fluctuations and local void fluctuations, it is expected that the latter will be the larger contributor to fluctuations in power. Thus with a void coefficient of 0.9, as long as the mean voids do not fluctuate more than $\Delta\alpha = 0.008$, the instantaneous reactivity will not exceed prompt criticality. A prime motive for this experiment is to investigate this kinetic stability. In particular, the stability function, P_R ,

introduced for heterogeneous boiling reactors⁽²⁴⁾ may play an important role. (The probability per second that in an undisturbed reactor the power is exceeding R times the mean power.)

This large negative void coefficient can be regarded as an advantage when considering questions of inherent safety.

Part II. $\text{UO}_3 \cdot \text{H}_2\text{O}$ - ThO_2 - H_2O System - D. E. Meneghetti

Material Bucklings and Initial Conversion Ratios

Calculations of material bucklings for a range of concentrations of the constituents are given in Table 3. Four neutron energy groups were used in the analyses: Group I, 1.35 to 10 Mev; Group II, 9.12 kev to 1.35 Mev; Group III, 0.4 ev to 9.12 kev; Group IV, 0 to 0.4 ev. The Group III capture cross section for thorium was adjusted in all cases to assure capture compatible with the effective resonance integral values computed by Dresner.

Table 3

CALCULATED MATERIAL BUCKLINGS FOR VARIOUS $\text{UO}_3 \cdot \text{H}_2\text{O}$ - ThO_2 - H_2O MIXTURES*

Grams of ThO_2 per liter of Slurry	H_2O V_f^{**}	Grams of $\text{UO}_3 \cdot \text{H}_2\text{O}$ per liter of Slurry					
		10	20	40	60	80	100
200	0.9	-0.00411	0.00215	0.00831	0.0115	0.0135	0.0149
	0.8	-0.00260	0.00239	0.00719	0.00962	0.0111	0.0122
	0.7	-0.00147	0.00241	0.00605	0.00785	0.00896	0.00972
	0.6	-0.000606	0.00225	0.00485	0.00612	0.00688	0.00741
400	0.9	-0.00594	0.000489	0.00703	0.0105	0.0127	0.0142
	0.8	-0.00419	0.000988	0.00613	0.00880	0.0105	0.0116
	0.7	-0.00282	0.00125	0.00520	0.00722	0.00846	0.00933
	0.6	-0.00171	0.00134	0.00422	0.00566	0.00654	0.00715
600	0.9	-0.00763	-0.00104	0.00584	0.00955	0.0119	0.0136
	0.8	-0.00564	-0.000308	0.00516	0.00806	0.00989	0.01117
	0.7	-0.00405	0.000181	0.00443	0.00664	0.00802	0.00899
	0.6	-0.00272	0.000478	0.00362	0.00522	0.00622	0.00691
1000	0.9	-0.0737	-0.00395	0.00353	0.00771	0.0104	0.0124
				(0.452) [†]	(0.326)	(0.263)	(0.223)
	0.8	-0.00833	-0.00277	0.00327	0.00658	0.00873	0.0102
				(0.458)	(0.331)	(0.266)	(0.277)
	0.7	-0.00634	-0.00186	0.00290	0.00549	0.00714	0.00831
		-0.00460		(0.464)	(0.337)	(0.271)	(0.231)
	0.6		-0.00115	0.00245	0.00437	0.00559	0.00644
				(0.472)	(0.344)	(0.278)	(0.237)

*185°C operating temperature; 500°C neutron temperature

**Volume fraction of water having density 0.88 gm/cm³ (185°C). Note that void fraction = $1 - [V_f(\text{H}_2\text{O}) + V_f(\text{UO}_3 \cdot \text{H}_2\text{O}) + V_f(\text{ThO}_2)]$.

[†]Initial conversion ratio (in brackets) i.e., Th^{232} consumed/ U^{235} consumed.

Calculated initial conversion ratios for 1,000 gm/liter ThO_2 mixtures are also listed in Table 3.

Geometrical Buckling and Criticality

To ascertain the effective geometrical buckling of the proposed water-reflected system consisting of the core region up to the flange and vertically downward to the bottom of the horizontal piping, a two-dimensional (x-z geometry) four-group calculation for k_{eff} was carried out using the P.D.Q. 704 code. The carbon steel of the core and piping were simulated by iron regions. The water reflector was taken to be at room temperature. For the following composition: 40 gm/liter $\text{UO}_3 \cdot \text{H}_2\text{O}$, 600 gm/liter ThO_2 , and 0.80 volume fraction of H_2O at a density of 0.88 gm/cm^3 (185°C) in the core, corresponding to a calculated material buckling of 0.000516, the system was essentially critical ($k_{\text{eff}} \approx 0.966$). The group cross sections and pertinent quantities for this core composition are given in Table 4.

Other compositions having similar material bucklings may be inferred from Table 3. For extrapolation to other core sizes, compositions, corresponding to both larger and smaller material bucklings may also be obtained from Table 3.

Table 4

REPRESENTATIVE GROUP CROSS SECTIONS AND RELATED QUANTITIES

$\text{U}^{235}\text{O}_3 \cdot \text{H}_2\text{O}$	40 gm/liter of slurry
ThO_2	600 gm/liter of slurry
Pressure	150 psi
Operating temperature	185°C
Water density (in core)	0.88 gm/cm^3
Neutron temperature (in core)	500°C
Volume fraction of water (in core)	0.80

HOMOGENIZED CORE CROSS SECTIONS

Group I $\beta_{\text{I}} = 0.574$ $\Sigma_{\text{a}} = 0.0696 \text{ cm}^{-1}$ $\nu\Sigma_{\text{f}} = 0.000657$ $3\Sigma_{\text{tr}} = 0.249$ $\Sigma_{\text{I} \rightarrow \text{II}} = 0.0693$	Group II $\beta_{\text{II}} = 0.426$ $\Sigma_{\text{a}} = 0.0954 \text{ cm}^{-1}$ ($\sigma_{\text{c}}^{\text{th}} = 0 \text{ barns}$) $\nu\Sigma_{\text{f}} = 0.000326$ $3\Sigma_{\text{tr}} = 0.812$ $\Sigma_{\text{II} \rightarrow \text{III}} = 0.0953$
Group III $\Sigma_{\text{a}} = 0.108 \text{ cm}^{-1}$ ($\sigma_{\text{c}}^{\text{th}} = 4.8 \text{ barns}$) $\nu\Sigma_{\text{f}} = 0.00515$ $3\Sigma_{\text{tr}} = 0.123$ $\Sigma_{\text{III} \rightarrow \text{IV}} = 0.0975$	Group IV $\Sigma_{\text{a}} = 0.0527 \text{ cm}^{-1}$ ($\sigma_{\text{c}}^{\text{th}} = 5.06 \text{ barns}$) $\nu\Sigma_{\text{f}} = 0.0732$ $3\Sigma_{\text{tr}} = 4.04$

$$p^{\text{th}} = 0.933$$

$$k_{\infty} = 1.305$$

$$B^2 \text{ (Material buckling)} = 0.00576 \text{ cm}^{-2}$$

$$k_{\text{eff}} \text{ (2-d analysis)} = 0.996$$

REFERENCES

1. Lane, MacPherson and Moslan, Fluid Fuel Reactors, Addison-Wesley Pub. Co., (1958).
2. Thermal Power Breeder Reactor Program, ORNL CF-59-7-129
3. Civilian Power Reactor Program, Part I, Summary of Technical and Economic Status as of 1959, USAEC-TID-8516 (1960).
4. Report of the Fluid Fuel Reactor Task Force, TID-8507.
5. Zmola, P. C., Brown, W. S., and Bailey, R. V., Power Removal from Boiling Homogeneous Reactors, TID-2505, pp 47-72
6. Zmola, P. C., and Bailey, R. V., Power Removal from Boiling Nuclear Reactors, ORNL CF-55-7-43 (July 1955)
7. Alexander, L. G., and Jaye, S., A Parametric Study of Rate of Power Removal from Homogeneous Boiling Reactors, ORNL CF-55-9-172 (1955).
8. Lane, J., et al., Aqueous Fuel Systems, ORNL CF-57-12-49
9. Widdoes, L. C., et al., A Preliminary Design and Feasibility Study of a Large-scale Boiling Slurry Plutonium Power Producer, ORNL CF-51-8-84 (1951).
10. Karmack, H. F., et al., Boiling Homogeneous Reactor for Producing Power and Plutonium, ORNL CF-54-8-238
11. Zeitlin, H. R., et al., Boiling Homogeneous Reactor for Power and U²³³ Production, ORNL CF-54-8-240 (1954).
12. Dickert, R. J., et al., A Preliminary Design Study of a 10-Mw Homogeneous Boiling Reactor Power Package for Use in Remote Locations, ORNL CF-53-10-23 (1953)
13. Zmola, P. C., Power Removal from a Boiling Slurry Blanket, ORNL CF-53-9-111 (1953).
14. Zmola, P. C., Comments on Boiling Slurry Blankets for Homogeneous Reactors, ORNL CF-55-9-125 (1955).
15. Zmola, P. C., Boiling Blanket for TBR-Power Utilization, ORNL CF-55-3-57 (1955).
16. Billerbeck, C. J., et al., Design of a Boiling Thorium Blanket, KT-188, MIT Protective School (1954).
17. Alichanow, A. I., et al., A Boiling Homogeneous Nuclear Reactor for Power, First International Conference on the Peaceful Uses of Atomic Energy, Paper No 624 (1955).
18. Benveniste, J., et al., Ideas on a Project for a Homogeneous Reactor, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, United Nations, Geneva (1958), Vol. 9, p. 415.

19. Zajie, V., Pfann, J., and Cregor, G., Design of Experimental 10-Mw Homogeneous Reactor Fueled with Circulating Uranium Oxide Suspension in Light Water. ibid., Vol. 9, p. 441.
20. Kreyger, P. J., et al., Development of a 250-kw Aqueous Homogeneous Single Region Suspension Reactor, ibid., Vol. 9, p. 427.
21. Bruyn, H. et al., The Design of a Small-scale Prototype of Homogeneous Power Reactor Fueled with Uranium Oxide Suspension, First International Conference on the Peaceful Uses of Atomic Energy, Paper No. 936 (1955).
22. The "State of the Art" on $\text{ThO}_2\text{-UO}_3$ slurries is contained in a series of Pennsylvania Advanced Reactor Quarterly Progress and Topical Reports, and in the Oak Ridge National Laboratory Quarterly Progress and Topical Reports. An excellent summing up of technology as of 1958 is contained in Ref. (1).
23. R. W. Deutsch, Computing Three-group Constants for Neutron Diffusion, Nucleonics 15 (1), 47 (1957).
24. C. H. Westcott, Effective Cross-section Values for Well-moderated Thermo Reactor Spectra, CRRP-680.
25. J. T. Thomas, et al., Direct Comparison of Some Nuclear Properties of U^{233} and U^{235} , NSE-1, 20 (1956).
26. J. A. Thie, Dynamic Behavior of Boiling Reactors, ANL-5849 (May 1959).