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**Nuclear Criticality Safety Assessment
of ORR, NBS, and HFBR
Fuel Element Shipping Package**

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ORNL/CSD/TM-77

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COMPUTER SCIENCES DIVISION

Nuclear Criticality Safety Assessment of
ORR, NBS, and HFBR Fuel Element Shipping Package

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(Sponsor: John H. Evans, Originator: J. T. Thomas)

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ABSTRACT

A fuel element shipping package employing a borated-phenolic foam as a thermal insulating material is designed to transport as many as seven fuel elements for use in the Oak Ridge Research Reactor, the Brookhaven Fast Beam Reactor, or the National Bureau of Standards Reactor. This report presents the criticality safety evaluation and demonstrates that the requirements for a Fissile Class I package are satisfied by the design.

I. INTRODUCTION

The nuclear criticality safety of a shipping package designed to transport as many as seven plate-type fuel elements is examined by calculational techniques. Three distinct packages are proposed, one for each of three sites having a light-water reactor. These are the Oak Ridge Research Reactor, the Brookhaven Fast Beam Reactor, and the reactor at the National Bureau of Standards. The three packages have similar neutronic characteristics, the same materials of construction, but differ slightly in their dimensions. The gross characteristics of a typical package are shown in Fig. 1.

The analysis is performed assuming there are nine fuel elements present in the package rather than the seven proposed. This modification is made because it facilitates the geometric description of the package in the calculation, and results in an overestimate of the neutron coupling between packages and of the k_{eff} of the arrays of packages.

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Fig. 1. Proposed Package Design

II. METHOD OF ANALYSIS

The neutron multiplication factors of the shipping package and of arrays of packages were calculated by the KENO IV code¹ and the Hansen-Roach neutron cross-section sets.² This combination of code and cross-section sets has been validated by calculation of critical experiments^{3,4} with fuel elements of the same fissile materials and configurations. The results of the validation with fuel elements are reported in Refs. 5 and 6. The results of calculations of critical experiments with the borated-phenolic foam are reported in Ref. 7. The conclusion of the comparison of calculations and experiments is that systems calculated to have a k_{eff} of 0.98 should be regarded as having a potential for criticality. The analysis is performed with HFBR fuel elements containing 350 g U(93.2) per element.

III. DESCRIPTION OF CODE INPUT

Each plate in a fuel element is described in the code by a box type and these are arranged to form a fuel element within a region of the steel grid. One-half the thickness of the steel forming the 3×3 matrix is associated with each element. When the matrix of fuel elements is described in the code, the correct steel thickness is specified between fuel elements; however, only one-half the steel thickness is represented for the outer surface of the matrix. This description is conservative in that it will result in larger calculated k_{eff} 's than would be measured.

The geometry description is given in Table 1. A fuel element and its associated section of the matrix is formed by stacking box types in the order 9, 7, 5, 3, twelve 1's, 2, 4, 6, and 8. The different box

Table 1. Geometric Representation of Package.

BOX TYPE 1		Mixture									
REGION											
1	CUBOID	1	+X = 2.8485E 00	-X = -2.8485E 00	+Y = 2.8940E-02	-Y = -2.8950E-02	+Z = 2.9027E 01	-Z = -2.9027E 01			
2	CUBOID	2	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 6.4000E-02	-Y = -6.4000E-02	+Z = 3.0162E 01	-Z = -3.0162E 01			
3	CUBOID	5	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
4	CUBOID	2	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
5	CUBOID	6	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
6	CUBOID	5	+X = 3.7700E 00	-X = -3.7700E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
7	CUBOID	10	+X = 3.8460E 00	-X = -3.8460E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8344E 01	-Z = -8.8344E 01			
BOX TYPE 2											
REGION											
1	CUBOID	1	+X = 2.8485E 00	-X = -2.8485E 00	+Y = 2.8940E-02	-Y = -2.8950E-02	+Z = 2.9027E 01	-Z = -2.9027E 01			
2	CUBOID	2	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 6.4000E-02	-Y = -6.4000E-02	+Z = 3.0162E 01	-Z = -3.0162E 01			
3	CUBOID	5	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
4	CUBOID	2	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
5	CUBOID	6	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
6	CUBOID	5	+X = 3.7700E 00	-X = -3.7700E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
7	CUBOID	10	+X = 3.8460E 00	-X = -3.8460E 00	+Y = 1.8540E-01	-Y = -1.8540E-01	+Z = 8.8344E 01	-Z = -8.8344E 01			
BOX TYPE 3											
REGION											
1	CUBOID	1	+X = 2.8485E 00	-X = -2.8485E 00	+Y = 2.8940E-02	-Y = -2.8950E-02	+Z = 2.9027E 01	-Z = -2.9027E 01			
2	CUBOID	2	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 6.4000E-02	-Y = -6.4000E-02	+Z = 3.0162E 01	-Z = -3.0162E 01			
3	CUBOID	5	+X = 3.1064E 00	-X = -3.1064E 00	+Y = 2.0060E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
4	CUBOID	2	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 2.0060E-01	-Y = -1.8540E-01	+Z = 3.0162E 01	-Z = -3.0162E 01			
5	CUBOID	6	+X = 3.5814E 00	-X = -3.5814E 00	+Y = 2.0060E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
6	CUBOID	5	+X = 3.7700E 00	-X = -3.7700E 00	+Y = 2.0060E-01	-Y = -1.8540E-01	+Z = 8.8027E 01	-Z = -8.8027E 01			
7	CUBOID	10	+X = 3.8460E 00	-X = -3.8460E 00	+Y = 2.0060E-01	-Y = -1.8540E-01	+Z = 8.8344E 01	-Z = -8.8344E 01			

Table 1. (Continued)

MIXTURE		MIXTURE	
REGION	1	REGION	1
1 CUMUL	1	1 CUMUL	1
2 CUMUL	2	2 CUMUL	2
3 CUMUL	3	3 CUMUL	3
4 CUMUL	4	4 CUMUL	4
5 CUMUL	5	5 CUMUL	5
6 CUMUL	6	6 CUMUL	6
7 CUMUL	7	7 CUMUL	7
8 CUMUL	8	8 CUMUL	8
9 CUMUL	9	9 CUMUL	9
10 CUMUL	10	10 CUMUL	10
11 CUMUL	11	11 CUMUL	11
12 CUMUL	12	12 CUMUL	12
13 CUMUL	13	13 CUMUL	13
14 CUMUL	14	14 CUMUL	14
15 CUMUL	15	15 CUMUL	15
16 CUMUL	16	16 CUMUL	16
17 CUMUL	17	17 CUMUL	17
18 CUMUL	18	18 CUMUL	18
19 CUMUL	19	19 CUMUL	19
20 CUMUL	20	20 CUMUL	20
21 CUMUL	21	21 CUMUL	21
22 CUMUL	22	22 CUMUL	22
23 CUMUL	23	23 CUMUL	23
24 CUMUL	24	24 CUMUL	24
25 CUMUL	25	25 CUMUL	25
26 CUMUL	26	26 CUMUL	26
27 CUMUL	27	27 CUMUL	27
28 CUMUL	28	28 CUMUL	28
29 CUMUL	29	29 CUMUL	29
30 CUMUL	30	30 CUMUL	30
31 CUMUL	31	31 CUMUL	31
32 CUMUL	32	32 CUMUL	32
33 CUMUL	33	33 CUMUL	33
34 CUMUL	34	34 CUMUL	34
35 CUMUL	35	35 CUMUL	35
36 CUMUL	36	36 CUMUL	36
37 CUMUL	37	37 CUMUL	37
38 CUMUL	38	38 CUMUL	38
39 CUMUL	39	39 CUMUL	39
40 CUMUL	40	40 CUMUL	40
41 CUMUL	41	41 CUMUL	41
42 CUMUL	42	42 CUMUL	42
43 CUMUL	43	43 CUMUL	43
44 CUMUL	44	44 CUMUL	44
45 CUMUL	45	45 CUMUL	45
46 CUMUL	46	46 CUMUL	46
47 CUMUL	47	47 CUMUL	47
48 CUMUL	48	48 CUMUL	48
49 CUMUL	49	49 CUMUL	49
50 CUMUL	50	50 CUMUL	50
51 CUMUL	51	51 CUMUL	51
52 CUMUL	52	52 CUMUL	52
53 CUMUL	53	53 CUMUL	53
54 CUMUL	54	54 CUMUL	54
55 CUMUL	55	55 CUMUL	55
56 CUMUL	56	56 CUMUL	56
57 CUMUL	57	57 CUMUL	57
58 CUMUL	58	58 CUMUL	58
59 CUMUL	59	59 CUMUL	59
60 CUMUL	60	60 CUMUL	60
61 CUMUL	61	61 CUMUL	61
62 CUMUL	62	62 CUMUL	62
63 CUMUL	63	63 CUMUL	63
64 CUMUL	64	64 CUMUL	64
65 CUMUL	65	65 CUMUL	65
66 CUMUL	66	66 CUMUL	66
67 CUMUL	67	67 CUMUL	67
68 CUMUL	68	68 CUMUL	68
69 CUMUL	69	69 CUMUL	69
70 CUMUL	70	70 CUMUL	70
71 CUMUL	71	71 CUMUL	71
72 CUMUL	72	72 CUMUL	72
73 CUMUL	73	73 CUMUL	73
74 CUMUL	74	74 CUMUL	74
75 CUMUL	75	75 CUMUL	75
76 CUMUL	76	76 CUMUL	76
77 CUMUL	77	77 CUMUL	77
78 CUMUL	78	78 CUMUL	78
79 CUMUL	79	79 CUMUL	79
80 CUMUL	80	80 CUMUL	80
81 CUMUL	81	81 CUMUL	81
82 CUMUL	82	82 CUMUL	82
83 CUMUL	83	83 CUMUL	83
84 CUMUL	84	84 CUMUL	84
85 CUMUL	85	85 CUMUL	85
86 CUMUL	86	86 CUMUL	86
87 CUMUL	87	87 CUMUL	87
88 CUMUL	88	88 CUMUL	88
89 CUMUL	89	89 CUMUL	89
90 CUMUL	90	90 CUMUL	90
91 CUMUL	91	91 CUMUL	91
92 CUMUL	92	92 CUMUL	92
93 CUMUL	93	93 CUMUL	93
94 CUMUL	94	94 CUMUL	94
95 CUMUL	95	95 CUMUL	95
96 CUMUL	96	96 CUMUL	96
97 CUMUL	97	97 CUMUL	97
98 CUMUL	98	98 CUMUL	98
99 CUMUL	99	99 CUMUL	99
100 CUMUL	100	100 CUMUL	100

Table 1. (Continued)

NOX TYPE	7	MIXTURE
1	CURBIO	1
2	CURBIO	2
3	CURBIO	3
4	CURBIO	4
5	CURBIO	5
6	CURBIO	6
7	CURBIO	10
NOX TYPE	8	
1	CURBIO	2
2	CURBIO	3
3	CURBIO	4
4	CURBIO	5
5	CURBIO	6
6	CURBIO	10
NOX TYPE	9	
1	CURBIO	2
2	CURBIO	3
3	CURBIO	4
4	CURBIO	5
5	CURBIO	6
6	CURBIO	10
REFLECTOR		
1	CURBIO	0
2	CURBIO	1
3	CURBIO	2
4	CURBIO	3
5	CURBIO	4
6	CURBIO	5

types are required to preserve the different water-channel thicknesses and the nonfuel-bearing end plates of the HFBR element. The materials occupying the geometric regions specified in this case are representative of a calculation in the damaged package evaluations. The materials and their number densities are identified and reproduced in Table 2. The end boxes of the fuel elements are represented as a smeared density which preserves the mass of aluminum. This is material 6 in region 4 of boxes 1 through 9 in Table 1. The reflector region description of Table 1 specifies the geometry in the region between the 3×3 steel matrix to the outer container of carbon steel. The material mixture in region 4 normally would be 8, the undamaged borated-phenolic foam insulation, but in the case depicted region 4 represents the result of damage to the insulation by exposure to fire.

The principal damage to the package will be a charring of the borated-phenolic foam insulation. Actual tests^{8,9} show that an average char depth from the outer surface will not exceed 6.4 cm. An overestimate of neutron coupling between damaged package would be observed if a larger char depth is assumed; therefore, a value of 7.6 cm was used in the evaluation of the damaged package.

IV. RESULTS OF CALCULATIONS

The computed multiplication factors for the undamaged package are presented in Table 3. It is evident that the absence of water from the fuel region of the package results in very low values for k_{eff} . This is consistent with previous results^{5,6} with these fuel elements. There is a large increase in k_{eff} when water occupies the fuel region; however, k_{∞} remains well below a value of unity.

Table 2. Description of Materials for Code Input.

MIXTURE	NUCLIDE	DENSITY	
1	92502	1.30703E-03	Uranium Oxide and Aluminum
1	92503	1.30707E-03	
1	92833	4.70502E-05	
1	92834	1.41241E-04	
1	8100	7.47300E-03	Aluminum
1	13100	5.23867E-02	
2	13100	6.02726E-02	
3	6100	1.73765E-02	Not used in study
3	1101	2.60647E-02	
3	17100	3.68925E-03	
4	502	5.00000E-02	
5	502	1.00000E 00	Water
6	13100	1.81190E-04	Aluminum
7	13100	1.81190E-04	Aluminum and Water
7	1101	6.32304E-02	
7	8100	3.16197E-02	Borated phenolic foam
8	6100	4.41300E-03	
8	1101	5.53800E-03	
8	8100	3.09800E-03	
8	5100	3.53600E-04	
8	14100	1.50400E-04	
8	11100	1.63600E-05	
8	17100	2.32800E-05	
8	13100	8.99500E-06	Borated phenolic foam and Wood
8	12100	9.88300E-06	
8	20100	6.05600E-05	
9	6100	6.07480E-03	
9	1101	7.20910E-03	
9	8100	3.89470E-03	
9	5100	3.11900E-04	
9	14100	1.32700E-04	
9	11100	1.44300E-05	Stainless Steel
9	17100	2.05300E-05	
9	13100	7.93400E-06	
9	12100	8.71700E-06	
9	20100	5.34100E-05	
10	200	1.00000E 00	Carbon Steel
11	100	1.00000E 00	
12	6100	6.03980E-03	Charred borated phenolic foam
12	1101	0.0	
12	8100	0.0	
12	5100	3.11900E-04	
12	14100	1.32700E-04	
12	11100	1.44300E-05	
12	17100	0.0	
12	13100	7.93400E-06	
12	12100	8.71700E-06	
12	20100	5.34100E-05	

Table 3. Computed Neutron Multiplication Factors for the Undamaged Package

Number of Packages	Conditions	$k_{eff} \pm \sigma$	
Single	Water in fuel region	0.669	0.008
Single	Water in fuel region, package closely reflected by water	0.670	0.008
Infinite array	Water in fuel region	0.812	0.007
Infinite array	Water in fuel region, water filling void between packages	0.812	0.007

Table 4 summarizes calculations of the damaged package condition. Again, one finds k_{∞} well below unity.

Table 4. Computed Neutron Multiplication Factors for the Damaged Package

Number of Packages	Conditions	$k_{eff} \pm \sigma$	
Single	No water present	0.033	0.002
Single	Water in full region	0.666	0.006
Single	Water in full region, package closely reflected by water	0.688	0.009
Infinite array	No water present	0.092	0.003
Infinite array	Water in fuel region	0.739	0.008
Infinite array	Water in fuel region, water filling void between packages	0.682	0.007

V. CONCLUSIONS

The evidence of this study shows that the package loaded with seven HFBR fuel elements meets the nuclear criticality safety requirements of a Fissile Class I package. In view of the comparative calculations of various similar fuel elements with different fissile material loadings reported,^{5,6} it may be concluded that the package may also be used as a Fissile Class I package for the ORR and the NBS fuel elements with fissile material loadings at least as large as 350 g $^{235}\text{U}/\text{element}$.

Fuel elements of similar construction used at the Oak Ridge National Laboratory, such as the PCA reactor (140 g $^{235}\text{U}/\text{element}$) and the BSR reactor (200 g $^{235}\text{U}/\text{element}$), may also be shipped in the container.

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