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FAST BREEDER BLANKET FACILITY
FBBF

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ABSTRACT

The work performed in the reporting period was primarily concerned with aspects of the pre-analysis (Task B) and the corresponding safety investigations of the Fast Breeder Blanket Facility (FBBF). Progress on the loading of the first configuration, testing experimental equipment, and performing check-out tests are also summarized (Task C).

It is necessary that a neutron poison (B_4C) be placed in the converter regions in order to hold the value of k_{eff} for a hypothetical flooded FBBF of future loadings below the licensed limit of 0.75. It appears that this limit on k_{eff} can be attained for all loadings if one of the 180° configurations consists of stainless steel double clad natural uranium rods. The safety of one of the most reactive configurations is investigated and the need for B_4C verified. In addition, the safety of other FBBF loadings is investigated.

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Task B (R. C. Borg)

B.1 Introduction

The object of this task is to perform a detailed pre-analysis of the first experimental sequence. Previous progress reports (comp. Ref. 1 and 2) have indicated the need for a high thermal neutron absorber to keep k_{eff} of an advanced-loaded hypothetically-flooded facility as low as possible. Since the welded inner and outer converter regions will be the same for all blanket loadings, this investigation had to be carried out prior to the final pre-analysis of the initial loading.

To enhance the safety features of the FBBF for the hypothetical flooding accident, a large thermal neutron absorber in the form of B_4C powder is to be vibrated into both the inner and outer converter regions. The investigations performed to verify the need for placing B_4C into the converters are given in Sec. B.2.

Safety of some of the possible loading schemes, described in Ref. 1, are investigated and results discussed in Sec. B.3.

B.2 Safety Study to Investigate B_4C in the Converters (R. C. Borg, N. A. Hanan, J. Arpa and O. H. Gailar)

2.1 Introduction

The initial Advanced Loading Safety Studies for the FBBF were performed with the inner and outer converters treated as single homogenized regions for the k_{eff} calculation. Originally, region cross sections were calculated based on a unit cell description for each converter. At the boundaries of the converters, the unit cell concept

does not apply since the material residing in these locations is different from that in the interior. Figure B.1 illustrates an improved mockup of the FBBF with the boundary areas specifically described as individual regions. These studies were necessary to investigate whether B_4C should be vibrated into the converters.

2.2 Region Dimensions of the FBBF Mockup For a Flooding Accident

2.2.1 Inner Converter (IC)

The inner converter which was originally considered as a single region is divided into three distinct regions (comp. Fig. B.1).

Region A: Inner converter inner boundary region.

This region contains water or B_4C mixed with water. The area of the region which does not contain any fuel pins is identical to the voided area between R_1 and R_2 . The value of R_2 in Fig. B.1 is calculated with the aid of Fig. B.2 by noting:

$$\frac{\pi}{6}(R_2^2 - R_1^2) = \frac{L^2\sqrt{3}}{4} - \frac{11}{6} \cdot \pi \frac{s^2}{4},$$

with

$$R_1 = 3.65125 \text{ cm},$$

$$L = 4s,$$

$$s \equiv \text{pitch} = 1.18872 \text{ cm},$$

thus

$$R_2 = 3.8529 \text{ cm}.$$

Region B: Homogenized inner converter region based on the unit cell description.

The value of R_3 is calculated by knowing that the volume (area) of this region must be equal to the volume (area) of the total number

$$R_1 = 3.6512 \text{ cm}$$

$$R_2 = 3.8529 \text{ cm}$$

$$R_3 = 15.2382 \text{ cm}$$

$$R_4 = 15.7988 \text{ cm}$$

$$R_5 = 16.1925 \text{ cm}$$

$$R_6 = 16.6357 \text{ cm}$$

$$R_7 = 21.2198 \text{ cm}$$

$$R_8 = 21.8948 \text{ cm}$$

$$R_9 = 22.1520 \text{ cm}$$

$$R_{10} = 22.8778 \text{ cm}$$

$$R_{11} = 39.7916 \text{ cm}$$

$$R_{12} = 56.9522 \text{ cm}$$

$$R_{13} = 73.00 \text{ cm}$$

Fig. B.1 FBBF Mockup for a Hypothetical Flooding Accident

Fig. B.2 One-Sixth Section of the Converters

of unit cells in the region. The basic equation is given by:

$$\frac{\pi}{6}(R_3^2 - R_2^2) = n_1 A_1,$$

with

$$R_2 = 3.8529 \text{ cm},$$

$$n_1 = \text{number of unit cells in a sector of } 60^\circ = 93,$$

$$A_1 = \text{area of unit cell} = 1.2237 \text{ cm}^2,$$

thus

$$R_3 = 15.2382 \text{ cm}.$$

Region C: Inner converter outer boundary region.

This region contains water or B_4C mixed with water depending on the investigation. The external dimension, R_4 (comp. Fig. B.1), is identical to 15.7988 cm.

2.2.2 Outer Converter (OC)

The outer converter is divided into three regions in the same way as the inner converter (comp. Fig. B.1). Calculation of the radial dimensions is slightly different. The area of the region near the boundary of the converters does not contain any fuel pins and is almost equal to one-third the total voided area of the outer converter region. Therefore, the radial dimensions for regions D and F were evaluated so that region F has twice the area of region D (comp. Fig. B.1). Region E has a volume (area) equal to that of the cell description for total number of fuel pins in the OC (in the same way as region B in the IC). Therefore, the values of R_6 and R_7 were calculated with the following expressions:

$$\frac{\pi}{6}(R_6^2 - R_5^2) = \frac{1}{2} \frac{\pi}{6}(R_8^2 - R_7^2),$$

$$\frac{\pi}{6}(R_7^2 - R_6^2) = A_2 n_2,$$

where

$$R_8 = 21.8948 \text{ cm},$$

$$R_5 = 16.1925 \text{ cm},$$

$$A_2 = \text{area of the unit cell of OC} = 2.7534 \text{ cm}^2,$$

$$n_2 = \text{number of unit cells in a } 60^\circ \text{ sector} = 33,$$

thus

$$R_6 = 16.6357 \text{ cm}$$

and

$$R_7 = 21.2198 \text{ cm}.$$

2.2.3 4.8% Enriched Uranium Blanket Region

Region G: Inner boundary region:

The outer radius of this region, where there are no fuel pins, can be calculated with the aid of Fig. B.3 and Fig. B.1 and the following equation:

$$\frac{\pi R_{10}^2}{6} - \frac{\pi R_9^2}{6} = L \frac{2\sqrt{3}}{4} - \frac{55}{3} A_3,$$

with

$$R_9 = 22.152 \text{ cm (from the construction of the facility),}$$

$$L = R_9 + 3s \text{ (from Fig. B.3),}$$

$$s \equiv \text{pitch} = 1.5958 \text{ cm},$$

$$A_3 \equiv \text{area of the unit cell in the 4.8\% blanket region} = 2.2054 \text{ cm}^2.$$

The factor $\frac{55}{3}$ accounts for the number of fuel pins inside the triangle with a side of length L , thus:

$$R_{10} = 22.8778 \text{ cm}.$$

Fig. B.3 One-Sixth of the FBBF 4.8% Blanket Region

Region H: Homogenized region based on the unit cell description.

The dimension of this region is calculated in the same way as Region B. This gives the value of R_{11} equal to 39.7916 cm.

2.2.4 1.3% Enriched Uranium and Natural Uranium Blanket Regions

The dimensions of the blanket regions containing the 1.3% enriched fuel pins are calculated in the same way as region B, i.e., the volume (area) of the region must be equal to the total volume (area) of the unit cells in the region. This gives the value of R_{12} equal to 56.9522 cm.

The external radius of the natural uranium region (R_{13}) is determined by the construction of the facility and is identical to 73.00 cm.

2.3 Calculation of Cross Sections

The set of cross sections for the additional four converter boundary regions was calculated using the HAMMER³ code. In order to determine group constants which would give the best description of the system and also the best approximation to the actual cross sections, several strategies were considered for the wet case. The models are described with the aid of Fig. B.4:

Model A: The unit cell of the inner (outer) converter as the central region is surrounded by a ring describing the boundary region and another ring consisting of the stainless steel wall. Determination of the dimensions of this modified unit cell was dictated by the conservation of the proportionality of the region volumes (configuration A in Fig. B.4).

Model B: The unit cell of the inner (outer) converter as the central region is surrounded by a ring describing the boundary region mixed with the stainless steel wall (configuration B in Fig. B.4).

Configuration A

- 1 - Unit cell
- 2 - H_2O
- 3 - SS

Configuration B

- 1 - Unit cell
- 2 - (H_2O + SS) mixed

Configuration D

- 1 - OC unit cell
- 2 - Water
- 3 - SS
- 4 - Water
- 5 - IC unit cell

Configuration E

- 1 - Unit Cell (IC)
- 2 - Water

Fig. B.4 Unit Cells for Group Constant Calculation
of the Converter Boundary Regions

Model C: The unit cell input for HAMMER was based on Fig. B.5 with inner and outer converter mid-planes as boundaries.

Model D: Use of the unit cell of the inner (outer) converter as the central region surrounded by several rings as described below:

- a. Ring of water in the inner (outer) converter
- b. Ring of stainless steel (wall)
- c. Ring of water in the outer (inner) converter
- d. Ring of the unit cell of the outer (inner) converter

The results of the cross section calculations were compared and those of configuration D were assumed to be the best values because they represent the actual physical characteristics in more detail and also give the most conservative values for the group constants, i.e., lowest value of absorption in the thermal energy group. Therefore, the group constants for the additional regions with maximum boron in both converters were calculated using only configuration D.

2.4 k_{eff} Calculation

Procedure for evaluating k_{eff} of the hypothetical flooding accident involves the determination of the group constants for each of the regions and mock-up of the facility. This was performed with the aid of HAMMER, as described in Section 3, and the 2DB - Code⁴ which was used to mock-up the facility and calculate the value of k_{eff} .

2.4.1 Mock-Up of the Facility

The geometrical description of the FBBF used as input to 2DB for the hypothetical flooding accident is illustrated in Fig. B.6 and B.7 (initial and improved models). The material specifications are given in Table B.1. See

Fig. B.5 FBEF Mock-Up for K_{eff} Calculation

Fig. B.6 Initial FBBF Mock-Up for Advanced-Loading Study

Fig. B.7 Improved FBBF Mock-Up for Advanced Loading Study

Table B.1
Material Description FBBF Mock-Up

1. Inner Converter Region
2. Outer Converter Region
3. Nat. U. Region
4. Source
5. Source Steel Plug
6. Axial Blanket
7. Reflector
8. Source Water (Below Source)
9. Base Plate Assembly
10. Non-Active Inner Converter Region
11. Concrete Base
12. 4.8% Enriched Fuel Region
13. 1.3% Enriched Fuel Region
14. Non-Active Radial Blanket Region
15. Lead on Top of the Axial Blanket
16. Inner Converter Inner Boundary Region
17. Region Between Converters
18. Outer Converter Outer Boundary Region
19. 4.8% Blanket Inner Boundary Region
20. Non-Active Outer Converter Region

also Ref. 2 and Sec. B.3 for further explanation of materials and regions.

The additional regions which appear in the improved model (comp. Fig. B.7), were described in Sec. 2.2 with two differences:

1. Region 17, in Fig. B.7, is the result of mixing the inner converter outer boundary region, the outer converter inner boundary region and the stainless steel wall. The cross sections for this region were obtained by appropriate flux-volume weighting.

2. Region 19, in Fig. B.7, is the result of mixing the 4.8% blanket inner boundary region with the wall between it and the outer converter. The group constants were calculated as described above.

For a hypothetical advanced loading flooding accident, water must be displaced from the 4.8% and 1.3% enriched uranium regions to keep k_{eff} well below one. Two strategies were considered for region 12 and region 13. The first option assumed placement of secondary boron-SS pins in region 12 and SS pins in region 13 to reduce the water volume fraction and also increase the macroscopic absorption cross section. In the second case, boron-SS pins in the 4.8% region were replaced by SS pins. See Sec. B.3 for further discussion.

2.4.2 Results and Conclusions of the Criticality Evaluation

The results of the criticality evaluation for the FBBF advanced loading for both 2DB mock-ups (initial and improved, comp. Figs. B.6 and B.7) with the converters containing and void of boron carbide are present in Table B.2.

It is seen from Table B.2 that the improved mock-up which explicitly describes the boron carbide boundary regions reduces the value of k_{eff} much more than in the previous model. In the first case where the secondary pins in the 4.8% enriched region are boron-SS, the value of k_{eff} is reduced from

Table B.2

 k_{eff} for New and Initial Configurations

Case	Converters	Blanket		New Configuration	Initial Configuration
		4.8%	1.3%	k_{eff}	k_{eff}
1.a	No B_4C	B-SS	SS	0.845	0.712
1.b	Max B_4C	B-SS	SS	0.674	0.709
2.a	No B_4C	SS	SS	0.923	0.784
2.b	Max B_4C	SS	SS	0.691	0.748

0.845 to 0.674. However, in the old configuration, the influence of B_4C is significantly less noticeable. Similar results are illustrated in case two, where the boron-SS pins are replaced by SS-pins.

In conclusion, for safety reasons, boron carbide should be vibrated into the converters because it definitely reduces the value of k_{eff} below 0.75 for a hypothetical flooding accident for one of the most reactive configurations.

B.3 Safety of FBBF Loading Schemes (R. C. Borg, K. Koch, N. Hanan, D. Waite, J. Arpa and O. H. Gailar)

3.1 Introduction

Safety of any loading sequence is primarily associated with the hypothetical flooding accident. The safety investigations for the initial loading and advance loading sequences can be described in two parts: changes in k_{eff} due to pitch variations, etc. (comp. Ref. 1) and the safety of a designated loading configuration. The investigations present in this progress report have been devised in such a way that both types of safety investigations are simultaneously evaluated.

The procedure for evaluating k_{eff} of hypothetical flooding accident involves determination of the group constants for each distinct region and mock-up of the facility. HAMMER and 2DB were used to evaluate the group constants and mock-up the facility, respectively.

The safety analysis of three configurations are presented. They consist of blanket loadings with:

1. single clad natural UO_2 pins,
2. double clad natural UO_2 pins,
3. advanced blanket loadings based on a combination of:

- a. stainless steel secondary rods with 4.8% enriched pins,
- b. stainless steel secondary rods with 1.3% enriched pins,
- c. natural uranium UO_2 pins.

For the unit cell description of regions not specifically present in this section, see Ref. 2.

3.2 Single Clad Natural Uranium Blanket

The single clad blanket consists of natural UO_2 fuel with aluminum clad. The unit cell description used as input to HAMMER is shown in Fig. B.8. The geometrical model of the FBBF used for the two-dimensional k_{eff} calculations is shown in Fig. B.9 with a material description given in Table B.3. (See also Ref. 2.)

The hexagonal pitch of the fuel pins was varied from 1.524 cm where the cladding of adjacent pins just touch, to a large pitch of 6.35 cm. Results of this investigation are illustrated in Fig. B.10 and in Table B.4.

The k_{eff} of the facility follows the same trends as the blanket k_{∞} as the pitch is increased. The blanket region strongly influences the value of k_{eff} up to about a 4.5 cm pitch. For a pitch greater than 4.5 cm, the contribution of the blanket to k_{eff} is negligible and the facility effective multiplication is determined by the converter regions. The k_{eff} of the flooded FBBF with a single clad blanket reaches a maximum of 0.813 for a pitch of about 2.1 cm.

3.3 Double Clad Natural Uranium Blanket

The double clad blanket consists of the same aluminum clad natural UO_2 pins as the single clad blanket. A secondary clad of either stainless steel or aluminum tubing is placed around the fuel pins. The secondary

<u>Region</u>	<u>Material</u>	<u>O.D. (in.)</u>
1	0.711% UO_2	0.546
2	Gap (O_2)	0.550
3	Al clad	0.600
4	H_2O	$\text{OD}_{\text{H}_2\text{O}} = \text{Pitch} \sqrt{\frac{6 \tan 30^\circ}{\pi}}$

Fig. B.8 Single Clad Blanket Unit Cell

Fig. B.9 2DB Mock-Up of FBBF for
Initial Loading Safety Investigation

Table B.3

2-D FBBF Region Descriptions

- 1 - Inner Converter
- 2 - Outer Converter
- 3 - Blanket
- 4 - Source
- 5 - Axial Blanket
- 6 - Reflector
- 7 - Source Drive Rod
- 8 - Water Below Source
- 9 - Concrete
- 10 - Steel Base and Spacers
- 11 - Lead Cap
- 12 - ICR Lower Pin Ends
- 13 - ICR Upper Pin Ends
- 14 - OCR Lower Pin Ends
- 15 - OCR Upper Pin Ends
- 16 - Source/ICR Transition
- 17 - ICR/OCR Transition
- 18 - OCR/Blanket Transition A
- 19 - OCR/Blanket Transition B

Nat. UO_2 Blanket Pitch (cm)

Fig. B.10 FBBF Safety Study Single Clad Blanket

Table B.4
Single Clad Blanket Results

Pitch (in)	(cm)	Number Density atoms/barn-cm	$k_{\infty}^{\text{blanket}}$	k_{eff}
0.600	1.524	0.0172581	0.55005	0.46919
0.620	1.575	0.0161626	0.65884	0.56458
0.640	1.626	0.0151682	0.73496	0.63576
0.655	1.664	0.0144814	0.77737	0.67684
0.668	1.697	0.0139233	0.80669	0.70584
0.673	1.709	0.0137172	0.81647	0.71565
0.740	1.880	0.0113457	0.89382	0.79654
0.770	1.956	0.0104788	0.90799	0.81329
0.800	2.032	0.0097077	0.91439	0.82148
0.900	2.286	0.0076703	0.90127	0.81566
1.000	2.540	0.0062129	0.86045	0.78145
1.200	3.048	0.0043145	0.75314	0.68594
1.500	3.810	0.0027613	0.59478	0.54255
1.750	4.445	0.0020287	0.48680	0.44674
2.000	5.080	0.0015532	0.40109	0.40184
2.250	5.715	0.0012272	0.33646	0.38803
2.500	6.350	0.0009941	0.28357	0.36926

cladding tubes have an ID of 1.5291 cm and an OD of 1.6967 cm. The unit cell description used as input to HAMMER is shown in Fig. B.11. The 2DB geometrical model is identical to that of the single clad blanket case (comp. Fig. B.9 and Table B.3).

The hexagonal pitch of the double clad fuel pins was varied from the minimum of 1.6967 cm where the secondary cladding of adjacent pins just touch to a pitch of 6.35 cm. The results of this investigation are shown in Figs. B.12 and B.13 and Tables B.5 and B.6.

As in the case of the single clad blanket, the k_{eff} of the FBBF follows the k_{∞} of the blanket. The blanket region influences k_{eff} up to about a 5 cm pitch with Al as secondary cladding and up to about a 4 cm pitch with stainless steel as secondary cladding. For a pitch greater than these values, the converters cause the value of k_{eff} to level off while the blanket k_{∞} continues to decrease.

The k_{eff} of the flooded FBBF with a double clad blanket reaches a maximum of about 0.80 for a pitch of 2.3 cm for aluminum secondary cladding and a maximum of about 0.62 for a pitch of 2.3 cm when stainless steel is the secondary clad. Both types of secondary cladding cause the maxima to be lower and also shift it to a larger pitch when compared to the single clad blanket.

<u>Region</u>	<u>Material</u>	<u>O.D. (in.)</u>
1	0.711% UO_2	0.546
2	Gap (O_2)	0.550
3	Al clad	0.600
4	H_2O	0.602
5	Secondary clad	0.668
6	H_2O	$\text{OD}_{\text{H}_2\text{O}} = \text{Pitch} \sqrt{\frac{6 \tan 30^\circ}{\pi}}$

Fig. B.11 Double Clad Blanket Unit Cell

Fig. B.12 FBBF Safety Study A1 Double Clad Blanket

Table B.5
Aluminum Double Clad Blanket Results

(in)	Pitch (cm)	Number Density atoms/barn-cm	$k_{\infty}^{\text{blanket}}$	k_{eff}
0.668	1.697	0.0139233	0.57767	0.47736
0.700	1.778	0.0126799	0.72395	0.60962
0.800	2.032	0.0097077	0.87970	0.77206
0.900	2.286	0.0076703	0.89282	0.79640
1.000	2.540	0.0062129	0.86271	0.77558
1.200	3.048	0.0043145	0.75953	0.68756
1.500	3.810	0.0027613	0.60160	0.54672
1.750	4.445	0.0020287	0.49242	0.45007
2.000	5.080	0.0015532	0.40763	0.40308
2.500	6.350	0.0009941	0.28595	0.38038

Fig. B.13 FBBF Safety Study SS Double Clad Blanket

Table B.6
Stainless Steel Double Clad Blanket Results

Pitch (in)	(cm)	Number Density atoms/barn-cm	$K_{\infty}^{\text{blanket}}$	K_{eff}
0.668	1.697	0.0139233	0.45104	0.38952
0.673	1.709	0.0137172	0.47048	0.40499
0.740	1.880	0.0113457	0.61903	0.54410
0.800	2.032	0.0097077	0.66602	0.59406
0.900	2.286	0.0076703	0.68305	0.61679
1.000	2.540	0.0062129	0.66882	0.60750
1.100	2.794	0.0051346	0.64031	0.58338
1.200	3.048	0.0043145	0.60568	0.55234
1.500	3.810	0.0027613	0.49745	0.45609
1.650	4.191	0.0022821	0.44746	0.41714
1.750	4.445	0.0020287	0.41666	0.40297
1.850	4.699	0.0018153	0.38803	0.39509
2.000	5.080	0.0015532	0.35129	0.38606
2.250	5.715	0.0012272	0.29647	0.37953
2.500	6.350	0.0009941	0.25237	0.37462

3.4 Advanced Loaded Blanket

For advanced FBBF blanket loadings, some of the natural-uranium rods in the radial blanket are replaced by 4.8% and 1.3% enriched fuel with secondary rods of stainless steel placed between the enriched pins. A large variety of different configurations can be obtained by combining the available 6060 rods of natural UO_2 , 2845 rods of 1.3% enriched UO_2 and 1510 rods of 4.8% enriched UO_2 ¹. The purpose of this investigation was to select a range of configurations for advanced blanket loadings and perform the hypothetical flooding accident criticality calculation for all selected configurations.

The HAMMER and 2DB computer codes have been used in this study for the cell calculations and the criticality evaluations, respectively.

3.4.1 Criticality

3.4.1.1 Selection of a Suitable Range of Configurations for the Radial Blanket

Presently, the exact configurations of advanced FBBF loadings have not been precisely defined. In accordance with this, a very conservative choice for the range of configurations to be evaluated in this study has been made. The most extreme configuration has been assumed in which all of the available uranium-enriched fuel is loaded into the radial blanket replacing some of the natural uranium fuel. For this purpose, the blanket is subdivided into three regions, as shown in Fig. B.14 which contains the 4.8%, the 1.3% and the natural uranium fuel respectively. The number density of UO_2 in each of the three regions is constrained to be identical

¹ There are 2300 rods of 4.8% enriched fuel; 790 of them are used in the converter regions (592 in the Inner Converter and 198 in the Outer Converter). The remaining 1510 rods are available for advanced blanket loadings.

Fig. B.14 Radial Blanket Regions for the Advanced Loading Design

and the total blanket thickness is constrained to be 51 cm. Therefore, since the fuel pellet diameter is different for each of the three enrichments, the pitch in each region is not the same and each region thickness will vary. By changing the pitch of the fuel pins in the regions, a wide range of different configurations has been studied. Starting with the smallest possible pitch in the 1.3% region (comp. Sec. 3.4.1.2), the pitch of each region has been progressively increased at the expense of the number of fuel pins in the natural uranium region. As the pitch of the pins in each region increases, the reactivity of the hypothetical flooded facility also increases until a trade-off between moderation and absorption is reached. Beyond this point (reactivity maximum), any further increase of the water content yields a reduction in k_{eff} .

3.4.1.2 Search for the Most Reactive Configuration

The search for the most critical configuration has been performed by evaluating a series of different radial-blanket-region thicknesses within the following boundaries:

- i) Lower Boundary - the configuration which corresponds to the minimum possible pitch of the 1.3% enriched fuel region¹.
- ii) Upper Boundary - the configuration in which only one ring of the natural uranium exists. A further increase of the pitch beyond this point would require a reduction of the number of loaded enriched fuel rods. All of the configurations have been generated by observing the following conditions and constraints:

¹The 1.3% enriched fuel rods have the smallest diameter (comp. Table B.7).

Table B.7

Fuel Pin Dimensions

	Natural Uranium	1.3%	4.8%
Pellet Diameter	.546"	.383"	.4200"
Clad	Al	Al	348 St.St.
Clad OD	.600"	.453"	.466"
Active length	48"	48"	36
Overall length	49 1/6"	54"	41 5/8"
Bottom hardware	.681"	3"	1"
Top hardware	.380"	3"	4 5/8"
Approx. Wt.	4 3/4 lbs.	3 lbs.	2 1/3 lbs.
Est. Clad ID	.550"	.391"	.426"
Clad Thickness	.025"	.031"	.020"
Clad Area	.04516 in ²	.04110 in ²	.02802 in ²
Gap Area	.00344 in ²	.00486 in ²	.00399 in ²
Fuel Area	.23414 in ²	.11520 in ²	.13854 in ²
Total	.2827 in ²	.16117 in ²	.17055
Clad VF	.160	.255	.184
Gap VF	.012	.030	.023
Fuel VF	.828	.715	.812

Condition 1

The dimensions of the three different types of fuels have been taken from Table B.7. The corresponding cell-data for the enriched fuel is illustrated in Fig. B.15. Cell data for the natural uranium pins is identical to that presented in Sec. B.3.2. Data corresponding to the two-dimensional FBBF mock-up and the nature of the different materials used in it are presented in Fig. B.16 and Table B.8 (comp. Sec. B.2 and Ref. 2).

Condition 2

The pitch for the three regions has been calculated for each configuration by first choosing a pitch for the 1.3% enriched fuel region and then constraining the smeared uranium number density to be the same in all three regions. The initial point corresponds to a pitch in which the 1.3% enriched fuel pins are touching each other.

Condition 3

A radial blanket thickness of 51 cm and the maximum number of loaded enriched fuel pins have been maintained for all configurations. Therefore, any increase in the pitches of each region, from the lowest bound configuration defined above, has been done at the expense of the radii R_1 and R_2 (comp. Fig. B.14) and the consequent reduction in the number of natural uranium pins. The upper bound configuration studied corresponds to the case in which only one ring of natural uranium fuel rods are left. The radii R_1 and R_2 are calculated with the following expression:

$$\begin{aligned}
 A_1 &= n_1 A_{\text{cell}}^1 = n_1 \pi r_{\text{cell}}^1{}^2 = n_1 \pi (0.525 p_1)^2 & 4.1 \\
 A_1 &= \pi (R_1^2 - R_0^2) \\
 A_2 &= \pi (R_2^2 - R_1^2)
 \end{aligned}$$

<u>Region</u>	<u>Material</u>	<u>4.8% O.D. (in.)</u>	<u>1.3% O.D. (in.)</u>
1	Fuel	0.420	0.383
2	Gap (O_2)	0.426	0.391
3	Clad	0.466	0.453
4	H_2O	$O.D._4 = Pitch \sqrt{\frac{4}{\pi} \times \frac{3}{2} \tan 30^\circ (1 - VF_{SS-rod})}$	
5	SS-rods	$O.D._5 = Pitch \sqrt{\frac{6 \tan 30^\circ}{\pi}}$	

Fig. B.15 Enriched Blanket Unit Cell

Fig. B.16 FBBF Mock-Up for Advance Loading Safety Study

Table B.8

2-D FBBF Advanced Loading Descriptions

1. Inner Converter
2. Outer Converter
3. Nat. UO_2 Blanket Region
4. Source
5. Axial Blanket
6. Reflector
7. Source Drive Rod
8. Water Below Source
9. Concrete
10. Steel Base and Spacers
11. Lead Cap
12. ICR Lower Pin Ends
13. ICR Upper Pin Ends
14. OCR Lower Pin Ends
15. OCR Upper Pin Ends
16. Source/ICR Transition
17. ICR/OCR Transition
18. OCR/Blanket Transition A
19. OCR/Blanket Transition B
20. 4.8% Enriched Blanket Region
21. 1.3% Enriched Blanket Region
22. Non-Active 4.8% Region
23. Non-Active 4.8% Region
24. Non-Active 1.3% Region
25. Non-Active 1.3% Region
26. Non-Active Nat. UO_2 Region

where

$$R_0 = 22.0345$$

$$i = 1 \quad 4.8\% \text{ region}$$

$$= 2 \quad 1.3\% \text{ region}$$

$$n_i = \text{number of rods available for the region}$$

$$n_1 = 1510 \text{ rods}$$

$$n_2 = 2845 \text{ rods}$$

$$A_{\text{cell}}^i = \text{area of the equivalent circularized cell (comp. Appendix 1)}$$

$$r_{\text{cell}}^i = \text{radius of the equivalent circularized cell}$$

$$p_i = \text{pitch of the triangular lattice}$$

Equation (4.1) does not account for irregular boundaries nor the intermingling of different fuel rods between the regions. The neglect of these boundary effects yields an underestimated value for R_1 and R_2 which will possibly cause the regions to be slightly undermoderated. Nevertheless, this error has been neglected in this study because the nature of the configuration selected is conservative enough to compensate for such underestimates.

Constraint 1 Minimum Thickness of the Natural U. Region

As the radius R_2 increases, the thickness of the Nat. U. region tends to 0 (comp. Fig. B.13). A minimum thickness of a circularized Nat. U. fuel cell has been imposed for this region.

$$R_3 - R_2 \geq p_3$$

where:

$$R_3 = 73.66 \text{ cm outer radius of the Nat. U. region}$$

$$R_2 = \text{inner radius of the Nat. U. region}$$

$$p_3 = \text{pitch of the triangular lattice in the Nat. U. region}$$

Constraint 2 Minimum Number of Nat. U. Rods

The minimum number of Nat. U. rods has been imposed to correspond to the number of rods of a single ring of touching Nat. U. equivalent-circular cells

$$n_3 \geq \frac{2\pi R'_2}{2r_{3, \text{ cell}}} = \frac{2\pi(R_2 + r_{3, \text{ cell}})}{2r_{3, \text{ cell}}} = \pi \left(1 + 1.9048 \frac{R_2}{P_3} \right)$$

where:

$$R'_2 = R_2 + r_{3, \text{ cell}}$$

3.4.1.3 Results of the Criticality Evaluation

The results of the criticality evaluation for the FBBF-Advanced Loading configurations are presented in Fig. B.17 and Table B.9. The 4.8% enriched region has the largest value of k_{∞} . As the pitch of the region increases, k_{∞} reaches a maximum of about 0.957 and then continues to decrease due to the increase in stainless steel absorption and reduction of moderation from the water. The value of k_{∞} for the natural uranium region has a maximum of about 0.912. It decreases with increased pitch but at a slower rate than the 4.8% enriched region. Since the natural uranium region does not contain any secondary stainless steel rods, moderation is greater and there is no loss of neutrons in a secondary absorber as in the case of the 4.8% enriched region. The values of k_{∞} for the 1.3% enriched region are the lowest. Again, this is due to the displacement of water by the secondary stainless steel rods and the additional absorption. The small size of the natural UO_2 region and its location at the outer edge of the blanket cause its contribution to k_{eff} to be less than the 4.8% enriched region. The k_{eff} of the facility reaches a maximum of about 0.741 which corresponds to a natural UO_2 pin pitch of about 1.9 cm. (See Table B.9 for the corresponding pitches of the other regions and the associated UO_2 number density.)

Fig. B.17 FBBF Safety Study Advanced Blanket

Table B.9

Advanced Loading Blanket Results

.711% Blanket Region		1.3% Blanket Region			4.8% Blanket Region			Number Density atoms/barn-cm	k_{eff}
Pitch (cm)	k_{∞}	Outer Radius (cm)	Pitch (cm)	k_{∞}	Outer Radius (cm)	Pitch (cm)	k_{∞}		
1.6403	.75252	46.763	1.1506	.53066	33.889	1.2620	.90516	.0148980	.62748
1.7199	.82399	48.539	1.2065	.63654	34.849	1.3233	.93993	.0135500	.69189
1.8105	.87180	50.578	1.2700	.68231	35.961	1.3930	.95660	.0122289	.72983
1.9010	.89874	52.636	1.3335	.68169	37.094	1.4626	.95418	.0110919	.74103
1.9915	.91180	54.712	1.3970	.65572	38.247	1.5323	.93828	.0101065	.73347
2.1725	.91184	58.907	1.5240	.57738	40.603	1.6716	.87955	.0084923	.68191
2.3536	.89246	63.153	1.6510	.49031	43.017	1.8108	.80443	.0072360	.59487
2.5346	.86145	67.438	1.7780	.41347	45.481	1.9501	.72261	.0062392	.49494
2.6831	.83239	70.976	1.8821	.35720	47.534	2.0644	.66699	.0055679	.44031

3.5 Additional Safety Investigations

Further safety studies need to be carried out for future loadings which consist of two different 180° loading configurations. From the investigation present in this section, it looks as though any configuration will be safe in terms of the hypothetical flooding accident, if half of the facility is loaded with the stainless steel double clad natural uranium loading. A first estimate for the maximum value for k_{eff} , based on the calculations presented in the previous section, would be approximately 0.72 for a configuration consisting of half the facility with secondary stainless steel clad and the other half without any secondary rods. These investigations are presently being considered and the results will be reported at a later date.

REFERENCES

1. FBBF Quarterly Progress Report for the period September 1, 1976 - December 31, 1976, Purdue University, PNE-76-116 (1976).
2. FBBF Quarterly Progress Report for the period January 1, 1977 - March 31, 1977, Purdue University, PNE-77-118 (1976).
3. D. J. Malloy, "The HAMMER System at Purdue University," PNE-76-106, October, 1975.
4. Little, W. W., Jr., and Hardie, R. W., "2DB, A Two-Dimensional Diffusion-Burnup Code for Fast Reactor Analysis," BNWL-640, 1968.
5. FBBF Quarterly Progress Report for the period January 1, 1976 - August 30, 1976, Purdue University, PNE-76-115 (1976).

Task C:

The objectives of this task are: (1) loading the first configuration of the FBBF; (2) testing experimental equipment and techniques on the FBBF; and (3) performing check-out tests required for licensing purposes and for safe operation of the FBBF. Progress on this task is summarized below.

C.1. Testing Experimental Equipment and Techniques (F. M. Clikeman, R. H. Johnson, D. W. Vehar, P. J. McDaniel, G. A. Harms, M. L. Carboneau, and H. P. Chou).

Preliminary testing for neutron spectroscopy, foil activation, and solid state track recorder measurements are underway. Although the FBBF is not yet available for experiments, testing of techniques is being carried out using the PUR-I reactor as well as a small ^{252}Cf source.

Two different types of proportional counters (proton-recoil and alpha-recoil) are being developed for neutron spectrum measurements in the FBBF. Testing of proton-recoil spectroscopy using leading-edge pulse shape discrimination has been completed. (D. W. Vehar, "A Gamma-Ray Discrimination System for Use with Proton-Recoil Proportional Counters," M.S. Thesis, Purdue University, 1977). Currently, the constant-fraction timing method is being investigated in an effort to improve pulse shape discrimination.

Preliminary testing of the alpha-recoil method of neutron spectroscopy has also been completed. (P. J. McDaniel, "An Alpha-Recoil Spectrometer", Ph.D. Thesis, Purdue University, 1977). This study indicated that additional gas fillings should be investigated. Further investigation of the problem of unfolding alpha-recoil spectra will also be necessary before this

technique can be applied in FBBF experiments.

Absolute counting procedures for neutron-activated foils are being developed. Preliminary work has been performed using a calibrated NaI (Tl) detector, a gamma-gamma coincidence system, and a beta-gamma coincidence system. Another counting technique will be the use of a calibrated Ge (Li) detector (on order).

Many activation rates are of direct interest (neutron capture by sodium, for example). Another purpose of foil activation measurements is to allow the use of an unfolding code to determine neutron spectra from activation rates. Two unfolding codes SAND-II⁽¹⁾ and CRYSTAL BALL⁽²⁾ have been obtained and are currently being tested with sample problems. Other unfolding codes have been obtained but have not yet been tested.

The solid state track recorder (SSTR) method of measuring fission rates is being developed. A small ²⁵²Cf source is being used to provide fission fragments for these experiments. Various etching techniques are being tested. Currently, the SSTR's are being examined after etching using an optical microscope. Both a scanning optical microscope and a scanning electron microscope are available on campus. Both of these techniques and spark counting will be considered for counting tracks from fission fragments.

C.2. Safety and Licensing Tests (F. M. Clikeman, P. J. Fulford, R. H. Johnson, T. P. Gwynn, D. E. Bartlett)

The control system for the FBBF must perform the functions proposed in the FBBF license application. The circuitry for the control system has been designed to meet this requirement. This circuitry (consisting of the

control panel, a bank of relays, and associated power supplies) is currently being assembled by FBBF personnel and preliminary testing of the equipment is being performed.

Two examples are given below illustrating the requirements for the control system. In these examples, the FBBF Laboratory is referred to as Room B28. The concrete enclosure shielding the FBBF is referred to as B28C.

In the discussion of the ventilation for the FBBF Laboratory, the license application submitted to the NRC stated: "B28 is provided with a supply of ventilation air blown in through three ducts fed from the existing main supply plenum in the Physics Building basement hallway. This air is a mixture of outside air and recirculated air from other parts of the building. Low leakage dampers on these ducts close automatically if the radiation monitors in B28 alarm, if the filter for B28C fails or is blocked, or if the fan for B28C fails. They may also be closed manually".

In the discussion of the door allowing access to the FBBF from outside of the shielding, the license application stated: "Access to the shielded area is controlled by the electric latch on the door of B28C. The latch is normally in the locked position. (The door can be opened manually from the inside). Supply of current allows the latch to unlock to allow entry from B28. For the current to flow the following conditions must be met:

- a. The position transducers must indicate that the source tube is in the cask.
- b. The clutch must be denergized (disconnecting the drive train).
- c. The below-facility neutron monitor and the B28C radiation monitor must both indicate that the neutron sources are in the storage cask.

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.

Final testing of the control system will take place after the control circuitry is installed in the FEBF Laboratory.

REFERENCES

1. W. N. McElroy, S. Berg, T. B. Crockett, and R. J. Tuttle, "Measurement of Neutron Flux Spectra by a Multiple Foil Activation Iterative Method and Comparison with Reactor Physics Calculations and Spectrometer Measurements", Nucl. Sci. Eng., 36, 15 (1969).
2. F. B. K. Kam and F. W. Stallman, "CRYSTAL BALL, A Computer Program for Determining Neutron Spectra from Activation Measurements, Oak Ridge National Laboratory, ORNL-TM-4601 (June 1974).