CRITICALITY SAFETY ANALYSIS--
MODEL 60 SHIPPING PACKAGE
FOR FFTF DRIVER FUEL PINS

C. L. Brown

November 1970

AEC RESEARCH &
DEVELOPMENT REPORT
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CRITICALITY SAFETY ANALYSIS--
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FOR FFTF DRIVER FUEL PINS

C. L. Brown

Criticality Research and Analysis Department
Physics and Engineering Division

November 1970

BATTELLE MEMORIAL INSTITUTE
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RICHLAND, WASHINGTON 99352
The Model 60 is a Fissile Class II shipping container designed for transporting FTR driver fuel pins. The design consists of an 18 x 18 x 112.5-inch metal birdcage with a centrally mounted 6-inch ID x 102.5-inch long containment vessel. The criticality safety evaluation shows that each container may be loaded with up to 120 FTR type fuel pins enriched to 31 wt% PuO₂-U(Nat)O₂ (6.75 kg Pu); and that a single Fissile Class II shipment may consist of up to 12 containers (1440 fuel pins). The Transport Index is 4.0.
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CRITICALITY SAFETY ANALYSIS--
MODEL 60 SHIPPING PACKAGE
FOR FFTF DRIVER FUEL PINS

C. L. Brown

INTRODUCTION

Design of a new shipping package for transporting FFTF driver fuel pins was begun in 1969. This design has now been completed by Battelle-Northwest and the WADCO Corporation. The package is designated as the Model 60. A safety analysis has been performed to provide the basis for necessary transportation approvals and permits. This report presents the criticality safety analysis for the Model 60. The structural analysis and radiological evaluation will be reported by the WADCO Corporation, who will also make the formal request for USAEC Certification and the DOT Special Permit.

SUMMARY

The Model 60 is a new Type B package, designed for Fissile Class II shipment of FFTF driver fuel pins. The package consists of a 6-inch Schedule 40 pipe, 102.5 inches long, centrally mounted inside of an 18 x 18 x 112.5-inch metal birdcage. A flange-type, bolted closure with a special gasket assures a water tight seal under normal and hypothetical accident conditions of transport. The proposed loading is 120 FTR type fuel pins (6.75 kg Pu) enriched up to 31 wt% PuO₂-U(Nat)O₂. At this loading, the Transport Index for the Model 60 is 4.0; and a single shipment may consist of up to 12 containers (1440 FTR fuel pins).
DISCUSSION

A. DESIGN DESCRIPTION

1. Basic Design

The need for the Model 60 arises from the need to ship 80- to 100-inch long FFTF fuel pins. The unique characteristic of the Model 60, therefore, is the 101-inch inside length of the containment vessel. The design is basically the same as used for the Model 10 and Model 55—namely, a steel pipe centrally mounted inside of a metal framework. A comparison of the sizes of this "family of packages" is shown in Table 1. The significantly larger weight of the Model 60 attests to its added structural rigidity. A picture of the Model is shown in Figure 1.

<table>
<thead>
<tr>
<th>Package</th>
<th>Overall Dimensions, in.</th>
<th>Pipe Schedule</th>
<th>ID, in.</th>
<th>Length, in.</th>
<th>Weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 10</td>
<td>16 x 16 x 65 1/2</td>
<td>40</td>
<td>4.0</td>
<td>61.5</td>
<td>200</td>
</tr>
<tr>
<td>Model 55</td>
<td>18 x 18 x 81</td>
<td>40</td>
<td>4.0</td>
<td>76.5</td>
<td>300</td>
</tr>
<tr>
<td>Model 60</td>
<td>18 x 18 x 112 1/2</td>
<td>40</td>
<td>6.0</td>
<td>102.5</td>
<td>800</td>
</tr>
</tbody>
</table>

2. Design Specifications

Design specifications for the Model 60 are summarized below:

Drawings
- H-3-29291 (Sheets 1 to 4)

Containment Vessel
- Pipe Size--6-inch Schedule 40 (Stainless Steel)
- Dimensions--6.07-inch ID x 101 1/4-inch Inside Length
FIGURE 1. Model 60 Shipping Package
• Wall Thickness--0.29 inches
• Bottom Plate--1-inch thick
• Flange--Neck Type; 150 pounds; welded to 6-inch pipe; 8 bolt holes
• Cover Plate--1.0-inch thick; 8 bolt holes
• Gasket--Flexitallic type; spiral wound 347 SS; canadian asbestos filler.
• Closure Bolts--3/4 inch (Nuts welded to flange)

Containment Vessel Insert (For FFTF Fuel Pins)
• Type Insert--Bundle of 120 steel tubes clamped together
• Tube Size--0.437-inch OD; 0.367-inch ID × full length of containment vessel
• Fuel Pin Capacity--120 fuel pins; one pin in each tube

Birdcage Framework
• Outside Dimensions--18 × 18 × 112.5 inches
• Frame--Angle Iron; 1 1/2- × 1/4-inch thick

Birdcage Structure
• Support Plates--6 plates; 18 × 18 × 3/16 inches equally spaced over frame length
• End Spokes--Four at each end; 1-inch Schedule 80 steel pipe
• Mesh Covering--Expanded Steel; Openings less than 2 × 2 inches

B. STRUCTURAL INTEGRITY

A structural analysis of the Model 60 was performed by the WADCO Corporation and will be reported in a separate document. Since the criticality safety evaluation is based directly on the conclusions of the structural analysis, the results are summarized below:
Under normal and hypothetical accident conditions of transport, as defined in USAEC Manual Chapter 0529, it is concluded that

- Containment vessel is water-tight
- Containment vessel will remain centered within the birdcage
- Excessive pressure buildup within containment vessel cannot occur
- Dimensions of birdcage framework cannot be significantly reduced
- Fissile material cannot escape from containment vessel.

C. PROPOSED PACKAGING REQUIREMENTS

1. Fuel Description
   The fissile material proposed for shipment in the Model 60 is described below:
   - Form: $\text{PuO}_2$-$\text{U} (\text{Nat})_2$ fuel pins
   - Enrichment: up to 31 wt% $\text{PuO}_2$-$\text{U} (\text{Nat})_2$
   - $^{235}$U Enrichment: up to 0.72 wt%
   - $^{240}$Pu content: at least 10 wt%
   - Fuel Density: not limited
   - Diameter of Fuel in Pin: 0.19 to 0.20 inch
   - Diameter of Clad Pin: 0.22 to 0.24 inch
   - Length of Fuel in Pin: up to 36.24 inches
   - Clad Material: 304 or 316 SS.
   (The actual pins to be shipped are expected to be in the 22 to 27 wt% $\text{PuO}_2$-$\text{U} (\text{Nat})_2$ range; and the $^{240}$Pu content is expected to be higher than 10 wt%.)

2. Proposed Model 60 Loading
   Up to 120 pins (6.75 kg plutonium)

3. Proposed Fissile Class
   Fissile Class II
D. BASIC CRITICAL PARAMETERS

This section gives the critical values used in the analysis. Basic values are as follows:

<table>
<thead>
<tr>
<th>Minimum Critical Number of Pins</th>
<th>Bare</th>
<th>Full Water Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Pins in Water</td>
<td>183</td>
<td>122</td>
</tr>
<tr>
<td>Fuel Pins in Air</td>
<td>3213</td>
<td>1785</td>
</tr>
</tbody>
</table>

1. Fuel Pins in Water

Critical approach experiments with 25.2 wt% PuO₂-U(Nat)O₂ prototype FFTF driver fuel pins in water were performed during 1969 to 1970. The results of these experiments are summarized in Table 2. The minimum critical number was found to be 149 pins at a lattice pitch of 0.9 inch.

The HAMMER code was found to conservatively predict the critical parameters for mixed oxide pins in water. A comparison of measured and calculated critical number of pins is shown in Table 2.

<p>| TABLE 2. Results of Critical Approach Experiments with 25.2 wt% PuO₂-U(Nat)O₂ Fuel Rods in Water |
| Plutonium: 11.88 wt% ²⁴⁰Pu; 1.55 wt% ²⁴¹Pu |
| Fuel Pin Dimensions: 0.200-inch OD pellet × 27 1/4-inch long fuel column; 0.015-inch stainless steel clad |
| Number of Pins for Criticality |</p>
<table>
<thead>
<tr>
<th>Lattice Pitch, In.</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>417 ± 5</td>
<td>---</td>
</tr>
<tr>
<td>0.60</td>
<td>219.2 ± 0.6</td>
<td>208</td>
</tr>
<tr>
<td>0.779</td>
<td>156.2 ± 0.8</td>
<td>149</td>
</tr>
<tr>
<td>0.900</td>
<td>149.8 ± 0.6</td>
<td>143</td>
</tr>
<tr>
<td>1.039</td>
<td>165.0 ± 0.2</td>
<td>155</td>
</tr>
<tr>
<td>1.200</td>
<td>232.6 ± 0.1</td>
<td>218</td>
</tr>
<tr>
<td>1.35</td>
<td>410 ± 10</td>
<td>---</td>
</tr>
</tbody>
</table>
Since the calculational method is conservative, the calculations were extended with confidence to the 31% PuO₂-U(Nat)O₂ enrichment and the 36-inch length. Results of these calculations are summarized in Table 3. It is concluded that the minimum critical number of pins of the type described in Paragraph C.1. is 122 pins; and, based on the calculated buckling, the minimum critical cylinder diameter is at least 8.22 inches.⁽⁶⁾

2. Fuel Pins in Air

Monte Carlo calculations have shown that the minimum critical number of 31% enriched pins with no ²⁴⁰Pu, but of the same size as described above and with full water reflection, is 1785 pins.⁽⁷,⁸⁾ For the bare system, the minimum critical number is estimated to be 3213 pins.

3. Fuel Pins in Model 60—Optimum Moderation

Calculations were performed to determine the maximum fraction of critical number represented by the 120 pins in the Model 60, assuming water flooded conditions. This was done by removing pins a few at a time to increase moderation, then comparing the actual number in the Model 60 to the calculated critical number at that particular moderation ratio. Results are shown in Table 4. It is concluded that with the stainless steel insert in place, the maximum fraction of a critical number of pins in the Model 60 is 0.41. This fraction occurs when the Model 60 contains 70 to 100 pins. If the insert is left out, the added moderation increases the fraction of a critical number from 0.41 to 0.50. (Note: The neutron absorption properties of the steel insert are neglected in this evaluation).
TABLE 3. Number of Fuel Pins for Criticality as a Function of PuO$_2$ Enrichment and Pin Length

Pin Diameter: 0.200 inch (Bare); 0.230 inch (stainless steel clad)
Plutonium: 11 wt% $^{240}\text{Pu}$; 1.55 wt% $^{241}\text{Pu}$

<table>
<thead>
<tr>
<th>Lattice Pitch, in.</th>
<th>Water to Fuel Volume Ratio</th>
<th>27.25-inch Length</th>
<th>Infinite Length</th>
<th>36-inch Length</th>
<th>Infinite Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exp. (a)</td>
<td>Calc. (b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>5.57</td>
<td>320</td>
<td>308</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>8.60</td>
<td>219</td>
<td>207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>12.80</td>
<td>173</td>
<td>165</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>16.32</td>
<td>153</td>
<td>146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>21.01</td>
<td>149</td>
<td>143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>26.24</td>
<td>165</td>
<td>149</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>38.37</td>
<td>233</td>
<td>218</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Critical Number of Fuel Pins

- 25.2 wt% PuO$_2$-UO$_2$
- 31.0 wt% PuO$_2$-UO$_2$

<table>
<thead>
<tr>
<th>25.2 wt% PuO$_2$-UO$_2$</th>
<th>31.0 wt% PuO$_2$-UO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.25-inch Length</td>
<td>36-inch Length</td>
</tr>
<tr>
<td>Exp. (a)</td>
<td>Calc.</td>
</tr>
<tr>
<td>320</td>
<td>272</td>
</tr>
<tr>
<td>219</td>
<td>185</td>
</tr>
<tr>
<td>173</td>
<td>146</td>
</tr>
<tr>
<td>153</td>
<td>128</td>
</tr>
<tr>
<td>149</td>
<td>122</td>
</tr>
<tr>
<td>165</td>
<td>125</td>
</tr>
<tr>
<td>233</td>
<td>165</td>
</tr>
<tr>
<td>308</td>
<td>251</td>
</tr>
<tr>
<td>207</td>
<td>171</td>
</tr>
<tr>
<td>165</td>
<td>135</td>
</tr>
<tr>
<td>149</td>
<td>118</td>
</tr>
<tr>
<td>127</td>
<td>112</td>
</tr>
<tr>
<td>142</td>
<td>114</td>
</tr>
</tbody>
</table>

---

a. From a plot of measured critical points
b. Calculations: HAMMER System

BNWL-1512
TABLE 4. Calculated Fraction of Critical Number Represented by 120 Pins in Water in the Model 60 Containment Vessel

(Full Water Reflection)

<table>
<thead>
<tr>
<th>Number of Pins in Model 60</th>
<th>Effective Lattice Pitch, in. (Hexagonal)</th>
<th>Calculated Critical Number of Pins at Vw/Vf</th>
<th>Fraction of Critical Number in Model 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 (max.)</td>
<td>0.475</td>
<td>4.91</td>
<td>0.40</td>
</tr>
<tr>
<td>110</td>
<td>0.497</td>
<td>5.48</td>
<td>0.40</td>
</tr>
<tr>
<td>100</td>
<td>0.521</td>
<td>6.17</td>
<td>0.41</td>
</tr>
<tr>
<td>90</td>
<td>0.550</td>
<td>7.02</td>
<td>0.41(b)</td>
</tr>
<tr>
<td>80</td>
<td>0.584</td>
<td>8.08</td>
<td>0.41</td>
</tr>
<tr>
<td>70</td>
<td>0.625</td>
<td>9.45</td>
<td>0.41</td>
</tr>
<tr>
<td>60</td>
<td>0.675</td>
<td>11.25</td>
<td>0.39</td>
</tr>
<tr>
<td>50</td>
<td>0.740</td>
<td>13.79</td>
<td>0.36</td>
</tr>
<tr>
<td>40</td>
<td>0.828</td>
<td>17.59</td>
<td>0.31</td>
</tr>
<tr>
<td>30</td>
<td>0.958</td>
<td>13.95</td>
<td>0.24</td>
</tr>
</tbody>
</table>

a. For the unreflected system, the critical number is about 540 pins.

b. Without the steel insert, the fraction of critical is about 0.50.

E. CRITICALITY SAFETY EVALUATION

Standards for criticality safety are given in USAEC Manual Chapter 0529. Evaluation of the Model 60 against these standards are presented below in a question-answer format. The objective of this evaluation is to demonstrate that a maximum specified shipment of 12 loaded Model 60 packages meets criticality safety requirements under credible transport conditions as defined in USAEC regulations. Basic critical parameters are taken from Part D of this report.
1. Single Package Evaluation

a. Is package designed and constructed and its contents so limited that it would be subcritical if it is assumed that

(1) Water fills the containment vessel;

(2) The contents are moderated to the most reactive credible extent consistent with the chemical and physical form of the content; and

(3) The containment vessel is fully reflected on all sides by water?(9)

Yes. Under the conditions stated, the most reactive arrangement of fuel pins in the Model 60 can represent no more than 0.41 of the critical number of pins (see Paragraph D.3 and Table 3).

In addition, the containment vessel diameter is <0.75 of the minimum critical diameter--6.07 inches compared to 8.22 inches for criticality.

It is pointed out that on the basis of the restricted geometry, 120 fuel pins in the Model 60 are adequately subcritical. For unrestricted geometry, however, the 120 pins are subcritical but not by more than about eight pins. Consequently, special rules are warranted for loading and unloading the Model 60—for example, limiting the number of pins together outside the model 60 to about 50 pins.

b. Under normal conditions of transport

(1) Will there be a release of radioactive material from the containment vessel?

No. Containment vessel remains leaktight under transport conditions.

(2) Will the effectiveness of the packaging be substantially reduced?

No. All-metal construction precludes damage under normal transport conditions.

(3) Will a mixture of gases or vapors develop in the cask and cause an increase of pressure or an explosion, which would significantly reduce the effectiveness of the package?
(4) Will the contents of an individual package remain subcritical? Yes. The effective fraction of a critical number of pins in a Model 60 cannot exceed 0.41.

(5) Will the geometric form of the package contents be substantially altered? No.

(6) Will there be leakage of water into the containment vessel? No. Containment vessel is leaktight.

(7) Will the effectiveness of the packaging be reduced by

- A reduction by more than 5% of the total effective volume of the packaging on which nuclear safety is assessed? No.

- A reduction by more than 5% in the effective spacing on which nuclear safety is assessed, between the center of the containment vessel and the outer surface of the packaging? No.

- Occurrence of any aperture in the packaging large enough to permit the entry of a 4-inch cube? (10) No.

c. If the packaging is subjected to the hypothetical accident conditions, will the package remain subcritical if it is assumed that

(1) The fissile material is in the most reactive credible configuration consistent with the damaged condition of the package and the chemical and physical form of the contents;

Yes. As designed, the Model 60 is water-tight. The minimum critical number for unmoderated pins is ~1785. The maximum Model 60 loading of 120 pins is 0.07 of this number.

If water flooding were to occur, the 120 pins would represent less than 0.45 of the critical number (see Table 4).
(2) Water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the chemical and physical form of the contents;

(3) There is reflection by water on all sides and as close as consistent with the damaged conditions of the package?

2. Package Array Evaluation

a. Is the number of undamaged packages which may be transported together so limited that five times that number would be subcritical in any arrangement, if closely reflected by water?

b. Assuming

(1) Optimum interspersed moderation,

(2) The fissile material is in the most reactive credible configuration consistent with the damaged condition of the package, the chemical and physical form of the contents, and controls exercised over the number of packages to be transported together;

In addition, the containment vessel diameter is <0.75 of the minimum critical diameter--6.07 inches compared to 8.22 inches for criticality.

Yes. Calculations show that twelve Model 60's may safely be shipped together as Fissile Class II (see Appendix A).

Yes. The structural evaluation of the Model 60 by WADCO shows that neither the package nor the fuel will be altered significantly to change nuclear reactivity. Consequently, the conclusions of Paragraph E.2.a. also apply here.
(3) Water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the chemical and physical form of the contents; and

(4) Close reflection by water; is the number of packages so limited that twice that number would be subcritical in any arrangement?(12)

c. What is the maximum number of Fissile Class II packages that may be transported together and the transport index assigned to each package?(13)

Twelve Model 60's. The Transport Index assigned to each package is 4.0 (see Appendix A).
REFERENCES


9. AEC Appendix 0529, Part II.C.1, Division of Operational Safety, AEC, Washington D.C.

10. AEC Appendix 0529, Part II.E.1 and 2, Division of Operational Safety, AEC, Washington D.C.

11. AEC Appendix 0529, Part II.F.2, Division of Operational Safety, AEC, Washington D.C.

12. AEC Appendix 0529, Part II.I.1, Division of Operational Safety, AEC, Washington D.C.

13. AEC Appendix 0529, Part II.I.2, Division of Operational Safety, AEC, Washington D.C.
APPENDIX A

ARRAY CALCULATION
(Ref. Paragraph E.2.a)

The Density Analogue Method is used to calculate the safe number of Model 60 packages \( N_s \) as follows:

\[
N_s = \frac{M_c}{M_e R m F \left( \frac{V_2}{V_1} \right)^S}
\]

Based on the specifications and assumptions in the report, \( N_s \) is calculated as follows:

\( M_c = 3213 \) pins

\( M_e = 120 \) pins

\( R = 20 \)

\( M = 2.5 \)

\( F = 5 \)

\( M_c \) is the critical mass of the unreflected sphere of fissile material. In this case, \( M_c \) is taken to be a close-packed cylindrical array of pins 36 inches long, which is a near approximation to the sphere and valid if \( M_e \) is considered on the same basis.

\( M_e \) is the equivalent mass of fissile material in the shipping package; in this instance taken to be 120 pins. This approach is conservative since the height to diameter ratio is very large.

\( R \) is the factor for array reflection. For Plutonium metal, \( R \) is \( \approx 20 \). For the 31 wt\% PuO\(_2\)-U(Nat)O\(_2\), \( R \) is taken also to be 20, which is conservative. The actual factor should be in the range of 10 to 15).

\( M \) is the factor to allow for interspersed moderation. The value of 2.5 is optimum.

\( F \) is the safety factor designated in USAEC regulations for Fissile Class II shipments.)
\[ V_2 = 597 \text{ liters} \] (\( V_2 \) is the overall volume of the Model 60 package).

\[ V_1 = 48.6 \text{ liters} \] (\( V_1 \) is the capacity of the Model 60 containment vessel).

\[ s = 1.9 \] (s is \( 2(1-f) \), where \( f \) is the fraction of a critical mass represented by the 120 pins).

Then

\[
N_s = \frac{3213}{(120)(20)(2.5)(5)} \left( \frac{597}{48.6} \right)^{1.9}
\]

\[ N_s = 12.6 \text{ Model 60's} \]

The "Transport Index" is

\[ \text{T.I.} = \frac{50}{12.6} = 4.0 \]
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