LOCAL MODIFICATION OF IRRADIATION CONDITIONS

by

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EBR-II Project

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ABSTRACT

Over the past two years, methods have been developed to analyze the detailed spatial variations in neutron- and gamma-flux levels that occur in heterogeneous reactors. These methods have been used to investigate the degree to which the irradiation conditions can be modified in a small region of the core and then to define a core-loading pattern for EBR-II tailored to provide a specified gamma-flux level in a particular experimental-irradiation subassembly (XX03). In the tailored core loading, the gamma-heating rate in the stainless steel components of the subassembly will be 39% less than the gamma-heating rate in the same position in the unperturbed core.

I. INTRODUCTION

Experimental-irradiation subassembly XX03, an instrumented subassembly, was designed for neutron irradiation at a controlled temperature. The desired temperature is to be obtained by gamma heating of the subassembly components. To achieve the correct temperature, the gamma flux in the subassembly must produce approximately 3.8 W/g in stainless steel.

Detailed distributions of the gamma-heating rate in EBR-II have recently been obtained by using an energy-balance technique to normalize distributions of rates of gamma-energy generation calculated with a transport-theory code. These results indicated that if XX03 were located in its intended position in the EBR-II reactor grid, with the reactor operating at 62.5 MWt, its gamma heating would be 47% too high (5.6 W/g in stainless steel). (All flux and heating-rate values in this report are given for the EBR-II reactor operating at 62.5 MWt.)

The purpose of the work reported here was to discover if the local environment in EBR-II could be modified to accommodate XX03 as designed. Detailed physics analyses show that this may be accomplished by inserting subassemblies containing less fuel than that in average driver subassemblies in the grid positions surrounding XX03.

Several possible core configurations were investigated. The first represented a typical EBR-II core loading. In the second configuration, XX03 was completely surrounded by stainless steel reflector subassemblies. In the third configuration, XX03 was surrounded by two stainless steel and four partially loaded driver subassemblies. The gamma-heating rate at the center of XX03 in these configurations was determined. Then, a modified configuration was determined based upon an interpolation of the gamma-heating rates in XX03 in the perturbed configurations and the gamma-heating rates in the unperturbed configuration. The modified configuration was found to produce the required gamma-heating rate in XX03.

Determination of the gamma-heating rate at the XX03 position in each configuration required the execution of neutron-transport and gamma-transport calculations. These calculations were done with methods and codes developed and adapted over the past two years and now used routinely by the EBR-II Project. These methods make use of a number of computer codes to assimilate and organize the approximately 700 individual atom densities necessary to completely describe the EBR-II reactor, subassembly by subassembly. The DOT380 neutron-transport code and the 22-group neutron-transport and 20-group photon-transport cross-section libraries, which have been checked by comparison with experimental data for ^{235}U and ^{238}U fission rates, control-rod worths, and melt-wire temperatures in EBR-II, were used. The final results of these calculations include the total fission rate in each subassembly in each EBR-II core-loading configuration studied, along with the gamma-heating rate at each position, in watts per gram of each of the major materials in EBR-II.

The calculated power in each subassembly in the selected configuration was studied to see that the power variation, both locally and globally in the reactor core, is within acceptable limits.

II. TYPICAL EBR-II CORE ENVIRONMENT

A typical EBR-II core loading may have between 40 and 50 experimental-irradiation subassemblies in the core and inner-blanket regions of the reactor. Figure 1 shows a typical loading pattern containing 43 experimental subassemblies.

The gamma-heating rate in each subassembly of this loading was determined using the ANL version of the transport-theory code DOT. The calculations were done in the following steps:

1. The neutron-flux distribution was computed with the transport code.
2. The gamma-source distribution was obtained at each spatial point by taking the inner product of the gamma-production cross-section matrix appropriate for the material at the point and the neutron-flux vector at the point.
3. The gamma flux that results from the computed gamma source was determined by using the transport code and gamma-ray scattering and total cross sections.
4. The rate of heat production was determined by multiplying the gamma-flux vector by the gamma-energy-absorption cross-section vector.
5. The rates of gamma-heat production were normalized by requiring that the total gamma energy deposited in the reactor per second equal the total energy of all the gamma rays produced in the reactor per second.

Figure 2 shows the gamma-heating rate, in watts per gram of stainless steel, at the core midplane in the first eight rows of the reactor. Figure 3 shows the gamma-heating rate in uranium as a function of subassembly position. The variation of the gamma source is indicated in Fig. 4, which shows the number of photons with energies between 1.35 and 1.8 MeV that are produced per cubic centimeter in each subassembly per second. The distribution of photon production in other energy ranges is similar. Figures 2 and 3 show the wide variation in heating rates per gram of uranium and of stainless steel, respectively, that may occur in a typical core loading.

C -- CONTROL ROD

P -- SIMULATED EXPERIMENTAL-IRRADIATION
SUBASSEMBLIES (~half-worth driver subassemblies)

S -- SAFETY ROD

SS -- STAINLESS STEEL REFLECTOR SUBASSEMBLY

SSCR -- STAINLESS STEEL CONTROL ROD

X -- ACTUAL EXPERIMENTAL-IRRADIATION SUBASSEMBLIES

NOT IDENTIFIED: DRIVER SUBASSEMBLIES -- ROWS 1-6

DEPLETED-URANIUM BLANKET SUBASSEMBLIES -- ROWS 7 AND BEYOND

Fig. 1. Typical EBR-II Core Loading

Fig. 2. Gamma-heating Rates (W/g) in Stainless Steel in Typical EBR-II Core Loading

Fig. 4. Gamma-source Distribution in Typical EBR-II Core Loading
(photons/cm³-sec; E: 1.35-1.8 MeV)

The average gamma-heating rate in stainless steel in the 5N3 positions (control-rod positions in row 5, on the flat of the hex) is 5.62 W/gm. These control-rod positions are used for instrumented subassemblies such as XX03 to facilitate making the necessary electrical connections. Subassembly XX03 was designed to operate in a gamma flux that would produce only 3.8 W/g in stainless steel. Therefore, it is necessary to modify the local core environment to reduce the gamma flux at the position of the subassembly.

III. MAXIMUM MODIFICATION OF LOCAL ENVIRONMENT

The differences in gamma-heating rates in similar subassemblies in the typical core loading discussed in Sec. II indicated that the gamma-heating rate in a specific subassembly could be altered significantly by changing the composition of the surrounding subassemblies. The maximum variation in the core loading that might possibly be made--taking into consideration the necessity of maintaining a critical core configuration and of avoiding excessive flux asymmetry (or tilt), which could lead to local overheating of some fuel subassemblies--is to replace all subassemblies adjacent to the subject subassembly with unfueled stainless steel reflector subassemblies.

Figure 5 shows a core-loading pattern with XX03 in position 5F3 and with stainless steel reflector subassemblies in the six surrounding positions. Neutron- and gamma-transport analysis of this core-loading pattern, done in the same manner as the previous calculations for the typical core loading, show that the gamma-heating rate in stainless steel in XX03 is reduced to 1.29 W/g. Figures 6 and 7 show the complete distribution of gamma-heating rates in stainless steel and uranium, respectively. The gamma-heating rates in other subassemblies in the perturbed sector of the reactor are reduced on the order of 30%. In other sectors, the gamma-heating rates are increased 4 to 20%. The neutron-flux, fission-rate, and gamma-source distributions are distorted in a similar manner and to approximately the same degree. Figure 8 shows the 1.35-1.8 MeV gamma-source distribution.

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DEPLETED-URANIUM BLANKET SUBASSEMBLIES -- ROWS 7 AND BEYOND

Fig. 5. Core-loading Pattern for Maximum Modification of Local Environment around Position 5F3

Fig. 6. Gamma-heating Rates (W/g) in Stainless Steel for Core Loading with Maximum Modification

Fig. 7. Gamma-heating Rates (W/g) in Uranium for Core Loading with Maximum Modification

Fig. 8. Gamma-source Distribution (photons/cm³-sec; E:1.35--1.8 MeV)
for Core Loading with Maximum Modification

IV. INTERMEDIATE MODIFICATION OF LOCAL ENVIRONMENT

The core modification described in Sec. III would result in a large (77%) reduction of the gamma-heating rate in subassembly XX03. However, such a large modification--six stainless steel subassemblies in one reactor sector--would severely distort the neutron flux and fission rate.

A less drastic core-loading modification would provide a significant modification of the gamma-heating rate in XX03 and distort the flux shape less severely. Figure 9 shows such a core loading. In this configuration, two stainless steel subassemblies are placed on the side of XX03 nearest the core center, where they are most effective. The other four positions adjacent to XX03 contain half-loaded subassemblies, which contain about half the fuel content of a normal driver.

In this configuration, the gamma-heating rate in XX03 is 2.6 W/g in stainless steel. Figure 10 shows a complete distribution of gamma-heating rates. Gamma-heating rates in the perturbed sector of the reactor are depressed on the order of 20%. In other sectors, the gamma-heating rates are increased 3 to 15%. The 1.35-1.8 MeV gamma-source distribution is shown in Fig. 11.

Both the neutron- and gamma-flux spectra in XX03 are softer in this configuration than in the typical core configuration discussed in Sec. II. The neutron spectra in XX03 in this core loading are compared with the unperturbed neutron spectra in Table I. The gamma spectra are compared in Table II.

V. OPTIMUM MODIFICATION OF LOCAL ENVIRONMENT FOR EXPERIMENTAL-IRRADIATION SUBASSEMBLY XX03

Subassembly XX03 was designed to be heated, during irradiation, by gamma-energy deposition in the stainless steel components of the subassembly at the rate of 3.8 W/g in stainless steel. The calculations described in Sec. II, III, and IV were used as a basis for defining a core-loading pattern in which the local environment around XX03 would produce the required gamma-flux field in XX03. It was estimated that six half-loaded driver subassemblies arranged in a ring around XX03 as shown in Fig. 12 would produce approximately the required heat-generation rate in XX03.

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NOT IDENTIFIED: DRIVER SUBASSEMBLIES -- ROWS 1-6

DEPLETED-URANIUM BLANKET SUBASSEMBLIES -- ROWS 7 AND BEYOND

Fig. 9. Core-loading Pattern for Intermediate Modification of
Local Environment around Position 5F3

Fig. 10. Gamma-heating Rates (W/g) in Stainless Steel for Core Loading with Intermediate Modification

TABLE I. Comparison of Neutron-flux Spectra in Unperturbed Core and in Core with Intermediate Modification

Group	Lower Energy Limit, keV	Neutron Flux, 10^{13} n/cm ² -sec	
		Unperturbed Core	Intermediate Core (Fig. 9)
1	3680	8.166	2.362
2	2230	15.280	6.004
3	1350	25.696	12.236
4	821	34.642	19.724
5	498	44.686	33.219
6	302	50.161	33.893
7	183	39.935	36.374
8	111	30.676	32.193
9	67.4	18.816	22.461
10	40.9	11.284	15.042
11	24.8	5.832	10.013
12	15.0	3.562	6.924
13	9.12	1.398	3.462
14	4.31	0.606	2.519
15	2.61	0.075	0.728
16	2.03	0.102	0.353
17	1.23	0.097	0.575
18	0.961	0.0087	0.116
19	0.583	0.0054	0.129
20	0.275	0.0013	0.063
21	0.101	0.0002	0.023
22	0.029	0.00002	0.003
Total		291.03	242.42

TABLE II. Comparison of Gamma-flux Spectra in Unperturbed Core and in Core with Intermediate Modification

Group	Lower Energy Limit, MeV	Gamma Flux, 10^{12} n/cm ² -sec	
		Unperturbed Core	Intermediate Core (Fig. 9)
1	10	0.2814	0.5610
2	8	1.0709	2.4117
3	7	0.4021	0.3327
4	6.5	0.8140	0.8011
5	6.0	1.4945	1.0718
6	5.5	2.4276	1.0512
7	5.0	10.851	1.7469
8	4.5	9.0839	2.8985
9	4.0	15.453	4.9595
10	3.5	21.870	6.7055
11	3.0	28.755	8.5159
12	2.6	46.490	12.4341
13	2.2	69.878	18.2273
14	1.8	127.07	34.0428
15	1.35	209.40	57.7611
16	0.9	206.51	61.1484
17	0.6	197.31	77.5021
18	0.4	98.401	142.455
19	0.2	11.649	86.9074
20	0.1	0.010	0.3604
Total		1052.7	521.5

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X -- ACTUAL EXPERIMENTAL-IRRADIATION SUBASSEMBLIES
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DEPLETED-URANIUM BLANKET SUBASSEMBLIES -- ROWS 7 AND BEYOND

Fig. 12. Core-loading Pattern for Optimum Modification of Local Environment for Subassembly XX03

Transport-theory analysis of this configuration, done as described in Sec. II, indicates that the heating rate in XX03 will be 3.4 W/gm. This is slightly less than the nominal design value of 3.8 W/gm. The difference, however, is in the conservative and preferred direction. Useful information will be obtained if the experiment is irradiated at or below the design temperature. Higher temperatures would reduce the significance of the data obtained.

Figure 13 shows the gamma-heating rate in each of the subassemblies in this core loading. The gamma-heating rate in the other subassemblies in the perturbed sector is reduced by about 10% relative to the unperturbed core. The gamma-heating rate in the other sectors is increased by less than 5%. Perturbations of the same magnitude occur in the neutron flux, fission rate, and gamma-source rate. Figure 14 shows the 1.35-1.8 MeV gamma-source distribution in the core.

Tables III and IV show how the neutron and gamma spectra in XX03 would be softened in this core in relation to an unperturbed core.

VI. MEASURED GAMMA-HEATING RATES AND UNCERTAINTIES

At this time, measurements that have been made of gamma-heating rates in EBR-II are not sufficient to corroborate the calculated values. Measurements made in run 25D (July 21-22, 1967) indicate that the gamma-heating rate in position 7D4 (row 7, sector D, fourth subassembly numbered clockwise) would be between 0.88 and 1.41 W/g (1.11 W/g nominal) in stainless steel at a reactor power of 62.5 MWt. This value can be compared to the average calculated value in the four 7N4 positions (sectors N = A, B, D, and E) that contain depleted-uranium blanket subassemblies in the unperturbed core (Fig. 1). However, the measurement was made in a stainless steel-reflected core. Therefore, in making this comparison, the effect of the stainless steel reflector must be accounted for. Calculated gamma-heating rates in row 7 with a depleted-uranium-blanketed core are 68% of the calculated gamma-heating rates in row 7 for the same core with a stainless steel reflector in rows 7 and 8. The nominal measured value for the gamma-heating rate adjusted for a depleted-uranium-blanketed core is, then, 0.75 W/g in stainless steel. This is 13% less than the calculated

Fig. 13. Gamma-heating Rates (W/g) in Stainless Steel in Core Loading with Optimum Modification to Accommodate Subassembly XX03

TABLE III. Comparison of Neutron-flux Spectra in Unperturbed Core and in Core with Optimum Modification to Accommodate Subassembly XX03

Group	Lower Energy Limit, keV	Neutron Flux, 10^{13} n/cm ² -sec	
		Unperturbed Core	Optimum Core for XX03 (Fig. 12)
1	3680	8.166	3.931
2	2230	15.280	8.803
3	1350	25.696	16.182
4	821	34.642	23.152
5	498	44.686	36.476
6	302	50.161	39.595
7	183	39.935	38.732
8	111	30.676	32.223
9	67.4	18.816	22.257
10	40.9	11.284	14.702
11	24.8	5.832	9.228
12	15.0	3.562	6.290
13	9.12	1.398	2.813
14	4.31	0.606	1.769
15	2.61	0.075	0.446
16	2.03	0.102	0.244
17	1.23	0.097	0.347
18	0.961	0.0087	0.068
19	0.583	0.0054	0.065
20	0.275	0.0013	0.026
21	0.101	0.0002	0.007
22	0.029	0.00002	0.0007
Total		291.03	256.8

TABLE IV. Comparison of Gamma-flux Spectra in Unperturbed Core and in Core with Optimum Modification to Accommodate Subassembly XX03

Group	Lower Energy Limit, MeV	Gamma Flux, 10^{12} n/cm ² -sec	
		Unperturbed Core	Optimum Core for XX03 (Fig. 12)
1	10	0.2814	0.4625
2	8	1.0709	1.8639
3	7	0.4021	0.3595
4	6.5	0.8140	0.8240
5	6.0	1.4945	1.1910
6	5.5	2.4276	1.4837
7	5.0	10.851	2.5631
8	4.5	9.0839	4.7829
9	4.0	15.453	8.2112
10	3.5	21.870	11.360
11	3.0	28.755	14.679
12	2.6	46.790	22.566
13	2.2	69.878	33.464
14	1.8	127.07	61.527
15	1.35	209.40	102.24
16	0.9	206.51	105.48
17	0.6	197.31	119.92
18	0.4	98.401	163.92
19	0.2	11.649	85.245
20	0.1	0.010	0.3612
Total		1052.7	742.0

average value of 0.865 W/g for a 7N4 position shown in Fig. 2. Considering the uncertainty of the measurement, this comparison cannot be taken to prove or disprove the accuracy of the calculated gamma-heating rates.

Also in run 25D, a melt-wire experiment was placed in position 2B1 (row 2, sector B). No wires melted in this test. It was estimated that melting of the lowest-temperature melt-wire would have indicated a gamma-heating rate equivalent to 5.6 W/g in stainless steel at a reactor power of 62.5 MWt. This value has approximately the same uncertainty ($\pm 25\%$) as the value for the gamma-heating rate in row 7. The calculated gamma-heating rate in a nonfuel subassembly in position 2B1 is 6.85 W/g in stainless steel, as shown in Fig. 2. The experiment tends to indicate a lower gamma-heating rate than the calculated value; but, again, the uncertainty is too large for any conclusion to be drawn concerning the accuracy of the calculated values.

In the absence of accurate integral measurements of gamma-heating rates in EBR-II, all calculated gamma-heating distributions in this report are based on microscopic cross sections, with the final results made to satisfy an energy balance. Verification of the accuracy of these calculational techniques must await the completion of definitive measurements. Until additional measurements are made, it may be assumed that the relative values for gamma-heating rates as a function of position are correct. However, it should be recognized that the absolute values may be adjusted when and if definitive measurements in one or more reactor grid positions become available.

VII. SUMMARY

Local neutron- and photon-flux levels were determined in a typical EBR-II configuration using transport-theory methods and data for microscopic neutron and photon cross sections. The distribution of gamma-heating rates from this calculation was normalized by an energy-balance technique which incorporated basic physics data for the gamma energy released in fission. This analysis indicated that the gamma-heating rate in the experimental-irradiation subassembly XX03 would be greater than the design value in an unmodified core environment.

A core configuration designed to provide the largest practical reduction of the gamma-heating rate in the core position of subassembly XX03 was then investigated. The gamma-heating rate in XX03 in this configuration was 77% less than the heating rate in the unperturbed core.

A core configuration designed to provide an intermediate amount of shielding for subassembly XX03 was then analyzed. In this configuration, two stainless steel subassemblies were on the side of XX03 nearest the core center, and four half-loaded driver subassemblies were in the other positions adjacent to XX03, as shown in Fig. 9. The gamma-heating rate in XX03 in this configuration was 54% less than in the unperturbed core.

Finally, a core configuration which will produce the desired gamma-heating rate in the experimental subassembly XX03 was determined. In this configuration, XX03 is shielded by six half-loaded driver subassemblies adjacent to XX03, as shown in Fig. 12. With this configuration, the total neutron flux incident on XX03 in position 5F3 with the reactor operating at 62.5 MWt will be equal to the unperturbed total neutron flux at position 5F3 with the reactor operating at 55.1 MWt.

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