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

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OAK RIDGE NATIONAL LABORATORY
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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.

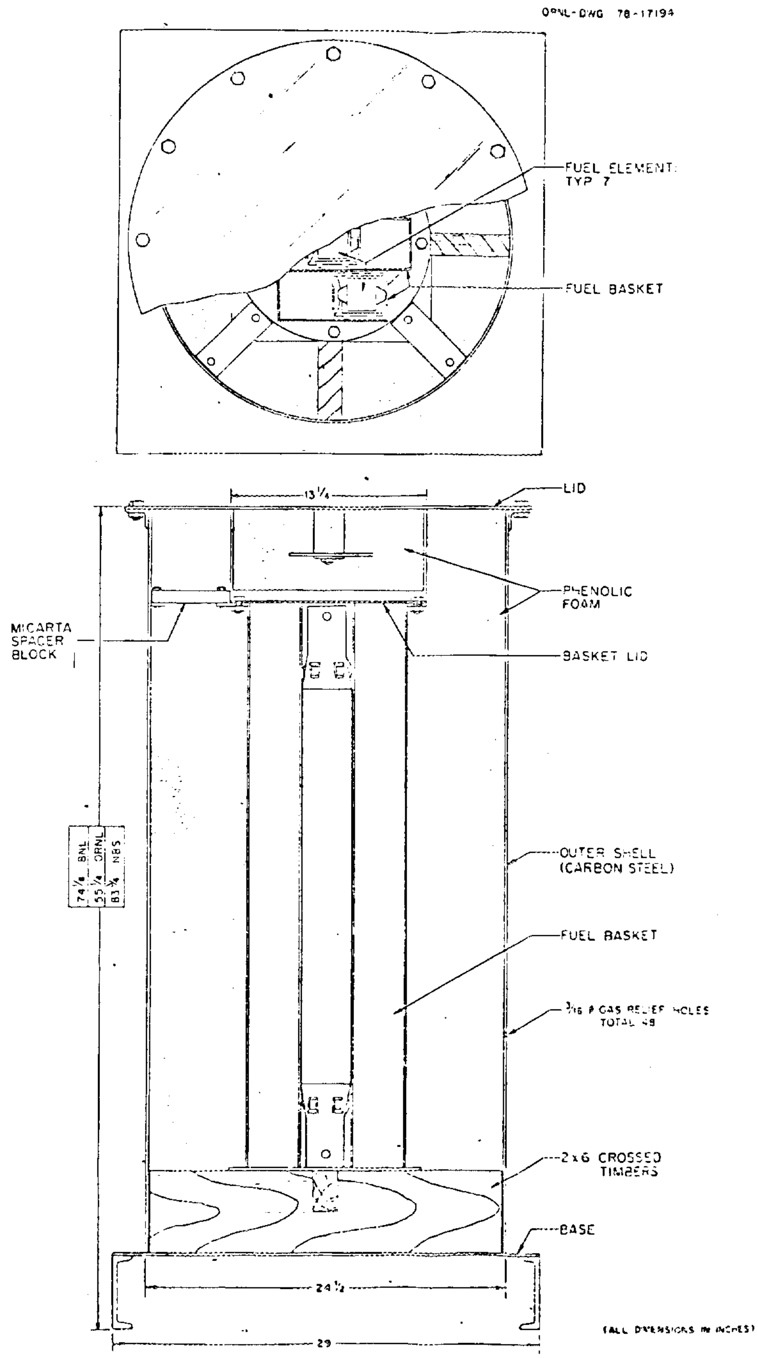

Fig. 1. Proposed Package Design

II. METHOD OF ANALYSIS

The neutron multiplication factors of the shipping package and of arrays of packages were calculated by the KENO IV code[1] 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

REGION		Mixture	+X	-X	+Y	-Y	+Z	-Z
1	CUBOID	1	+X = 2.8485E 00	-X =-2.8485E 00	+Y = 2.8950E-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 = 2.8950E-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 =-2.0060E-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 =-2.0060E-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 =-2.0060E-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 =-2.0060E-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 =-2.0060E-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 = 2.8950E-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)

BOX TYPE 4

REGION		Mixture	+X	−X	+Y	−Y	+Z	−Z
1	CUBOID	1	+X = 2.8485E 00	−X =−2.8485E 00	+Y = 2.8950E−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 =−2.1340E−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 =−2.1340E−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 =−2.1340E−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 =−2.1340E−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 =−2.1340E−01	+Z = 8.8344E 01	−Z =−8.8344E 01

BOX TYPE 5

REGION								
1	CUBOID	1	+X = 2.8485E 00	−X =−2.8485E 00	+Y = 2.8950E−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 = 2.1340E−01	−Y =−2.0060E−01	+Z = 3.0162E 01	−Z =−3.0162E 01
4	CUBOID	2	+X = 3.5814E 00	−X =−3.5814E 00	+Y = 2.1340E−01	−Y =−2.0060E−01	+Z = 3.0162E 01	−Z =−3.0162E 01
5	CUBOID	6	+X = 3.5814E 00	−X =−3.5814E 00	+Y = 2.1340E−01	−Y =−2.0060E−01	+Z = 8.8027E 01	−Z =−8.8027E 01
6	CUBOID	5	+X = 3.7700E 00	−X =−3.7700E 00	+Y = 2.1340E−01	−Y =−2.0060E−01	+Z = 8.8027E 01	−Z =−8.8027E 01
7	CUBOID	10	+X = 3.8460E 00	−X =−3.8460E 00	+Y = 2.1340E−01	−Y =−2.0060E−01	+Z = 8.8344E 01	−Z =−8.8344E 01

BOX TYPE 6

REGION								
1	CUBOID	1	+X = 2.8485E 00	−X =−2.8485E 00	+Y = 2.8950E−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 = 2.1340E−01	−Y =−1.9050E−01	+Z = 3.0162E 01	−Z =−3.0162E 01
4	CUBOID	2	+X = 3.5814E 00	−X =−3.5814E 00	+Y = 2.1340E−01	−Y =−1.9050E−01	+Z = 3.0162E 01	−Z =−3.0162E 01
5	CUBOID	6	+X = 3.5814E 00	−X =−3.5814E 00	+Y = 2.1340E−01	−Y =−1.9050E−01	+Z = 8.8027E 01	−Z =−8.8027E 01
6	CUBOID	5	+X = 3.7700E 00	−X =−3.7700E 00	+Y = 2.1340E−01	−Y =−1.9050E−01	+Z = 8.8027E 01	−Z =−8.8027E 01
7	CUBOID	10	+X = 3.8460E 00	−X =−3.8460E 00	+Y = 2.1340E−01	−Y =−1.9050E−01	+Z = 8.8344E 01	−Z =−8.8344E 01

Table 1. (Continued)

BOX TYPE 7

REGION		Mixture						
1	CUBOID	1	+X = 2.8485E 00	-X =-2.8485E 00	+Y = 2.8950E-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 = 1.9050E-01	-Y =-2.1340E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
4	CUBOID	2	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 1.9050E-01	-Y =-2.1340E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
5	CUBOID	6	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 1.9050E-01	-Y =-2.1340E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
6	CUBOID	5	+X = 3.7700E 00	-X =-3.7700E 00	+Y = 1.9050E-01	-Y =-2.1340E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
7	CUBOID	10	+X = 3.8460E 00	-X =-3.8460E 00	+Y = 1.9050E-01	-Y =-2.1340E-01	+Z = 8.8344E 01	-Z =-8.8344E 01

BOX TYPE 8

REGION								
1	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
2	CUBOID	5	+X = 3.1064E 00	-X =-3.1064E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
3	CUBOID	2	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
4	CUBOID	6	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
5	CUBOID	5	+X = 3.7700E 00	-X =-3.7700E 00	+Y = 2.5400E-01	-Y =-3.0540E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
6	CUBOID	10	+X = 3.8460E 00	-X =-3.8460E 00	+Y = 2.5400E-01	-Y =-3.8140E-01	+Z = 8.8344E 01	-Z =-8.8344E 01

BOX TYPE 9

REGION								
1	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
2	CUBOID	5	+X = 3.1064E 00	-X =-3.1064E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
3	CUBOID	2	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 3.0162E 01	-Z =-3.0162E 01
4	CUBOID	6	+X = 3.5814E 00	-X =-3.5814E 00	+Y = 2.5400E-01	-Y =-2.5400E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
5	CUBOID	5	+X = 3.7700E 00	-X =-3.7700E 00	+Y = 3.0540E-01	-Y =-2.5400E-01	+Z = 8.8027E 01	-Z =-8.8027E 01
6	CUBOID	10	+X = 3.8460E 00	-X =-3.8460E 00	+Y = 3.8140E-01	-Y =-2.5400E-01	+Z = 8.8344E 01	-Z =-8.8344E 01

REFLECTOR

REGION								
1	CORE BDY	0	+X = 1.1538E 01	-X =-1.1538E 01	+Y = 1.2192E 01	-Y =-1.2192E 01	+Z = 8.8344E 01	-Z =-8.8344E 01
2	CYLINDER	8	RADIUS = 2.3380E 01	+Z = 8.8344E 01	-Z =-8.8344E 01			
3	CYLINDER	9	RADIUS = 2.3380E 01	+Z = 9.5400E 01	-Z =-9.5400E 01			
4	CYLINDER	12	RADIUS = 3.1000E 01	+Z = 1.0311E 02	-Z =-1.0294E 02			
5	CYLINDER	11	RADIUS = 3.1320E 01	+Z = 1.0343E 02	-Z =-1.0358E 02			
6	CUBOID	0	+X = 3.1380E 01	-X =-3.1380E 01	+Y = 1.0360E 02	-Y =-1.0360E 02	+Z = 1.1380E 02	-Z =-1.1380E 02

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	1.30703E-03	
1	92833	4.70802E-05	
1	92834	1.41241E-04	
1	8100	7.47300E-03	
1	13100	5.23867E-02	
2	13100	6.02726E-02	Aluminum
3	6100	1.73765E-02	Not used in study
3	1101	2.60647E-02	
3	17100	8.68325E-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	6.32394E-02	
7	8100	3.16197E-02	
8	6100	4.41300E-03	Borated phenolic foam
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	
8	12100	9.88300E-06	
8	20100	6.05600E-05	
9	6100	6.03980E-03	Borated phenolic foam and Wood
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	
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	Stainless Steel
11	100	1.00000E 00	Carbon Steel
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}U/element.

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

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