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

58-4-66

External Transmittal Authorized

COPY NO. 109

DATE: April 18, 1958
SUBJECT: Some Nuclear Characteristics of Spherical
Double-Blanket Reactors
TO: Distribution
FROM: Melvin Tobias and T. B. Fowler

ABSTRACT

A number of cases have been studied to determine some of the nuclear characteristics of double-blanket reactors. The reactor geometry is spherical, the average temperature is 280°C , the core I.D. is 4 ft and the pressure vessel I.D. is 9 ft in all cases. The core is contained in a $\frac{1}{2}$ -in. Zircaloy tank, while the blanket is divided into two regions by another $\frac{1}{2}$ -in. Zircaloy shell. The region adjacent to the core is either 0.5 or 1-ft thick. Comparison is made of reactors in which either the inner or outer blanket region contains 4000 g Th/liter as ThO_2 slurry in D_2O while the other blanket region holds thorium concentrations of 0, 500, or 1000 g Th/liter. The effects of introducing an 8% poison fraction into the core and 3 g U^{233} /kg Th into the blanket are examined individually. It is found that reactivity effects are negligible if the inner blanket contains 4000 g Th/liter and settling occurs in the dilute outer region. On the other hand, for a concentrated outer blanket, large reactivity additions are to be expected on removing the thorium from the dilute inner region. Some fuel and thorium inventory reductions appear possible if a concentrated inner blanket is used. Information has also been obtained concerning power distributions and core-wall thermal flux.

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.

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, express 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 to the extent that such employee or contractor prepares, handles, or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

I. Summary

It has been suggested that a high concentration thorium oxide blanket for a breeder reactor might be managed by operation as a fluidized bed rather than as a circulating slurry. Two forms of blanket have been assumed in this study, both of which might be called double-slurry blankets. The first can be associated with fluidization of a high concentration slurry in a narrow region adjacent to the core and allowing fines to circulate in a larger outer blanket which would have a much lower thorium concentration. The other approach involves fluidization of a low concentration slurry in the narrow inner blanket, the outer blanket being the region of high thorium concentration. Both of these conceptions have been compared with each other and with the single-region blanket system from a nuclear standpoint in spherical geometry and the following observations may be made:

1. If the region next to the core contains the high concentration slurry (4000 g Th/l) and settling occurs in the outer region, reactivity effects should be negligible. There is practically no change in critical concentration in the core for outer blanket concentrations between 0 - 1000 g Th/l. This result appears independent of the presence or absence of poison in the core or fuel in the blanket. The same constant behavior was noted for both 6-in. and 1-ft inner blankets.
2. In contrast, if the outer region contains 4000 g Th/l and the inner blanket thorium concentration changes, then the core critical concentration undergoes substantial changes. It is clear that large reactivity additions will accompany settling in the inner blanket.
3. The breeding ratios for reactors with concentrated inner blankets are generally higher than those with concentrated outer blankets. No double blanket case showed any important breeding ratio advantage over a single-region blanket.
4. The concentrated outer region cases showed much the largest inventories of fuel and thorium. On the other hand, it was noted that it may be possible, without loss in breeding ratio, to reduce inventories significantly from those in a single-region blanket system if a high concentration inner blanket is used.

5. In all cases where 3 g U^{233} /kg Th was assumed present in the blankets, between 82 and 85% of the total reactor power is generated in the core. Between 14 and 16% of the power was generated in the inner blanket for the high concentration cases and up to 12% when the inner region was low in thorium.
6. The ratio of core-wall thermal flux to core-average thermal flux ranged between 0.35 and 0.61. This ratio depended almost entirely upon the concentration of thorium present in the blanket region adjacent to the core and decreased with increasing thorium concentration. At a given core power, the inner wall power density for 4000 g Th/l in the blanket would be about three-fourths that for 1000 g Th/l in the blanket.

II. Description of the Cases Studied

Computations were performed for both "double-blanket" reactors and for "single-blanket" (or two-region) breeders. The double-blanket is supposed to consist of a region (Region III) of $\frac{1}{2}$ - or 1-ft thickness filled with a very high concentration of thorium (4000 g/l). This is surrounded by a $1\frac{1}{2}$ - or 2-ft thick region (Region V) containing 500 g Th/l. Both fertile regions have been assumed to be ThO_2 slurries in heavy water. The central spherical fuel region (Region I), 4 ft in diameter is the usual uranyl sulfate-heavy water solution. The reactor temperature was 280°C. For simplicity, absorptions in sulfur, higher isotopes, and protactinium have been neglected. Regions I, III, and V were separated by $\frac{1}{2}$ -in. thick zirconium tanks (Regions II and IV); the outer vessel (Region VI) was 347 stainless steel, 6-in. thick and 9-ft I.D. Figure 1 illustrates the arrangement numbering and actual dimensions of the various regions.

A total of 28 cases were examined, which may be divided up into four groups:

1. "Standard" reference cases of 1000 g Th/l blankets
 - a. Two regions; 4-ft core, $2\frac{1}{2}$ -ft blanket containing no fuel.
 - b. Two regions; 4-ft core, $2\frac{1}{2}$ -ft blanket containing 3 g U^{233} /l.
 - c. Six regions; Region III, 6 in., Region V, 2 ft.
 - d. Six regions; Region III, 1 ft, Region V, $1\frac{1}{2}$ ft.

Fig. 1 - Diagram and Notation of Double-Blanket Reactors

2. Six-Region Reactors, Region III containing 4000 g Th/l and 6-in. thick.
 - a. Region V, heavy water only.
 - b. Region V, 500 g Th/l.
 - c. Region V, 1000 g Th/l.
 - d. Region III contains 3 g U²³³/kg Th; Region V contains heavy water only.
 - e. Regions III and V contain 3 g U²³³/kg Th; Region V contains 500 g Th/l.
 - f. Regions III and V contain 3 g U²³³/kg Th; Region V contains 1000 g Th/l.
 - g, h, i. Same as cases a, b, and c above except core contains 8% poison fraction based on fuel absorption cross section.
3. Six-Region Reactors, Region III containing 4000 g Th/l and 1-ft thick.
 - a, b, c. Same as a, b, c above except for thickness of Region III.
 - d, e, f. Same as d, e, f above except for thickness of Region III.
4. Six-Region Reactors, Region III 6-in. thick; Region V contains 4000 g Th/l.

 - a. Region III contains heavy water only.
 - b. Region III contains 500 g Th/l.
 - c. Region III contains 1000 g Th/l.
 - d. Region III contains heavy water only. Region V contains 4000 g Th/l and 3 g U²³³/kg Th.
 - e. Region III contains 500 g Th/l. Regions III and V contain 3 g U²³³/kg Th.
 - f. Region III contains 1000 g Th/l. Regions III and V contain 3 g U²³³/kg Th.
 - g, h, i. Same as cases a, b, c of this group except the core contains 8% poison fraction based on fuel absorption cross section.

The cases were selected so as to study the effects of individual parameters and conditions, such as the thickness of Region III, the presence of core poisons, and the presence of fuel in the fertile regions. In the 4th set of cases, the effect of reversing the relative concentrations in Regions III and V (i.e. Region V contains 4000 g Th/l while Region III contains 0, 500 or 1000 g Th/l) is examined.

III. Results

A. Critical Concentrations and Breeding Ratios

The primary aim of this study is to determine the effect on criticality of settling of the slurry in the dilute fertile region. Critical mass and breeding ratio are reported in the accompanying tables.

Table I.

Critical Concentrations and Breeding Ratios for
Reactors with Blankets Containing 1000 g Th/l

Case	Inner Blanket Thickness, ft	Blanket Fuel Concentration, gm U ²³³ /kg Th	Critical Core Concentration g U ²³³ /l	Breeding Ratio
a	*	0	3.52	1.19
b	*	3	3.28	1.19
c	0.5	0	3.50	1.18
d	1.0	0	3.52	1.18

* One fertile region 2-1/2 ft thick.

Table II

Critical Concentrations and Breeding Ratios for
Double-Blanket Reactors with 4000 g Th/l in
Region III; Region III 6 in. Thick

Case	Blanket Fuel Concentration g U ²³³ /kg Th (Regions III and V)	Region V Th Concen- tration g/l	Core Poison Fraction (Σ_p/Σ_a^{23})	Critical Core Con- centration g U ²³³ /l	Breeding Ratio
a	0	0	0	3.89	1.08
b	0	500	0	3.89	1.19
c	0	1000	0	3.89	1.20
d	3	0	0	3.51	1.03
e	3	500	0	3.51	1.19
f	3	1000	0	3.51	1.20
g	0	0	0.08	4.40	1.00
h	0	500	0.08	4.40	1.12
i	0	1000	0.08	4.40	1.13

Table III

Critical Concentrations and Breeding Ratios for
Double-Blanket Reactors with 4000 g Th/l in
Region III; Region III 1-ft thick. No

Core Poisons

Case	Blanket Fuel Concentration g U ²³³ /kg Th	Region V Th Concentration g/l	Critical Core Concentration g U ²³³ /l	Breeding Ratio
a	0	0	3.87	1.15
b	0	500	3.87	1.20
c	0	1000	3.87	1.20
d	3	0	3.52	1.13
e	3	500	3.53	1.19
f	3	1000	3.53	1.20

Table IV

Critical Concentrations and Breeding Ratios for
Double-Blanket Reactors with 4000 g Th/l in
Region V; Region III 6-in. thick

Case	Blanket Fuel Concentration g U ²³³ /kg Th (Regions III and V)	Region III Th Concentration g/l	Core Poison Fraction Σ_p / Σ_a^{23}	Critical Core Concen- tration g U ²³³ /l	Breeding Ratio
a	0	0	0	2.59	1.10
b	0	500	0	3.22	1.17
c	0	1000	0	3.50	1.17
d	3	0	0	2.42	1.12
e	3	500	0	3.01	1.15
f	3	1000	0	3.25	1.16
g	0	0	0.08	2.90	1.03
h	0	500	0.08	3.64	1.10
i	0	1000	0.08	3.96	1.10

Table I shows the expected slight reduction of breeding ratio due to insertion of a zirconium tank in the blanket. The effect of the zirconium upon critical core concentration is seen to be unimportant. The presence of 3 g U^{233} /kg Th reduces the required core concentration by 0.2 g/l while the breeding ratio remains the same within the number of significant figures cited.

A slight increase in critical concentration is observed in going from case c to case d; the outer zirconium tank has been moved farther from the core so that slurry (high absorption cross section material) has replaced the zirconium (weak absorber) in a region 0.5 ft from the core.

Comparing the reactors of Table I with any of those in the following tables shows that no important improvement in breeding gain results from the use of a 4000-g Th/l region. (An appreciable reduction in core critical concentration is obtained in some cases in which the 4000 g Th/l is placed in the outer region—(compare cases b and c of Table I with cases a, b, c, d, e, f, of Table IV) but this is offset by decreased breeding gain and greatly enlarged inventories of fertile material and bred fuel).

Tables II and III indicate that when the 4000 g/l region is next to the core no important reactivity increases are likely to occur as a result of settling in the outer fertile region. For example, the critical concentrations of reactors a, b, c in Table II are the same to three significant figures which means that they differ by amounts of the order of 0.005 g/l or less. An increment of 0.005 g U^{233} /l would correspond here to a Δk of about 2×10^{-5} . This result is independent of the presence of poisons in the core or of fuel in the blankets. On the other hand, if the more dilute blanket is next to the core and settling occurs, very large reactivity increases will take place.

B. Inventories

Table V shows the inventories (external circulating systems excluded) of fuel and thorium for the various cases where the blankets contain 3 g U^{233} /kg Th. The total amount of U^{233} includes 3 kg for core fuel. It is seen that the lowest inventory of fuel and thorium occurs for a double-blanket reactor with a 6-in. region containing 4000 g Th/l adjacent to the core with heavy water only in the outer blanket. The inventories for this case are less than half those of the single blanket "standard" 1000 g Th/l case. However, the breeding ratio is only 1.03 compared with 1.19 for the standard case. If, however, 500 g Th/l are used in the outer blanket, the breeding ratio is equal to that of the standard case, while the inventories are still significantly reduced (over 15). No advantage is gained in increasing the thickness of the heavy blanket with heavy water only in the outer blanket, for the inventories are not reduced and the breeding ratio is below that of the single-blanket reactor. Inventories rise sharply as fuel and thorium are added to the outer blanket, reflecting the large relative size of that region. (A 4-ft diameter core contains 949 liters; a 6-in. thick inner blanket, 938 liters; a 2-ft thick outer blanket is 8800 liters.)

C. Power Distribution

The fraction of total power generated in the various regions is shown in Table VI for reactors containing 3 g U^{233} /kg Th in the blankets. Little variation in the fraction of power generated in the core is noted, nor is there much change in the fraction of power generated in Region III whether it is 0.5 or 1-ft thick for the same thorium concentrations in the outer blanket. If the outer blanket is the high-concentration region a sizeable portion of the total blanket power is generated there. In contrast, if the inner blanket is the concentrated zone, the dilute outer region generates only about 1% of the total power or less than 8% of the blanket power.

Table V.

U^{233} and Th Inventories in Blankets of Various Reactor Types Considered for
Cases Where 3 g U^{233} /kg Th is Present in Blankets

Reactor Type	g Th/l in more Dilute Blanket	Breeding Ratio (no core poisons)	U^{233} Inventory, kg			Th Inventory, kg		
			Region III	Region V	Total*	Region III	Region V	Total
Single-Blanket, 1000 g Th/l	-	1.19	-	-	32	-	-	9700
Double-Blanket, 4000 g Th/l in Region Adjacent to Core; Region III, 0.5 ft thick	0 500 1000	1.03 1.19 1.20	11 11 11	0 13 26	14 27 40	3752 3752 3752	0 4382 8764	3752 8134 12516
Double-Blanket, 4000 g Th/l in Region Adjacent to Core; Region III 1 ft. thick	0 500 1000	1.13 1.19 1.20	28 28 28	0 11 22	31 42 53	9312 9312 9312	0 3666 7332	9312 12978 16644
Double-Blanket, 4000 g Th/l in Outermost Blanket Region; Region III 0.5 ft thick	0 500 1000	1.12 1.15 1.16	0 1.4 3	105 105 105	108 109 111	0 469 938	35056 35056 35056	35056 35525 35994

* Total U^{233} inventory includes amounts in Region III and Region V plus 3 kg for core inventory.
 External circulating system volumes not included.

TABLE VI

Fraction of Power Generated in Core and Blankets of Various Reactor Types Considered

where 3 g U²³³/kg Th is Present in Blankets. No Core Poisons

Reactor Type	g Th/l in more Dilute Blanket	Fraction of Total Power Generated in Reactor			
		Core	Region III	Region V	Total Blanket
Single-Blanket, 1000 g Th/l	-	0.82	(0.12)*	(0.06)*	0.18
Double-Blanket, 4000 g Th/l in Region Adjacent to Core; Region III 0.5 ft thick	0 500 1000	0.83 0.82 0.83	0.17 0.14 0.14	0 0.04 0.03	0.17 0.18 0.17
Double-Blanket, 4000 g Th/l in Region Adjacent to Core; Region III 1 ft thick	0 500 1000	0.84 0.84 0.843	0.16 0.15 0.144	0 0.01 0.013	0.16 0.16 0.16
Double-Blanket, 4000 g Th/l in Outermost Blanket Region; Region III 0.5 ft thick	0 500 1000	0.83 0.844 0.85	0 0.091 0.12	0.17 0.064 0.03	0.17 0.16 0.15

* Not a double-blanket reactor. Indicated fraction of total power is that generated in regions equivalent to a 0.5-ft thick Region III and a 2-ft thick Region V.

D. Ratio of Inside Core Wall Thermal Flux
to Core Average Thermal Flux

The ratio of inside core wall thermal flux to average core thermal flux appears to depend principally on the concentration of thorium in the region adjacent to the core. No important variation due to the presence of core poisons, blanket thickness, outer blanket concentration or blanket U^{233} concentration was noted. The ratios cited in Table VII decrease with increasing Region III thorium concentration.

Table VII

Ratio of Inside Core Wall Thermal Flux to
Average Core Thermal Flux

<u>Region III Th Concentration</u> g Th/l	<u>Inside Core Wall Thermal Flux</u> Core Average Thermal Flux
0	0.61
500	0.50
1000	0.45
4000	0.35

ACKNOWLEDGMENT

The calculations were performed using an Oracle code devised by C. W. Nestor (see ORNL CF-57-5-14 and CF-57-5-49) and an IBM-704 code (WANDA). The authors wish to thank Verner Anderson and Mrs. Betty Maskewitz of the K-25 Computing Facility for their assistance with the IBM code.

APPENDIX

Nuclear Constants Employed

The calculation of critical concentrations and breeding ratios was performed using a two-group diffusion method which assumes that all fissions occur at thermal energies. The diffusion constants and ages employed were the following (see CF 58-1-79):

A. Thorium Oxide - D₂O Slurries.

g Th/l	p	D ₁ , cm	D ₂ , cm	τ ₂ cm	Σ _a ⁰² cm ⁻¹
0	1.0	1.645	1.245	212.5	0
500	0.66	1.565	1.198	213	6.244 x 10 ⁻³
1000	0.534	1.5	1.156	215	1.249 x 10 ⁻²
4000	0.098	1.195	1.005	252.5	4.995 x 10 ⁻²

where p, D₁, D₂, τ, and Σ_a⁰² are resonance escape probability, fast group diffusion coefficient, slow group diffusion coefficient, Fermi age and thermal macroscopic cross section of thorium oxide, respectively.

B. U²³³ Macroscopic Absorption Cross Section

g U ²³³ /l	Macroscopic Absorption Cross Section, cm ⁻¹
1.5	1.458 x 10 ⁻³
3	2.916 x 10 ⁻³
12	1.166 x 10 ⁻²

C. Zircaloy, Steel, and Heavy Water

<u>Material</u>	<u>D₁, cm.</u>	<u>D₂, cm.</u>	<u>τ, cm²</u>	<u>Σ_a, cm⁻¹</u>
Zircaloy	1.265	0.5316	4194	4.91 x 10 ⁻³
Steel	0.36	0.39	214	0.16
D ₂ O	1.645	1.245	212.5	4.44 x 10 ⁻⁵

gcb

DISTRIBUTION

1. HRP Director's Office
Rm. 259, Bldg. 9204-1
2. G. M. Adamson
3. V. Anderson, K-25
4. S. E. Beall
5. A. M. Billings
6. E. G. Bohlmann
7. S. E. Bolt
8. E. S. Bomar
9. J. R. Brown
10. W. D. Burch
11. R. H. Chapman
12. R. D. Cheverton
13. H. C. Claiborne
14. E. L. Compere
15. R. S. Crouse
16. J. S. Culver
17. D. G. Davis
18. R. J. Davis
19. J. R. Engel
20. J. L. English
21. D. E. Ferguson
22. J. D. Flynn
23. C. H. Gabbard
24. W. R. Gall
25. J. C. Griess
26. R. S. Greeley
27. P. A. Haas
28. P. H. Harley
29. P. N. Haubenreich
30. J. W. Hill
31. E. C. Hise
32. C. J. Hohanadel
33. G. H. Jenks
34. D. T. Jones
35. S. I. Kaplan
36. P. R. Kasten
37. F. Kertesz
38. J. O. Kolb
39. R. B. Korsmeyer
40. K. A. Kraus
41. C. G. Lawson
42. R. E. Leuze
43. R. A. Lorenz
44. M. I. Lundin
45. R. N. Lyon
46. W. L. Marshall
47. J. P. McBride
48. H. F. McDuffie
49. H. A. McLain
50. R. A. McNees
51. J. R. McWherter
52. R. L. Moore
53. L. F. Parsly, Jr.
54. F. N. Peebles
55. M. L. Picklesimer
56. S. A. Reed
57. D. M. Richardson
58. G. W. Rivenbark
59. R. C. Robertson
60. M. W. Rosenthal
61. H. C. Savage
62. C. L. Segaser
63. E. M. Shank
64. M. D. Silverman
65. M. J. Skinner
66. I. Spiewak
67. R. W. Stoughton
68. J. A. Swartout
69. E. H. Taylor
70. D. G. Thomas
71. D. S. Toomb
72. W. E. Unger
73. R. Van Winkle
74. A. M. Weinberg
75. K. W. West
76. J. C. Wilson
77. C. E. Winters
78. F. C. Zapp
- 79-80. REED Library
- 81-82. Central Research Library
- 83-84. Document Reference Library
- 85-99. Laboratory Records
100. ORNL-RC
101. F. C. Moesel, AEC, Washington
- 102-108. Westinghouse PAR Project
- 109-123. TISE-AEC