Redux Analysis of D₂O Reflected Plutonium Foils at Low Temperature

William J. Zywiec, Anthony J. Nelson

November 19, 2019
Introduction

- “Small critical mass” concepts
  - Thin foils
  - Non-absorbing low temperature moderating reflectors
Jarvis and Mills performed experiments at Los Alamos in the 1960s

- Results indicated that critical masses of 290-384 grams could be achieved with $^{235}\text{U}$ (93%), polyethylene sheets, and beryllium reflector blocks in a cubic array
- Experiments performed on the Comet vertical lift machine
Jarvis and Mills performed experiments at Los Alamos in the 1960s

- Results indicated that critical masses of **290-384 grams** could be achieved with $^{235}\text{U}$ (93%), polyethylene sheets, and beryllium reflector blocks in a cubic array
- Experiments performed on the Comet vertical lift machine
- They also performed calculations showing that the critical mass could be as low as **250 grams** if the $^{235}\text{U}$ fuel were redistributed

Fig. 4. The Comet critical assembly machine showing the minimum critical mass experiment with the core in the disassembled position.
Introduction

Be metal reflector 12.5 inches thick

High Density Polyethylene Moderator

Fig. 5. Critical conditions for a polyethylene and $^{235}\text{U}$ foil core in a beryllium reflector.
# Introduction

<p>| Table I. Critical Conditions for a Hydrogenous Core in a Thick Beryllium Reflector |
| --- | --- | --- | --- | --- |</p>
<table>
<thead>
<tr>
<th>Moderate Material</th>
<th>Fuel Cell Cross Section (In.)</th>
<th>Fuel Cell Height (In.)</th>
<th>Beryllium Reflector Thickness (In.)</th>
<th>Weight of Core Moderator Material (kg)</th>
<th>Average Moderator Thickness Between Foils (In.)</th>
<th>Critical Mass 235U (grams)</th>
<th>Atomic Ratio H/235U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>6.0 x 6.125</td>
<td>5.75</td>
<td>12.5</td>
<td>3.327</td>
<td>0.271**</td>
<td>299</td>
<td>375</td>
</tr>
<tr>
<td>Density = 0.961 g/cc</td>
<td>4.75</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.749</td>
<td>0.224**</td>
<td>292</td>
<td>316</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>6.0 x 6.125</td>
<td>5.75</td>
<td>12.5</td>
<td>3.215</td>
<td>0.256**</td>
<td>301</td>
<td>359</td>
</tr>
<tr>
<td>Density = 0.928 g/cc</td>
<td>4.75</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.656</td>
<td>0.211**</td>
<td>296</td>
<td>301</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>6.5 x 6.625</td>
<td>6.75</td>
<td>12.0</td>
<td>4.506</td>
<td>0.2097</td>
<td>303</td>
<td>232</td>
</tr>
<tr>
<td>Density = 0.947 g/cc</td>
<td>5.75</td>
<td>&quot;</td>
<td>&quot;</td>
<td>3.839</td>
<td>0.167**</td>
<td>303</td>
<td>232</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>8.0 x 8.125</td>
<td>7.75</td>
<td>11.5</td>
<td>7.331</td>
<td>0.625</td>
<td>456</td>
<td>540</td>
</tr>
<tr>
<td>Density = 0.888 g/cc</td>
<td>6.50</td>
<td>&quot;</td>
<td>&quot;</td>
<td>6.148</td>
<td>0.520</td>
<td>422</td>
<td>489</td>
</tr>
<tr>
<td>Lucite</td>
<td>8.0 x 8.125</td>
<td>8.00</td>
<td>11.5</td>
<td>9.670</td>
<td>0.625</td>
<td>466</td>
<td>390</td>
</tr>
<tr>
<td>Density = 1.132 g/cc</td>
<td>6.56</td>
<td>&quot;</td>
<td>&quot;</td>
<td>8.034</td>
<td>0.540</td>
<td>433</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td>5.20</td>
<td>&quot;</td>
<td>&quot;</td>
<td>6.248</td>
<td>0.420</td>
<td>417</td>
<td>282</td>
</tr>
<tr>
<td></td>
<td>3.76</td>
<td>&quot;</td>
<td>&quot;</td>
<td>4.463</td>
<td>0.342</td>
<td>460</td>
<td>182</td>
</tr>
</tbody>
</table>

**These six stackings had uranium foil on all six sides of the fuel cell.
Introduction

- Olson and Robkin published a paper **1970** called “A New Small Mass Critical Configuration” in the *ANS Transactions*
  - Modeled a sheet of $^{235}\text{U}$ or $^{239}\text{Pu}$ surrounded by $\text{D}_2\text{O}$
  - Temperature of core and moderator was lowered to 4K (boiling point of $^4\text{He}$)
  - With and without edge reflection around $\text{D}_2\text{O}$

![Graph](image.png)

*Fig. 1. Critical mass of $^{235}\text{U}$ as a function of core height for assumed core neutron temperatures of 10, 20, and 30°K.*
Introduction

- In 1977, Yates published a paper, citing Olson and Robkin’s paper.
  - Modeled spherical shells of $^{235}$U and $^{239}$Pu instead of thin sheets
  - Did not use edge reflectors
  - Did not model the system at low temperature

Fig. 1. Critical mass of $^{235}$U as a function of core height for assumed core neutron temperatures of 10, 20, and 30°K.
In 1977, Yates published a paper, citing Olson and Robkin’s paper.

- Modeled spherical shells of $^{235}\text{U}$ and $^{239}\text{Pu}$ instead of thin sheets
- Did not use edge reflectors
- Did not model the system at low temperature
- “Critical masses” were slightly lower than Olson and Robkin’s results at room temperature

Fig. 1. Critical mass of $^{235}\text{U}$ as a function of core height for assumed core neutron temperatures of 10, 20, and 30°K.
### Introduction

- In **1977**, Yates published a paper, citing Olson and Robkin’s paper.
  - Modeled spherical shells of $^{235}\text{U}$ and $^{239}\text{Pu}$ instead of thin sheets
  - Did not use edge reflectors
  - Did not model the system at low temperature
  - “Critical masses” were slightly lower than Olson and Robkin’s results at room temperature
  - Performed a hand calculation to determine the ”critical mass” at 4K

![Graph showing critical mass as a function of core height](image)
Introduction

- Jarvis and Mills critical masses (1967)
  - 290-384 grams with $^{235}\text{U}$, polyethylene, and beryllium blocks
  - Experimentally validated results
  - Used a design that is consistent with what most nuclear criticality safety engineers consider to be optimal conditions for criticality
Introduction

- Jarvis and Mills critical masses (1967)
  - 290-384 grams with $^{235}$U, polyethylene, and beryllium blocks
  - Experimentally validated results
  - Used a design that is consistent with what most nuclear criticality safety engineers consider to be optimal conditions for criticality

- Olson and Robkin “critical masses” (1970)
  - 35 grams with $^{235}$U and 22 grams with $^{239}$Pu at 4K (65 cm of D$_2$O reflection)
  - Models only
Introduction

- Jarvis and Mills critical masses (1967)
  - 290-384 grams with $^{235}$U, polyethylene, and beryllium blocks
  - Experimentally validated results
  - Used a design that is consistent with what most nuclear criticality safety engineers consider to be optimal conditions for criticality

- Olson and Robkin “critical masses” (1970)
  - 35 grams with $^{235}$U and 22 grams with $^{239}$Pu at 4K (65 cm of D$_2$O reflection)
  - Models only

- Yates “critical mass” (1977)
  - 15.6 grams with $^{239}$Pu at 4K (220-240 cm box of D$_2$O)
  - Models only
  - No low temperature calculations
Introduction

- Anomalies of Nuclear Criticality
  - 16 grams of $^{239}\text{Pu}$ inside of a 55-gallon drum filled with $\text{D}_2\text{O}$ at 4K

WHAT!?!
We reperformed Yates’ calculations for $^{239}$Pu with MCNP6.2 and ENDF/B-VII.1 nuclear data.

1. Initial calculations were performed at room temperature with $S(a,B)$ cross sections
2. Used `makxsf` tool to adjust cross section temperatures to 4K
3. Did not use $S(a,B)$ cross sections at low temperature
Redux Analysis

390-gram $^{239}$Pu spherical shell at Room Temperature
Redux Analysis

\[ D_2O \text{ reflected } ^{239}\text{Pu spherical shell at 4K, 220 cm edge length} \]
Redux Analysis

88.4-gram “minimum critical mass”

D$_2$O reflected $^{239}$Pu spherical shell at 4K (60 cm OD)
Conclusions

- Our results show that Yates’ “minimum critical mass” should have been closer to 88.4-95 grams of $^{239}\text{Pu}$, not 15.6 grams.

- In the next revision of *Anomalies of Nuclear Criticality*, the section on small critical mass concepts should be edited.
  - Other sections that reference old or outdated calculations should also be reviewed for accuracy.

- There is a need for low-temperature critical benchmark experiments.
  - The results of these calculations are not accurate.
  - The density of the system was held constant, which is not realistic.
“That’s bananas.”

- Will Zywiec

(upon hearing about a 15.6-gram minimum critical mass for the first time)