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PRELIMINARY DESIGN OF A BASIC RADIATION
EFFECTS REACTOR (BRER)

by

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION.	5
II. DESIGN SUMMARY.	6
III. SITE AND BUILDINGS.	9
A. Reactor Building	9
B. Service Building.	11
C. Plant Services	11
IV. REACTOR DESIGN DESCRIPTION.	13
A. Core	13
B. Reflector	14
C. Cooling System	15
D. Shielding.	18
E. Control Rods and Drives	19
F. Fuel and Reflector Handling	20
G. Experimental Facilities.	21
H. Instrumentation	24
V. PHYSICS CALCULATIONS.	27
A. Introduction.	27
B. Survey of Likely Reflector Materials	27
C. Spectra in a Real Reflector	29
D. Effect of Moderating Shield	31
E. Effect of Lead Density.	32
F. Control.	32
G. Conclusions.	33
VI. RADIATION HEATING IN REFLECTOR	34
VII. CONTAINMENT.	36
VIII. COSTS	38
APPENDICES	
A. HEAT TRANSFER AND FLUID FLOW	39
B. MATERIALS	43
BIBLIOGRAPHY.	44

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Reactor Summary Data	7-9
2.	Reactor Scram Interlocks and Alarms	25
3.	Thirteen Group Cross Sections	28
4.	Composition and Fluxes of the Two-Region Reactor	29
5.	The Composition of Reactor Models No. 7-19	30
6.	Total Neutron Flux in Lead and Aluminum Reflectors	31
7.	Total Neutron Flux in Lead Reflector at Different Densities.	32
8.	Summary of the Gamma Heating in the BRER Reactor.	35
9.	Cost Summary	38

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Reactor Building Elevation.	45
2.	Reactor and Service Buildings Plan View at Main Floor	46
3.	Reactor Building Plan View at Balcony Level	47
4.	Reactor Building Plan View at Basement Level	48
5.	Fuel Assembly.	49
6.	Reflector Element	50
7.	Plan View of Core, Reflector, and Shield	51
8.	Elevation View of Core, Reflector, and Shield	52
9.	Coolant Flow Diagram.	53
10.	Control Rod Drive	54
11.	Neutron Spectra in the Reflector Region for Various Materials at Radius = 20 cm (Probs. 1-6)	55
12.	Neutron Spectra in the Reflector Region for Various Materials at Radius = 80 cm (Probs. 1-6)	55
13.	Medium Energy for Various Reflector Materials (Probs. 1-6).	56

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
14.	Neutron Distribution in Lead and Aluminum Reflectors at Radius = 29 cm (Probs. 15 and 17).	56
15.	Neutron Distribution in Lead and Aluminum Reflectors at Radius = 49 cm (Probs. 15 and 17).	57
16.	Neutron Distribution in Lead and Aluminum Reflectors at Radius = 110 cm (Probs. 15 and 17).	57
17.	Medium Energy of Neutron Flux as a Function of Radius (Probs. 15 and 17)	57
18.	Neutron Distribution for Probs. 11 and 12 at Radius = 43 cm .	58
19.	Effectiveness of Boron in Reducing Thermal Flux Introduced by a Moderating Shield. Radius = 86 cm (Probs. 11 and 12) .	58
20.	Medium Energy of Neutron Flux as a Function of Radius (Probs. 18 and 19)	58
21.	Volumetric Gamma Ray Sources in a Lead Reflector	59
22.	Energy Fluxes in a Lead Reflector Due to Gamma Ray Absorption	60
23.	Gamma Heating Rates in a Lead Reflector	61
24.	Core Center Channel Temperatures.	61
25.	Temperature Profile in Inner Reflector Through Coolant Holes	61

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I. INTRODUCTION

For a number of years there has been in existence at the Argonne National Laboratory, and elsewhere, a program to make quantitative irradiation studies in nuclear reactors. A special-purpose reactor is needed to meet the requirements of current and expanding studies of fundamental radiation damage and radiation effects on many substances for the development of reactor materials. The need for such a reactor is particularly important for solid state research and other investigations of the effect of fast neutrons in the range of energies over several thousands electron volts. Information has been accumulated about the property changes produced, but there are essentially no reliable quantitative data correlating property changes with the magnitude and energy distribution of the neutron fluxes responsible for the changes.

The design of the Basic Radiation Effects Reactor (BRER) presented herein stems from two main requirements:

1. a fairly high-level, high-energy neutron flux with minimal thermal neutron and gamma-ray background is desired;
2. the peak of the neutron-energy spectrum should be variable within the approximate range from 10 to 1000 kev.

The first requirement is most easily met by a fast reactor and, for this reason, the proposed concept is based on a small fast core operating at 1 Mw and cooled by NaK. The requirement of providing various neutron spectra having different peak energies is met by surrounding the small fast core with a large lead reflector. Calculations show that neutron energy spectrum is peaked at about 500 kev in the reflector region immediately adjacent to the core. The spectrum is broadened and the peak of the neutron spectrum is lowered in the outer portions of the reflector. It is possible to influence the spectrum by replacing segments in a portion of the lead reflector by elements of lower atomic number, such as aluminum, iron, and zirconium.

Calculations also indicate that the gamma-ray heating in the BRER reflector is greatly reduced as compared to a thermal reactor with equivalent fast flux, so that it will be possible to make irradiation studies at

fast fluxes as much as 100 times higher with the same gamma heating. This is particularly important for the irradiation of specimens in cryostats at temperatures near that of liquid helium, at which the heat removal capacity of the sample cooling system is very limited.

In addition to the foregoing, the BRER system provides some additional advantages which make for simpler and safer operations of research reactors. A large volume for irradiations is available in the reflector for a relatively modest reactor power. Since the space available for irradiations is restricted to this reflector region, a degree of safety is provided because insertion or removal of samples has little effect on system reactivity. Samples can be inserted or removed by means of rabbit tubes without disturbing reactor operation. Also, because of the low thermal flux, sample activation is reduced and handling of the irradiated samples is simpler. The reactivity lifetime of the core is very long and, hence, long cycle times at relatively constant power are possible with comparatively small control requirements.

The reactor should be located where there is a suitable scientific staff and adequate auxiliary experimental facilities with which to carry out the special research which is possible with this reactor. For this reason, it is proposed that the reactor be located at the Argonne National Laboratory. In addition to well-qualified groups at Argonne, there are several universities in the Middle West which have relatively large solid state irradiation programs in progress. The concentration of universities and research contractors in this area would benefit by having a Basic Radiation Effects Reactor situated at Argonne.

II. DESIGN SUMMARY

The Basic Radiation Effects Reactor (BRER) is a small fast core surrounded by a segmented radial reflector. The NaK-cooled fast core operates at a thermal power of 1 Mw, with all the reactor heat being rejected to the atmosphere through a secondary heat exchange system. The secondary heat exchange system is another NaK loop which dissipates heat to the atmosphere by means of an air-blast cooler. The reactor core is composed of small-diameter rods of uranium-zirconium alloy, arranged in a close-packed triangular pattern. The maximum core loading is approximately 60 kg of U^{235} . Reactor control is effected by moving control rods in the reflector region immediately adjacent to the core. Reactor instrumentation and fuel handling are similar to other heterogeneous reactor systems.

Relatively large volumes for experiments are available in the large radial reflector surrounding the core. Due to its segmented construction, it is possible to replace discrete regions of the reflector with different

materials. There are a large number of possible locations for samples in the reflector, and, in addition, a lesser number of through holes which can be used for experimental through loops. Great effort has been directed toward providing maximum flexibility for placing experiments in the reflector. The power dissipated in the reflector is quite low; consequently, it is air cooled.

The physics of the BRER system has been investigated, using a 15-group set of cross sections, for a series of reflector materials. The materials studied are lead, aluminum, iron, zirconium, depleted uranium, and natural uranium. Based on the criterion of producing two widely spaced and relatively sharply peaked neutron spectra, these preliminary calculations indicate that a major portion of the reflector would be lead, with an aluminum region starting at some intermediate point and extending to the outer edge of the reflector.

The reactor design presented includes the necessary features of a complete research reactor facility. Since it is proposed that the reactor be located near a densely populated area, it is housed in a steel pressure containment vessel. Office and laboratory space are provided in a service building adjacent to the reactor building. The layout of the reactor buildings is shown in Figures 1 and 2. The cost of the entire reactor facility is estimated at 2.95 million dollars. This comprises the cost of the entire reactor complex, but does not include any experimental instrumentation and apparatus. The design parameters of the reactor are summarized in Table 1.

Table 1

REACTOR SUMMARY DATA

<u>Power</u>		
Reactor power		1.0 Mwt
Maximum		
Heat flux		110 watts/cm ²
Specific power		25 kw/kg
Power density		0.21 Mw/liter
Max/avg power ratio		1.50
<u>Dimensions</u>		
Core		
Diameter		20.3 cm
Length		21.6 cm
Volume		6.9 liters
Reflector (inner and outer)		
Inside diameter		36 cm
Outside diameter		431 cm
Length		183 cm

Table 1 (Cont'd.)

Elements

Core

Fuel rod diameter	1.03 cm
Fuel alloy	U ²³⁵ + 2% Zr
Cladding	Zircaloy-2
Cladding thickness	0.051 cm
Number of fuel rods	252
Fuel loading	60 kg U ²³⁵
Total heat transfer surface	1.36 m ²
Maximum centerline fuel temperature	285°C
Maximum fuel surface temperature	210°C
<u>Reflector</u>	
Element shape	Hexagonal
Width across flats	17.5 cm
Material	Lead + steel cladding
Number of elements	211

Primary Cooling System

Coolant	NaK
Flow rate	11.4 liters/sec
Core flow area	79 cm ²
Velocity	143 cm/sec
Temperature	
Core inlet	66°C
Core outlet	177°C
Nitrogen blanket overpressure	2.7 atm
System pressure drop	0.9 atm

Secondary Cooling System

Coolant	NaK
Flow rate	11.4 liters/sec
Temperatures	
Heat exchanger inlet	49°C
Heat exchanger outlet	160°C
System pressure	1.0 atm
Air-blast cooler	
Air flow rate	39,650 liters/sec
Air pressure	1.0 atm
Air temperature rise	22°C

Reflector Cooling System

Coolant	Air (induced draft)
Flow rate (@ blower inlet)	3110 liters/sec
Air temperature rise	36°C
Air pressure	1.0 atm
System pressure drop	0.1 atm

Table 1 (Cont'd.)

<u>Control</u>	
Type of control	Reflector
Rods	
Diameter	5.1 cm
Material	Lead + steel cladding
Location	Inner reflector
Number	12
Safety Plug	
Diameter	35 cm
Material	Lead + steel cladding
Location	Inner reflector, below core
Number	1
<u>Experimental Facilities</u>	
Peak Neutron Flux	$3 \times 10^{13} \text{ n}/(\text{cm}^2)(\text{sec})$
Predominate Neutron energy range	10 - 1000 kev
Nominal hole size	10.8 cm
Horizontal holes	
Through	12
Thimble	4
Vertical holes	
Through	25
Thimble	2

III. SITE AND BUILDINGS

The BRER facility comprises two adjoining buildings: the reactor building and the service building. Since the plant will be located on a site at Argonne, the reactor is housed in an airtight steel containment building shell. The reactor heat is dissipated to the atmosphere by an air-blast cooler located outside the steel shell. Building ventilation and reactor cooling air is exhausted to a 27.5-m (90-ft) exhaust stack located next to the reactor building. The service building is a single-story structure of conventional masonry construction. The service building houses laboratories, offices, shop, and space for cryostat refrigerators.

A. Reactor Building

Figure 1 is an elevation view of the reactor building, and shows the location of the reactor components. The diameter of the cylindrical portion of the shell is 21.4 m (70 ft). The overall height, including hemispherical top and hemiellipsoidal bottom heads, is 30.5 m (100 ft). The main floors of the reactor and service buildings are at a common elevation of 122 cm (4 ft) above grade level, so that lines can be brought into the reactor building basement above grade. The bottom of the steel shell is 7.0 m (23 ft)

below grade. The shell is 1 cm (0.40 in.) thick; its construction is similar to that of the EBWR containment shell. The part of the shell below grade is encased in concrete inside and out. The inside of the shell above the main floor level is lined with a 30-cm (1-ft) thick concrete missile shield.

As shown in Figure 1, the reactor is located at the center of the building. The horizontal center line of the core is 91 cm (3 ft) above the main floor. The components of the primary NaK cooling system are located in shielded cells arranged vertically alongside one face of the reactor shield. Access to the cells is via openings left in the cell walls which are bricked up after the equipment is in place. Directly underneath the reactor is the subreactor room, which provides space for the terminal connections and piping required for test loops. The control rod drives are located in a room underneath the subreactor room.

The layout of the building at various levels is shown in Figures 2, 3, and 4. There are two laboratories and a personnel decontamination room on the main floor level along the outer perimeter of the shell. Directly above these rooms are the control room and reactor operations office. As shown in Figure 3, the tops of the reactor and the control room are connected by a balcony around the inside of the building shell. The top of the shielded cell next to the reactor is flush with the reactor top and forms additional floor space adjacent to the top of the reactor. There are two stairways leading from the balcony to the main floor. The top of the fuel storage pit is at the main floor level. There are 7.6 m (24 ft) horizontal clearance access at three faces of the reactor shield and 4.0 m (12 ft) at two faces.

The pumps and tank for the secondary NaK heat transfer loop, as well as the reflector cooling blower, are located in the basement (Figure 4). There is one stairway leading from the basement to the main floor.

Some additional features of the reactor building design are listed as follows:

1. Air locks - The main personnel air lock between the reactor and service building has 91-cm (3-ft) by 214-cm (7-ft) doors with a distance of 214 cm (7 ft) between them. The air lock design is similar to that of EBWR. The emergency air lock is 122 cm (4 ft) in diameter. Access for large equipment is provided by a large 275-cm (9-ft) by 4.0-m (12-ft) freight door which can only be opened during reactor shutdown.

2. Crane - The heaviest piece of equipment is the 8.2 tonne (9 ton) fuel-handling cask. The building crane is a 9.1-tonne (10-ton) capacity, circular track type. The distances from the crane hook to the reactor top and main floor are 7.3 m (24 ft) and 11.6 m (38 ft), respectively.

3. Elevator - An elevator in the reactor building runs from the basement to the top of the reactor. The size of the car is 183 cm (6 ft) by 183 cm (6 ft). The lift capacity is 1.8 tonne (2 tons).

4. Heating and Air Conditioning - The reactor building is cooled by three 16.8-kcal/sec (20-ton) air-conditioning units. This refrigeration capacity will maintain a maximum temperature differential of $\sim 8.3^{\circ}\text{C}$ (15°F) between the average inside temperature of the reactor building and the ambient outdoor temperature. Each unit has an air-circulation capacity of 3300 liters/sec (7000 cfm). One of these units draws in about 1410 liters/sec (3000 cfm) of fresh air, which is mixed with 1890 liters/sec (4000 cfm) of recirculating air. The fresh air-circulation system is operated in conjunction with the reflector cooling air so that 1410 liters/sec (3000 cfm) of fresh air is continuously taken in for building ventilation while the reactor is operating. Two of the three air-conditioning units have steam heating coils. When heat is required, manual steam valves are opened.

To prevent outleakage of radioactivity, both the air intake duct and exhaust stack are equipped with automatic shutoff dampers. The dampers are actuated by radioactivity monitoring instruments which are adjusted to act at a predetermined maximum activity level of the atmosphere in the reactor building.

5. Radioactive NaK Disposal - It is necessary that radioactive NaK be allowed to decay for about 10 half-lives (~ 1 week) before handling and disposal. A 5680-liter (1500-gal) storage tank, located under a removable slab in the basement floor, serves this purpose.

B. Service Building

The overall dimensions of the service building are 12.2 m (40 ft) by 30.5 m (100 ft). The layout of the service building is shown in Figure 2. The building is cooled by an air conditioner with 12.6-kcal/sec (15-ton) capacity. The air-conditioning unit has a steam coil for heating. The building has an intercom system which is connected with the reactor building.

C. Plant Services

1. Electrical

Power for the facility is supplied by 440, 220, and 110-volt circuits. The total power requirement is about 400 kva. Emergency electrical power is supplied by a station battery with a motor-generator set. Long-term shutdown power is provided by a 10-kw gasoline engine-driven generator.

2. Water

Both domestic and laboratory water supplies are available in the service and reactor buildings.

3. Compressed Air

Compressed air is supplied to both buildings by a compressor in the service building.

IV. REACTOR DESIGN DESCRIPTION

A. Core

The design of the core for BRER is not particularly critical. Since the requirements are apparently met by an existing design, namely, that of the EBR-I, Mark III core, this design is used as a reference for the purposes of this report.

The EBR-I, Mark III core⁽¹⁾ was designed to eliminate reactivity changes associated with possible fuel rod bowing produced by rapid power oscillations. Each fuel rod has three longitudinal ribs (Figure 5) which maintain the spacing between rods. At the center of each hex assembly is a tightening rod which applies a lateral clamping action to the bundle of fuel rods when it is turned from the top of the fuel assembly. The hexagonal core assemblies are, in turn, clamped tightly together by a series of wedge clamps which apply radial pressure at the core center line.

Although the conclusion from the recently completed series of stability tests on the Mark III core⁽²⁾ is that the reactor can be safely operated at full power with all of the spacer ribs between rods removed, it is evident that the hexagonal cans give some overall support to the core. For this reason the BRER core should incorporate suitable features to insure rigidity, a feature which eliminates reactivity changes due to fuel rod bowing.

A typical fuel assembly is shown in Figure 5. The core comprises seven of these hexagonal assemblies arranged as shown in Figures 7 and 8. Each hexagonal assembly is composed of a hex steel shroud, measuring 7.30 cm (2.875 in.) across flats. The approximate core diameter is 20.3 cm (8 in.) and the length is 21.6 cm (8.5 in.); the gross core volume is 6.9 liters (422 in.³).

The fuel rods are highly enriched U^{235} alloyed with 2% zirconium and clad with Zircaloy-2 to a thickness of 0.051 cm (0.020 in.). The rods are arranged in a hexagonal pattern within the hex shroud. Each shroud contains 36 rods, 1.03 cm (0.404 in.) in diameter. The overall length of the fuel rod is 210 cm (83 in.). The non-uranium portions are a long steel handle attached to the upper end of the uranium rod for fuel-handling purposes, and a short 5.1-cm (2-in.) zirconium extension at the lower end for alignment of the fuel rod in a grid plate at the bottom of the hexagonal shroud.

The 2% zirconium fuel alloy used in the EBR-I core has shown some dimensional changes on postirradiation measurements of fuel rods. The changes have shown up mainly as a slight increase in the diameter of the lower (coolant inlet) ends of the fuel rods with an accompanying slight

decrease in rod length. While this has not caused any adverse effect on the operation of the reactor and has occurred only after a great number of operating hours, it points up the fact that a different fuel alloy may be a better choice for the BRER core.

The reactor vessel is a double-walled tank consisting of a 0.32-cm ($\frac{1}{8}$ -in.) thick by 30.5 cm (12-in.) OD inner tank and a 0.8 cm ($\frac{5}{16}$ -in.) thick by 33.3-cm ($13\frac{1}{8}$ -in.) OD outer tank. The overall length of the vessel is 231 cm (91 in.). The outer tank is supported at about its midpoint by a support ring which rests on the inner fixed structure (control rod region) of the reflector. The inner tank is welded to the outer tank at the top flange only, and is thus free for thermal expansion inside the outer tank. Differential expansion of the two tanks at the points where the coolant lines join is absorbed by double-walled coolant lines extending back to the outside of the shield. The annular space between core and inner tank above the coolant outlet line is filled with slabs of steel shielding to the top of the vessel.

B. Reflector

The experimental facilities are located in the reflector region of the reactor. Figure 7 is a section through the horizontal midplane of the reactor and shows the layout of reflector and shield surrounding the core. The reflector consists of two regions: (1) a fixed inner region, and (2) an outer region consisting of removable hexagonal assemblies. An elevation view of the reactor is shown in Figure 8.

The inner region is formed by two steel shells; the annulus between the shells is filled with lead. The inner region has the dual function of supporting the reactor vessel and providing a place for locating the control rods. The inside diameter of the inner shell is 36.5 cm ($14\frac{3}{8}$ in.). There is a gap between the inner shell and the reactor vessel for air flow. The outer shell is irregularly shaped to fit the pattern required by the inner row of removable hexagonal assemblies. There are twelve control rod guides located as close to the core vessel as space limitations permit. The diameter of each control rod is 5.1 cm (2 in.). Access to the experimental facilities in the inner reflector region is limited to five 10.8-cm ($4\frac{1}{4}$ -in.) diameter vertical through holes. There is an annular space for flow of cooling air around the plugs for these experimental holes. Additional cooling air for the inner, high-heat region of the reflector flows in the cooling holes shown in Figure 7.

The design of the outer reflector region allows changes to be made in the structural composition of discrete areas (or the whole outer reflector, if desired) in order to change the flux spectrum for individual experiments. The outer region is composed of 211 hexagonal assemblies

arranged around the inner reflector. A protruding section of the reflector has been provided to allow more space for some experiments which require a further degraded spectrum than can be obtained within the main cylindrical boundary of the reflector.

A typical outer reflector hexagonal assembly is shown in Figure 6. The major portion of the reflector elements are lead. Because of the poor structural properties of lead, it is necessary to encase it in steel cans. The hexagonal steel jacket is 17.5 cm (6.89 in.) across flats and 0.157 cm ($\frac{1}{16}$ in.) thick. The overall length of the assembly, including the end fixture, is 210 cm (83 in.). The inner cylindrical portion of each hex assembly is removable in five segments to form a hole into (or through) the assembly for placing experiments. The total weight of a lead reflector assembly is 532 kg (1170 lb). The production of different neutron spectra and flux levels at specific points in the reflector is made possible by the use in some assemblies of other materials, such as aluminum, zirconium, or iron. For these assemblies the steel cladding is unnecessary, but the construction in all other details will be the same as the steel-clad lead assemblies.

The reflector assemblies are supported at the bottom by an integral alignment fixture which fits into a grid structure. The grid structure comprises two 2.54-cm (1-in.) thick steel plates spaced 15.2 cm (6 in.) apart. The two plates are held apart by spacers and the space between them acts as a coolant plenum at the bottom of the reflector. The grid structure rests on supports cast into the bottom shielding. The supports, in turn, rest on large steel beams, also cast into the shielding, which are designed to carry the large concentrated weight of the reflector. The inner fixed reflector region, with integral control rod guides, is bolted in place at the center of the grid structure.

The vertical alignment of the hexagonal reflector assemblies is provided by a close fit of their bottom alignment fixtures into the grid structure. The reflector elements are removed and replaced from above through the rotating shutdown shield. A reflector assembly may be removed for change of reflector material, or the inner cylindrical pieces can be removed separately to provide a vertical experimental access hole.

C. Cooling Systems

1. Reactor Cooling

The diagram for the reactor coolant flow is shown in Figure 9. The primary reactor coolant is the eutectic NaK alloy [78%K, 22% Na with a melting point of -11°C (12°F)]. Coolant enters the annular space between the vessel and the seven fuel assemblies via a 10.2-cm (4-in.) diameter inlet line and flows down to the bottom of the vessel, where the flow direction is reversed, and the coolant passes up through the grid plate and

around the fuel rods. Coolant flow continues up past the lower ends of the steel fuel rod handles and leaves the inside of the hex cans via overflow holes in the cans. The coolant leaves the overflow plenum via a 10.2-cm (4-in.) diameter overflow line leading to the primary heat exchanger. A seal between the inlet and outlet coolant plenums is effected by a steel plate which contacts the outer surfaces of the hex cans and the inner surface of the reactor vessel. The NaK flows from the heat exchanger to the 2840-liter (750-gal) supply tank in the basement. The primary pumps take suction from this supply tank.

The secondary coolant is also NaK. Secondary coolant is pumped from the 3785-liter (1000-gal) supply tank through the shell side of the primary heat exchanger. The NaK coolant then flows to a finned-tube, air-blast heat exchanger where its heat is dissipated to the air. The flow from the air-blast cooler returns to the supply tank.

a. Primary Heat Exchanger

The primary NaK-NaK heat exchanger (Figure 9) is a conventional counterflow two-pass shell and two-pass U-tube type, using 1.59-cm ($\frac{5}{8}$ -in.) OD by 0.165-cm (0.065-in.) wall tubing with an effective length of 427 cm (14 ft). The heat exchanger is an all carbon steel construction; it is located in a shielded cell in the reactor building basement.

b. Air-blast Cooler

The secondary system heat is dumped by a forced-air-cooled heat exchanger (Figure 9) with horizontal cooling coils. The unit has six layers of tubes, each containing 35, for a total of 210 tubes and a gross heat transfer area of 2320 m² (25,000 ft²). Air is circulated by three motor-driven fans operating in parallel. Total power requirement is 11.2 kw (15 hp). The air-blast cooler is located outside the reactor building.

c. Pumps

There are two pumps each on the primary and secondary coolant loops, one for operation and one for standby (Figure 9). The primary and secondary pumps are rated at 15.8 liters/sec (250 gpm), 15.20 m (50 ft) head, handling 93°C (200°F) NaK. The pump construction is all carbon steel. The primary pumps are located in separate shielded cells in the reactor building basement.

d. Valves

The primary and secondary system valves are Y-type globe valves with bellows seal and remote operators. Carbon steel is the material of construction.

e. Piping

The primary and secondary system piping is schedule 40 carbon steel with welded joints. The primary system piping is 10.2 cm (4 in.) in diameter. The secondary system piping is 7.6 cm (3 in.) in diameter.

f. Inert Gas Blanket

The entire exposed surface of NaK is blanketed with nitrogen to prevent reaction with air. Although argon is the most frequently used gas for sodium and NaK systems operating at high temperatures, it is permissible to use nitrogen for the BRER low-temperature system. Secondary effects on the structural materials (such as nitriding) are not a problem at the temperatures in this system. To maintain a low level of atmospheric contamination, a gas cleanup system is provided through which the nitrogen can be continuously recirculated and purified. Continuous circulation is also desirable as a means of preventing excessive sodium aerosol buildup in the gas.

The blanket gas is supplied at a pressure of about 2.7 atm (25 psig). This operating pressure results in a net positive pressure differential of the primary NaK over the secondary side of the primary heat exchanger. Leaks in the primary heat exchanger are apparent by the appearance of radioactive NaK in the secondary NaK loop.

g. Coolant Cleanup

Due to the low operating temperature of the NaK loops, no special precautions are necessary for the removal of oxides from the NaK. The supply tanks in the basement act as large diffusion cold traps, and any oxides formed merely precipitate out in them. As an added precaution, there is a bypass filter on the supply tank effluent.

h. Emergency and Shutdown Cooling

The instantaneous rate of core temperature rise on loss of coolant flow (assuming reactor scram) is low enough so that a time of about 20 seconds is available to switch over and start the spare primary coolant pump in event of pump failure. If interruption of coolant flow is caused by failure of electrical power, the pump is automatically changed over to a battery emergency power supply backed up by a gasoline engine-driven generator. For a long-term shutdown cooling there is a thermal convection loop in the primary coolant circuit (Figure 9). Operation of the convection loop requires the opening of a normally closed outlet valve on the convection loop and closing a normally open valve on the primary heat exchanger inlet. Both valves are remotely operated and the change

can be made in a few seconds. The finned tube cooler of the convection loop will remove 20 kw of heat for a maximum NaK temperature of 149°C (300°F); the required air rate is 1180 liters/sec (2500 cfm). This rate of heat removal is adequate for cooling the reactor after it has been shut down for about 10 minutes. The air flow for the convection loop is supplied by an induced-draft blower located in the reactor building.

2. Reflector Cooling

The flow diagram for the reflector cooling system is shown in Figure 9. Air is drawn into the upper shield cavity through ducts in the shield. Air flows down through the cooling passages in the reflector and into the lower plenum formed by the parallel plates of the grid structure. The air is drawn from the lower plenum by a line leading to the blowers in the basement. The air is filtered and discharged to the air manifold which connects to the exhaust stack. The induced-draft cooling system maintains the inside of the shield cavity at a pressure below that of the reactor building and thereby prevents the escape of radioactive material into the reactor building. The activity of the reflector cooling air, due to 110-min argon-41, is about 1×10^{-5} microcuries/cm³. Since this is below the activity level of the stack effluent from the CP-5 reactor at Argonne, discharge of the BRER reflector cooling air to the atmosphere is permissible.

a. Blower

The reflector blower is a turbocompressor rated at 3100 liters/sec (6600 cfm) at 0.17 atm (2.5 psi) differential pressure when handling air at an inlet temperature of 66°C (150°F).

b. Filters

The discharged air is filtered by high-efficiency, high-temperature, AEC-type exhaust filters.

D. Shielding

The reactor is shielded radially with type L-S (limonite and steel punchings) heavy concrete (density: 4.6 gm/cm³, 219 lb/ft³) (see Figure 8). The shield is 460 cm (15 ft) high and 183 cm (6 ft) thick. The calculated dose at the surface of the shield for 1-Mw operation is 1 mr/hr. The inside surface of the concrete is faced with permanent forms of steel plate installed prior to pouring of the bulk concrete. The penetrations in the radial shield consist of those holes for horizontal experiment access.

The concrete shielding below the reactor is 122 cm (4 ft) thick. The penetrations in the bottom shield are the holes for vertical experimental access, control rods, and the safety plug.

The top shielding of the reactor comprises a rotating steel plug of 427-cm (14-ft) diameter and of 91-cm (3-ft) thick removable heavy concrete blocks. The 30-cm (1-ft) thick steel plug provides shielding during reactor shutdown for any necessary transfer operations in the reflector. Access to the rotating steel plug is gained by removing the top shield blocks. The penetrations in the top shielding (steel plug and concrete blocks) correspond to the pattern for vertical access holes in the lower shield.

The cells for the radioactive NaK loop equipment adjacent to the reactor shield have walls of heavy concrete 61 cm (2 ft) thick.

E. Control Rods and Drives

1. Control Rods

The reactor control rods are located in the inner fixed section of the reflector. There are 12 rods close to the core vessel at the inside edge of the inner reflector. The rods are spaced equally on a 48-cm (19-in.) diameter circle.

The control rods are steel tubes, of 5.1-cm (2-in.) OD with a 0.318-cm ($\frac{1}{8}$ -in.) wall, filled with lead for a length of 244 cm (8 ft) from the upper end. The overall length of the rod is 580 cm (19 ft); the portion below the lead-filled section is hollow and forms the extension to the control rod drive.

2. Control Rod Drives

The design of the control rod drive (see Figure 10) is mainly influenced by the small space available for the drive due to the close spacing of the control rods. The adopted design features two parallel lead screws driving a magnetic latch which attaches to the control rod. The lead screws are mounted in a frame which guides the latch and forms the body of the drive. There is a spring assist on scram which imparts acceleration to the control rod when the latch is released (de-energized). An air dashpot at the bottom of the drive decelerates the rod at the end of the stroke. The rod drive stroke is 76 cm (30 in.). Power from the drive motor is supplied to one of the lead screws through a jointed shaft and worm gear. The position indicator runs off the bottom end of one of the lead screws and is located at the bottom end of the drive. The scram time required for full control rod travel from start of motion to the dashpot is ~300 milliseconds.

3. Safety Plug

Additional control of reactivity is provided by a 35-cm (14-in.) diameter safety plug located immediately below the core vessel. The safety plug is operated by an air cylinder which, on pressurization, lifts the plug

up into the reflector. In the event of power failure, the air valves assume the normally open position and allow the plug to drop away from the reactor. Reflector cooling air which passes through the annulus between the core and reflector also passes through cooling holes in the safety plug before exiting to the lower plenum. The safety plug is not normally used for reactivity adjustment during operation and, accordingly, it is either in the fully in or fully out position.

F. Fuel and Reflector Handling

1. Core

The core-fueling system consists of the usual components for heterogenous reactor cores, namely, a fuel coffin, coffin carriage, crane, and a shielded pit for fuel storage. The first step in fueling is removal of the center top shield block (Figure 8). This exposes the top of the reactor core vessel. A coffin carriage is set in place over the hole above the vessel. The core vessel cover is unbolted with a long-handled wrench and removed. Additional blanket nitrogen is supplied from the gas system during fueling to keep air from diffusing to the NaK surface while the vessel is open. The fuel coffin is placed in the carriage with the crane. The coffin gripper is lowered into the upper part of the core tank, within a few inches of the tops of the fuel rods. The coffin is then positioned directly over the selected rod by turning handwheels on the carriage; the alignment is made visually through a shielded sight tube in the coffin. The rod is withdrawn into the coffin and removed to the fuel-washing pit. The fuel rod is then lowered into the washroom (located in the reactor building basement) and the adhering NaK film is removed by a series of washes in alcohol and water. This operation is observed through a shield glass window in the washroom. The rod is pulled back into the coffin and placed in a fuel storage hole. The insertion of a fuel rod into the core requires the same steps (except washing) performed in the reverse order.

a. Fuel Coffin

The fuel coffin has a 76-cm (30-in.) OD at the base and is 244 cm (8 ft) in overall length. The lead shield thickness is 30 cm (12 in.). The total coffin weight is about 8.2 tonne (9 tons). The inside diameter of the coffin is large enough to accommodate a complete core subassembly.

b. Fuel Storage

Due to the low rate of emission of shutdown heat of the fuel rods, they can be stored without special provisions for cooling. It is, however, necessary to wash residual NaK from the rods before storing. After washing, the rods are placed in individual holes in the fuel storage

pit. In addition to storage holes for individual fuel rods, there are larger spaces for storing the large reflector elements, experimental loop parts such as cryostats, etc., and complete 36 rod fuel subassemblies.

2. Reflector

Rearrangement of the reflector region constitutes a major effort which requires the removal of the top shield blocks. All of the subsequent transfer operations are conducted from the large-diameter steel rotating shield immediately beneath the top shield blocks. In most instances it will be necessary to remove, or at least disconnect, those vertical loops which protrude through the rotating shield in order that it is free to turn. The shield is rotated on its ball-bearing support with an electric motor driving through a reduction gearing. A hole at a desired reflector location is obtained by rotating the steel shield and moving shield blocks in a radial slot to the proper radius. Additional holes in the steel shield are located in a fixed pattern for the installation of loops. The handling procedure for the reflector elements is similar to that for the core.

G. Experimental Facilities

A salient feature of BRER is the fact that thermal neutron fluxes are negligible in the reflector. This is particularly important for those low-temperature irradiations planned for BRER, because thermal neutrons give rise to large gamma-ray fluxes due to radiative capture. The resulting gammas cause high heating rates in samples. Heretofore, in thermal reactors, this was the factor limiting the fast flux to which a sample could be exposed; the limits imposed by the heat-removing capability of existing liquid helium cryostats used to cool the samples to temperatures of 4 to 20°K. In the BRER it is possible to irradiate samples at these low temperatures at fast fluxes of the order of 100 times higher (for equivalent refrigeration capacity) than is possible in a thermal reactor, thus shortening irradiation times considerably.

The reactor is designed so that the volume available for experiments is outside the reactor core. The core is a source which provides the neutrons for experimental volumes in the surrounding reflector. The variations in neutron spectra are obtained through changing the material composition of the reflector as required. It is necessary that the region of the reflector immediately adjacent to the core be reserved for control rods. This requirement is met by an arrangement which provides an inner reflector of fixed composition for the control rods, surrounded by a segmented outer reflector.

Figure 7 is a plan view of the reactor. The hexagonal shape of the outer reflector elements is chosen to minimize the gamma streaming between adjacent elements. The protruding section of the outer reflector provides additional thickness for further degradation of neutron energies.

1. Types of Experiments

The experiments planned fall into two main categories: (1) the before-after type, and (2) the continuous in-pile irradiation type. In the before-after experiments, samples are irradiated for a given time at a given flux and temperature. Measurements on the samples are made before their insertion and after removal from the reactor. In the in-pile irradiation experiments, measurements are made on the samples while they are in the reactor. In both types of experiments cyclic operation is envisioned wherein the samples are irradiated for a time, the reactor is shut down, measurements are made, and the reactor is started again to continue the irradiation. In the case of the before-after experiments, this implies a rapid sample removal and insertion scheme, such as a rabbit tube. Irradiation periods ranging from minutes to weeks (and perhaps as high as several months) are contemplated.

The temperatures of the irradiations are as low as 4°K and as high as 1000°C. It is possible that some experiments will be done at temperatures as high as 2000°C. Pressures higher than about 20 atm are not likely. High vacuum will be used, most often in insulating jackets for low-temperature experiments. Temperatures in the 4-80°K region (liquid helium to liquid N₂) are obtained with a 300-watt (or perhaps higher capacity) liquid helium cryostat similar to the type used by Blewitt⁽³⁾ at Oak Ridge. Temperatures above 80°K are obtained with liquid nitrogen bottles and circulating helium as the heat transfer medium. In some experiments liquid nitrogen coolant may be used directly. The high temperatures are obtained with electric heaters.

2. Method of Installing Vertical Experiments

As shown by Figure 7, there are five 10.8-cm ($4\frac{1}{4}$ -in.) diameter vertical holes in the inner reflector located at a radius of 35 cm (13.8 in.) from the core center. In the outer reflector there are a total of 211 elements. The outer ring of 54 elements are semipermanent and contain dispersed boron to absorb thermal neutrons from the shield. All of the elements in the outer reflector are potential locations for experiments; however, due to the required top and bottom shield penetrations, a lesser number can be used for complete loops extending through the reflector. The selected pattern for these holes is shown in Figure 7. The through-hole pattern consists of 10 concentric rings, with each ring having two holes 180 degrees apart, for a total of 20 holes. The inner and outermost rings have radii of 47 cm (18.5 in.) and 116 cm (45.6 in.), respectively. The average distance between rings is 7.6 cm (3.0 in.).

There are holes in the lower shield at these 25 locations (inner and outer reflector), which are filled with concrete shield plugs. There are also removable steel plugs in the top rotating shutdown shield at these

25 locations. For those experiments which are of the bayonet type and do not extend completely through the reactor, it is necessary to remove only a top shield plug. It is possible to install this type of experiment from the subreactor room also, provided it can be assembled from sections no longer than ~183 cm (6 ft). In addition to the 25 holes in the inner and outer reflector, there are two holes in the extended section of the reflector at a radius of 162 cm (64 in.); however, access to these holes is from the top only.

Figure 8 shows the installation of vertical and horizontal loops. The installation of a vertical through loop involves the following steps:

- (1) Remove concrete top shield blocks.
- (2) Remove plug in steel rotating shield.
- (3) Remove plugs from the center of the hexagonal reflector element.
- (4) Remove bottom concrete shield plug.
- (5) Lower test section of loop into place in reflector.
- (6) Make connections to external lines at the top and bottom of straight section.
- (7) Replace concrete top shield blocks.

It is possible to locate the external equipment for the loop either in the basement or on the main floor. The external line from the top of test section fits into a slot in the top shield, which leads into the space between the top concrete shield blocks and the rotating shutdown shield. This slot permits the installation of a test section with the inlet line already connected, and reduces the reactor downtime for leak testing to piping connections in situ. Likewise, there are horizontal holes in the subreactor room wall leading out to the main basement area. Pipe ducts in the face of the reactor shield connect the reactor top, main floor, and basement.

Additional flexibility in changing experiments is provided by concrete shield plugs in the large top shield blocks at each hole location. This makes it possible to change those experiments which do not involve piping connections without removing the large top shield blocks.

3. Method of Installing Horizontal Experiments

The method of installing a horizontal experiment is similar to that for the vertical experiments. There are six possible loop penetrations in each direction, for a total of twelve. In order to avoid interference of these holes [of 10.8-cm ($4\frac{1}{4}$ -in.) diameter] in the shield, their centers are displaced 6 cm above and below the centerline of the core. In order to

install a horizontal experiment, it is first necessary to place a line of special reflector elements in the row where the test section will be installed. These elements have a horizontal hole perpendicular to parallel faces of the hexagonal element. Due to the vertical displacement of the horizontal holes, it is necessary to provide two types of elements for this purpose. With the scheme of twelve horizontal holes shown, it is possible to gain horizontal access to the reflector at 15-cm (6-in.) increments of radius. In addition to the twelve through holes, there are four horizontal beam holes in line with the center of the core.

As with the 25 vertical holes, it is not necessarily expected that all holes would be in use at a given time, since the space limitations for equipment at the outside of the shield are dominant. However, because the provision for these holes requires only that the biological shield be constructed with the penetrations, there is very little additional inconvenience and cost in providing them.

H. Instrumentation

The BRER reactor instrumentation consists of the usual nuclear and non-nuclear components used in a liquid metal-cooled fast reactor system. The main components of instrumentation are as follows:

1. Nuclear Instruments

- a. Linear Operating Instrument (1 channel) - is a linear dc amplifier for accurate measurement of reactor power over the full operating range. Output is recorded on a strip chart recorder.
- b. Power Safety Circuit (3 channels) - is a linear dc amplifier which operates a meter that indicates reactor power in the high power range and operates the high power level trip circuits.
- c. Log Power and Period Safety Circuit (3 channels) - is a logarithmic amplifier which operates log power and period meters and operates the short-period trip circuits. Log power and period information from one of the amplifiers is recorded on a strip chart recorder. The range of this amplifier overlaps the top of the startup circuit and extends one decade beyond full power.
- d. Startup Circuit (2 channels) - consists of a linear pulse pre-amplifier and amplifier which operate a dual scaler and a log count rate and period circuit. The pre-amplifier input is supplied by an absolute fission counter.

2. Shutdown and Alarm System

The various operating parameters, fail-safe interlocks, and manual controls which can cause a reactor scram and/or an audible alarm are listed in Table 2.

Table 2

REACTOR SCRAM INTERLOCKS AND ALARMS

Condition	Reactor Scram	Panel Light and Audible Alarm
Neutron level high	X	X
Positive period too short	X	X
Negative period too short	X	X
Core temperature high	X	X
Reactor coolant flow low		X
Reactor coolant inlet temperature high		X
Reactor coolant outlet temperature high		X
Heat Exchanger outlet temperature high		X
Reflector temperature high	X	X
High coolant air temperature at exhaust filters		X
Secondary system coolant flow low		X
Reflector coolant flow low		X
Reactor tank NaK level low	X	X
Reactor tank NaK level high	X	X
Radiation level high (detectors at main floor, subreactor room, exhaust filters and stack effluent, also building air monitor)		X
Loss of neutron detector high voltage supply		X
Control power failure	X	X
Manual scram at control panel	X	X
Radioactivity in secondary coolant	X	X

3. Non-nuclear Instruments

a. Thermocouples

Temperatures are monitored at various points in the reactor core as follows:

- (1) Fuel rods
- (2) Inlet and outlet coolant plenums
- (3) Upper plenum seal plate
- (4) Core clamping plate
- (5) Core vessel wall.

Temperatures in the reflector are also measured at:

- (1) Various points in inner reflector
- (2) Representative elements in outer reflector
- (3) Air temperatures in inlet and outlet coolant plenums.

Connections to the thermocouples in the core are made in a gastight box containing hermetically sealed connectors. Lead wires run from the connectors through a nozzle in the reactor vessel wall in a special conduit to a patch board in the control room.

Thermocouples are also located at various points in the primary and secondary coolant systems and the reactor shield.

b. Flow Meters

Electromagnetic flow meters are used for measuring the NaK flow. Rotameters are used for measuring the flow of cover gas from the cover gas supply system. Pitot tubes in the air exit lines are used to measure the flow of reflector cooling air.

c. Level Indicators

Liquid level indicators are provided for measurement of the NaK level in the reactor vessel, NaK supply tanks, and radioactive NaK storage tank.

d. Pressure Gauges

Pressure signals for remote pressure indicators and recorders are supplied by strain-gauge-type pressure transducers. Signals for low-pressure warning and scram signals are supplied by Mercoid switches.

e. Recorders

Standard strip chart recorders are used for recording system temperatures, pressures, flux, period and coolant flow rates.

V. PHYSICS CALCULATIONS

A. Introduction

One-dimensional, thirteen-group calculations by diffusion theory have been made on UNIVAC to examine the neutron spectra produced in various reflector materials surrounding an EBR-I-type fast core. The calculations were made on the basis of a spherical geometry.

For the preliminary survey, a two-region system was assumed and full-density reflector regions, consisting of natural uranium, depleted uranium, iron, aluminum, zirconium, and lead, were studied. The second series of calculations was based on a more realistic system from an engineering standpoint, although the spherical geometry was retained. Some investigation of the influence of a moderating biological shield on the spectra in the outer region of the reflector has also been made.

Table 3 gives the thirteen-group cross sections used in the calculations. NaK was mocked up by using sodium cross sections, but reducing the sodium atomic density to reproduce the macroscopic scattering cross section of NaK in the kev region. The cross sections for H₂O are artificial in the sense that down-scattering is allowed to only four lower groups (this was because of the UNIVAC code limitations). The calculated age (Table 3), however, is reasonable.

B. Survey of Likely Reflector Materials

In Problem Nos. 1-6, the flux distribution in the reflector of a simple two-region reactor system (core and reflector) has been determined for iron, aluminum, zirconium, lead, and depleted and natural uranium in the reflector. The structure and composition of the reactor is given in Table 4. The spectra were normalized so that

$$\int_0^{\infty} \Phi(u) du = 1 \quad , \quad (1)$$

where u is the lethargy and $\Phi(u)$ the neutron flux as a function of lethargy. The total neutron flux per one-megawatt core power is given in Table 4. Figures 11 and 12 show the neutron spectra at distances of 20 cm and 80 cm from the center of the core, respectively. The curves for depleted uranium have been omitted from the figures because they are practically coincident with natural uranium. The flux level at 20 cm is almost independent of the reflector material. Near the outer boundary of the reflector we have, in the case of uranium, a very low neutron flux level (Table 4), but the half-width of this neutron spectrum is small.

Table 3

THIRTEEN GROUP CROSS SECTIONS (cm⁻¹) Σ_{j+n} total cross section for scattering from group j into group j+n Σ_a total removal cross section

	j 1	2	3	4	5	6	7	8	9	10	11	12	13
Group Lower Energy (J235)	1 353 Mev	0 498	0 183	0 0674	0 0248	9120 ev	3350	1234	454	200	6	0 4	0
Σ_A	0 144	0 122	0 108	0 111	0 137	0 194	0 302	0 452	0 592	1 01	2 88	4 32	20 84
$3\Sigma_{tr}$	0 691	0 792	1 01	1 37	1 73	2 02	2 30	2 74	4 03	5 47	10 08	14 40	63 96
$\nu\Sigma_f$	0 165	0 147	0 168	0 204	0 264	0 360	0 540	0 780	1 02	1 68	4 80	7 20	43 9
ν	2 65	2 55	2 5	2 5	2 5	2 5	2 5	2 5	2 5	2 5	2 5	2 5	2 47
Σ_{j+1}	0 055	0 042	0 021	0 007	0	0	0	0	0	0	0	0	0
Σ_{j+2}	0 0163	0 0117	0 005	0 003	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 0045	0 0028	0 0016	0	0	0	0	0	0	0	0	0	0
Σ_{j+4}	0 0014	0 0008	0	0	0	0	0	0	0	0	0	0	0
$n = 0 048 \cdot 10^{24} \text{ atoms/cm}^3$													
U238													
Σ_A	0 128	0 063	0 036	0 022	0 017	0 024	0 026	0 029	0 031	0 034	0 072	0 018	0 083
$3\Sigma_{tr}$	0 662	0 72	0 936	1 30	1 73	1 87	1 87	2 02	2 02	2 16	1 66	1 30	1 44
$\nu\Sigma_f$	0 067	0	0	0	0	0	0	0	0	0	0	0	0
ν	2 65	0	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+1}	0 072	0 042	0 022	0 0074	0	0	0	0	0	0	0	0	0
Σ_{j+2}	0 021	0 0117	0 005	0 002	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 0060	0 0028	0 0016	0	0	0	0	0	0	0	0	0	0
Σ_{j+4}	0 0019	0 0008	0	0	0	0	0	0	0	0	0	0	0
$n = 0 048 \cdot 10^{24} \text{ atoms/cm}^3$													
NaK													
Σ_A	0 0036	0 0044	0 0033	0 0033	0 0041	0 0047	0 0155	0 0155	0 0042	0 0038	0 0011	0 00155	0 0057
$3\Sigma_{tr}$	0 073	0 116	0 116	0 116	0 145	0 163	0 434	0 544	0 145	0 109	0 109	0 12	0 132
Σ_{j+1}	0 00257	0 0041	0 0033	0 0033	0 0041	0 0046	0 015	0 015	0 004	0 0038	0 0009	0 0007	0
Σ_{j+2}	0 00077	0 00025	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 00021	0 00006	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+4}	0 00007	0 00002	0	0	0	0	0	0	0	0	0	0	0
$n = 0 1210 \cdot 10^{24} \text{ atoms/cm}^3$													
Fe													
Σ_A	0 0623	0 0203	0 0086	0 0104	0 0141	0 0115	0 0216	0 022	0 0315	0 0426	0 0165	0 0424	0 153
$3\Sigma_{tr}$	0 544	0 527	0 801	0 876	1 119	0 88	1 781	1 781	2 544	2 80	2 80	2 80	2 85
Σ_{j+1}	0 059	0 016	0 008	0 0097	0 0131	0 0103	0 021	0 021	0 0303	0 041	0 01	0 013	0
Σ_{j+2}	0 00229	0 00270	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 00085	0 0016	0	0	0	0	0	0	0	0	0	0	0
$n = 0 0848 \cdot 10^{24} \text{ atoms/cm}^3$													
Al													
Σ_A	0 0241	0 019	0 0146	0 0123	0 0094	0 0063	0 0063	0 0063	0 0063	0 00754	0 00211	0 00362	0 0121
$3\Sigma_{tr}$	0 2894	0 5427	0 5970	0 5065	0 3618	0 2352	0 2442	0 2442	0 2442	0 2442	0 2442	0 2442	0 2442
Σ_{j+1}	0 0171	0 0177	0 0145	0 0121	0 009	0 006	0 006	0 006	0 006	0 0072	0 0018	0 0024	0
Σ_{j+2}	0 00513	0 00123	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 00142	0 0003	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+4}	0 00045	0 00009	0	0	0	0	0	0	0	0	0	0	0
$n = 0 06025 \cdot 10^{24} \text{ atoms/cm}^3$													
Zr													
Σ_A	0 0345	0 018	0 0125	0 009	0 0083	0 0074	0 0074	0 0069	0 0065	0 0088	0 00254	0 0023	0 005
$3\Sigma_{tr}$	0 3825	0 6375	1 02	1 084	1 02	0 893	0 893	0 829	0 765	0 893	0 778	0 778	0 783
Σ_{j+1}	0 0241	0 0137	0 0106	0 008	0 0075	0 0065	0 0065	0 0061	0 0056	0 008	0 0017	0 0013	0
Σ_{j+2}	0 0072	0 0026	0 0078	0	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 002	0 0063	0 0023	0	0	0	0	0	0	0	0	0	0
Σ_{j+4}	0 00063	0 00019	0	0	0	0	0	0	0	0	0	0	0
$n = 0 0425 \cdot 10^{24} \text{ atoms/cm}^3$													
Pb													
Σ_A	0 037	0 00337	0 0017	0 0026	0 0025	0 0025	0 0035	0 0035	0 0035	0 0043	0 00016	0 0002	0 005
$3\Sigma_{tr}$	0 485	0 451	0 575	0 931	0 992	1 041	1 043	1 059	1 084	1 10	1 12	1 12	0 78
Σ_{j+1}	0 0218	0 0027	0 0016	0 0025	0 0024	0 0024	0 0035	0 0035	0 0035	0 0043	0 001	0 0013	0
Σ_{j+2}	0 0126	0 00057	0	0	0	0	0	0	0	0	0	0	0
Σ_{j+3}	0 0023	0	0	0	0	0	0	0	0	0	0	0	0
$n = 0 033 \cdot 10^{24} \text{ atoms/cm}^3$													
C													
Σ_A	0 0306	0 0375	0 0455	0 056	0 060	0 060	0 060	0 060	0 060	0 0726	0 017	0 0133	0 000265
$3\Sigma_{tr}$	0 3614	0 554	0 771	0 988	1 06	1 06	1 06	1 06	1 06	1 06	1 06	1 06	1 06
Σ_{j+1}	0 0306	0 038	0 045	0 056	0 060	0 060	0 060	0 060	0 060	0 0726	0 0169	0 0132	0
$n = 0 0803 \cdot 10^{24} \text{ atoms/cm}^3$													
B10													
Σ_A	0 035	0 057	0 125	0 171	0 250	0 414	0 647	1 035	1 67	2 67	8 48	38 81	185 77
$3\Sigma_{tr}$	0 360	0 635	0 995	0 995	1 164	1 862	2 56	3 72	5 63	6 48	26 24	117 25	558 14
Σ_{j+1}	0 0141	0 036	0 0476	0 037	0 032	0 048	0 048	0 048	0 048	0 058	0 0124	0 0097	0
$n = 0 015 \cdot 10^{24} \text{ atoms/cm}^3$													
H2O ^a													
Σ_A	0 104	0 208	0 346	0 519	0 686	0 788	0 848	0 859	0 860	0 930	0 374	0 494	0 019
$3\Sigma_{tr}$	0 309	0 671	1 043	1 138	1 401	1 56	1 67	1 7	1 7	1 7	1 73	1 77	6 87
Σ_{j+1}	0 0665	0 136	0 225	0 332	0 439	0 504	0 541	0 549	0 488	0 903	0 349	0 491	0
Σ_{j+2}	0 023	0 046	0 077	0 118	0 157	0 180	0 194	0 174	0 361	0 026	0 025	0	0
Σ_{j+3}	0 0084	0 016	0 028	0 043	0 057	0 066	0 063	0 133	0 01	0 0018	0	0	0
Σ_{j+4}	0 005	0 010	0 016	0 025	0 033	0 039	0 050	0 004	0 0007	0	0	0	0
$n = 0 0334 \cdot 10^{24} \text{ molecules/cm}^3$													

^aThe calculated age to 0.4 ev is 31.2 cm²

Table 4

COMPOSITION AND FLUXES OF THE TWO-REGION REACTOR

Prob. No.	Outer Boundary (cm)		Materials in Region I (Volume Percentages)	Materials in Region II (Volume Percentages)	Total Neutron Flux in Region II for 1-Mw Core Power [n/(cm ²)(sec)] Distances from Center	
	Region I (core)	Region II (reflector)			20 cm	80 cm
1	10	100	55.3 U, ^a 29.7 NaK, 15 Fe	100 Fe	7.44×10^{13}	1.17×10^{12}
2	10	100	66.5 U, ^a 18.5 NaK, 15 Fe	100 Al	5.32×10^{13}	2.10×10^{12}
3	10	100	52.2 U, ^a 32.8 NaK, 15 Fe	100 Zr	8.24×10^{13}	2.71×10^{12}
4	10	100	55.4 U, ^a 29.6 NaK, 15 Fe	100 Depleted U (99.8 U ²³⁸ , 0.2 U ²³⁵)	4.15×10^{13}	3.30×10^9
5	10	100	54.4 U, ^a 30.6 NaK, 15 Fe	100 Natural Uranium	4.42×10^{13}	6.34×10^9
6	10	100	59 U, ^a 26 NaK, 15 Fe	100 Pb	7.99×10^{13}	5.92×10^{12}

^a93% enriched uranium

In order to specify the neutron spectra of various materials in the reflector, their medium lethargy U_m (corresponding to energy E_m), defined by

$$\int_0^{U_m(r)} \phi(u, r) du = \frac{1}{2} \int_0^\infty \phi(u, r) du, \quad (2)$$

has been calculated as a function of position (Fig. 13). The medium energy E_m is nearly constant for uranium and lead in the range $50 \text{ cm} < R < 100 \text{ cm}$ because of their low elastic slowing down power.

C. Spectra in a Real Reflector

A second series of calculations (Probs. 7-19) was made in which more realistic material compositions for the reflector were used, still using the spherical model. This series of problems was based on a six-region geometry, namely, (1) core, (2) NaK region around core, (3) structural steel and void region, (4) inner reflector, (5) outer reflector, and (6) moderating shield (in some problems). The material compositions of these various regions are listed in Table 5. In those cases where the volume percentages do not total 100%, the balance is void. It should be kept in mind that the listings of relative volume fractions of NaK and uranium in the core are not realistic from a practical viewpoint. This arises from the fact that the total volume of the core was held constant in the calculations, and the increasing loadings of U²³⁵ required for criticality were obtained at the expense of NaK. This does not alter the validity of the calculated spectra in the reflector.

Table 5
THE COMPOSITION OF REACTOR MODELS NO 7 19

Prob No	Critical Mass (kg U)		Region Number						
			1	2	3	4	5	6	7
7 10	60 0	Outer bound (cm)	10	15 24	18 26	28 73	100		
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb		
		Vol percentage	77 8 15	100	22 6	13 Variable	6 2 89 9		
11	59 5	Outer bound (cm)	10	15 24	18 26	28 73	100	200	
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb	C	
		Vol percentage	76 3 8 7 15	100	22 6	13 80 3	6 2 89 9	100	
12	59 6	Outer bound (cm)	10	15 24	18 26	28 73	100	200	
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb	C B ¹⁰	
		Vol percentage	76 5 8 5 15	100	22 6	13 80 2	6 2 89 9	97 0 3 0	
13	62 6	Outer bound (cm)	10	15 24	18 26	28 73	100		
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb		
		Vol percentage	80 4 4 6 15	100	22 6	13 80 2	6 2 67 4		
14	59 6	Outer bound (cm)	10	15 24	18 26	28 73	100	200	
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb	C B ¹⁰	
		Vol Percentage	76 5 8 5 15	100	22 6	13 80 2	6 2 89 9	98 0 2 0	
15	59 7	Outer bound (cm)	10	15 24	18 26	28 73	130		
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb		
		Vol percentage	76 6 8 4 15	100	22 6	13 80 2	6 2 67 4		
17	64 2	Outer bound (cm)	10	15 24	18 26	28 73	130		
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Al		
		Vol percentage	82 4 2 6 15	100	22 6	13 80 2	89 9		
18	59 7	Outer bound (cm)	10	15 24	18 26	28 73	100	200	
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb	H ₂ O B ¹⁰	
		Vol percentage	76 6 8 4 15	100	22 6	13 80 2	6 2 89 9	97 5 2 5	
19	59 5	Outer bound (cm)	10	15 24	18 26	28 73	100	110	200
		Material	U ⁹³ NaK Fe	NaK	Fe	Fe Pb	Fe Pb	Fe B ¹⁰	H ₂ O
		Vol percentage	76 4 8 6 15	100	22 6	13 80 2	6 2 89 9	97 3	100

In the calculations, the reflector materials chosen for study were aluminum and lead, since these two materials are representative of the variations that can be obtained. The calculated neutron spectra in the reflector are shown as a function of distance from the core center in the series of Figures 14 to 16. Figure 14 shows the spectrum in lead and aluminum reflectors at 29 cm, and is representative of what is available at the experimental holes closest to the core. The distribution is relatively independent of reflector material at this point. Figure 15 compares the spectra for lead and aluminum outer reflectors at 49 cm. Here a difference in reflector material is evident. Figure 16 compares the lead and aluminum spectra at 110 cm. The spectral shapes do not change much from this point to the edge of the reflector (at ~130 cm). The medium energy E_m of the neutron flux for the lead and aluminum outer reflectors is shown in Figure 17. A comparison of the total fluxes for the lead and aluminum is given in Table 6. The flux decreases by about an order of magnitude from the inner to the outer boundary of the outer reflector.

Table 6

TOTAL NEUTRON FLUX [$n/(cm^2)(sec)$] IN LEAD AND
ALUMINUM REFLECTORS

(Core Power = 1 Mw)

Material	Prob.	Distance from Core Center - cm				
		29	49	69	89	110
Lead	15	5.1×10^{13}	2.5×10^{13}	1.3×10^{13}	6.6×10^{12}	2.6×10^{12}
Aluminum	17	3.3×10^{13}	1.2×10^{13}	5.4×10^{12}	2.5×10^{12}	9.5×10^{11}

D. Effect of Moderating Shield

The influence of a moderating shield on the outer reflector spectra has been examined in problems 11, 12, 14, 18 and 19. Figures 18 and 19 show the flux spectra for a lead outer reflector surrounded by a graphite shield. The graphite is pure in one case and contains 3% B¹⁰ in the other. Figure 18 shows the spectrum at 43 cm; it is the same for either borated or pure graphite. On the other hand, Figure 19 shows a significant thermal flux contribution due to the pure graphite at a radius of 86 cm. As shown, the 3% B¹⁰ is effective in hardening the spectrum. Other calculations indicate that as little as 0.10% B¹⁰ is effective in hardening the spectrum in the outer reflector.

In order to check the effect of a different moderating shield on the reflector spectrum, problem 18 was run using a water shield containing 2.5% B¹⁰. Also, the effect of a "thermal flux barrier" of borated iron (10 cm thick) between outer reflector and water shield was examined in problem 19. The flux distribution is nearly the same in both cases. Figure 20 shows the medium energies of the two neutron spectra as a function of radius. The boron in water is equally effective in reducing the thermal flux in the outer reflector as it is in the graphite of problems 11 and 12.

The conclusion is that a borated barrier between the reflector and biological shield will effectively filter out the thermal flux produced in the shield. The configuration of problem 19 most closely represents the practical engineering design, wherein it is planned to provide a thermal neutron shield by placing boron in the outer row (or rows) of reflector elements. The total flux and spectral distribution of problem 19 are similar to those of problems 15 and 17.

E. Effect of Lead Density

The effect of decreasing the density of the lead in the outer reflector (i.e., using lead shot in steel cans) is shown by comparing the results of problems 7 (solid Pb) and 13 (Pb shot). Table 7 lists the calculated fluxes for these problems.

Table 7

TOTAL NEUTRON FLUX [$n/(cm^2)(sec)$] IN LEAD REFLECTOR AT
DIFFERENT DENSITIES

(Core Power = 1 Mw)

Material	Prob.	Distance from Core Center - cm				
		29	43	57	72	86
Solid Lead	7	4.9×10^{13}	2.8×10^{13}	1.6×10^{13}	8.8×10^{12}	3.7×10^{12}
Lead Shot	13	3.8×10^{13}	2.2×10^{13}	1.3×10^{13}	6.9×10^{12}	2.9×10^{12}
Solid Lead with graphite shield	14	5.0×10^{13}	2.9×10^{13}	1.8×10^{13}	1.0×10^{13}	5.4×10^{12}

The effect of the decreased lead density is a lowering of the total neutron flux due to increased leakage. The spectrum is relatively unaffected by the density decrease. Included for comparison in Table 7 are the fluxes for problem 14, for the case of a lead reflector surrounded by a moderating shield. This flux is more representative of a real system since those problems without the moderating shield force the flux to zero at the edge of the outer reflector.

F. Control

Because the core radius is only 10 cm and the cross sections for fast neutrons are low, the reflector has a great influence on the reactivity of the system, and the reactor may be controlled by changing the amount of lead in the inner reflector. Problems 7 through 10 were run to investigate the effect of void fraction in the inner reflector on reactivity. From results of these calculations it is estimated that the 12 control rods have a total worth of about 1.5% $\Delta k/k$. This worth will no doubt have a different value in a calculation which more accurately represents the true reactor geometry.

G. Conclusions

Of the materials examined, lead is perhaps the most attractive from the standpoint of high neutron intensity per unit core power and low gamma-ray background in the core. The spectrum in the lead, however, becomes increasingly broad as the distance from the core is increased. Therefore, lead might be replaced by aluminum in a sector, or sectors, of the reflector.

The goal of two widely spaced and fairly sharp spectra has not really been achieved. The use of resonance absorbers or materials having cross section "windows" constitutes an interesting possibility for further spectrum shaping.

VI. RADIATION HEATING IN REFLECTOR

One of the major advantages claimed for BRER is the reduced heating rates of samples under irradiation due to the low level of gamma flux. Accordingly, fairly detailed radiation heating calculations have been made.

The heat generation external to the reactor core in the vessel wall and inner and outer reflector arises from the absorption of gamma rays from four sources, namely:

- (1) prompt fission gammas,
- (2) fission product decay gammas,
- (3) gammas from inelastic neutron scattering, and
- (4) gammas from radiative neutron capture.

It was found that beta-ray heating can be neglected.

All gamma rays were assumed to fall into one of five energy groups: 1, 2, 4, 6, and 8 Mev per photon. Published data⁽⁴⁾ on prompt fission gammas and fission product decay gamma spectra were used to determine the gamma generation rates from processes (1) and (2). The calculated neutron fluxes from the thirteen-group cross-section data were used to calculate the gamma generation rates due to processes (3) and (4). The gammas arising due to inelastic scattering were assumed to have an energy of 1 Mev. The gammas arising from radiative neutron capture were assumed to be independent of neutron energy and to originate according to the spectrum of Deloume.⁽⁴⁾ The resulting calculated volumetric gamma sources for the five energy groups are shown in Figure 21. The source term for the core is essentially constant for all groups, and this is due to the fact that the major contribution is from fission product and prompt fission gammas which are assumed to originate uniformly throughout the core. The thickness of the control rod region is greater in the present design than in the model used for the calculations; however, the difference is not enough to affect the results significantly.

It was necessary to calculate the gamma-ray energy fluxes throughout the core and reflector in order to find the heat generation rates. This was done with the aid of the IBM-704 computer, using a code for slab geometry which calculates energy fluxes at a point, given a volume source of photons which can be treated as an exponential function, and the total gamma absorption cross sections for each of the groups. From the curves of Figure 21, it can be seen that the gamma sources can be treated as exponentials, although it was necessary to subdivide the outer reflector to obtain a better approximation. The computer solution fails if the gamma source strength is constant, as it was in the core and reactor vessel regions. To obtain the flux contributions due to these sources it was necessary to solve the following equation,

$$\phi(a) = \frac{QE}{2\sigma_s} \left\{ 2E_2(\sigma a) + \sigma a E_1(\sigma a) - 2E_2(\sigma a + \sigma_s t) - (\sigma a + \sigma_s t) E_1(\sigma a + \sigma_s t) \right\}, \quad (3)$$

where

- $\phi(a)$ = energy flux at the point in question, Mev/(cm²)(sec)
 Q = volumetric source, photons/(cm³)(sec)
 E = photon energy, Mev
 σ_s = absorption cross section for source region, cm⁻¹
 t = thickness of source region, cm
 $\sigma_a = \sum \sigma_i a_i$
 σ_i = absorption cross section for the i^{th} shield, cm⁻¹
 a_i = thickness of the i^{th} shield, cm.
 E_1 and E_2 are exponential integrals plotted in Ref. 4.

Equation (3) was solved to obtain the contributions due to gamma absorption in the core and vessel wall.

The calculated total energy fluxes, from all sources, for each of the five energy groups are plotted in Figure 22. The total heat generated in each region was obtained by again approximating the flux functions as exponentials and calculating a maximum-to-average flux ratio for the region, assuming slab geometry. This maximum-to-average ratio, together with the flux at the edge of the region, the actual volume of the spherical region, and the energy absorption cross section for the region for each energy group were used to calculate the rate of heat generation in the region. The results of these calculations for the lead reflector are listed in Table 8.

Table 8

SUMMARY OF THE GAMMA HEATING
IN THE BRER REACTOR

Region	Heating Rate (kw)
Reactor Vessel	5
Inner Reflector	57
Outer Reflector	35
Total	97

Of further interest are the heating rates in samples of different materials which might be located in the lead reflector. Calculations for heating of small samples of aluminum and iron were done at different radial locations in the reflector. The results are presented graphically in Figure 23. Also included is the heating rate curve for the lead reflector. Because a number of pessimistic assumptions were made in the calculations, it is believed that the heating rates shown by the curves of Figure 23 are upper limits and that actual heating rates will be lower. It should be kept in mind that the curves show the heating rates of relatively small aluminum and steel samples placed in a lead reflector. The calculations for heat removal from the reflector by the air coolant are summarized in Appendix A.

VII. CONTAINMENT

The basic research activities for the BRER reactor require that the facility be located at Argonne National Laboratory for maximum usefulness. Accordingly, suitable containment is integrated into the design.

The two main sources of energy in a NaK-cooled system are: (1) the nuclear excursion, and (2) the NaK-air reaction. The release of the energy of the NaK-air reaction, of course, requires initial rupture of the reactor vessel and/or piping for its release. A great deal of work has been done in studying the maximum possible energy releases in the EBR-II reactor for design of the reactor containment.^(5,6) The EBR-II design is based on a primary tank for the reactor core and sodium which will withstand a postulated nuclear energy release of 137 kg (300 lb) of TNT equivalent (1.5×10^5 kcal) without breaching. However, should the nuclear blast be large enough to rupture the primary tank, with consequent dispersal of hot sodium into the building air, the reactor containment shell will withstand the pressure buildup generated by the sodium-air reaction. The EBR-II containment shell is designed for a nominal pressure of 2.6 atm (24 psig), although it is actually capable of withstanding a pressure of ~6 atm (75 psig) without failing. This 2.6 atm (24 psig) corresponds to a sodium-air reaction energy release of 4540 kg (10,000 lb) of TNT equivalent, corresponding to the highly efficient dispersal, and complete reaction, of some 1370 kg (3000 lb) of sodium in air. This corresponds to an energy release of 5×10^6 kcal.

With the BRER reactor it is not practical to enclose the core vessel in a similar blast-resisting type of primary tank, due to the necessity of placing control rods and experiments as close to the core as possible. The alternate procedure of enclosing the core plus reflector offers little further advantage, since it is difficult to insure the integrity of such a structure in view of all the necessary penetrations for control rods, experimental loops, and the like. Instead, the line that has been followed is to place sufficient reinforcement in the reactor biological shield so that it will also act as a primary missile shield for those pieces of the core and reflector which would tend to become air-borne as a result of a nuclear explosion. No attempt is made to seal in the NaK; hence any nuclear excursion (of sufficient magnitude to break the primary tank) will most certainly be accompanied by a NaK-air reaction.

The answer as to the quantity of NaK likely to be involved in such a reaction gives the pressure specification for the BRER containment shell. The total NaK inventory of the primary system is 1590 kg (3500 lb), of which only some 454 kg (1000 lb) (inventory of reactor vessel, heat exchanger, piping, and pumps) is likely to escape if the system is ruptured. Complete reaction of this quantity of NaK results in an energy release of 1.1×10^6 kcal,

or below that postulated for EBR-II by a factor of about 5.* In order to calculate the buildup of pressure in the shell due to the release of this energy to the building atmosphere, it is assumed that rapid transfer takes place, and no credit for the heat capacity of the reaction products or the shell is claimed. The gross volume of the containment shell is 9.15×10^6 liters ($323,000 \text{ ft}^3$); however, it is assumed that only the part of the shell above the main floor, or 6.50×10^6 liters ($230,000 \text{ ft}^3$) is available for expansion. On this basis, it is found that the resulting air temperature is 310°C (590°F) and the pressure is 1.95 atm (14 psig). The required shell thickness, assuming a steel working stress of 1060 kg/cm^2 (15,000 psi), is 1 cm (0.40 in.). Since the allowable stress remains constant up to 343°C (650°F) and the steel temperature would obviously be lower than the maximum air temperature, the calculation is conservative. Furthermore, experimentally it is difficult to actually attain the maximum theoretical pressure and temperature in a sodium-air reaction.⁽⁶⁾

The NaK-air reaction results in a depletion of the air content of the pressure shell, which causes a negative building pressure on cooling. Accordingly, it is necessary to provide relief valves which will bleed in outside air when this situation arises. Examination of the negative design pressures for a number of similar shells⁽⁷⁾ indicates that this pressure differential should not be allowed to exceed $\sim 2.6 \text{ cm Hg}$ (0.5 psig) for the BRER shell.

It is not possible to guarantee that the reactor biological shield will be completely effective in stopping nuclear explosion missiles. This is especially true in view of those experimental installations in BRER which must, of necessity, extend through the shield. Consequently, it is also necessary to provide a secondary missile shield lining the inside of the pressure shell. This is shown in Figure 1. An examination of other pressure shell designs indicates that a one-foot (30-cm) thickness of concrete will give adequate protection.

A further hazard in the BRER system is the NaK-concrete reaction. This is accounted for in the design by lining the inside of the biological shield with steel.

*The heat of formation of K_2O on a weight basis is less by a factor of about 2 than for Na_2O .

VIII. COSTS

The estimated costs for the BRER project are summarized in Table 9. This includes direct costs of engineering design, construction, and fabrication and installation of reactor components. The cost of experimental equipment is not included. On this basis, the overall cost of the BRER project is \$2,947,000, of which \$500,000 represents the core fabrication. The cost of uranium in the core is not included.

Table 9

COST SUMMARY

Construction, Fabrication, and Assembly

Site and Buildings

Reactor Building	\$ 707,500	
Office and Service Building	232,500	
Utilities	100,000	
Site Improvement	<u>50,000</u>	\$1,090,000

Reactor Components

Core Vessel	\$ 5,000	
Reflector Elements and Support Structure	100,000	
Core and Reflector Cooling Systems	105,600	
Fuel Handling System	40,000	
Rotating Shutdown Shield Plug	30,000	
Control Rods and Drives	100,000	
Experimental Facilities (Shield plugs, access holes, etc.)	10,000	
Instrumentation	125,000	
Shielding	<u>76,400</u>	\$ 592,000

Total Direct Construction Cost (less core)		1,682,000
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General and Administrative Cost (14% of DCC)		235,500
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Subtotal		<u>\$1,917,500</u>
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Engineering Design and Inspection (16% of DCC + GAC)		307,000
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Subtotal		<u>\$2,224,500</u>
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Contingencies (10%)		<u>222,500</u>
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Total Project Cost (excluding core)		<u>\$2,447,000</u>
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Core Fabrication		<u>500,000</u>
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Total Project Cost (including core)		<u><u>\$2,947,000</u></u>
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Appendix A

HEAT TRANSFER AND FLUID FLOW

A. Core Heat Removal

The BRER core consists of 1.03-cm diameter fuel rods arranged on a triangular pitch. The coolant is the eutectic NaK alloy (22% Na, 78% K). The bulk NaK temperature rise across the BRER core is 111°C (200°F); the NaK inlet temperature is 66°C (150°F) and the outlet is 177°C (350°F). The inlet temperature is a reasonable minimum that can be expected, based on the temperature approach-ambient air limitation of the secondary cooling system. The bulk coolant temperature rise of 111°C (200°F) is reasonable, based on operating experience with EBR-I.

The core power output is one megawatt. The required flow for this power and the NaK temperature rise of 111°C (200°F) is 11.4 liters/sec (180 gpm). The temperature profiles in a central coolant channel were calculated using this coolant flow rate and temperature rise, and are shown in Figure 24. The calculations were based on an overall maximum-to-average power ratio of 1.5. The NaK film coefficient was obtained from the Martinelli equation:

$$\text{Nu} = 7.0 + 0.025 \text{ Pe}^{0.8} \quad , \quad (\text{A-1})$$

where

$$\text{Nu} = \text{Nusselt No.} = hD/k$$

$$\text{Pe} = \text{Peclet No.} = DGC_p/k \quad ,$$

which gives a heat transfer coefficient,

$$h = 1.63 \text{ cal}/(\text{cm}^2)(\text{sec})(^\circ\text{C}) \text{ [or } 12,000 \text{ Btu}/(\text{hr})(\text{ft}^2)\text{]}$$

for a NaK flow of 11.4 liters/sec (180 gpm) .

As shown by the curves of Figure 24, the maximum fuel rod center temperature is 285°C (546°F) and the maximum fuel rod surface temperature is 210°C (410°F). The maximum NaK film temperature drop is 14°C (26°F). Table 1 gives a summary of the core heat transfer parameters.

B. Pressure Drops in NaK System

The pressure drops in the NaK circuit were calculated for a maximum flow rate of 15.8 liters/sec (250 gpm) and are summarized in the following table.

Table A-1

SUMMARY OF PRESSURE DROPS IN PRIMARY NaK CIRCUIT

	<u>atm</u>	<u>psi</u>
Core pressure drop	0.25	3.7
Heat exchanger	0.0068	0.1
Piping	<u>0.63</u>	<u>9.2</u>
	0.887	13.0

The NaK pumps are rated at 15.8 liters/sec (250 gpm) at a head of 2.22 atm (18 psig).

C. Reflector Cooling

1. Method of Calculation

The cooling air for the inner reflector flows through annular spaces around the control rods and in the space between the core vessel and reflector. Because of the high heating rates in the innermost region, additional cooling holes are located between the control rods. This area of the reflector is the only place where heat removal is a problem.

In order to calculate temperature distributions in the reflector, a one-dimensional slab geometry was employed and an exponential heat generation rate was used for Q in the analytical expression for the temperature Laplacian:

$$\nabla^2 T = \frac{Q}{K} = -\frac{Q_0 e^{-mx}}{k} \quad .$$

For the slab case,

$$\nabla^2 T = \frac{d^2 T}{dx^2} = -\frac{Q_0 e^{-mx}}{k} \quad , \quad (A-2)$$

where

Q_0 = volumetric heat generation rate at the edge of the region

k = thermal conductivity of the region

$-m$ = slope of the heat generation curve throughout the region

T = temperature.

Successive integration of Eq. (A-2) gives

$$T = - \frac{Q_0 e^{-mx}}{m^2 k} + Cx + D \quad . \quad (A-3)$$

The constants C and D will, in general, differ for each material in a region; however, they are calculated for each segment of a region by applying suitable boundary conditions, such as

- (1) continuity of heat flux at a solid-solid interface,
- (2) continuity of temperature at a solid-solid interface,
- (3) Newton's law of cooling at a solid-air interface, and
- (4) adiabatic surface at the outer radius of the region.

The heat transfer coefficients at the solid-air interfaces were calculated according to the correlations⁽⁸⁾

$$h = 0.00124 \frac{G^{0.8}}{D^{0.2}} \text{ cal/}(\text{sec})(\text{cm}^2)(^\circ\text{C}) \quad , \quad (A-4)$$

or

$$h = 0.0037 \frac{G^{0.8}}{D^{0.2}} \text{ Btu/}(\text{hr})(\text{ft}^2)(^\circ\text{F}) \quad ,$$

where

G = mass velocity, gms $(\text{cm}^2)(\text{sec})$ or lb/ $(\text{ft}^2)(\text{hr})$

D = equivalent diameter, cm or ft.

The air flow throughout the reflector is orificed so that the rise of air temperature is the same in all coolant channels. An inlet temperature of 29°C (85°F) and a temperature rise of 36°C (65°F), resulting in an outlet temperature of 66°C (150°F), is the base for the heat removal calculations.

2. Results

The results of the calculations of the temperature profile are shown graphically in Figure 25. The maximum lead temperature is 233°C (451°F) at the inside edge of the inner reflector. The total air flow required for the inner reflector is 2020 liters/sec (4300 cfm), measured at blower intake conditions. The outer reflector requires 1090 liters/sec (2320 cfm). Heat transfer coefficients range from $0.00615 \text{ cal/}(\text{sec})(\text{cm}^2)(^\circ\text{C})$ [$45 \text{ Btu/}(\text{hr})(\text{ft}^2)(^\circ\text{F})$] in the control rod annulus to $0.00058 \text{ cal/}(\text{sec})(\text{cm}^2)(^\circ\text{C})$ [$4.3 \text{ Btu/}(\text{hr})(\text{ft}^2)(^\circ\text{F})$] in the outer rows of the outer reflector.

Pressure drops are different in the different coolant channels, but the dominant pressure loss occurs in the control rod annulus and is 0.1 atm (1.5 psi). The pressure drop in the outer reflector is only 3.3 cm H₂O (1.3 in.). Therefore, the outer reflector flow must be orificed in order to use a single blower for all the cooling air. It is planned to orifice the reflector elements individually rather than the outer reflector as a whole, so that larger amounts of cooling air are available at given locations, if needed, for experiments.

Appendix B

MATERIALS

The possibility of using carbon steel for the BRER reactor vessel instead of austenitic stainless steel was considered. Since carbon steel is satisfactory from the standpoint of corrosion, the choice was made on the basis of potential radiation damage. A review of the literature indicated several important features of radiation damage in steels as follows:

(1) By employing notch-impact tests, it has been shown that carbon steels exhibit a ductile-brittle transition temperature,⁽⁹⁾ whereas this phenomenon is much less pronounced in austenitic stainless steels.⁽¹⁰⁾ Further, this temperature tends to increase with total irradiation.

(2) All steels suffer a loss of ductility and an increase in hardness after neutron irradiation.^(9,11,12)

(3) The ultimate tensile strength and yield strength increase with neutron irradiation.

(4) Although the total nvt of neutrons above 1 Mev in energy is commonly used in comparing radiation damage data, it has been shown that the spectral variations between irradiation facilities can have a large effect on relative damage.⁽¹³⁾

The yearly integrated neutron dose for the BRER core vessel is 4×10^{20} nvt of >1.3 -Mev energy neutrons. The ductile-brittle transition temperature in carbon steel may be increased to near the operating temperature of the reactor for an integrated dose of only 5×10^{18} nvt (>1 Mev). Since the safe region for radiation damage can be extended at least an order of magnitude with austenitic stainless steels and the additional cost is relatively minor, stainless steel is the selected material for the reactor vessel and structure for the inner reflector. Corrosion considerations permit the use of carbon steel for the air-cooled outer reflector cans and the external piping, pumps, and heat exchangers for the NaK core-cooling system.

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FIG. 1
REACTOR BUILDING ELEVATION

FIG. 2
REACTOR AND SERVICE BUILDINGS
PLAN VIEW AT MAIN FLOOR

FIG. 3
REACTOR BUILDING PLAN VIEW AT BALCONY LEVEL

FIG. 4
REACTOR BUILDING PLAN VIEW AT BASEMENT LEVEL

FIG. 5
FUEL ASSEMBLY

FIG. 8
ELEVATION VIEW OF CORE, REFLECTOR AND SHIELD

FIG. 9
COOLANT FLOW DIAGRAM

FIG. 10
CONTROL ROD DRIVE

FIG. 11
NEUTRON SPECTRA IN REFLECTOR REGION FOR VARIOUS MATERIALS
AT RADIUS = 20 cm (PROBS 1-6)

FIG. 12
NEUTRON SPECTRA IN REFLECTOR REGION FOR VARIOUS MATERIALS
AT RADIUS = 90 cm (PROBS 1-6)

FIG. 13
MEDIUM ENERGY FOR VARIOUS REFLECTOR MATERIALS (PROBS 1-6)

FIG. 14
NEUTRON DISTRIBUTION IN LEAD AND ALUMINUM REFLECTORS
AT RADIUS = 29 cm (PROBS. 15 & 17)

FIG. 15
NEUTRON DISTRIBUTION IN LEAD AND ALUMINUM REFLECTORS
AT RADIUS = 49 cm (PROBS 15 & 17)

FIG. 16
NEUTRON DISTRIBUTION IN LEAD AND ALUMINUM REFLECTORS
AT RADIUS = 110 cm (PROBS 15 & 17)

FIG. 17
MEDIUM ENERGY OF NEUTRON FLUX AS A FUNCTION OF RADIUS (PROBS 15 & 17)

FIG. 18
NEUTRON DISTRIBUTION FOR PROBS. 11 & 12 AT RADIUS = 43 cm

FIG. 19
EFFECTIVENESS OF BORON IN REDUCING THERMAL FLUX INTRODUCED BY
A MODERATING SHIELD - RADIUS = 86 cm (PROBS 11 & 12)

FIG. 20
MEDIUM ENERGY OF NEUTRON FLUX AS A FUNCTION OF RADIUS (PROBS 18 & 19)

FIG. 21
VOLUMETRIC GAMMA RAY SOURCES IN A
LEAD REFLECTOR

FIG. 22
ENERGY FLUXES IN A LEAD REFLECTOR
DUE TO GAMMA RAY ABSORPTION

FIG. 23
GAMMA HEATING RATES
IN A LEAD REFLECTOR

FIG. 24
CORE CENTER CHANNEL TEMPERATURES

FIG. 25
TEMPERATURE PROFILE IN INNER REFLECTOR THROUGH
COOLANT HOLES