JUL 1 1960

X-822

MASTER

OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

ORNL
CENTRAL FILES NUMBER

60-4-110

External Distribution Authorized

COPY NO. 72

DATE: April 29, 1960

SUBJECT: Gamma and Beta Heat Generation Rates in the HFIR Core

TO: Distribution

FROM: Neil Hilvety

ABSTRACT

A calculation has been made to determine the fuel plate heat fluxes resulting from after shutdown fission product heating. Fission product source strengths were obtained via the IBM Internuc code. Slab geometry was assumed. The results indicate that the maximum heat flux will occur slightly inboard of the center of the fuel annulus, with the heat flux at the inner annulus radius running about 8% below the maximum, and the outer radius heat flux 10% below the maximum. For decay times of 1.0, 10, 10^2 , 10^3 , 10^4 , and 10^5 seconds the maximum calculated fuel plate heat fluxes are 42.0, 30.0, 18.0, 9.5, 4.0, and 1.3×10^3 Btu/hr-ft², respectively.

The core coolant gamma heating rate during reactor operation has also been calculated using the same techniques, but including the fission and capture gamma sources. Average coolant gamma heat generation rate is about 33 watts/cc at the start of the fuel cycle, and 57 watts/cc after the fission products build up.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report. The information is not to be abstracted, reprinted or otherwise given public dissemination without the approval of the ORNL patent branch, Legal and Information Control Department.

32 001

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Introduction

One of the factors which is important in establishing the required delay time between shutdown of the HFIR and opening of the pressure vessel for removal of the core is that of after shutdown heat generation within the core. This study represents an attempt to determine the required heat removal capacity as a function of time after shutdown. The fuel plate heat fluxes along the core horizontal midplane have been calculated as a function of time after shutdown for shutdown times of 1.0 to 10^5 seconds. Gamma sources considered are the fission products and aluminum activation.

Another parameter investigated, which is of considerable interest in the calculation of radiolytic gas production, is that of gamma heating in the core coolant during reactor operation. The method of calculation used was the same as that for the after shutdown heating, except that additional gamma sources were included (prompt fission, U235 capture, H capture, and Al capture gammas).

Methods of Analysis

The basic simplifying assumption made in this analysis was that of geometry. The active core was assumed to consist of two infinite slabs, each 12 cm thick and separated by a distance of 14 cm. The entire reactor thus consists of 3 infinite slabs, the center slab representing the flux trap region. (see Figure 1). The composition of each of these slabs was assumed to be 4/9 aluminum and 5/9 water by volume.

The first portion of this study was concerned with calculating the after shutdown fuel plate heat fluxes, consequently, the only sources of concern are those of fission product and structural material decay. The fission product and Al decay gamma sources are assumed to be uniformly distributed in the outer slabs, while the center slab contains only a uniformly distributed Al decay gamma source. Since it is intended that the operating core power density be nearly uniform throughout the active core, the uniform source distribution appears to be a reasonable assumption. Approximation of the fuel annulus by two infinite slabs greatly simplifies the calculation, and should result in slightly high heat generation values. The contribution to the core midplane heating rates due to the portion of the infinite slabs extending beyond the actual HFIR active core height is quite small due to the total path lengths involved. Since the flux trap region is assumed to consist of 4/9 aluminum, the assumed geometry more nearly represents the core when the core is installed in the reactor, with the irradiation sample in place. Heating rates will increase slightly when the flux trap contains only water; however, this increase will be small.

The fission product source strengths were obtained from the IBM Internuc code calculations of T. B. Fowler.¹ This code calculation provides values of gamma and beta source strength as a function of operating power level, operating time, and time after shutdown. The gamma source strengths are given in 12 energy

3.

Figure 1.
Assumed Core Geometry

Source
Slab

Equations for Calculating
Energy Deposition Rates

$$1 \quad G_1 = \frac{N}{2} \mu_e E \sum_{n=1}^2 \frac{A_n}{\mu_{tn}} \left\{ E_2[\mu_{tn} a] - E_2[\mu_{tn} (a + h)] \right\}$$

$$2 \quad G_2 = \frac{N}{2} \mu_e E \sum_{n=1}^2 \frac{A_n}{\mu_{tn}} \left\{ E_2[\mu_{tn} d] - E_2[\mu_{tn} (d + l)] \right\}$$

$$3 \quad G_3 = \frac{N}{2} \mu_e E \sum_{n=1}^2 \frac{A_n}{\mu_{tn}} \left\{ 2 - E_2[\mu_{tn} d] - E_2[\mu_{tn} (h - d)] \right\}$$

$$\mu_{tn} = \mu_t (1 + \alpha_n)$$

groups, with values of photons/sec and Mev/sec. Total source strengths of both gammas and betas are also given. An operating time of 15 days at 100 MW power level was assumed for the HFIR core. The gammas originating from induced activity in the aluminum structural material were approximated by assuming average operating flux values² of 5×10^{14} thermal neutrons/cm²-sec and 1×10^{15} fast neutrons/cm²-sec with aluminum capture cross sections of $\sigma_a \text{ fast} = 0.024$ barns and $\sigma_a \text{ thermal} = 0.2$ barns.

The equations used for calculating the energy absorption rates were obtained from Rockwell,³ and are indicated in Figure 1. These equations were evaluated for each of the gamma sources for points located at 0, 3, 6, 9, and 12 cm from the flux trap. The total heat generation rates thus obtained were multiplied by the appropriate conversion factors to convert the heating rates into fuel plate heat fluxes (40 mil plates and 50 mil coolant channels were assumed).

The average core density was used in conjunction with the water gamma absorption coefficients, μ/ρ , to calculate total gamma absorption. Since the values of μ/ρ for Al and water are nearly equal,³ the value for water was used since it is generally higher and should thus result in slightly higher calculated heating rates. The gamma absorption was divided between the aluminum and water in proportion to their relative weight fractions. All of the betas were assumed to be absorbed within the fuel plates.

A point isotropic energy absorption buildup factor of the exponential type,

$$B = A_1 e^{-\alpha_1 t} + A_2 e^{-\alpha_2 t},$$

was employed. Again, the values for aluminum and water are approximately equal for equal numbers of relaxation lengths,⁴ so the values for water were used since the water buildup factors are generally slightly higher.

In order to evaluate the core coolant gamma heating rate during operation, the same techniques were used with the prompt fission and U235, Al, and H₂O capture gamma sources included. The prompt fission and U235 capture gammas were assumed to follow the relationship,⁵

$$N_u(E) = 8.81 e^{-1.01E} \text{ photons/Mev-fission.}$$

This source strength was evaluated for 1 Mev energy intervals between 0 and 8 Mev to obtain source strengths in total photons per second and average photon energy for each interval. The aluminum capture gamma spectrum was taken from Mittleman⁶ and Braid.⁷ Five groups were considered. The water capture (hydrogen capture) gammas consist of one 2.23 Mev photon/capture. Hydrogen absorption cross sections of $\sigma_a \text{ fast} = 0.00941$ barns and $\sigma_a \text{ thermal} = 0.284$ barns were used in conjunction with the previously listed flux values. The fission product decay gamma sources from the Internuc code calculation for a 1 second shutdown time were used.

The gamma and beta sources considered in this study are summarized in Table 1. The spectrum of each of these sources is also indicated. Table 2 summarizes the fission product source strengths obtained from the IBM Internuc code.

Table 1

Gamma and Beta Sources Considered

<u>Source</u>	<u>Spectrum</u>												
1. Fission Product Decay Beta and Gammas	As given by IBM Internuc calculation (see Table 2)												
2. Al^{28} Decay Beta and Gammas	One 1.78 Mev photon/disintegration, 2.87 Mev beta energy/disintegration												
3. Al Capture Gammas	<table> <tr> <th><u>Energy</u></th><th><u>Mev/capture</u></th></tr> <tr> <td>0.5 Mev</td><td>0.041</td></tr> <tr> <td>2.5</td><td>0.799</td></tr> <tr> <td>4.0</td><td>2.525</td></tr> <tr> <td>6.0</td><td>1.033</td></tr> <tr> <td>7.724</td><td>2.276</td></tr> </table>	<u>Energy</u>	<u>Mev/capture</u>	0.5 Mev	0.041	2.5	0.799	4.0	2.525	6.0	1.033	7.724	2.276
<u>Energy</u>	<u>Mev/capture</u>												
0.5 Mev	0.041												
2.5	0.799												
4.0	2.525												
6.0	1.033												
7.724	2.276												
4. H Capture Gammas	One 2.23 Mev photon/capture												
5. Prompt Fission Gammas	$N_u(E) = 7.6 e^{-1.01E}$												
6. U^{235} Capture Gammas	$N_u(E) = 1.21 e^{-1.01E}$												

Table 2
Fission Product Gamma and Beta Source Strengths¹

Shutdown Time, sec →	1.0	10.	10 ²	10 ³	10 ⁴	10 ⁵
Avg. Photon Energy, Mev	Source Strength, photons/cc of core-sec					
0.30	8.109 x 10 ¹³	6.699 x 10 ¹³	4.879 x 10 ¹³	3.176 x 10 ¹³	1.795 x 10 ¹³	8.165 x 10 ¹²
0.63	16.71	13.79	10.01	6.609	3.712	14.76
1.10	6.969	5.605	3.891	1.810	0.5478	1.783
1.55	4.308	3.634	2.487	1.374	0.5632	2.391
1.99	2.324	1.816	1.181	0.6386	0.2828	0.3105
2.38	1.552	1.262	0.7917	0.3644	0.0854	0.1774
2.75	0.8844	0.6574	0.2993	0.0716	0.0043	0.0023
3.25	0.6386	0.4511	0.1936	0.0430	0.0024	0.0013
3.70	0.4766	0.3391	0.1431	0.0310	0.0018	0.0010
4.22	0.2301	0.1563	0.0616	0.0042	-	-
4.70	0.1111	0.0701	0.0230	0.0013	-	-
5.25	0.0529	0.0332	0.0097	0.0004	-	-
Beta Energy Release Rate, Mev/cc-sec	5.092 x 10 ¹⁴	3.431 x 10 ¹⁴	2.005 x 10 ¹⁴	1.065 x 10 ¹⁴	4.632 x 10 ¹³	1.422 x 10 ¹³

Basis: 15 day operation at 100 MW, 44.8 liter active core volume.

Results

The results of this study are summarized in Table 3 and Figures 2 through 5.

Discussion

Figure 2 is a plot of the calculated total active core energy release rate (fission product plus aluminum activation gammas and betas) and core mid-plane energy absorption rates as a function of shutdown time. This figure indicates that the fuel plate heating rates are essentially a constant fraction of the energy release rate regardless of shutdown time, the maximum fuel plate heating rate being about 75% of the energy release rate.

Table 3 lists the calculated core midplane fuel plate after shutdown heat fluxes. These fuel plate heat fluxes are plotted in Figures 3 and 4 to indicate the radial heat flux distribution (Figure 3) and the variation of heat flux with shutdown time (Figure 4). The fuel plate shutdown heat fluxes presented here supersede the earlier preliminary estimates of average fuel plate heat fluxes made by Gift.⁸ The two sets of results agree reasonably well, the earlier prediction being slightly lower at short shutdown times and higher at long shutdown times. Adjusting the shutdown beta source strength of reference 8 to conform with that used here brings the results to within 10% agreement at all shutdown times.

It can be seen from Figure 3 that the maximum shutdown fuel plate heat flux occurs slightly inboard of the center of the fuel annulus. The heat generation rate at the inside radius of the active core is about 8% below the maximum, and the outer active core radius heating rate is about 10% below the maximum. The nonsymmetry is due to the contributions to the gamma heating rate resulting from photons originating in the flux trap and opposite side of the fuel annulus.

When the core is removed from the reactor vessel, the flux trap region may consist entirely of water. Under these conditions the fuel plate heating rates indicated in Table 3 and Figures 3 and 4 would tend to be increased somewhat due to the decreased attenuation of gammas originating in the opposite side of the fuel annulus. However, there would be no photons originating in the flux trap region. This would counteract at least to some extent, the decreased flux trap attenuation. Since the contribution of the gammas originating in the opposite side of the annulus is a small fraction of the total heating rate (less than 5%), any increase in fuel plate heat fluxes due to removal of the irradiation sample will be small.

The plot of calculated core coolant gamma heating rate during reactor operation, Figure 5, indicates a radial energy deposition distribution similar to that of the after shutdown heating, except for a more pronounced peaking near the center of the fuel annulus. Average core coolant heating rates are 33 watts/cc for the fresh core and 57 watts/cc for the spent HFIR core.

Measurements in the MTR⁹ indicate the heating rate in the beryllium reflector at the surface of the 40 x 70 cm lattice to be about 5 watts/gm, at a reactor power

Figure 2.

32 009

Table 3
Calculated Fuel Plate Heat Fluxes at Core Midplane

Shutdown Time, sec →	1.0	10.	10^2	10^3	10^4	10^5
Location, Distance from Core Center- line, cm	Fuel Plate Heat Flux, Btu/hr-ft ²					
7	38,643	27,310	16,444	8,433	3,655	1,170
10	41,301	29,456	17,875	9,205	4,005	1,300
13	41,969	30,002	18,002	9,420	4,110	1,339
16	40,897	29,132	17,663	9,095	3,957	1,282
19	37,783	26,671	16,037	8,233	3,574	1,142

Basis: 40 mil plates, 50 mil coolant channels, 44.8 liter active core volume, 15 days reactor operation at 100 MW.

Figure 3.

Figure 4.

Figure 5.

level of 30 MW. If one uses this measured value to predict a heating rate at the surface of the HFIR active core, and using an equivalent diameter for the MTR lattice such that the cross sectional area is equal to the MTR 40 x 70 cm lattice, the predicted heating rate for the 100 MW HFIR would be 41.5 watts/gm. The agreement with the spent core case of Figure 5 is rather fortuitous. Such factors as the different spectrum and escape fractions for the two reactors and the inclusion of heating sources other than core gammas in the measured MTR value are, of course, important. However, this comparison indicates that the predicted heating rates are reasonable.

Nomenclature

A_n	Buildup factor constant
a	Distance from source slab to dose point, cm
B	Buildup factor, $B = A_1 e^{-\alpha_1 t} + A_2 e^{-\alpha_2 t}$
d	Distance from inside surface of source slab to dose point, cm
E	Gamma energy, Mev/photon
$E_2(b)$	Exponential integral
G	Heat generation rate, Mev/cc of core-sec
h	Thickness of source slab, cm
l	Thickness of flux trap slab, cm
N	Source strength, photons/cc-sec
$N_u(E)$	Prompt fission and U235 capture gamma source strength, photons/Mev-fission
α_n	Buildup factor constant
μ_e	Energy absorption coefficient, cm^{-1}
μ_t	Mass absorption coefficient, cm^{-1}
ρ	Density, gm/cc
σ_a	Neutron absorption cross section, barns

Bibliography

1. Fowler, T. B., Internuc IBM Code Calculations, October-November, 1959.
2. Cheverton, R. D., personal communication, April 11, 1960.
3. Rockwell, T., III, "Reactor Shielding Design Manual", March 1956, TID-7004.
4. Blizzard, E. P., "Nuclear Radiation Shielding", September 17, 1956.
5. Ashley, R. L., and D. S. Duncan, "Theoretical Calculation of Attenuation of γ Radiation from a Swimming Pool Type Reactor", August 15, 1957, NAA-SR-1921.
6. Mittleman, P. S., and R. A. Liedtke, "Gamma-rays from Thermal Neutron Capture", Nucleonics, Vol. 13, No. 5, pp 50-51, May 1955.
7. Braid, T. H., "Neutron Capture Gammas from Various Elements", Physical Review, Vol. 102, pp 1109-1123, May 15, 1956.
8. Gift, E. H., "Some Preliminary Calculations of Shielding, Core Shutdown Cooling Requirements and Thermal Shield Heat Generation in the High Flux Isotope Reactor", March 4, 1960, CF-60-3-40.
9. Huffman, J. R., "The Materials Testing Reactor as an Irradiation Facility", July 6, 1953, IDO-16113-PPCo.

Distribution

1. E. G. Bohlmann
2. R. B. Briggs
3. R. D. Bundy
4. C. A. Burchsted
5. R. H. Chapman
6. T. G. Chapman
7. A. Chetham-Strode
8. R. A. Charpie
9. R. D. Cheverton
10. H. C. Claiborne
11. T. E. Cole
12. C. W. Collins
13. J. A. Cox
14. F. L. Culler
15. J. E. Cunningham
16. E. P. Epler
17. W. K. Ergen
18. W. R. Gall
19. W. R. Gambill
20. J. P. Gill
21. J. C. Griess
22. C. D. Griffies
23. L. A. Haack
24. N. Hilvety
25. H. W. Hoffman
26. J. E. Jones
27. P. R. Kasten
28. M. I. Lundin
29. J. A. Lane
30. R. N. Lyon
31. E. R. Mann
32. H. A. McLain
33. J. R. McWherter
34. R. L. Moore
35. L. C. Oakes
36. F. N. Peebles
37. R. C. Robertson
38. R. E. Schappel
39. M. J. Skinner
40. I. Spiewak
41. R. S. Stone
42. J. A. Swartout
43. A. Taboada
44. M. Tobias
45. D. W. Vroom
46. A. M. Weinberg
- 47-51. C. E. Winters
52. Central Research
53. REED Library
54. Document Reference Library
- 55-69. Laboratory Records
70. ORNL-RC
71. D. H. Groelsema, AEC,
Washington
- 72-86. TISE-AEC

9 SEP 1950
STAT