UC-80
Reporting Date: July 1974
Issued: August 1974

Preliminary Study of Plasma Nuclear Reactor Feasibility

by

H. H. Helmick
G. A. Jarvis
J. S. Kendall*
T. S. Latham*

*United Aircraft Research Laboratories, East Hartford, CT 06108

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

This work was supported by the Research Division, Office of Aeronautics and Space Technology, National Aeronautics and Space Administration, NASA contract #W-13721.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $4.00; Microfiche $1.45

CONTENTS

PRELIMINARY STUDY OF

PLASMA NUCLEAR REACTOR FEASIBILITY

by

H. H. Helmick
G. A. Jarvis
J. S. Kendall
T. S. Latham

ABSTRACT

An engineering working group was formed by the National Aeronautics and Space Administration to assess the feasibility of performing a series of nuclear cavity reactor critical experiments which would provide basic reactor physics and engineering data for future higher power gaseous UF_6 and uranium plasma core reactor experiments. The joint engineering working group comprised personnel from the Los Alamos Scientific Laboratory and the United Aircraft Research Laboratories. Included in the scope of the investigations were estimates of costs and the establishment of a test schedule for the cavity reactor experiments. In addition, residual materials and test facilities formerly used for the solid core nuclear rocket development programs were inventoried and inspected to determine their suitability for use in the series of cavity reactor experiments.

The principal conclusions of the study are that (1) residual beryllium reflector segments, control drums and drive motors, and a pressure vessel from the solid core nuclear rocket development program can be assembled in the LASL Critical Experiments Facility to perform initial cavity reactor experiments at minimum cost, and (2) the Remote Maintenance, Assembly, and Disassembly building at the Nuclear Rocket Development Station is an ideal facility in which to perform future high-power reactor experiments.

I. INTRODUCTION

Since 1955 researchers have considered the prospects for producing nuclear energy by fissile fuel in the gaseous state. Most of this work was concentrated on the gaseous nuclear reactor technology required for high-performance space propulsion systems. However, in addition to high-thrust, high-specific-impulse space propulsion applications, gaseous fueled nuclear reactors offer several new options for meeting future energy needs.[1-3]

A joint engineering working group was formed by the National Aeronautics and Space Administration (NASA), comprising personnel from the Los Alamos Scientific Laboratory (LASL) and the United Aircraft Research Laboratories (UARL). The objective of this group was to define and describe a series of nuclear-critical experiments that would provide design data for a plasma reactor prototype. Included in the scope of the investigations were estimates of costs and the establishment of a test schedule for the critical experiments. In addition, materials and facilities formerly used for the solid-core nuclear rocket development program were inventoried and inspected to determine their suitability for the proposed experiments. The conclusions and recommendations of the working group are presented at the end of this report.

Extraction of power from the fission process with nuclear fuel in gaseous form allows operation at much higher temperature than conventional nuclear reactors. Higher operating temperature, in general, leads to more efficient thermodynamic cycles and, in the case of fissioning uranium plasma reactors, results in applications using direct coupling of energy in the form of electromagnetic radiation. The continuous reprocessing of gaseous nuclear fuel leads to a low steady-state fission product inventory in the reactor and limits the buildup of long half-life transuranium elements. It is possible that hydrodynamic instabilities could introduce safety problems, and these effects must be understood and controlled.

Applications for this reactor require significant research and technology development. Some of these applications are:

1. Advanced closed-cycle gas turbine-driven electrical generators.
2. Magnetohydrodynamic (MHD) power conversion systems for generating electricity.
3. Photochemical or thermochemical processes, such as dissociation of hydrogenous materials (for example, water) to produce hydrogen.
4. Direct pumping of lasers by fission fragment energy deposition in UF_6 and lasing gas mixtures.
5. Optical pumping of lasers by thermal or nonequilibrium electromagnetic radiation from fissioning UF_6 gas or fissioning uranium plasmas.

Cavity reactor experiments and theoretical analyses performed over the past 15 yr demonstrated that available analytical techniques for calculating cavity reactor nuclear characteristics are reasonably accurate.[4-8] These historic studies provide a basis for selecting additional experiments to demonstrate the feasibility of plasma core nuclear reactors. Results of the past work are reviewed in Appendix A.

The United Aircraft Research Laboratories have been engaged in research on different phases of gaseous and plasma technology since 1959. This work has been supported under NASA contracts monitored by the Joint AEC-NASA Space Nuclear Systems Office (Contracts NASw-847, NASw-768, and SNPC-70) and the NASA Lewis Research Center (Contracts NAS3-3382, NAS3-13446, NASA3-13459, and NAS3-17342), under Air Force contracts monitored by Edwards Air Force Base (Contracts AF04(611)-7448 and AF04(611)-8189), and under Corporate sponsorship. UARL activities have demonstrated hydrodynamic containment of 6000°K uranium plasma produced by radiofrequency heating. Extensive experimental and theoretical work developed practical techniques for extracting radiant energy from hot plasmas. These efforts were aimed at developing the technology needed for high-efficiency nuclear powered rocket systems.[1-3]

Drawing on this background experience, the study group has formulated the program plan described in this report.

II. PROGRAM PLAN

A long-range program plan for establishing the feasibility of fissioning UF_6 gas and uranium plasma reactors has been formulated to conform with the key milestones program designated by NASA and illustrated in Fig. 1. The plan comprises the performance of a series of experiments with reflector-moderated cavity reactors. Cores of systematically increasing complexity will progress from simply distributed uranium foil to gaseous UF_6 fuel. The ultimate goal is design of a 5-MW self-critical fissioning uranium plasma reactor. The 5-MW reactor will be capable of generating intence photon fluxes needed to demonstrate

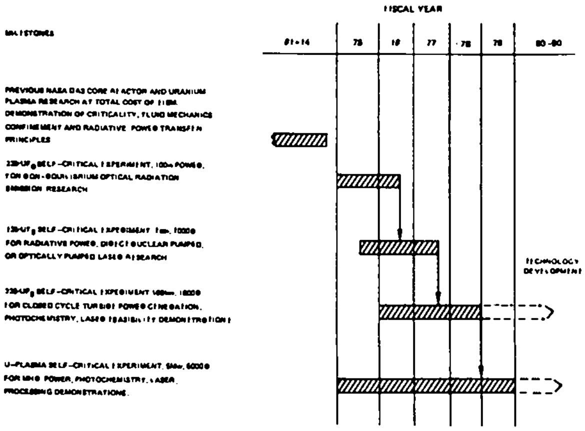


Fig. 1. Key milestones for proposed NASA program of research on plasma core reactors.

the feasibility of high thermal-efficiency electrical power generation as well as other high-power applications. Each experiment in the series would yield the data required to plan the succeeding step.

The program plan begins with the design of a beryllium cavity-reactor reflector on an available critical assembly machine developed for the Rover nuclear propulsion program. This construction will use beryllium components, control drums, control actuators, and instrumentation that remain from the Rover program.

Some preliminary criticality measurements using uranium metal foil as fuel will provide an initial control drum reactivity calibration and reactivity worths of structural materials.

The gaseous fuel experiments start with a self-critical UF_6 system operating at essentially zero power. This initial phase is primarily for reactor physics studies and a preliminary examination of nonequilibrium optical radiation from the fissioning UF_6. For these experiments the UF_6 temperature is controlled in the 300 to 500°K range by circulating a heated inert gas in the region surrounding the UF_6 core vessel.

In the next step, the UF_6 will flow through the reactor core to an external waste-heat removal system. Operation will be in the 1- to 10-kW power range at temperatures up to 500°K. Power may be extracted in the form of heat or in the form of nonequilibrium radiation.

Subsequently, a flow system employing a buffer gas for hydrodynamic containment of the UF_6 will be incorporated. Operation will be up to 100 kW at temperatures as great as 1500°K. Radiation channels will be introduced for radiant energy removal. This reactor experiment is expected to provide a means of testing thermodynamic cycles and applications of nonequilibrium optical radiation.

The emphasis will then switch from UF_6 fuel to uranium plasmas in a reactor designed to operate at 5 MW and at temperatures up to 6000°K. This will provide the means for demonstrating applications, such as high-efficiency MHD electrical power generation and the direct use of radiant power for photochemical processing. Direct pumping of lasers by fission-fragment action, as well as optical pumping of lasers by thermal or nonequilibrium electromagnetic radiation from the fissioning uranium plasma,will also be investigated.

The reactor experiments with power up to 10 kW could conveniently be performed at the Los Alamos Critical Experiments Facility, and special shielding would permit operation at higher power. Experiments extending into the megawatt range could readily be accommodated at the Nevada Reactor Development Station (NRDS), if part of that facility were reserved for this purpose.

III. AVAILABILITY OF EXPERIMENTAL FACILITIES AND REACTOR COMPONENTS

A. LASL Facilities

The facilities of the LASL Critical Experiments Group include three remotely controlled critical assembly laboratories, called Kivas, equipped with a variety of critical assembly machines of varying complexity. A central control building houses control rooms, offices, and laboratory space. Parts of these facilities are available for the initial phases of the plasma core reactor project.

The cavity-type assemblies will be on the "Mars" critical assembly machine (Fig. 2) located in Kiva 1. This machine was built early in the Rover program and was used for neutronic and core optimization studies for the Kiwi, Phoebus, and Nuclear Furnace reactors. Beryllium-reflected cavity reactor experiments were also performed on this machine.[7,8] Figure 2 shows the Mars machine with a Phoebus II reflector installed. The overall size is similar to that of the planned cavity assemblies. Some of the 18 control drum actuators are visible above the reflector.

The principal features of the Mars machine are:

1. A framework that includes a base plate for supporting the reflector, an upper platform for mounting the existing control drums, and a personnel platform.

2. Provision for removing a fueled core from the reflector. The core is supported on the platen of a hydraulic cylinder, which is centered beneath the reflector and can be retracted as a safety device.

3. Provision for removing the core from beneath the machine. The lowered core assembly rests on a cart that may be rolled out on guide rails from beneath the reflector to provide easy access for alterations to the core.

B. Nevada Reactor Development Station Facilities (NRDS)

Tests in the megawatt power range that would constitute the latter phases of the plasma core reactor program could not be done at Los Alamos without constructing a costly new facility. One of the working group's assignments was to examine the facilities of the NRDS to determine, in a preliminary way, their suitability for the higher power tests As a result of inspection trips to the NRDS, reasonable features for accommodating the advanced tests were identified.

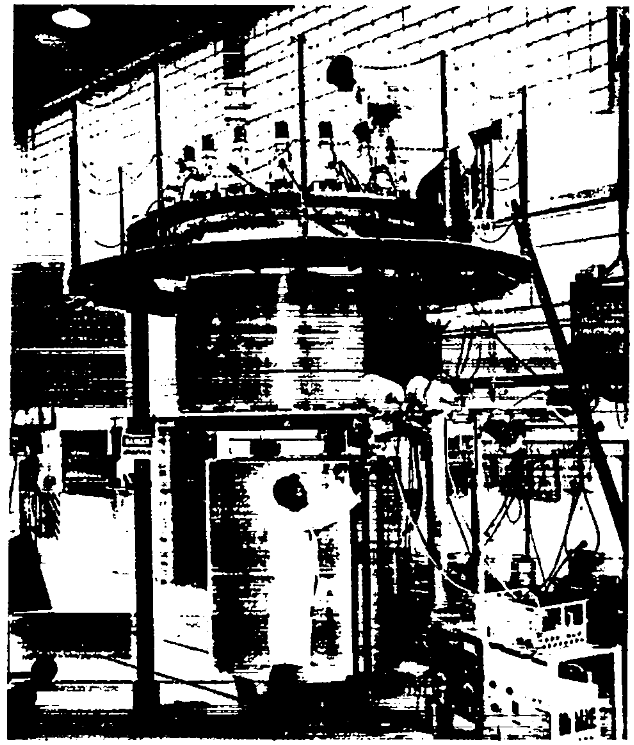


Fig. 2. Mars Critical Assembly Machine.

Because of dismantling operations currently going on at the Nevada site, an early decision on the use of this facility is necessary if costly site restoration is to be avoided. The following items would be appropriate for full-power tests.

1. The complete Remote Maintenance Assembly Disassembly (R-MAD) building, as the facility presently exists, including assembly and disassembly bays, remote control manipulators, and shield windows. The reactor tests could be performed in the disassembly bay which would provide not only radiation shielding for personnel but also a containment structure that probably will be required for environmental protection.

2. The Remote Engine Installation Vehicle and the controls for this vehicle. These items foreseeably would be useful for transferring core assemblies from the assembly bay to the disassembly bay for tests.

C. Available Reactor Materials and Controls

The key to the capability of providing a beryllium reflected cavity reactor within modest budget limitations is the availability of Rover beryllium components located at Los Alamos and the NRDS.

A survey team, which visited the NRDS, identified and tagged the various beryllium components and other materials useful to the plasma core reactor project. These parts include the reflectors from 11 Rover/NERVA reactors and represent an original cost of approximately $5 million. Appendix B lists the components and gives dimensions and quantities of materials.

IV. CRITICAL ASSEMBLIES AND TEST REACTORS

A preliminary design for a beryllium reflected cavity reactor that can be fabricated from the available materials and components is presented in Appendix C.

A. Uranium Foil Core

The first fuel loadings will use available enriched uranium foil (2.8-in.-wide, 16-in.-long, and 0.003-in.-thick). Foils will be attached to thin aluminum plates distributed initially to mock up neutronically a uniform uranium density in the cavity. Approaches to criticality will involve steps in accordance with specific operating plans based on the standard operating procedures for the Pajarito Site Critical Assembly Facility, LA-4037-SOP, Rev.

Early experiments will include the following:

1. Initial critical mass determination with uranium foils arranged in a standard reference configuration.
2. Calibration of the control drums and assessment of the overall control drum reactivity worth.
3. Evaluation of the reactivity worth of structural aluminum.
4. Evaluation of the reactivity penalty due to holes required in later experiments for introducing UF_6 gas and for observing optical effects.

B. Hybrid Fuel Geometry

Some useful experiments have been planned using a hybrid fuel mix composed partly of either uranium foils or solid uranium-graphite fuel elements and partly of UF_6 gas in appropriate containers. This arrangement has the advantage of permitting experience with UF_6 handling in a stable reactor environment. The hybrid fuel mode would permit low-pressure operation of the gaseous fuel, and should define some of the nuclear-safety problems of subsequent assemblies.

C. Static UF_6 Gas Core

Another core will be designed with gas nearly filling the cavity volume. The UF_6 container will consist of a double-walled aluminum vessel, Fig. 3, with temperature controlled by a heated gas flowing between the inner and outer walls. Graphite wool, because of its very low neutron absorption, will be used for thermal insulation outside the vessel.

A second static UF_6 fuel configuration will use a container with radius $\sim$ 8 cm less than the cavity radius. This arrangement will mock up conditions in later experiments when the gaseous fuel is restricted in radius by a tangentially injected inert buffer gas.

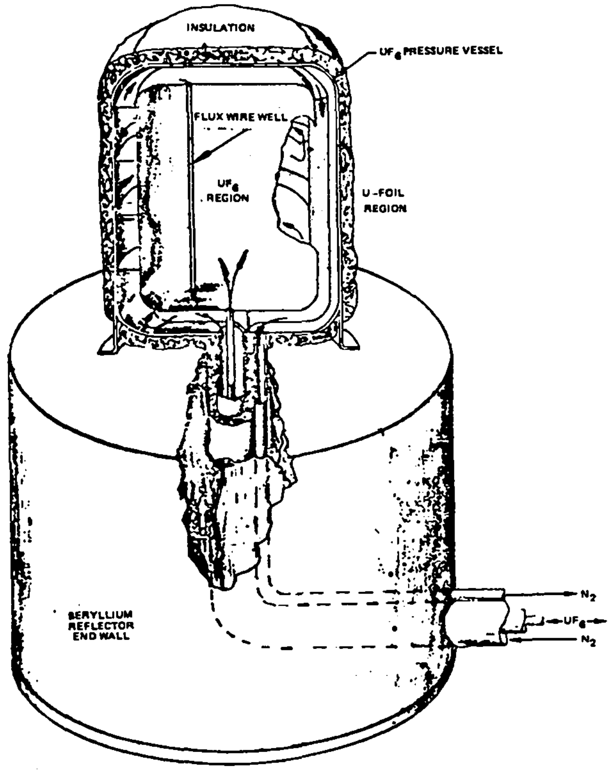


Fig. 3. Cavity reactor core insert.

D. Flowing UF_6 Cores

Two categories of flowing UF_6 experiments are planned. The first is for reactor operation in the 1- to 10-kW power range and at temperatures to 500°K. Because of the low heat capacity of the critical mass of UF_6 gas, heat removal is necessary to permit steady power operation at constant temperature. Uranium hexafluoride will be flowed through the core and cooled externally. Some neutronic parameters will be measured, including critical mass, neutron mean lifetime, temperature coefficient of reactivity, and reactivity worths of structural materials. The control drum worth will be rechecked, and nonequilibrium radiation will be studied.

The second category is for reactor operation in the 10- to 100-kW power range and at temperatures to 1500°K. The hot UF_6 will be kept away from the walls of the core vessel by an inert buffer gas, such as argon, injected tangentially into the fuel chamber. Reactivity changes due to radiation heat transfer channels and materials associated with the buffer gas injection system will be evaluated. Experiments will include observations of heat extraction for thermodynamic cycles, laser excitation, and applications of nonequilibrium radiation.

E. Uranium Plasma Test Reactor

New technology is required for this phase; in particular, the most suitable form for the uranium fuel must be determined. Because ionization and probable complete breakup of UF_6 will lead to very high plasma pressures, reactor startup may best be initiated with UF_6 followed by a shift to pure uranium as the operational power is approached. The pure uranium fuel might be introduced in the form of uranium wire or pellets that would evaporate upon entering the plasma core.

The planned 5-MW power will produce a 6000°K plasma that will be isolated from the confining vessel by a buffer gas. The Phoebus II pressure vessel seems suitable to contain the reactor for these high-power tests. The design will provide for tests of the appropriateness of radiant energy for MHD cycles, photochemical processing, and possibly laser excitation.

As a possible modification, driver elements consisting of gas-cooled uranium-graphite fuel may be used to permit the uranium plasma to operate at a lower pressure than would be possible if all the uranium fuel were in the gaseous state.

V. RADIATION EMISSION EXPERIMENTS

A. Cavity Reactor

Because one of the major functions of the plasma core reactor is to provide energy in the form of electromagnetic radiation, the radiation emission in each of the reactor experiments should be investigated. Initially, because of the very low power, observable optical radiation is unlikely. At higher power, for example, with the 10-kW UF_6 gas core, detectable electromagnetic radiation is anticipated; therefore, intensity and spectral measurements are planned. This power, however, will not be obtained until late in the second year of the proposed activities.

B. Parka Assembly

Studies can be undertaken sooner with Parka, another critical assembly machine developed for the Rover program. This assembly has the graphite-uranium fueled core, beryllium reflector, and control system of a Kiwi-B Rover reactor. A hydrogenous neutron flux trap of polyethylene will be installed along the axis of the core. This adaptation will provide a neutron flux boost adequate to drive an optical effects tube containing UF_6 and other gases. It can be constructed quickly and inexpensively. Also, early and useful hydrodynamic containment experiments may possibly be run in the modified Parka core.

C. Godiva

Another available irradiation facility is the LASL Godiva IV prompt burst reactor. When used in the burst mode with a polyethylene-moderated optical test cavity, thermal neutron fluxes of 3×10^{18} can be obtained, leading to fission densities in small UF_6 gas samples equal to those expected in a high-power test reactor. Intensity and spectral measurements of the resulting radiation are planned.

VI. SCHEDULE AND COST ESTIMATES

A. Test Schedule

The recommended program plan and test schedule are shown in Table I. Salient features of the plan are the performance of reactor physics experiments at LASL during the first three years followed by hot gaseous tests that could be performed at NRDS.

B. Cost Estimates

The cost-estimate schedule, Table II, summarizes the funding requirements for an early demonstration of a high-power plasma core reactor using radiant energy extraction. The funding allows for maintenance and site modification at NRDS.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. A series of cavity reactor critical experiments can be performed at LASL with an approximately 100-cm-long by 100-cm-diam cylindrical cavity surrounded by an approximately 50-cm-thick beryllium reflector-moderator. This arrangement will accommodate the static and flowing UF_6 systems described in the program plan.

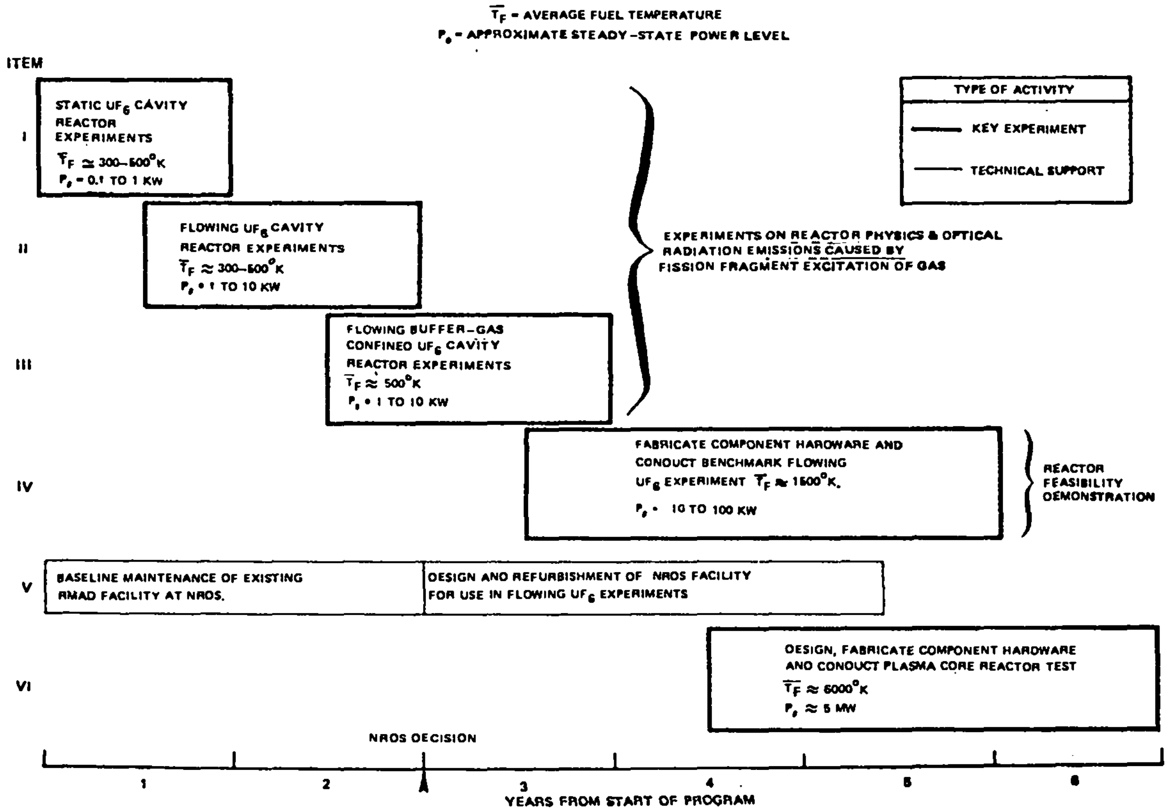
TABLE II

COST ESTIMATES FOR SERIES OF CAVITY REACTOR EXPERIMENTS FY 1974 - FY 1979

	UARL	LASL	NRDS	TOTAL
FY-1974	~\$205K	~\$245K	~\$ 75K	~\$525K
FY-1975	~\$400K	~\$450K	~\$150K	~\$1x10^6
FY-1976	~\$550K	~\$650K	~\$800K	~\$2x10^6
FY-1977	-	-	-	\$5-10x10^6
FY-1978	-	-	-	\$5-10x10^6
FY-1979	-	-	-	\$5-10x10^6

TABLE I

RECOMMENDED PROGRAM PLAN FOR SERIES OF CAVITY REACTOR EXPERIMENTS



2. Reflector materials, control drums with drive motors, and a pressure vessel are available and adaptable for use at minimum cost. Experienced staff and fully operational, remotely controlled test facilities are also available at LASL.

3. Results of these experiments would yield basic reactor physics and engineering data, culminating in a plasma core reactor. Intermediate goals would be

a) Design criteria and operating procedures for handling systems providing a steady, controlled flow of UF_6,

b) Design criteria for neutronic control of cavity systems with flowing gaseous UF_6,

c) Characterization of possible fission-fragment induced optical radiation from fissioning UF_6 gas, and

d) Design requirements for argon buffer gas flow control and argon/uranium-hexafluoride separator systems.

4. Higher power tests (100-kW flowing UF_6 and 5-MW plasma core) can be performed economically in the R-MAD building at NRDS.

B. Recommendations

1. The series of cavity reactor experiments should be started at LASL immediately.

2. Research and development on non-nuclear technologies required for the flowing UF_6 cavity reactor experiments also should be initiated as soon as possible.

3. Steps to preserve the operational capability of the NRDS R-MAD facility should be initiated at once. The dismantling and disposing of essential equipment should be stopped. and a maintenance program should be established to preserve the R-MAD building and equipment from further deterioration.

APPENDIX A

REVIEW OF CAVITY REACTOR EXPERIMENTS AND ANALYSES

Reflector-moderated cavity reactor concepts were first discussed in Refs. 4 and 5. Several experimental programs established critical masses in cavity reactor configurations for comparison with theoretical calculations. The first of these programs was conducted at LASL and used the assembly shown in Fig. A-1.[6,7] This assembly had a cavity length and diameter both equal to 100 cm, a reflector-moderator of a 50-cm-thick layer of heavy water, and a 0.475-cm-thick aluminum liner between the cavity and the heavy water. The critical mass of ^{235}U in the form of a metal foil liner was 6.0 kg. Two-dimensional neutron transport calculations reported in Ref. 8 yielded a multiplication factor of 1.01 for this configuration. (A value of 1.00 would agree perfectly with the experimental results.)

Another assembly similar to that shown in Fig. A-1 had a 79-cm-long, 39.5-cm-diam cavity, two 35.5-cm and 47-cm-thick beryllium reflector-moderators, and aluminum cavity supports for a ^{235}U foil liner and for several arrangements of ^{235}U-graphite elements.[7] Calculations in Ref. 8 of the multiplication factor for several experiments using this assembly agreed to within ± 2% of the measured value or, correspondingly, to within ± 6.7% of the experimental critical masses.

Additional cavity reactor experiments were conducted at the Idaho Falls National Reactor Testing Station (NRTS).[9-16] A basic configuration is shown in Fig. A-2. In this experiment the cavity length and the diameter of the fuel container were both 121.9 cm; however, the internal diameter of the 1.27-cm-thick aluminum tank containing the heavy water was 182.9 cm. The heavy water was 88.9-cm thick. Figure A-2 shows that a simulated rocket engine exhaust nozzle was incorporated in this assembly. The critical mass of ^{235}U in the form of UF_6 was 17.27 kg.

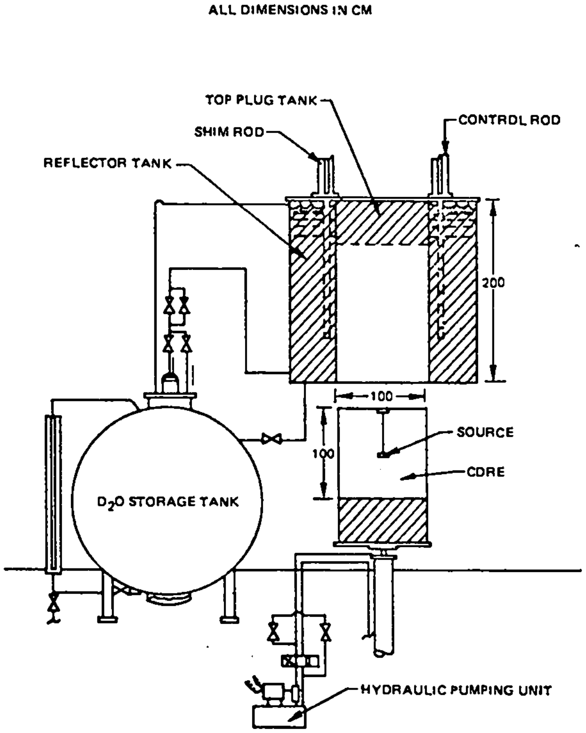


Fig. A-1. Los Alamos Scientific Laboratory cavity reactor assembly.

The multiplication factor from Ref. 14 calculated by the two-dimensional neutron transport theory was within 1.0% of that indicated by experiment.

Results of early analytical studies[6,8] demonstrated that cavity reactor critical masses are very sensitive to neutron poisons in the reflector-moderator region, particularly at the boundary between the reflector-moderator and the nuclear fuel. These studies also demonstrated that light water is unsuitable as a reflector.

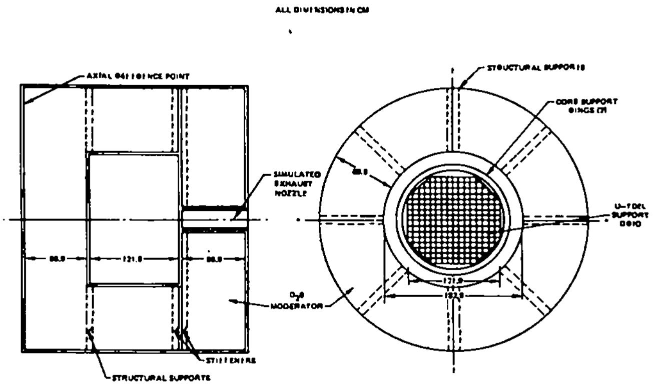


Fig. A-2. Idaho nuclear cavity reactor assembly.

APPENDIX B

AVAILABLE REACTOR COMPONENTS

Table B-I lists the radial dimensions of the Rover/NERVA reactor reflectors. Table B-II lists the number of reflectors and other beryllium materials available at Los Alamos and the NRDS.

Eighteen control drums equipped with boron neutron absorbers and stepping motor actuators are available at LASL for use in the reactor control system.

The available Phoebus II pressure vessel is adequate to contain the plasma core reactor at the anticipated high-pressure operations.

TABLE B-I

GROSS DIMENSIONS OF ROVER REFLECTORS

Reflector Type	Number of Sectors	Outer Radius (in.)	Inner Radius (in.)
Phoebus II	18	39.18	31.18
Kiwi-B	12	24.62	20.12
Pewee (Modified Kiwi-B Sectors)	9	18.69	14.38 av
Pewee Ring	1	14.38 av	10.75

TABLE B-II

INVENTORY OF AVAILABLE ROVER REACTOR BERYLLIUM REFLECTORS

Component	Number Available
Phoebus II Reflector including beryllium control drum cylinders	2
Phoebus II Mockup Reflector composed of layered curved plates	1
LASL Kiwi-B and Westinghouse NRX Reflectors including beryllium control drum cylinders	9
Pewee Reflectors including beryllium control drum cylinders	2
Nuclear Furnace Reflector	2
Honeycomb Beryllium Reflector mockup blocks 2.8 in. x 2.8 in. x 16 in. or simple fractions thereof (1700 kg)	

APPENDIX C

PRELIMINARY CAVITY ASSEMBLY DESIGN

A. Beryllium Reflector Design

The reflector will use beryllium from most of the Rover reactors, including Kiwi-B, NERVA, NRX, Pewee, Phoebus II, Nuclear Furnace, and Honeycomb critical assemblies. Figure C-1 shows parts of

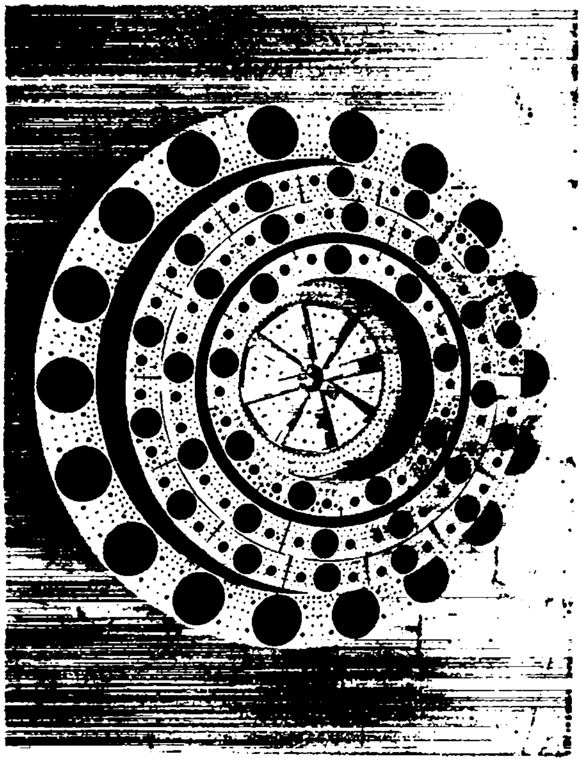


Fig. C-1. Available Rover beryllium reflector component types.

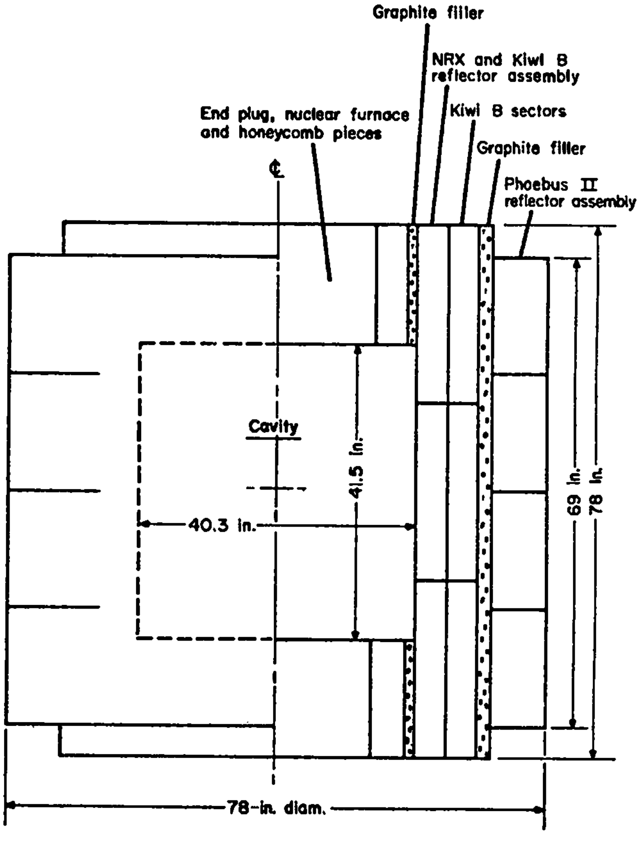


Fig. C-2. Beryllium reflector mockup.

several of the Rover reflectors arranged to form a cross section of the proposed reflector. Holes for control drums, coolant flow, tie rods, and beryllium density adjustment may be seen in the Pewee, Kiwi-B, and Phoebus II sectors. Beryllium cylinders are available to fill all control drum holes.

The reflector is to be composed of three parts, the cylindrical wall and the upper and lower end plugs. Figure C-2, an axial cut, identifies major reflector components by location and shows the overall cavity and reflector dimensions.

The beryllium end plugs will extend 19 in. into each end of the cylindrical reflector, leaving a cavity 40-in. long. The end plugs are composed of parts of Pewee and Nuclear Furnace reflector components and Honeycomb blocks.

B. Treatment of Gaps and Voids in the Beryllium

Figure C-2 shows two major gaps in the proposed cylindrical beryllium reflector. The first and largest is a 2-in.-wide annular gap between the outside surface of the second Kiwi-B layer and the inside surface of the Phoebus II reflector. The second is a 1-1/2-in.-wide annular gap in the end plugs between the outside surface of the Pewee reflector and the inside surface of the Kiwi-B reflector.

Results of criticality calculations on a detailed model of this cavity reactor geometry, using the two-dimensional neutron transport code TWOTRAN, are summarized in Table C-I. Little reactivity is lost in filling the outer gap with graphite.

For an overall view on the limitations of filling voids in the beryllium with graphite, criticality calculations were extended to a spherical model of a 50-cm-radius cavity reactor having a reflector radius of 100 cm. A 5-cm-thick annular zone of graphite was introduced into the reflector, and the reactivity loss was computed for various locations of the graphite zone. Figure C-3 shows the graphite penalty plotted as a function of the location of the graphite zone. Particularly in the outer two-thirds of the reflector, voids may be filled with graphite without serious reactivity loss. However, in the inner one-third of the reflector, graphite is a poor substitute, and fillers should be beryllium.

Calculations with one- and two-dimensional codes provided estimates of the expected reactivity penalty resulting from lowering the beryllium density. Table C-II, which summarizes these results, shows that the two codes reasonably agree.

TABLE C-I

EFFECT OF GRAPHITE IN REFLECTOR GAP

Reflector Composition	Reactivity Loss Δk	Reactivity Loss $	Critical Mass Increase (%)
Full-density beryllium (critical mass 3.82 kg U)	--	--	0
2-in. graphite between radii 28.18 and 31.18 in.	-0.0010	-0.14	+0.5
1-1/2-in. graphite between end plugs and Kiwi-B beryllium	-0.0051	-0.68	+2.5

TABLE C-II

CALCULATED PENALTY FOR REDUCED BERYLLIUM DENSITY

	One-Dimension DTF Code	Two-Dimension TWOTRAN Code
Density Reduction (%)	8.5	2.0
Reactivity Loss ($)	2.36	0.55
Reactivity to Density Ratio ($/%)	0.28	0.25

C. Reactivity Control

The reactivity of the proposed critical assembly will be controlled by the 18 rotating control drums in the Phoebus II outer layer of the reflector.

Several computations of varying complexity established the reactivity change to be expected from rotating the boron vanes from their innermost to outermost positions.

The first model calculated was a 50-cm-radius spherical cavity with a 50-cm-thick beryllium reflector. Calculations with the one-dimensional neutron transport code DTF gave a critical mass of 3.26-kg U (93.5% ^{235}U). A boron shell at the control drum "in" position resulted in a reactivity reduction of 8\$. Correcting for the fraction of the boron shell that the actual control drums would occupy in an equivalent cylindrical reactor geometry yielded a control drum reactivity swing of roughly 3.2\$.

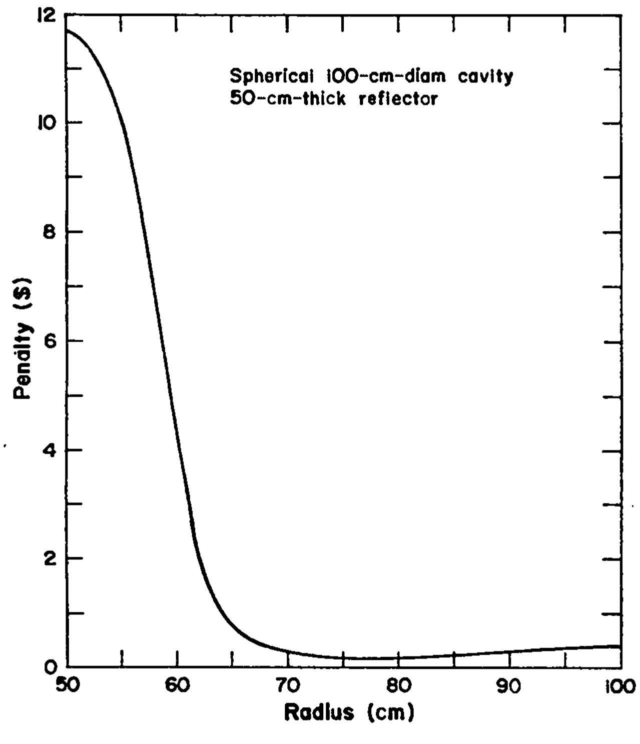


Fig. C-3. Reactivity loss from substitution of 5-cm-thick graphite shell for beryllium.

One model represented was a cylindrical reactor with dimensions very close to the proposed assembly. Computations with the two-dimensional neutron transport code TWOTRAN, for a full-density reflector and control drums represented by a boron sheath, give a value of 4.0\$ for the control drum reactivity swing.

Another calculation with the Monte Carlo KENO code included a detailed model of the control vane geometry. In this case the indicated reactivity change was 3.7\$, corresponding to the full control drum swing.

Based on these calculations, reactivity control with the 18 Phoebus drums seems adequate. However, if for any reason a greater reactivity swing is desired, it can be provided by linear control vanes introduced into the gap between the Phoebus II and Kiwi-B reflector components.

REFERENCES

1. J. S. Kendall and T. S. Latham, "Summary of Fluid Mechanics and Engine Characteristics Research on the Nuclear Light Bulb Engine Concept," AIAA Paper No. 70-689, AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

2. G. H. McLafferty, "Investigation of Gaseous Nuclear Rocket Technology Summary Technical Report," United Aircraft Research Laboratories report H-910093-46 (November 1969).

3. G. H. McLafferty and H. E. Bauer, "Studies of Specific Light Bulb and Open-Cycle Vortex-Stabilized Gaseous Nuclear Rocket Engines," United Aircraft Research Laboratories report F-910093-37 (September 1967). (Also issued as NASA CR-1030.)

4. G. I. Bell, "Calculations of the Critical Mass of UF_6 as a Gaseous Core with Reflectors of D_2O, Be, and C," Los Alamos Scientific Laboratory report LA-1874 (February 1955).

5. G. Safonov, "The Criticality and Some Potentialities of Cavity Reactors," RAND Corporation Research memorandum RM-1835 (July 1955).

6. G. A. Jarvis and C. C. Byers, "Critical Mass Measurements for Various Fuel Configurations in the LASL D_2O Reflected Cavity Reactor," AIAA Paper No. 65-555, AIAA Propulsion Joint Specialist Conference, June 1965.

7. G. A. Jarvis and C. C. Byers, Los Alamos Scientific Laboratory, internal document.

8. C. B. Mills, "Reflector Moderated Reactors," Nucl. Sci. Eng. 13, 301 (August 1962).

9. G. D. Pincock and J. F. Kunze, "Cavity Reactor Critical Experiment, Vol. I," General Electric Company (September 1967). (Issued as NASA CR-72234.)

10. G. D. Pincock and J. F. Kunze, "Cavity Reactor Critical Experiment, Vol. II," General Electric Company report GESP-35 (May 1968). (Also issued as NASA CR-72415.)

11. G. D. Pincock and J. F. Kunze, "Cavity Reactor Critical Experiment, Vol. III," General Electric Company report GESP-129 (November 1968). (Also issued as NASA CR-72384.)

12. G. D. Pincock and J. F. Kunze, "Cavity Reactor Critical Experiment, Vol. IV," Idaho Nuclear Corporation report IN-1336 (October 1969). (Also issued as NASA CR-72550.)

13. G. D. Pincock and J. F. Kunze, "Cavity Reactor Critical Experiment, Vol. V," Idaho Nuclear Corporation report IN-1340 (November 1969). (Also issued as NASA CR-72577.)

14. W. B. Henderson and J. F. Kunze, "Analysis of Cavity Reactor Experiments," General Electric Company report GEMP-689 (January 1969). (Also issued as NASA CR-72484.)

15. J. F. Kunze, J. H. Lofthouse, C. G. Cooper, and R. E. Hyland, "Benchmark Gas Core Critical Experiment," Nucl. Sci. Eng. 47, 59 (January 1972).

16. J. F. Kunze and P. L. Chase, "Critical Experiments on a Modular Cavity Reactor," Idaho Nuclear Corporation report IN-1376 (May 1970). (Also issued as NASA CR-72681.)

JJ:289(140)