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FAST BREEDER BLANKET FACILITY
FBBF

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for the period January 31, 1976
— December 31, 1977

Edited by
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ABSTRACT

The work performed in the reporting period January 1, 1976 to December 31, 1977 was primarily concerned with the construction of the Fast Breeder Blanket Facility (FBBF), acquisition of experimental equipment, outlining the experimental program, preanalysis of the initial loading configuration and investigation of the safety of the initial loading and advanced loadings.

In Sec. I, the need for such a facility as the FBBF is discussed. Those institutions and individuals contributing to the realization of the facility are acknowledged. The detailed physical description of the FBBF, operational procedures and controls, radiation shielding and experimental equipment are presented in Sec. II. An important design characteristic of the FBBF is its ability to simulate the blanket spectrum of a large fast breeder reactor, comparison of spectra are given in Sec. III. Also in Section III, the source axial distribution, reaction rate comparisons, breeding of plutonium and gamma-ray energy deposition rates are discussed. Safety was of major importance in the design of the FBBF, in Section IV some of the safety aspects of the initial loading and advanced loadings are described. Experimental capabilities of the facility are outlined in Sec. V. Individuals involved in the administration and supervision of the facility are noted in Sec. VI. Section VII shows a color photograph of an interim loading (120°) of the first blanket.

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I. INTRODUCTION
(K.O. Ott)

I.A. The Importance of Breeding

Nuclear fission will have to play an important role in providing energy for industrialized and developing countries. The only naturally found fissile material, ^{235}U , occurs with 0.7% in natural uranium. Therefore, only from high grade uranium ore can ^{235}U be produced economically. High grade ore is in short supply, but the "fertile" isotopes ^{238}U and ^{232}Th are found in abundance. Thus large scale production of nuclear energy, over a period of many decades, requires the conversion of fertile nuclei in fissile ones. This conversion is technically realized in "converter reactors" (e.g., LWR: D_2O moderated reactors such as the CANDU; or high temperature gas cooled reactors). Converter reactors can stretch the uranium supply by recycling the generated fissile material. However, only through breeding, i.e., through enhanced conversion, such that more fissile nuclei are produced than are consumed for the conversion, can the abundant fertile material provide energy on a world scale for millennia.

The most efficient technical realization of the breeding process is in the fast breeder reactor, (FBR), especially its sodium cooled version (often called LMFBR, Liquid Metal Fast Breeder Reactor). An FBR consists of a "core" in which most of the power and most of the neutrons are produced and of a blanket, surrounding the core, in which a substantial part of the breeding occurs. The Purdue Fast Breeder Blanket Facility has been built for researching, in a close mock-up, the physics of neutrons and γ -quanta fields in various blanket configurations. This information will provide the basis for a more efficient design and operations of FBR blankets.

The need for substantial additional research on fast reactor blankets was recently pointed out in a special report by the Nuclear Energy Agency Committee on Reactor Physics under the title "The Present Status of Fast Reactor Physics;" Chapter 4 of this report covered "Blanket Physics."

The first series of blanket configurations will address uranium fueled blankets; at a later time, thorium fueled blankets can be considered. In thorium fueled blankets, ^{233}U is produced which can be used as light water reactor (LWR) fuel. Supply of ^{233}U by FBRs allows then the installation and operation of LWRs to continue for centuries.

I.B. Inaccuracies in Blanket Physics

Most of the experimental and theoretical neutron physics efforts in the U.S. Liquid Metal Fast Breeder (LMFBR) development program have been concerned with the performance and design problems of the cores in the fast reactors. Relatively little emphasis has been given to the blankets. Consequently, the inaccuracies in the neutron and γ -quanta physics is much larger in blankets than in cores. The subsequent discussion of the reactor physics uncertainties is based on the respected Section in the Proposal for this project as submitted to ERDA.

The studies on the ZPR and ZPPR critical assemblies of the Argonne National Laboratory have mocked-up the reactor cores (or benchmark cores) in great detail but not the blankets. In fact, UO_2 fuel platelets have not been used in blanket regions of the reactor mock-ups assembled on the ZPPR facility before 1972¹. The only operating U.S. fast reactor, the EBR-II has had its inner four depleted uranium metal blanket rows changed to a stainless steel reflector². The Fast Test Reactor (FTR)³ is designed to have a nickel-rich reflector and also the SEFOR⁴ reactor did not contain a blanket. Thus, there is not enough experimental information available on the spatial distributions of neutrons, γ 's and the power density as well as on the neutron and γ spectra in realistic fast reactor blankets. The available information from the ZPR and ZPPR experimental programs also suffers from the heterogeneity effects present in the platelet geometry of the blanket mock-up compositions.

Theoretical studies on accurate predictions of neutronic, γ and power distributions in fast reactor blankets are confronted with the difficulty of the transition nature of the neutron spectra existing in the rather thin (≈ 40 cm thick) radial (or axial) blankets. The radial blanket adjoins the core and the thermal-shield (reflector) regions which have

different compositions from that of the blanket; therefore an equilibrium neutron spectrum does not exist in the blanket. The methods of calculation based on utilizing fine group equilibrium spectra for generating broad group neutron cross sections for blankets (as in the MC² Code⁵) have led to poor comparisons with reaction rate distributions measured in reactor blankets. Also the ²³⁸U capture rate and the power distributions in the reactor blankets have not been predicted as accurately as in the core regions. The uncertainties in the ²³⁸U capture rate distribution affect those in the blanket power distribution increasingly with reactor operation as the bred plutonium starts producing larger and larger fractions of the power generated in the blanket. Improvements in these predictions can be expected from the newer methods (SDX⁶) which employ transition spectra for the broader group constant collapsing.

The evaluation effort on neutron cross sections to generate data files for reactor calculations, e.g., the ENDF/B Versions I, through IV have also been geared towards improving calculated predictions in the core region of the fast reactors. Thus, for example, the new ENDF/B versions are tested against measured data for criticality, reaction rate ratios (at core center) and material worths on a set of critical assemblies. The improvements achieved in predicting core physics-parameter measurements by cross section improvements have not always brought greater success in predicting the blanket physics-parameter measurements.⁷ Little information is available on thorium in fast reactor blankets, and on the thorium cross sections in typical blanket spectra.

Fast reactor blankets generate a considerable fraction of their power due to γ absorption, since the γ source from the reactor core is

preferentially absorbed in the blanket. The prompt and delayed γ rays carry about 14% of the energy generated in fission and their spatial absorption-energy distributions do not follow the spatial fission distributions. Measurements of γ -ray absorption-energy have been performed with Thermoluminescent detectors (TLD's) in ZPPR assemblies⁸ and in EBR-II criticals.^{9,10} The confidence in the measurements with the TLD's and the γ energy deposition calculations based on a set of γ production and transport cross sections needs to be improved. There is a need for measurements of γ -ray magnitudes, spectra and spatial distributions in the blankets of fast reactors. Unfortunately, such measurements are plagued by the high background due to the $^{238}\text{U}(n,\gamma)$ reaction and the natural activity of uranium in the blanket.

The uncertainties in the time-dependency (over the blanket fuel-cycle time) of the blanket power magnitude and spatial distributions may force reactor designers to overcool the blankets and not obtain the desired reactor coolant outlet temperatures. The loss in plant efficiency may become quite an economic penalty during the long-term operation of a fast reactor. The uncertainties in the temperature distribution create problems for the reactor designers in terms of the uncertainties in the resultant thermal stresses and deflections.

I.C. The Purdue Fast Breeder Blanket Facility, FBBF

The Purdue Fast Breeder Blanket Facility, FBBF, has been built to allow--through appropriate research--a sizable reduction of the uncertainties described above. The results will provide the basis for a more efficient design and operation of fast breeder blankets with uranium or thorium fuel. No plutonium is needed for the mock-up of a blanket. Furthermore, the blanket itself is not a reactor, neither is the small converter region in which the neutron spectrum is adjusted to match the spectrum in a reactor. Neutrons are provided by a radioactive source. Therefore, a blanket mock-up facility is a safe system and can be built and operated on a university campus.

In this report, the basic design features, the typical neutronics characteristics and the experimental capabilities are described (Sections II, III, and V). Safety considerations are presented in Sec. IV.

The research to be conducted with this facility is of high educational value. A special dual-level laboratory course is being devised to allow for a much broader utilization of the FBBF in undergraduate and graduate education.

I.D. Acknowledgements

The planning, design and building of the Purdue Fast Breeder Blanket Facility was only possible through the strong and continuous encouragement, help, and support by many:

The former AEC Division for Nuclear Education and Training (DNET) strongly encouraged us to pursue a project of this kind. The DNET, now part of the Department of Energy (DOE) provided the necessary uranium dioxide fuel rods on a loan basis; about 11,000 UO_2 rods of various enrichments (4.8%, 1.3% and natural uranium) have been obtained on loan. In addition, the acquisition of the fuel and further planning of the facility had been supported by a \$12,250 grant by the same agency.

Specifically acknowledged is the help of Dr. R.J. Neuhold in locating the needed types and quantities of fuel rods in various surplus stockpiles.

Several utilities encouraged us to forcefully proceed with this project because of its importance for long-term efficient generation of electrical power; among them Commonwealth Edison, Public Service Indiana, Consumers Power, Detroit Edison, and Cincinnati Gas and Electric.

A \$3,000 grant by Gulf General Atomics supported some of the design work. The bulk of the detailed design work and the construction has been supported by \$225,000 grant from the Electric Power Research Institute, EPRI. Most of the instrumentation has been purchased from funds received from Purdue University (\$50,000) and from Purdue Electric Power Center, PEPC (\$20,000). The first research phase, including most of the preparatory research and the work needed for the licence has been supported in part by the Department of Energy (DOE, formerly by ERDA) with a research contract in the amount of \$303,585.00. Furthermore, DOE also provided the neutron source (^{252}Cf) on a loan basis.

A precondition for this project was the interest and the cooperation of the Purdue University Administration, especially of Dean John C. Hancock. Administratively, the financial-support, the contract-negotiations, and the construction phase were the most difficult phases. The continued and intensive cooperation of Professor Paul S. Lykoudis, Head of the School of Nuclear Engineering, was vital for this project during these phases. The realization of the FBBF project is largely due to his intensive help and effort in finding the needed support and solving all administrative problems.

Special thanks is due to the Physical Plant and the Central Machine Shop of Purdue University for their excellent cooperation in the design

and construction of the facility; Tom Bennett and Charles Schenke are thanked for their numerous suggestions in improving the facility design.

Several former and current students of the School of Nuclear Engineering contributed significantly to the early feasibility studies (C.W. Terrell), the conceptual design (F.G. Krauss), the safety, neutronics and shielding investigations (L.L. Luck, K.R. Boldt, D.J. Malloy J.E. Arpa, D.W. Vehar, J.L. Westbrook, J.A. Meniscalco, and P.J. McDaniel). Special thanks are due to Dr. Bal Raj Sehgal who significantly contributed to the physics design of the FBBF during his appointment as visiting professor at Purdue University.

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II. DETAILED DESCRIPTION OF THE PURDUE UNIVERSITY
FAST BREEDER BLANKET FACILITY
(P.J. Fulford, P.M. Clikeman and R.H. Johnson)
II.A. General

(P.J. Fulford)

The laboratory consists of an experimental assembly located inside a shielded room (Room B28C) which is in turn situated inside a large facility room (Room B28). Associated with the facility (see Figs. II.1 and II.2) are various pieces of experimental equipment, operational and experimental instrumentation and some service facilities.

II.A.1. The Experimental Assembly (Spring 1978 Configuration)

The assembly consists of a pseudo-line source of fast neutrons, a set of two concentric annular cylinders containing enriched uranium and some sodium to transform the source spectrum, the annular blanket (experimental) region surrounded by a reflector, an upper blanket, a source drive mechanism, a source storage cask, and associated structural components. The assembly is shown in Fig. II.3. A detailed description of each of these components is given below. Subsequent sections describe the shielding and the laboratory facilities.

II.A.2. Sources and Source Tube

The four sources are doubly-encapsulated ^{252}Cf sources, ORNL model NSD, positioned in a tube to represent a pseudo-cosine line source. The source capsules are stainless steel and are illustrated in Fig. II.4.

The source tube is 316 stainless steel tube 12.95 mm (0.510 in.) inside diameter and 25.4 mm (1 in.) outside diameter with a welded lower hemispherical cap. The lower cap has a cross bar on its lower surface that matches a slot in the source receptacle in the storage cask. The upper

Fig. II.1: Cross-sectional view of the FBBF laboratory showing the FBBF inside the concrete blockhouse (Room B-28C).

Fig. II.2: Floor plan of the FBBF Laboratory.

Fig. II.3: Cross-sectional view of the FBBF experimental assembly.

Fig. II.4: Source Capsule

end of the tube has an enlarged 35.5 mm (1.40 in) diameter, is threaded, and has two wrench flats. A soft copper ring sits in a sealing surface on the upper end. A cap screw makes the seal. This top cap was screwed and peened into place at Oak National Laboratory, producing a triple-encapsulated source assembly.

At the bottom end of the tube a small partially compressed coil spring supports the string of 316 stainless steel 12.7 mm (0.5 in) diameter steel spacers and the source capsules. A similar spring is at the top of the string. The springs are to reduce any shock loads on the source capsules. The assembly including the capsule spacing is shown in Fig. II.5.

II.A.3. Source Guide Tube

The source guide tube, Fig. II.5, provides a smooth uninterrupted guide for movement of the source tube and its extension rod through the experimental assembly down to the middle of the source storage cask. It is a 316 stainless steel tube 38.1 mm (1.5 in) inside diameter and 50.8 mm (2.0 in) outside diameter. The inner diameter is honed to a 32 rms microfinish. The tube extends from the top of the upper blanket to the locating surface on the lower plug in the storage cask central pipe. It is held at its upper end by a screwed brass bushing which sits in the upper blanket can top plate. This bushing provides the physical stop against source overtravel. It is physically locked against removal by the source drive package (see Fig. II.3).

II.A.4. Inner Transformer Zone

This zone is contained in a welded 316 stainless steel annular cylindrical can. The can is 320 mm (12.6 in) outside diameter, and 1.09 m (43 in) high with a 58.9 mm (2.3 in) diameter central through-hole. The can contains

Fig. II.5: Source tube and source guide tube.

Fig. II.6: Inner Transformer

Fig. II.7: Outer transformer

528 of the 4.8% enriched pins located on a 12 mm (0.474 in) tight triangular pitch by an upper grid plate in the can. The remaining space in the can is filled with B_4C packed in place. The packed density of the B_4C is 1.54 g/cm^{-3} and the loaded weight was 21.59 kg. The can is shown in Fig. II.6.

The loaded can weighs approximately 670 kg. It rests on the base assembly and its located by pins concentrically to the facility vertical centerline.

The bottom plate of the cylinder is 12.7 mm (0.50 in.) thick and the top 19 mm (0.75 in.). The walls are 14 gauge.

II.A.5. Outer Transformer Region

This zone is contained in a sealed stainless steel annular cylindrical can and is illustrated in Fig. II.7. The inside annulus diameter is 32 mm (1.26 in) and the outside diameter is 443 mm (17.45 in). This zone contains an approximately circular zone of 4.8% enriched pins spaced on a 17.93 mm (0.706 in) hexagonal pitch. Unequal-sided hexagonal-shaped 316 stainless steel pins containing frozen sodium are located between the fuel pins. There are 198 fuel pins and 396 sodium pins. The fuel pins are located by 4.5 mm (0.187 in) aluminum grid plates at the bottom. The balance of the space is filled with B_4C powder with a packed density of 1.33 g/cm^{-3} . Two 22.9 mm (0.90 in) inside diameter experimental reentrant probe tubes are provided at 180° spacing. They are accessible through 38.1 mm (1.5 in) diameter plugs screwed into the top plate of the cylinder. A fuel pin or some sodium pins can be placed in these holes to minimize spectrum perturbations.

The cylinder weighs approximately 340 kg. It is 0.63 mm (0.25 in) higher than the inner transformer can thus supports the upper blanket. The can sits on the lower base plate assembly and is located by pins.

II.A.6. Radial Blanket Region

The radial blanket region is the annular volume between the inside of the radial reflector pans and the outside face of the outer transformer can. The lower surface is the top of the base plate assembly. There are 5976 15.2 mm (0.6 in) diameter natural U pins located in this region on a 1.70 cm (0.67 in) hexagonal pitch.

Six 60° segment 4.5 mm (0.187 in) thick aluminum grid plates locate these pins at both their top and bottom ends. The lower grid plates are screwed to the base plate. The upper grid plates are screwed to the top of the reflector can and the upper blanket can. The bottom end of the fuel pin locates in the hole in the grid plate while an aluminum dowel pin locates the top of the fuel pin through the grid plate. The fuel pins have aluminum or stainless steel tubes, termed secondary cladding or filler tubes, over them for experimental purposes. A typical arrangement is shown in Fig. II. 8. The filler tubes are 15.29 mm (0.602 in) ID, 16.97 mm (0.668) OD by 1.238 mm (48.7 in) long. A small number of pins are removable for experiment access. At these sites the top grid plates are drilled out to the full pin diameter (plus a clearance).

II.A.7. Reflector Region

A nominal 152 mm (6 in) thick annular zone composed of about two-thirds mild steel and one-third salt by volume surrounds the radial blanket region. The material is contained in 18 cans, each one-third of the zone height and 60° of the perimeter. The can is sectioned with the inner zone containing an average 21.8 kg (48 pounds) of salt and the outer zone containing six 28 mm (1.5 in) thick curved mild steel plates. A typical can is shown in Fig. II. 9. The cans are bolted together to form a continuous zone. Each can weighs on the average a total (salt and steel) of 329.5 kg (726 pounds).

Fig. II.8: Typical arrangement of radial blanket fuel pins and secondary cladding.

Fig. 11.9: Reflector can

II.A.8. Upper Blanket

The upper blanket currently provides shielding above the transformer region, supports the drive mechanism, locates the top end of the source guide tube, and supports the inner edge of the blanket upper grid plates. Access is provided to the top of the outer transformer region by two 144 mm (4.5 in) diameter hand access holes. The blanket dimensions are 58.9 mm (2.32 in) inside diameter, 443 mm (17.45 in) outside diameter and 282.4 mm (11.12 in) high. The blanket can is shown in Fig. II.10.

The upper blanket is essentially a welded 316 stainless steel can filled with lead. The bottom plate is 12.7 mm (0.5 in) thick as are the top plate and the side walls. The lead has been cast in two layers, the bottom one being 203 mm (8 in) thick, and the top 50.8 mm (2 in). They are separated by a thin asbestos sheet. The bottom layer of lead can be replaced by 25.4 mm (1 in) diameter natural U metal slugs currently available at Purdue.

The can weighs approximately 367 kg (810 pounds) and the lead plugs weigh 32 kg (70 pounds) each.

II.A.9. Base Plate Assembly

The base plate assembly consists of a number of steel plates laying horizontally across the top of the opening of the storage well. These plates support and locate the transformer cans, the radial blanket, and the reflector cans. They also provide gamma and neutron shielding between the source cask and the experimental assembly proper.

The bottom plate is the load bearing member. It is a full circle 1.727 m (68 in) diameter 102 mm (4 in) thick, carbon steel plate bolted to a bearing ring located in a stepped recess at the top of storage cask well. The top of the bearing ring is 102 mm (4 in) below the floor to provide clearance at the top of the drive mechanism. This plate has a central 66.5 mm (2.62 in)

Fig. II.10: Upper blanket can

the diameter hole for the source guide tube

A central plate 17.3 mm (0.68 in) thick and 443 mm (17.45 in) diameter sits on top of the bottom plate and supports the inner and outer transformer cans. This plate is screwed to the base plate. The top surface has the locating holes for the matching locating pins on the bottom of the outer transformer can. This plate has a central 91.9 mm (3.62 in) diameter hole.

Two concentric annular, 180°-segmented rings of 130 mm (3.12 in) thick plain steel plate are located under the radial blanket region. The inner, middle and outer diameters are respectively, 0.457 mm (18 in), 1.135 mm (44.7 in) and 1.473 mm (58 in). The split diameter is chosen as two-thirds of the blanket region width to allow for experiments using different length pins in the inner part of the blanket. They are split 180° to allow different experiments in each sector as well. The various plate thicknesses are chosen so that the fueled portions of the pins in the transformer regions and the natural U pins in the blanket align in a horizontal plane. The lower blanket grid plates rest on and are screwed to these plates. A 26.7 mm (1.25 in) thick segmented plate nominally 1.463 mm (58 in) inner diameter, 1.778 mm (70 in) diameter outer diameter plain steel plate sets on the base plate to support the reflector cans.

The plates are painted with a red primer rust preventative. The bottom plate weighs almost exactly 1810 kg (4000 pounds) and is the heaviest item to be lifted by the service hoist. The inner and outer blanket 180° segments weigh 210 kg (460 pounds) and 342 kg (753 pounds) respectively.

II.A.10. Source Storage Cask

The source storage cask is a segmented concrete cylinder semipermanently located in the cask well in the floor of the experimental room. The vertical

center line of the experimental assembly is common with the centerline of the storage cask. The source tube travels up and down along this axis between its storage position and its experimental position.

The cask is normally 2.42 m (95.5 in) high by 1.52 m (60 in) in diameter to provide approximately 0.76 m (30 in) of ordinary concrete shielding in every direction from the source tube when it is in its stored position. A further 305 m (12 in) of reinforced concrete outside the cask forms the well for the cask and is considered permanent. A 9 m (0.35 in) layer of "Boraflex 50" containing 12 kg (26.41 lbs) of B_4C is spread over the top of the cask as a thermal neutron shield.

The cask was cast in place in nine full height segments. The central segment is an octagon 462 m (18.2 in) across flats with a central 2 inch schedule 40 pipe. The eight peripheral segments are aligned with the octagon faces in a pinwheel arrangement so that no faces line up with the center hole. The segments were cast using greased plain sheet steel forms resting on a 25 m (1 in) bottom plate and in a cylindrical sheet steel can. The purpose of the segments is to facilitate disassembly at the end of the facility life. It is anticipated that jacks may have to be used to break the segments loose and full length rods with lugs have been cast into the concrete for this purpose. Each segment weighs about 1130 kg (2500 pounds).

The central pipe contains a polyethylene slug at its lower end. A machined steel cap at the top of the slug is screwed tightly to a rod that passes through the polyethylene and is welded to the cask bottom plate. This cap has a machined outer diameter that locates the bottom end of the source guide tube radially, a cross slot that provides a torque resistance to the source tube string, and a conical seat for the source tube to rest on

at the bottom of its travel. A curved stainless steel pipe 19.3 mm (0.76 in) inside diameter is cast in one peripheral segment as a provision to locate a neutron detector in the storage cask. The tube ends at the source lower end (in the stored position). The upper end of the tube is aligned with an access tube cast into the floor of the experimental room (facing roughly in the direction of the instrumentation boxes on the room wall).

II.A.11. Source Drive String and Drive Mechanism

A 316 stainless steel rod is attached to the top cap of the source tube by a mechanical bayonet connection. This rod provides the male half of the connection, full diameter shielding in the guide tube, and a physical stop to prevent source overtravel. The mechanical connection is a small steel cam sitting in a slot and held in by a spring. Pushing down on the rod and rotating 90° while restraining the source tube will release the connection. A stop prevents over-rotation when making the connection. This extension rod is 198 mm (7.82 in) long and 35.5 mm (1.40 in) diameter. Both it and the outer surface of the source tube are "Magnaplated" (a propriety form of teflon coating) to reduce friction with the guide tube. Both the rod and the source tube upper end diameters prohibit their passing out through the 25.7 mm (1.01 in) hole in the bushing at the top of the guide tube after assembly. The mechanical connection provides a degree of azimuthal freedom for source string alignment.

The upper end of the source extension rod is rigidly pinned to a 25.4 mm (1 in) diameter 316 stainless steel drive rod that has a rack gear mounted in it. The tube and rack are long enough to accomodate the required vertical travel of the source string between its stored and experimental positions.

A small 3 mm (0.12 in) clearance exists at the top end between the experimental position and the physical stop.

In addition to the rack the drive rod has a full length slot in which a roller runs to prevent rotation. This keeps the rack and the pinion of the drive engaged. The drive rod runs through the brass cap at the top of the guide tube and is further supported by three rollers, at 90° intervals, on the drive support. When the source is fully raised the top end of the drive rod extends into a clearance hole in the bottom layer of the ceiling beams.

The source drive package is bolted to the top of the upper blanket and traps the bushing at the top of the guide tube. It is locked in place by a security padlock and hasp to the blanket to inhibit unauthorized source removals. The package consists of a reversible 100 volt stepping motor, a gear train, a clutch, a brake, a pinion gear, position transducers, and a mounting frame. The clutch is electrically operated independently of the rest of the drive and performs the function of a remote quick-disconnect. It is a unique magnetic-particle type ("Soft-Step") and does not have clutch plates or springs as such. It is located between the pinion gear and the brake. When deenergized, it allows the source string to fall into the storage cask by gravity. The clutch supply voltage limits the force that can be applied by the drive to the source string. The brake is similar in construction to the clutch.

The source drive limits are set by microswitches mounted on the drive packages and activated by the drive rod. A ten-turn precision potentiometer is geared to the pinion gear and provides the primary indication of the source position. The stepping function of the motor is not currently utilized. The time to raise the source into position is 0.5 minutes.

The drive motor, brake, and clutch supply currents are controlled from the control panel located outside the experimental room. A manual switch located inside the experimental room is provided in the clutch supply line.

II.A.12. Fuel Pins

The various types of fuel pins available for use in the facility are shown in Fig. II.11. Their dimensions are also listed in Table II.1.

II.A.13. Material Constituents

A list of the number densities for the various materials is given in Table II.2.

Table II.3 gives some of the more important areas for the main components.

13% ENRICHED UO_2
 PELLET DIA. .383
 AL CLAD .031

4.8% ENRICHED UO_2
 PELLET DIA. .420
 SS CLAD .020

NATURAL UO_2
 PELLET DIA. .548
 AL CLAD .028

Fig. II.11: Fuel pin dimensions

TABLE II.1
Fuel Pin Dimensions

	<u>Natural Uranium</u>	<u>1.3%</u>	<u>4.8%</u>
Pellet Diameter	0.546"	0.383"	0.42"
Clad	Al	Al	348 St.St.
Clad OD	0.600"	0.453"	0.466"
Active Length	48"	48"	36
Overall Length	49 3/8"	54"	41 5/8"
Bottom Hardware	0.681"	3"	1"
Top Hardware	0.990"	3"	4 5/8"
Approx. Wt.	4 3/4 lbs.	3 lbs.	2 1/3 lbs.
Est. Clad ID	0.550"	0.391"	0.426"
Clad Thicken	0.025"	0.031"	0.020"
Clad Area	0.04516 in ²	0.4110 in ²	0.02802 in ²
Gap Area	0.00344 in ²	0.00486 in ²	0.00399 in ²
Fuel Area	0.23414 in ²	0.11520 in ²	0.13854 in ²
Total	0.2827 in ²	0.16117 in ²	0.17055 in ²
Clad VF	0.160	0.255	0.164
Gap VF	0.012	0.030	0.023
Fuel VF	0.828	0.715	0.812

TABLE II.2

Number Densities for FBBF Materials and Regions (atoms/barn-cm)

SS-304 ($\rho = 7.75$ gm/cc, Fe = 69% wt%, Mn = 2%, Cr = 19%, Ni = 10%)

Fe 0.0576672

Mn 0.0016992

Cr 0.0170555

Ni 0.0079500

SS-316 ($\rho = 7.75$ gm/cc, Fe = 67.5% wt%, Ni = 12%, Cr = 17%, Mn = 1%, Mo = 2.5%)

Fe 0.0564136

Ni 0.0095400

Cr 0.0152602

Mn 0.0008496

Mo 0.0012162

Carbon Steel ($\rho = 7.75$ gm/cc, Fe = 99.35% wt%, C = 0.2%, Mn = 0.45%)

Fe 0.0830325

C 0.00077720

Mn 0.00038231

Aluminum ($\rho = 2.702$ gm/cc)

Al 0.0603111

Nat. UO_2 Fuel ($\rho = 10.97$ gm/cc, 0.94TD, MW = 270.028 $\frac{\text{gm}}{\text{gmole}}$)

U-235 0.0001656

U-238 0.0228562

O 0.0460435

1.3% enriched UO_2 fuel ($\rho = 10.97$ gm/cc, 0.94TD, MW = 270.011 gm/gmole)

U-235 0.0002990

U-238 0.0227012

O 0.0460004

Number Densities for FBBF Materials and Regions (atoms/barn-cm)

4.8% enriched UO_2 fuel ($\rho = 10.97$ gm/cc, 0.94TD, MW = 269.905 gm/gmole)

U-235 0.0011044

U-238 0.0219048

O 0.0460184

 B_4C , inner transformer (21.59 kg, $\rho = 2.52$ gm/cc, Packing fraction 0.6124)

B-10 0.013323

B-11 0.053963

C 0.016821

 B_4C , outer transformer (23.313 kg, $\rho = 2.52$ gm/cc, Packing fraction 0.5358)

B-10 0.011655

B-11 0.047211

C 0.014717

Sodium, outer transformer (61.08 kg, $\rho = 0.97$ gm/cc, Packing fraction 0.9179)

Na 0.023324

TABLE II.3

Horizontal Plane Cross Section

Source	Material	Outer Radius (cm)	Area (cm ²)
Cf Source	Cf	0.635	1.2668
(1) Space	void	0.6477	0.05118
Source Holder	SS-316	1.270	3.7491
Space	void	1.905	6.3338
Source Guide Tube	SS-304	2.540	8.8674
Space	void	2.8575	5.3838
Inner Transformer			
Inner wall	SS-304	3.4925	12.6677
Active Region	Mix	15.79956	745.9038
Outer Wall	SS-304	15.9893	18.9489
Space	void	16.129	14.0961
Outer Transformer			
Inner Wall	SS-304	16.31874	19.3416
Active Region	Mix	21.97176	680.0196
Outer Wall	SS-304	22.1615	26.3072
Blanket			
Inner	Mix	56.810	8596.1641
Outer	Mix	73.660	6906.5386
Reflector			
Inner Wall	C1020	74.0103	162.5112
Salt Region	Salt	77.978	1894.5185
Wall	C1020	78.3283	172.0151
Steel Region	C1020	87.630	4849.6587
Outer Wall	C1020	88.900	704.3234
			24828.6665

II.B. Operating Controls (P.J. Fulford)

II.B.1. Motor Drive for Source String

The motor is a single-speed reversible AC motor. It is controlled by a switch on the control panel. The circuit for the power supply to the motor is completed if all the following conditions are met:

- a. The door to the shielded area is closed and latched.
- b. The source drive string is positioned above the "source down" limit.
- c. The source drive is positioned below the source upper travel limit. This limit is several inches above the normal experimental "source up" position.
- d. The operating key is inserted into the "operating" switch.
- e. The conditions for the remote-disconnect latch are satisfied.

Condition (b) is applicable only when the source string is being driven up. This is meant to limit the upward travel short of the mechanical stop.

To drive the source beyond the "source up" limit requires removing a mechanical limit stop from the drive and bypassing the limit switch.

II.B.2. Solenoid-Activated Remote-Disconnect

The source assembly is attached to the source drive only if current is flowing to the remote solenoid. Otherwise, the weight of the source assembly causes the sources to fall freely into the storage cask.

The power circuit to the source remote-latch is completed if all the following conditions are met:

- a. The door to B28C is closed and latched.
- b. The operating key is inserted in the "operating" switch.
- c. The source assembly is positioned below the source upper travel limit position.

- d. None of several "source drop" switches located in or near the room are activated.
- e. The "source unlatch" switch is not activated on the control panel.
- f. A.C. power is available.

II.B.3. Electric Door Latch Control

Access to the shielded area is controlled by the electric door latch. The latch is normally in the locked position. Supply of current allows the latch to unlock. For the current to flow the following conditions must be met:

- a. The source drive string must be above the "source down" limit.
- b. The source remote-disconnect mechanism must be in the "disconnect" position.
- c. The below-facility neutron monitor and the shielded-space radiation monitor must both indicate low level.
- d. The operating key must be inserted in the "door open" switch.
(thus the key cannot be in the "operating" switch.)
- e. The "door open" pushbutton is activated.
- f. A.C. power is available.

A secondary security padlock is also on the door.

II.B.4. Control Panel

The control panel is located in the facility room with a direct view of the shielded room door and far enough away to require the presence of one person to operate the "door open" button for another person to open the door of the shielded facility. It is also positioned so as to be in a low level area during source transferral operations.

II.C. Radiation Shielding (P.J. Fulford)

The shielding allows the following operations to be performed without undue hazard.

- a) rearranging the experimental assembly with the source in the stored position.
- b) entering the experiment room (B28C) with the source stored to retrieve experimental data.
- c) work in the facility room (B28) with the source in the raised position.
- d) hold classes and perform other usual operations in the surrounding portions of the Physics building.
- e) handle and store low level radiation sources such as foils and fuel pellets.

II.C.1. FBBF Experimental Area

The shielded room (B28C) walls and ceiling form the biological shielding for the FBBF facility when the source is in the raised (experimental) position. In the lowered (stored) position the storage cask is the shield as the residual radiation of the experimental assembly will be minimal.

The walls are nominally 653 mm (32 in) thick composed of 4 rows of concrete blocks filled with a high density mortar. The blocks are hollow load-bearing blocks conforming to ASTM standards 1949 C90-59 grade A. The blocks in each row are offset by half their width and half their height from the next row neighbors to minimize streaming. The high density mortar is Chemtree 1-20-26, a proprietary iron-ore type of material. Its density is a minimum 3.3 g-cm^{-3} (205 pounds/cubic foot). The mixture of the concrete in the blocks and the high density mortar in and around the blocks was treated

during the design calculations as ordinary concrete.

The room ceiling is three layers of reinforced cast concrete beams weighing approximately 1 ton each. The bottom layer is set into the walls halfway on a stepped ledge. The beams are installed offset from their vertical neighbors by a half-width to minimize streaming. The total thickness is 813 mm (32 in). The bottom layer has a 127 mm (5 in) hole at the location of the experimental assembly centerline to provide clearance for the source rod extension tube. A continuous 0.1 mm (4 mil) plastic sheet is laid over this bottom layer and taped to the top of the walls to minimize air-in leakage to the room through the ceiling. The beams can support a further loading of approximately 300 kg/m^2 (60 pounds/sq. ft) if this should be required.

An interior wall of the same composition and thickness as the exterior wall blocks direct leakage out of the doorway. To prevent secondary scattering two further concrete blocks (solid) columns are installed (dry) in the maze passage giving a tortuous path for scattering.

II.C.2. Fuel Handling Shielded Hood

A ventilated box with 25.4 mm (1 in) steel walls is provided for handling objects where there exists a possibility of dust dispersal such as opening a fuel pin to insert foils. The interior cross section of the box is 305 mm X 505 mm (12 in by 12 in) and the interior length is 3.05 m (10 ft). Hatches are provided along the top of the box and at each end for access. Air is drawn from the back of the box through a long slot and passed through a HEPA filter before being exhausted to the atmosphere. Air enters the box through the hatch openings which are sized and regulated to maintain a nominal 0.5 m-s^{-1} (100 fpm) face velocity.

A piece of 25 mm X 25 mm (1 in X 1 in) angle iron is welded along the bottom of the box to provide a holding groove for fuel pins. Lights are

installed at each end for visibility. The hatch covers can be clamped closed against rubber gaskets when not open. The box and its supports are sufficiently strong to allow lead blocks to be installed in it for further shielding if this should be required.

II.D. Experimental Equipment
(F.M. Clikeman and R. H. Johnson)

Several major pieces of experimental equipment have been acquired for the FBBF laboratory. These include a Ge(Li) detector, a computerized data acquisition system, and a thermoluminescent dosimeter (TLD) reader. Experiments for which this equipment will be used are described in Section V.

The Ge(Li) detector is a Canberra model 7229 with a resolution of 2 keV (FWHM) and relative efficiency of 13% at the 1332 keV photopeak of ^{60}Co . The detector (together with its preamplifier and cryostat) is provided with a shield against background radiation. The shield assembly allows for 8 inches of lead above the detector and around the side of the detector; 1.5 inches of steel shielding is located below the detector. (The liquid nitrogen in the cryostat also provides some shielding below the detector.)

A Canberra Scorpio 3000 system provides the FBBF laboratory with data acquisition, graphics display, and data analysis capabilities. This system is based on a PDP-11/04 minicomputer with 28K words of core memory. A separate 16K words of core memory is present for storage of pulse height spectra during data acquisition. The system includes two analog-to-digital converters which can be configured for two-parameter data acquisition. The system also includes a dual floppy disk drive for program and data storage and a DECwriter for use as an input and hard-copy output device.

The Scorpio 3000 software operates under the Digital Equipment Corporation RT-11 operating system; either single job or foreground/

background modes of operation may be selected. The RT/SCORPIO software package includes all routines used during data acquisition and provides standard functions such as peak area and centroid computation for efficiency and energy calibration. The SCORPIO/SPECTRAN software package provides the necessary routines for a quantitative isotopic analysis of gamma-ray spectra measured with a Ge(Li) detector; similar software is available for analysis of spectra measured with a NaI(Tl) detector.

Gamma heating measurements will be made using thermoluminescent (TLD) dosimetry. Dosimeters selected for the initial measurements are $\text{CaF}_2:\text{Dy}$ crystals, $1/8" \times 1/8" \times 0.035"$. Calcium fluoride was selected as the TLD dosimeter after considering factors such as the atomic number of the dosimeters, fading and sensitivity.

Readout of the dosimeters will be accomplished with a Harshaw model 2000-A TL detector and model 2000-B automatic integrating picoammeter. This system provides linear heating rates for the analysis as well as, thermal isolation and thermoelectric cooling of the phototube. The analyzer system, with its wide range of heating rates, high temperature range and sensitivity allows a wide range of TLD materials to be analyzed. A built in Radiumactivated NaI(Tl) light source and provisions for flowing dry gas through the sampling chamber permit a high degree of reproducibility in the analyzer system. The system also permits all of the common geometries of TLD's, including powders, to be analyzed. Both X-Y recorders and strip chart recorders are available for readout of the picoammeter as well as the digital current integrator.

In addition to the TLD analyzer, a furnace for both pre- and post-annealing of the dosimeters is available. The furnace is capable of temperatures in excess of 300° C, allowing it to be used with all of the more common TLD dosimeters. A rotating exposure holder has been built which will allow all of the dosimeters to be exposed to a uniform exposure and then to be grouped on the basis of uniformity of response. Calibrated gamma sources are also available to determine the absolute calibration of the TLD's and analyzer system.

III. NEUTRON AND GAMMA-RAY FLUXES (R.C. Borg and R.H. Johnson)

III.A. Neutron Energy Spectra Comparison (R.C. Borg, J.H. Paczolt and D.M. Waite)

One of the basic objectives of the FBBF is to generate spectra in the blanket which are similar to spectra found in a large fast breeder reactor blanket. The conceptual design study¹ indicated a good match between spectra generated by the FBBF and a typical 1000 MWe fast breeder reactor. A number of modifications have been implemented into the original design. Therefore, it is desirable to compare spectra generated from the final design of the FBBF with typical fast breeder reactor blanket spectra.

The physical and geometrical characteristics of the FBBF and a modified 1000 MWe Clinch River Breeder Reactor (CRBR)² were mocked-up with the one-dimensional computer code LAZARUS³. The desired neutron flux calculations were performed to determine the spectrum. In these comparisons, the blanket of the modified CRBR was identical to the initial loading of the FBBF.

The normalized spectrum from each calculation for the blanket interface, middle of the inner blanket, inner and outer blanket interface and middle of the outer blanket are plotted in Figs. III.1 to III.3. The midpoint of each group is connected for better comparison. For all illustrated space points the spectrum calculated for the FBBF is very representative of the spectrum calculated for the modified CRBR. Thus, one of the basic objectives of the FBBF to generate spectra characteristics of large fast breeder reactors have been accomplished.

Fig. III.1: FBBF and modified CRBR spectrum at the inner blanket interface and at the midplane of the inner blanket.

Fig. III.2: FBBF and modified CRBR spectrum at the inner and outer blanket interface.

Fig. III.3: FBBF and modified CRBR spectrum at the midplane of the outer blanket.

III.B. Source Axial Distribution

(R.C. Borg, M.P. Sohn, J.H. Paczolt and D.M. Waite)

III.B.1. Fluxes and Reaction Rates

Previously, axial and radial reaction rate traverses were calculated from fluxes generated by a line source with an axial chopped cosine strength distribution.⁴ These initial investigations showed that sample blanket region axial reaction rate traverses fit a chopped cosine extremely well. The ^{252}Cf source in the FBBF is not a line source but actually consists of four point sources of different strength. Their positions in the source rods predetermined to give a chopped cosine flux distribution in the blanket region, with the maximum value at the axial mid-plane. In this subsection, comparison of the total flux and sample reaction rates generated from both the line source and discrete point sources are investigated.

The calculational procedure and two-dimensional model needed for the source distribution investigations are the same as those used for the sample reaction rate calculations presented in Ref. 4. The same 21-group constant set is also used, since the 26-group library mentioned in Ref. 4 is presently still not available. The inherent problem of the 21-group library lower energy group structure will not hamper the interpretation of results since the contributions of the lowest energy group are neglected as was suggested.⁴

The axial shape of the flux and reaction rates are directly influenced by the strength and position of the four discrete sources. In Fig. III.4 and III.5, the axial shape of the total flux, at the converter blanket and blanket midplane, is illustrated. The solid line represents the flux generated from a line source. The smallest dashed lines indicate the flux generated from the calculation with four discrete sources. The maximum value of the total flux, generated by the discrete source, at the converter blanket

Fig. III.4: Axial flux shape at the converter-blanket interface.

Fig. III.5: Axial flux shape at the blanket midplane.

interface is shifted slightly above the center line, (comp. Fig. III.4). Further out into the blanket the maximum value of the total flux generated by the discrete sources is much closer to the axial midplane. As indicated in both figures, the discrete point sources generate a flux shape which is very close to the flux shape associated with cosine shaped line source.

A second investigation considered sample reaction rate traverses at the blanket midplane. The ^{238}U capture and ^{239}Pu fission rates calculated from fluxes generated by the line source and discrete point sources are illustrated in Figs. III.6 and III.7. A cosine fit of the discrete source result is also given. Reaction rates match the cosine fit very well for the two source versions. In Figs. III.8 and III.9 radial traverses of the ^{238}U capture rate and ^{239}Pu fission rate for the two source version are illustrated. The difference between the two source specifications becomes smaller as the distance from the converter-blanket interface is increased. In the converter regions the match is not extremely good as would be expected. Since most experiments are performed in the blankets this slight mismatch should not matter. It will be corrected for comparisons with actual experiments.

The material presented in this section indicates that the axial flux distribution in the blanket generated with the discrete sources follow a chopped cosine distribution and give a flux shape comparable to shapes generated by a line source. The difference between the flux generated by the line source and the discrete sources decreases as comparisons are made further into the blanket.

III.B.2. Breeding of Plutonium

It is of interest to estimate the minute quantity of plutonium which will be bred in the FBBF. The approximate 10.5×10^6 grams of ^{238}U in the blanket are assumed to interact with a neutron flux generated from the 10^{10} neutron

Fig. III.6: Axial traverse of ^{238}U capture rate at the blanket midplane.

Fig. III.7: Axial traverse of ^{239}Pu fission rate at the blanket midplane.

Fig. III.8: Radial traverse of ^{238}U capture rate at the blanket midplane.

Fig. III.9: Radial traverse of ^{239}Pu fission rate at the blanket midplane.

source for one year. No down time was considered in this estimate. After a year of continual operation approximately 5.1×10^{-4} grams of ^{239}Pu will have been bred. These plutonium atoms are embedded in comparatively much larger quantities of ^{238}U with a ratio of 0.05 parts per billion. The only way to detect this low production rates of plutonium is through the radioactive decay of ^{239}Np .

III.C. Gamma-Ray Energy Deposition Rates
(R.H. Johnson, J.H. Paczolt)

Gamma-ray energy deposition measurements using thermoluminescent dosimetry (TLD) will be part of the experimental program for the FBBF. One-dimensional discrete ordinates calculations have been made of the gamma-ray heating rates to aid in planning the TLD measurements. Gamma-rays are produced throughout the FBBF by radiative capture, fission, and inelastic scattering. Gamma-rays are also emitted by the ^{252}Cf spontaneous fission source. Because the gamma-ray flux is therefore strongly dependent on the neutron flux, a coupled neutron and gamma-ray transport calculation was performed for the preanalysis of the gamma-ray heating rates.

ANISN-W,⁵ a one-dimensional discrete ordinates code including treatment of anisotropic scattering, was obtained from the Radiation Shielding Information Center (RSIC) of Oak Ridge National Laboratory. The DLC-37/EPR cross section set^{6,7} based on ENDF/B-IV data was also obtained from RSIC. DLC-37/EPR contains coupled (100-neutron, 21-gamma-ray groups) P_8 cross sections as well as neutron and gamma-ray kerma (kinetic energy relaxed in material) factors for many important elements.

The large number of neutron groups in DLC-37/EPR necessitated group collapsing in order to perform the preanalysis calculations on the Purdue dual CDC-6500 system. ANISN-W was used for the group collapsing to 23 neutron groups. Slight modifications of ANISN-W were found necessary for the correct collapsing of a coupled cross section set.⁸

An S_4, P_3 calculation was performed for the preanalysis using a one-dimensional model of the FBBF⁹ and a transverse leakage correction. The TLD measurements will give, to a first approximation, the gamma-ray

energy deposition rate in the material surrounding the dosimeter. Several different materials are of interest. Preanalysis calculations of the gamma-ray energy deposition rates in type 316 stainless steel, lead, and UO_2 are shown in Figs. III.10, III.11, and III.12. (Heating rates in uranium were obtained by extrapolation¹⁰) The calculations are normalized to represent a radial traverse along the axial midplane of the blanket. These results can be used in planning the TLD measurements.

A different cross section set will be used for the final calculations because DLC-37/EPR has two shortcomings. First, a thermal temperature of 800°K was used in producing DLC-37/EPR; as a result, cross sections in the resonance region are higher than they should be for room temperature. Second, delayed gamma rays from fission are not included in DLC-37/EPR. Further calculations will be made using ANISN-W and a new cross section set. It will be necessary to use a two-dimensional transport code for the final calculations, especially if heating rates near the top and bottom of the radial blanket (or actually in the axial blanket) are to be calculated.

Fig. III.10: S_4, P_3 ANISN-W calculation of gamma-ray energy deposition rate in type 316 stainless steel for blanket height of 159.52 cm.

Fig. III.11: S_4, P_3 ANISN-W calculation energy deposition rate in lead for blanket height of 159.52 cm.

Fig. III.12: S_4, P_3 ANISN-W calculation of gamma-ray energy deposition rate in natural UO_2 for blanket height of 159.52 cm.

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IV. SAFETY STUDIES

(R.C. Borg, K.R. Koch, D.M. Waite, J.H. Paczolt)

The FBBF is a fast neutron subcritical facility. Thus, for normal operation, there is an insignificant number of low energy and thermal neutrons due to the absences of moderating materials. Safety of the FBBF is primarily concerned with the hypothetical flooding accident, which would inject water, as a moderator, into the system causing moderation of neutrons which would then decrease the degree of subcriticality. Since the FBBF is located below ground level, flooding could possibly occur if there were a fire and large amounts of water were necessary to extinguish it. The FBBF is designed so that it could not accidentally become critical or come close to a critical state for any flooded condition.

There are a number of safety design considerations implemented into the construction of the FBBF to eliminate the possibility for accidental proximity to criticality. The easiest way to assure subcriticality for the hypothetical flooding accident, is to displace water by physically reducing voided regions. This is especially necessary for the converter regions which contain 4.8% enriched material. Boron carbide was vibrated into the voided area of the converters. Besides displacing water it has the added safety feature of being a high thermal neutron absorber. The impact of B_4C on the fast neutron spectrum has been shown to be negligible but it significantly increases the degree of subcriticality for the hypothetical flooding accident. To further eliminate the possibility of water saturation in the converters, they are separately welded shut.

Another safety feature implemented into the construction of the FBBF is the used of secondary stainless steel and aluminum cladding in the blanket region for the initial loading. The secondary cladding has two functions,

primarily for normal operation to investigate the effect of stainless steel and aluminum in the blanket and secondly to physically displace water of a hypothetical flooding accident. These two design considerations illustrate the care which was taken in the development of the FBBF to assure that under accidental flooding it would still be substantially subcritical.

IV.A. Initial Loading Sequence

The safety investigations of the initial loading sequence can be described in two parts: Change in k_{eff} due to pitch variations, type of secondary clad and blanket thickness¹ and the safety of a designated loading configuration. The first type of investigation was completed for 360° loading configurations and the results reported in Ref. 2. In Ref. 2 it was shown that, for all of the initial 360° loadings in the first sequences, the FBBF would be substantially subcritical for a hypothetical flooding accident.

The procedure for evaluating k_{eff} of a hypothetical flooding accident involves the determination of group constants for each distinct region with the HAMMER³ code and evaluating k_{eff} with 2DB⁴.

The value of k_{eff} for the initial loading of the FBBF, with partial blanket loadings, are given in Table IV.1. It was assumed that there were 35 cm of water on the top and sides. The tabulated values of k_{eff} are proportional to the blanket thickness and well below the 0.75 limit specified by the license for the initial loading.

It is also of interest from a safety point of view, to know the values of k_{eff} for the normal operation of the facility. These calculations were based on the one-dimensional description reported in Ref. 5. The LAZARUS² code was used to calculate the values of k_{eff} illustrated in Table IV.2. Again,

TABLE IV.1

Values of k_{eff} for Hypothetical
Flooded Initial Blanket Loading

	k_{eff}
Full Blanket	0.432
Half Blanket	0.382
No Blanket	0.341

TABLE IV.2

Values of k_{eff} for Initial
Blanket Loading

Full Blanket	0.303
Half Blanket	0.292
No Blanket	0.209

as was seen for the hypothetical flooded case, as the blanket thickness increases, k_{eff} becomes larger and is well below the $0.45 k_{eff}$ -limit specified by the license for normal operation.

IV.B. Future Loading Schemes

Further safety studies need to be carried out for future loadings which consist of placing enriched material in the blanket, to simulate bred plutonium, and investigating two or three different 180° or 120° loading configurations. From the investigations presented in Ref. 2, it looks as though all configuration will be safe in terms of the hypothetical flooding accident. But further investigations still need to be carried out to varify the safety of individual future loadings.

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V. EXPERIMENTAL CAPABILITIES
(F.M. Clikeman and R.H. Johnson)

V.A. Reaction Rate Measurements

(F.M. Clikeman, R.H. Johnson, G.A. Harms,
H.P. Chou, and T.P. Gwynn)

A broad category of experiments which will be performed is the systematic determination of reaction-rate data throughout the blanket region of the FBBF. Two different experimental techniques will be used. The first technique is the activation of various foils in the FBBF followed by the measurement of the foil activities. Among the more important activities included in this technique is the ^{239}Np activity from the irradiation of ^{238}U foils because this is a direct measurement of the ^{239}Pu breeding rate. The second technique is the use of solid state track recorders (SSTR) to measure the fission rates of ^{235}U , ^{238}U , ^{237}Np , and ^{239}Pu . Many of the reaction rates which will be measured are of interest in themselves. All of the measured reaction rates may be used as input to unfolding codes such as SAND-II¹ for determination of neutron energy spectra.

The foils chosen for activation all have gamma-ray emitting activation products. All of the foils can be counted using the Ge(Li) detector discussed in Section II.C.4. The Scorpio 3000 data acquisition system (discussed in that same section) has software for the analysis of gamma-ray spectra measured with the Ge(Li) detector. The high resolution of the Ge(Li) detector will aid in the measurement of many reaction rates

(such as ^{238}U capture) in which the gamma-ray background is high. Some of the foils used, however, will give relatively "clean" gamma-ray peaks of interest; such foils may be counted with a NaI(Tl) detector. An automatic sample changer is available for use with a NaI(Tl) detector; the feasibility of interfacing the sample changer with the Scorpio 3000 is being investigated. Software for the quantitative analysis of NaI(Tl) spectra is also available for the Scorpio 3000 system.

The solid-state track recorder technique² will be used to measure fission rates. In this technique thin (approximately $10\text{ }\mu\text{g}/\text{cm}^2$) fissile or fissionable sources are sandwiched with an SSSTR and placed in the neutron flux of interest. Fission fragments from the source embed themselves in the recording material causing radiation damage along their tracks. The tracks can then be revealed by chemical etching to enlarge the tracks.

Two types of SSSTR's have been investigated, glass and polycarbonate film. Glass currently appears to be the better material for measurements in the FBBF. Several methods for counting the tracks have been investigated. Equipment for photographing the SSSTR's through a microscope has been acquired and tested; tracks seen in the photographs are counted by hand. This method is accurate but quite time-consuming. The spark counting method has been tested but currently the accuracy of this technique is poor. A third method, the use of a scanning optical microscope, is being investigated for possible development. A scanning optical microscope is available and could be interfaced with a microcomputer for data analysis and data logging.

V.B. Gamma-Ray Heating Rate Measurements (TLD)
 (F.M. Clikeman and K.R. Koch)

Gamma-ray heating rate measurements will be made in the blanket region of the FBBF to yield information about the transport of energy by gamma rays. The measurements will be made using thermoluminescent dosimeters (TLD's). Similar measurements have been made at Argonne National Laboratory using the ZPR-3 and ZPPR facilities.^{3,4} The use of TLD's is simple and straightforward. A TLD is irradiated in an experimental facility. The TLD is removed and "read" (see Section II.C.4 for a discussion of the TLD reader). The TLD reader heats the TLD and measures the light subsequently emitted.

TLD's must be carefully calibrated because their response varies greatly; a turntable has been constructed for calibrating the TLD's with a ⁶⁰Co source. Corrections must be made for the neutron response of the TLD; measurements of the neutron spectrum will be used in doing this. The remaining difficulty in analyzing the results of the TLD measurements is in relating the absorbed dose in the TLD to the gamma-ray heating rates in the different materials in the FBBF. Work at Argonne National Laboratory has shown that the use of cavity ionization theory is necessary.³

V.C. Neutron Energy Spectrum Measurements
 (F.M. Clikeman, R.H. Johnson, K.O. Ott,
 D.W. Vehar, G.A. Harms, and A.L. Hilton)

Two different methods will be used to measure neutron energy spectra in the FBBF. The more direct method will use proton-recoil proportional counters. The other method will be the unfolding of the reaction rate measurements discussed in Section V.A. to yield neutron spectra; new techniques for such "foil unfolding" are being developed.

Proton-recoil detectors filled with a hydrogen-rich gas utilize the elastic scattering reaction between an incident neutron and a hydrogen nucleus in the gas. The recoil proton loses its energy by producing ionization as it passes through the gas. The distribution of pulse heights output from the detector will therefore correspond to the energy distribution of recoil protons in the detector. The neutron-proton elastic scattering cross section is large, well known, and isotropic below 10 Mev. As a result of the isotropy of the n-p scattering reaction, all proton energies less than or equal to the incident neutron energy are equally probable. The neutron energy distribution $\phi(E)$ can be obtained by differentiation of the proton-recoil energy distribution $P(E)$, such that⁵

$$\phi(E) = -E/NT\sigma(E) \, dP(E)/dE.$$

In the above equation, N is the number of hydrogen atoms in the effective volume of the counter, T is the time-duration of the measurement, and $\sigma(E)$ is the n-p elastic scattering cross section.

Any gas-filled proportional detector is sensitive to gamma radiation. In general, the gamma ray interacts in the walls of the counter producing a photoelectric or Compton electron which enters the detector fill-gas

where it produces ionization and is counted. Electronic gamma-ray discrimination is possible because the specific ionization of recoil protons is higher than that of electrons produced by the gamma rays. In methane at a pressure of two atmospheres, for example, a 100-keV proton has a range of about 0.5 mm, while an electron has a range of about 8 cm at the same energy. As a result, the ionization from a recoil proton occurs with a much smaller spatial extension than does that from an electron, and the rise time of a neutron event will be much shorter and better defined than that of a gamma-ray event. A block diagram of the electronics for measuring proton-recoil spectra is shown in Fig. V.1.

Measured reaction rates (see Section V.A.) will be used as input to computer codes such as SAND-II¹ and CRYSTAL BALL⁶ that determine neutron spectra from such reaction rate information. The STAY'SL code of Perey⁷ will also be investigated for possible use. A method for incorporating fine structure in the unfolded spectra based on neutronics calculations will be investigated (see Ref. 8, for example). An unfolding method using a multigroup approach is also being developed at Purdue. Neutron spectra obtained from such foil unfolding programs will be compared directly with spectra measured by proton recoil; comparisons will also be made with theoretically determined spectra.

Fig. V.1.: Block Diagram of Electronics

V.D. Future FBBF Loadings
 (P.M. Clikeman and R.H. Johnson)

Experimental capabilities of the FBBF facility include the ability to determine fission rates, neutron capture rates, gamma ray absorption rates and neutron spectra in a simulated fast breeder reactor (FBR) blanket. The techniques and capabilities to make each of these measurements have been previously discussed in this and other reports.

The first experiment will be to provide benchmark data on a clean, simple-geometry, simulated FBR blanket. This initial blanket will have the typical UO_2 and stainless steel number densities but will have no sodium. Instead, the sodium will be partially simulated by the aluminum cladding of the UO_2 fuel rods. Succeeding experiments will vary the number densities of the aluminum and stainless steel to determine the effect of these materials. The effect of varying the number density of the UO_2 (by varying the spacing between the fuel rods) on the reaction rates and neutron spectra will also be investigated.

Subsequent blanket loadings will permit experiments that will investigate the effects of the buildup of fissile materials in the blanket. The bred plutonium will be simulated by using slightly enriched (1.3%) aluminum clad UO_2 fuel rods in the blanket to replace some of the aluminum clad natural UO_2 rods in the initial blanket loadings and experiments. The effects of shuffling the bred plutonium to the outer regions of the blanket will be simulated by loading the slightly enriched fuel rods into the outer blanket locations.

Experiments to investigate the effects of blanket thickness are also planned. The initial experiments will be performed with a 51 cm thick blanket, but this will be reduced to 34 cm for later experiments.

The possibility of leaving one 180° sector of the blanket as a reference region for future experiments is being considered. Calculations show the possibility of using two 180° blanket sectors with different fuel and material loadings at the same time. Initial experiments are designed to verify this capability. If one 180° sector is left as a reference blanket it can be used to develop and test new experimental techniques, as a typical FBR neutron spectrum for other experiments, and as a reference spectrum for comparison of experimental results between different blanket loadings.

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VI. ADMINISTRATION AND SUPERVISION
(F.M. Clikeman)

The research program of the Purdue Fast Breeder Blanket Facility project is guided by a committee of the principle investigators. This committee, chaired by the project director, Professor K.O. Ott, --in coordination with the DOE/EPRI Project Management Group-- determines the direction and goals of the research, outlines the approaches, and reviews the progress of the work. Direct supervision of research in the areas of theory and computational methods are provided by Professors Ott and R.C. Borg. The computer calculations for the various phases of the project are supervised by Professors Borg, O.H. Gailar, and R.H. Johnson. The experimental research, scheduling, and day to day operation of the FBBF facility is supervised by the director and codirector of the FBBF Laboratory, Professors F.M. Clikeman and Johnson.

The safety of the FBBF operations and radiation monitoring are reviewed and handled by the university Radiological Control Officer, Professor Paul Ziemer, and his staff. The safety aspects of all major modifications to the facility and experiments are reviewed by the University Radiological Control Committee, consisting of experienced senior staff members representing all of the schools of the university that use or work with ionizing radiation and chaired by Professor John Christian.

The licenses for the facility and the material used for the research, as for all NRC licenses held by the university, are handled and administered by the Radiological Control Office. All contractual arrangements and negotiations for research projects at the university are handled by the contracts office of the Purdue Research Foundation. Auditing of the project accounts and financial reports are provided by the University Business Office.

VII. COLOR PHOTOGRAPH OF PARTIALLY LOADED BLANKET
(F.M. Clikeman)

This photograph of the FBBF facility shows the partially loaded initial blanket. The center of the picture shows that outer transformer can with the upper axial blanket can and source drive mechanism mounted on it. The lead plug visible in the upper blanket is removable to provide access to one of the two experimental locations in the outer transformer region. A number of the yellow reflector cans that surround the facility and partially support the upper grid plate are also visible. The natural uranium oxide fuel rods are located in the top and bottom grid plate by pins. The different colored pins in the upper grid plate indicate whether the rods have stainless steel sleeves (gold), aluminum sleeves (blue) or are experimental rod positions (red).