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OF THE UNIVERSITY OF CALIFORNIA • LOS ALAMOS • NEW MEXICO

CRITICAL DATA FOR NUCLEAR SAFETY GUIDANCE
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CRITICAL DATA FOR NUCLEAR SAFETY GUIDANCE

Compiled by
H. C. Paxton

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</tr>
</tbody>
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INDIVIDUAL UNITS

Homogeneous, water-moderated systems

Figures 1 and 2 represent critical masses and critical volumes of homogeneous, water-moderated spheres of Oy(93.2), both bare (except for thin-wall container) and water-reflected.\(^{(1-6,31)}\) Estimates of corresponding diameters of infinite critical cylinders appear in Figure 3, and thicknesses of infinite critical slabs in Figure 4.\(^{(4,6,11,12,32)}\) Effective extrapolation lengths of Figures 27 and 28 are used for the shape conversions that are involved. Similar data for water-moderated Pu\(^{239}\) appear in Figures 5-8,\(^{(4,6-8,32,33)}\) and for U\(^{233}\) in Figures 9-12.\(^{(4,6,8-10,34)}\) The idealized metal-water mixtures of Figures 1-12 (> 2 kg/liter) are denser, hence more limiting, than usually encountered.

Inhomogeneous water-moderated Oy

Figure 13 shows how the minimum critical mass of a water-moderated, water-reflected lattice of Oy(93.5) pieces (optimum spacing) depends upon size of piece.\(^{(26,35)}\) Though measurements were on 1" cubes, 1/2" cubes, and 1/8" diameter rods, data appear in terms of approximate diameters of equivalent spheres. Surface-to-surface spacings that correspond to minima in critical mass vary from 0.7" for the 1" cubes to 0.6" for the 1/8" rods.

Oy at reduced U\(^{235}\) content

Minimum critical masses of homogeneous, water-moderated, water-reflected Oy are given as functions of U\(^{235}\) content of the Oy in Figure 14a.\(^{(24,36-38)}\) Also shown are minimum critical masses of water-moderated lattices in the enrichment range through which these critical masses are less than those for homogeneous systems.\(^{(29,39)}\) Similarly, Figure 14b displays minimum critical volumes. Critical masses of unmoderated Oy(93.5) metal vs. U\(^{235}\) concentration appear in Figure 15.\(^{(6)}\)
Fig. 7

Estimated critical diameters of infinite cylinders
Homogeneous water moderated, U-Pu (no nitrate).

Pu\textsuperscript{239} density - kg Pu\textsuperscript{239}/liter
Minimum critical mass of flooded Oy (93.5) metal lattices as a function of oralloy unit size.
Critical mass vs. U-235 concentration of oralloy metal. (The shaded strip represents the range of uncertainty in the value of U-235 concentration below which oralloy metal cannot be made critical.)

Fig. 15. - 23 -
Poisoned solutions

The influence of excess nitrate on critical mass of water-reflected Pu\textsuperscript{239} solutions is presented in Figure 16.\textsuperscript{(7)} Observations on effects of heterogeneous poisons in U\textsuperscript{235} solutions are summarized in Table I\textsuperscript{(40-43)} and Figure 17. The figure shows the influence of various degrees of Pyrex poisoning on the critical height of 20"-diam. aqueous solutions of U\textsuperscript{235}, both bare and water-reflected. The Raschig rings with which one point was obtained were 2.375" OD x 2" ID x 2.375" long and were packed randomly throughout the solution volume.

Data from the Physical Constants Testing Reactor\textsuperscript{(36)} establish the quantity of uniformly-distributed boron that is required to reduce to unity the $k_\infty$ of a fissionable mixture. For Oy(3.04% U\textsuperscript{235})\textsubscript{O}\textsubscript{3} - polyethylene mixtures, 0.37 atom B per atom of U\textsuperscript{235} (17 gm B/kg U\textsuperscript{235}) protects against criticality for the entire range of H/U\textsuperscript{235}; at H/U\textsuperscript{235} = 1430, $k_\infty = 1$ without boron. In the case of an Oy(2% U\textsuperscript{235})\textsubscript{F}\textsubscript{4} - paraffin mixture at H/U\textsuperscript{235} = 195, 0.25 atom B per atom of U\textsuperscript{235} gives $k_\infty = 1$, from which it is estimated that 0.26 atom B per atom of U\textsuperscript{235} (\~{}12 gm B/kg U\textsuperscript{235}) protects for all H/U\textsuperscript{235}.

Systems with nonhydrogenous diluents

Some effective cross sections from reactivity coefficient data and resulting dilution exponents for bare Oy(94) (Godiva), Oy(94) in an 8-1/2"-thick U reflector (Topsy), and bare Pu (Jezebel) are listed in Table II.\textsuperscript{(44)} In terms of the dilution exponent $n(x)$ for the material $x$, the critical mass of fissionable material diluted homogeneously with the volume fraction $F$ of the material $x$ is

$$m_c = m_{co}(1-F)^{-n}, \text{ } F \ll 1,$$

where $m_{co}$ is the critical mass of the undiluted system. In the cases of D\textsubscript{2}O, graphite ($\rho_o = 1.67 \text{ gm/cm}^3$) and BeO ($\rho_o = 2.86 \text{ gm/cm}^3$) diluting unreflected Oy($\~{}93$),\textsuperscript{(45-47)} data exist over an extended range.
# Table I.

**U\(^{235}\)** **Solutions with Heterogeneous Poisons**

<table>
<thead>
<tr>
<th>Container</th>
<th>Solution</th>
<th>Reflector</th>
<th>Poison</th>
<th>Critical Height</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oy (~ 93):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15&quot; diam. ss cylinder</td>
<td>(\text{Oy}<em>2)(<em>2)(</em>{\text{F}})(<em>2)(</em>{\text{U}})(</em>{235}) = 73.0</td>
<td>water</td>
<td>136 steel rods, 7/8&quot; diam. (49.2%/o of core)</td>
<td>37.5&quot;</td>
</tr>
<tr>
<td>30&quot; x 60&quot; Al tank</td>
<td>(\text{Oy}<em>2)(<em>2)(</em>{\text{F}})(<em>2)(</em>{\text{U}})(</em>{235}) = 78.7</td>
<td>water (half-reflected)</td>
<td>10 boral partitions, 2.3&quot; wide (3/8&quot; boral, ~ 0.3 gmB/cm(^2))</td>
<td>6.9&quot;</td>
</tr>
<tr>
<td>10&quot; diam. Al cylinder in 1/4&quot;-thick Cu</td>
<td>(\text{Oy}<em>2)(<em>2)(</em>{\text{F}})(<em>2)(</em>{\text{U}})(</em>{235}) = 52.6</td>
<td>water outside 1/4&quot; Cu</td>
<td>33.7%/o Cu~0.15&quot; thick, min. spacing ~ 3/4&quot;</td>
<td>60&quot;</td>
</tr>
<tr>
<td>42&quot; diam. ss tank</td>
<td>(\text{Oy}<em>2(</em>{\text{F}})(<em>{\text{U}})(</em>{235}) \leq 360 \text{ gm} \text{U}_{235}/\text{liter}</td>
<td>concrete (on sides)</td>
<td>random-packed, Pyrex raschig rings, 1.5&quot;Dx1.5&quot; highx7/64&quot; wall (17.8 %/o Pyrex containing 12-1/2 %/o B(_2)O(_3))</td>
<td>subcritical at 460 liters solution</td>
</tr>
<tr>
<td><strong>Oy (~ 87):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20&quot; diam. Al cylinder</td>
<td>(\text{Oy}<em>2(</em>{\text{F}})(<em>{\text{U}})(</em>{235}) = 81.4</td>
<td>water on sides, bottom</td>
<td>Pyrex tubing, or rings \leq 2&quot; ID (\sim 4 %/o B): 7.8 %/o glass</td>
<td>9.75&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td></td>
<td>9.45 %/o glass</td>
<td>11.6&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td></td>
<td>11.5 %/o glass</td>
<td>13.6&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td></td>
<td>13.3 %/o glass</td>
<td>19.6&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td></td>
<td>13.95 %/o glass</td>
<td>30.1&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td></td>
<td>16.7 %/o glass</td>
<td>subcritical at 36&quot; depth</td>
</tr>
<tr>
<td>same except</td>
<td></td>
<td></td>
<td>Pyrex tubing, or rings \leq 2&quot; ID (\sim 4 %/o B): 7.8 %/o glass</td>
<td>9.75&quot;</td>
</tr>
<tr>
<td>H/U(_{235}) = 141</td>
<td></td>
<td></td>
<td>9.45 %/o glass</td>
<td>11.6&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>same,</td>
<td></td>
<td>11.5 %/o glass</td>
<td>13.6&quot;</td>
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<td>13.3 %/o glass</td>
<td>19.6&quot;</td>
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<td>13.95 %/o glass</td>
<td>30.1&quot;</td>
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<td>16.7 %/o glass</td>
<td>subcritical at 36&quot; depth</td>
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<tr>
<td>same except</td>
<td></td>
<td></td>
<td></td>
<td>12.5&quot;</td>
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<tr>
<td>H/U(_{235}) = 276</td>
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<td>subcritical at 36&quot; depth</td>
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</table>
CRITICAL HEIGHTS of 20-in-diam STAINLESS STEEL CYLINDERS

CONTAINING PYREX-POISONED SOLUTIONS of $\text{O}_2(87.4)\text{O}_2 (\text{NO}_3)_2$

Fig. 17. - 27 -
TABLE II.
SELECTED MATERIAL REPLACEMENT RESULTS FOR TOPSY, GODIVA, AND JEZEBEL

<table>
<thead>
<tr>
<th>Element (x)</th>
<th>Density (g/atom/cm³)</th>
<th>$\sigma_{a}(x)$ [barn]</th>
<th>$\sigma_{a}(x)$ [barn]</th>
<th>$\sigma_{n}(x)$ [barn]</th>
<th>$\sigma_{n}(x)$ [barn]</th>
<th>Dilution exponent</th>
<th>Dilution exponent</th>
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<tr>
<td>C</td>
<td>0.185</td>
<td>-0.022</td>
<td>2.13</td>
<td>0.86</td>
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<td>2.17</td>
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<td>O</td>
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<td>0.023</td>
<td>2.22</td>
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<td>Al</td>
<td>0.100</td>
<td>-0.006</td>
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<td>2.14</td>
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<td>Cr</td>
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<td>Mn</td>
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<td>2.70</td>
<td>0.95</td>
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<td>Fe</td>
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<td>Cu</td>
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<td>Zr</td>
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<tr>
<td>Nb</td>
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<td>0.068</td>
<td>3.99</td>
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<tr>
<td>Mo</td>
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<td>-1.82⁶</td>
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<tr>
<td>U²³⁸</td>
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<td>-3.60⁶</td>
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<tr>
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<td></td>
<td>1.20</td>
<td>2.00</td>
</tr>
</tbody>
</table>

(Footnotes on next page)
TABLE II Footnotes

\[ a \bar{\sigma}_a(x) = \bar{\sigma}_c(x) - \bar{\sigma}_f(x) - \Delta\gamma \bar{\sigma}_s(x), \text{ where } \bar{\sigma}_c \text{ and } \bar{\sigma}_f \text{ are capture and fission cross-sections (suitably averaged), } \Delta\gamma \text{ is the increase in neutron effectiveness per central scattering and } \bar{\sigma}_s \text{ is scattering cross section.} \]

\[ b \text{ The critical mass of a system diluted by the volume fraction } F(x) \text{ of element } x, m_c(x), \text{ is related to the critical mass of the undiluted system } m_c(0), \text{ according to } m_c(x)/m_c(0) = [1-F(x)]^{-B}; \text{ if } F(x) \ll 1. \text{ Where } \rho_o(x) \text{ is the normal density of } x \text{ in gm-atom/cm}^3, \]

\[ n(x) = 1.20 - \rho_o(x) \left[ 0.735 \bar{\sigma}_{tr}(x) - 12.82 \bar{\sigma}_a(x) \right], \text{ for Topsy; } \]

\[ n(x) = 2.00 - \rho_o(x) \left[ 2.25 \bar{\sigma}_{tr}(x) - 14.27 \bar{\sigma}_a(x) \right], \text{ for Godiva; } \]

\[ n(x) = 2.00 - \rho_o(x) \left[ 1.846 \bar{\sigma}_{tr}(x) - 9.964 \bar{\sigma}_a(x) \right], \text{ for Jezebel.} \]

\[ c \text{ These values are used for normalization.} \]
(Figure 18). Figure 19 gives critical masses of bare and U-reflected cylinders of Pu diluted by Al, Fe, U, and Th. \(^{(48)}\)

**Systems at reduced density**

The dependence of critical mass \((m_c)\) upon core density \((\rho)\) has been determined for several spheres or nearly equilateral cylinders. \(^{(6,13)}\)

Values of \(n\) in the relation \(m_c = \text{const} \left(\frac{\rho}{\rho_o}\right)^{-n}\) are

- 1.20 for Oy(94) metal in 8-1/2" U reflector
- 1.57 for Oy(93) \(\text{H}_3\text{C}\) in 8" thick U reflector
- 1.88 for Oy(93) \(\text{O}_2\text{F}_2\) solution at \(\text{H}/\text{U}^{235} = 230\) in thick water reflector (possibly influenced by void geometry)
- \(\sim 1.1\) for Pu\(^{239}\) metal in a reflector corresponding to thick U (from Figure 22)

Where density of both core and reflector of a spherical system are changed by the ratio \(\rho/\rho_o\), and the ratio of reflector thickness to core radius is maintained, then \(n = 2\) (the value for an unreflected spherical core).

In the case of an infinite slab, the critical mass per unit area is necessarily independent of \(\rho\).

**Spherical systems with various reflectors**

Critical masses of unmoderated Oy (93.5) metal spheres are given for various reflectors as functions of reflector thickness in Figures 20 and 21, with supplementary data in Table III. \(^{(6)}\) Figure 22 gives critical masses of \(\text{U}^{233}\) metal, \(\delta\)-phase Pu\(^{239}\) and \(\alpha\)-phase Pu\(^{239}\) in terms of the critical mass of Oy (93.5) metal in a reflector of the same composition and thickness. \(^{(34,49-51)}\)

As the existing data show no distinction between nonmoderating and moderating reflectors (of limited thickness), these curves provide a basis for estimating critical masses of the other materials from the abundant data for Oy.
Bare Homogeneous Spheres of Ox (93) and Moderators Other Than Light Water

Critical mass - kg U^{235}

Volume fraction of 0y (93) metal at 18.8 gm/cm^3
Spherical Critical Masses of Pu diluted with other metals

volume fraction of Pu at 14.2 gm/cm³

Fig. 19. - 32 -
Fig. 20.
Fig. 21. - 34 -
### TABLE III.
CRITICAL MASSES OF SPHERICAL ORALLOY (93.5 w/o U-235) WITH VARIOUS REFLECTORS

Data Adjusted to the Following Standard Reflector Thicknesses.

<table>
<thead>
<tr>
<th>Reflector (ρ-gm/cm³)</th>
<th>1 in.</th>
<th>2 in.</th>
<th>4 in.</th>
<th>infinite</th>
<th>Effective σₜᵣ-cm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be (QMV, ρ = 1.84)</td>
<td>29.2</td>
<td>20.8</td>
<td>14.1</td>
<td>~8.9</td>
<td>~0.25</td>
</tr>
<tr>
<td>BeO (ρ = 2.69)</td>
<td>21.3</td>
<td>15.5</td>
<td>16.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC (ρ = 14.7)</td>
<td>21.3</td>
<td>16.5</td>
<td>~16.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U (ρ = 19.0)</td>
<td>30.8</td>
<td>23.5</td>
<td>18.4</td>
<td>16.1</td>
<td>0.25</td>
</tr>
<tr>
<td>W-alloy (~92% W, ρ=17.4)</td>
<td>31.2</td>
<td>24.1</td>
<td>19.4</td>
<td></td>
<td>~0.25</td>
</tr>
<tr>
<td>Paraffin</td>
<td>(32.6)</td>
<td></td>
<td></td>
<td>21.8</td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>(33.5)</td>
<td>~24.0</td>
<td>22.9</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td>D₂O</td>
<td>(27)</td>
<td></td>
<td>21.0</td>
<td>~13.6</td>
<td></td>
</tr>
<tr>
<td>Cu (ρ = 8.88)</td>
<td>32.4</td>
<td>25.4</td>
<td>20.7</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Ni (ρ = 8.88)</td>
<td>33.0</td>
<td>25.7</td>
<td>(21.5)</td>
<td>19.6</td>
<td>0.23</td>
</tr>
<tr>
<td>Al₂O₃ (ρ = 2.76)</td>
<td>35.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite (CS-312, ρ=1.69)</td>
<td>35.5</td>
<td>29.5</td>
<td>24.2</td>
<td>~16.7</td>
<td>0.18</td>
</tr>
<tr>
<td>Fe (ρ = 7.87)</td>
<td>36.0</td>
<td>29.3</td>
<td>25.3</td>
<td>23.2</td>
<td>0.19</td>
</tr>
<tr>
<td>Zn (ρ = 7.04)</td>
<td>29.8</td>
<td>25.0</td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Th (ρ = 11.48)</td>
<td>33.3</td>
<td></td>
<td></td>
<td>~0.14</td>
<td></td>
</tr>
<tr>
<td>Al (2S, ρ = 2.70)</td>
<td>39.3</td>
<td>(35.5)</td>
<td>(32)</td>
<td>&lt;30.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Ti (ρ = 4.50)</td>
<td>39.7</td>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td>Mg (ρ = 1.77)</td>
<td>41.0</td>
<td></td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
</tbody>
</table>
CRITICAL MASSES OF $U^{233}$, $\delta$-Pu$^{239}$, and $\alpha$-Pu$^{239}$

IN TERMS OF CRITICAL MASS OF $U^{235}$ METAL AT SAME

REFLECTOR COMPOSITION and THICKNESS

○ $\delta$-Pu ($\rho = 15.7$ gm/cm$^3$)

△ $U^{233}$ ($\rho = 18.5$ gm/cm$^3$)

□ $\alpha$-Pu ($\rho = 19.5$ gm/cm$^3$)

Dotted symbols for Oy reflector

\[ \frac{m_c(x)}{m_c(U^{235})} \]

$\text{m}_c(U^{235})$-kg [Content of Oy (93.5) at $\rho = 18.8$ gm/cm$^3$]

Fig. 22.
No such range of reflector data exists for solutions. It has been observed that the same thickness of iron is essentially equivalent to the inner two inches (or less) of a thick water reflector about U\textsubscript{235} solution.\footnote{13} Similar replacements show that plexiglas is a slightly more effective reflector than water. Figure 23 shows critical height of a 10\"-diameter U\textsubscript{235} solution (0.337 kg U\textsubscript{235}/liter) as a function of thickness of lateral water reflector and of lateral furfural reflector.\footnote{6} The critical height of a slab of U\textsubscript{235} solution (0.483 kg U\textsubscript{235}/liter), 4\' wide x 6\" thick, vs. thickness of Al reflector on each face is given by Figure 24.\footnote{11}

Cylinders of various height/diameter ratios

Ratios of critical masses of cylinders (height h, diameter d) to those for spheres appear vs. h/d in Figure 25 for U\textsubscript{235} solutions\footnote{2} and in Figure 26 for Oy(93.5) metal.\footnote{6,32} For extrapolation to broad slabs and long cylinders, the following alternative representation is more convenient. The interrelationships between critical cylinders of various height/diameter may be given in terms of effective extrapolation lengths, $\delta_c$, which satisfy

$$\left(\frac{2.405}{d}\right)^2 + \left(\frac{\frac{\pi}{h} + 2\frac{\delta_c}{h}}{2}\right)^2 = B_s^2$$

where $B_s^2$ is an assumed constant buckling (e.g., that of the corresponding sphere). Such extrapolation lengths are shown by Figure 27 for families of solution cylinders that are either bare or water-reflected, and similarly by Figure 28 for metals.\footnote{52}

Other shapes

Investigations of the possibility of large-volume solution storage in annular cylinders led to the data of Figures 29 and 30, which apply to critical annuli with inner cylinder Cd-lined and water-filled.\footnote{5,53} Similar data exist for solution annuli with internal water but no Cd, and without either water or Cd.
Critical Height as a Function of the Thickness of a Water or Furfural Reflector on the Lateral Surface of a 10-in.-dia Aluminum Cylinder Containing an Enriched $^{235}$U Solution.
UNCLASSIFIED
ORNL-LR-DWG 24579

Fig. 24.

H: $U^{235}$ ATOMIC RATIO = 50.1

CRITICAL HEIGHT of a 6-in.-thick SLAB of $U^{235}$ SOLUTION as a FUNCTION of THICKNESS of Al on EACH FACE of the SLAB
Critical Volumes of Elements in Operating Solution Relative to Spheroidal Values

Fig. 25. - 40 -
Fig. 26.
EFFECTIVE EXTRAPOLATION LENGTHS FOR CYLINDERS OF OY(93.2)O₂F₂ SOLUTION

- Water-reflected (roll)
- H/O²⁺ = 44
- H/O²⁺ = 380 (normalized)
- Sphere values
- Infinite slab
- Infinite cylinder

Fig. 27.
EFFECTIVE EXTRAPOLATION LENGTHS FOR CYLINDERS OF
ERALLOY (93.5) AND DELTA-PHASE PLUTONIUM METAL

\[ h/d \quad (1+h/d) \]

- Oy-sphere values (15.8 g/m Oy/cm²)
- Pu-sphere values (15.65 g/m Pu/cm²)
- water-reflected Oy(93.5)
- water-reflected Pu
- hard Oy(93.5)
- infinite slab

Fig. 28.
Critical Heights of Cylindrical Annuli Containing Aqueous Solutions of 93.2\% U^{235}-Enriched Uranyl Fluoride as a Function of the Thicknesses of the Annuli: H:U^{235} Atomic Ratio = 50.4

Fig. 29. - 44 -
Critical Heights of Cylindrical Annuli Containing Aqueous Solutions of 93.2% \( \text{U}^{235} \)-Enriched Uranyl Fluoride as a Function of the Thicknesses of the Annuli: \( \text{H:U}^{235} \) Atomic Ratio = 309.

Fig. 30.
Table IV gives results of a few observations on critical Oy(\sim 93) metal annuli in various reflectors.

Critical and subcritical data on several solution-filled crosses and diagonal pipe intersections appear in Table V. \cite{5}

**Metal-solution systems**

Figure 31 shows the relation between critical thickness of a 10" x 16" slab of Oy(\sim 90) metal vs. \textsuperscript{235}U concentration of a uranyl nitrate solution in which the slab is immersed. \cite{54} The solution is a cylinder 30" diam. x 28" high. From these data and measurements on 16" x 20" slabs, the curves of Figure 32 for slabs in infinitely-thick solution have been deduced. With the 10" x 16" slab, 1 gm Cd per liter of solution (as cadmium nitrate) compensates for 7 gm \textsuperscript{235}U per liter.

The critical thickness of a 5" x 8" slab of Oy(\sim 90) metal on the axis of a 9.45" diam. x 16" cylinder of uranyl nitrate solution appears in Figure 33 vs. \textsuperscript{235}U concentration in the solution. \cite{55}

**Some subcritical observations**

Numerous multiplication measurements, while not establishing actual critical configurations, have been sufficient to show that certain systems are subcritical. A few conservatively subcritical systems that help fill gaps in critical data follow (others appear in Tables I and V).

1a) Close-packed array of 4 polyethylene containers (7-1/4" ID x 1/4" wall) containing 7"-deep Oy(\sim 93)O\textsubscript{2}F\textsubscript{2} solution at \textsubscript{H/235U} = 260 (480 gm \textsuperscript{235}U per container), standing on stainless-steel floor of a hood. \cite{56}

1b) Close-packed array of 6 of the units of 1a) after precipitation of the uranium as a 2-1/4"-deep peroxide layer at \textsubscript{H/235U} \sim 75; 5"-thick uranium-free solution above the peroxide. Apparently less reactive than 1a).
<table>
<thead>
<tr>
<th>reflector (material, thickness)</th>
<th>critical mass (kg Oy)</th>
<th>critical height (in. Oy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot; normal U, complete (some excess)</td>
<td>82.7 ± 0.3</td>
<td>3.01</td>
</tr>
<tr>
<td>3&quot; normal U, complete</td>
<td>55.9 ± 0.3</td>
<td>2.03</td>
</tr>
<tr>
<td>3&quot; polyethylene, complete</td>
<td>60.6 ± 0.3</td>
<td>2.20</td>
</tr>
<tr>
<td>2&quot; CS-312 graphite (inner cyl. completely filled)</td>
<td>78.5 ± 0.3</td>
<td>2.86</td>
</tr>
<tr>
<td>2&quot; graphite crucible, same as last except without top reflector (wall extends 5&quot; above base of Oy)</td>
<td>97 ± 2</td>
<td>3.54</td>
</tr>
<tr>
<td>1&quot; normal U in 2&quot; polyethylene, complete</td>
<td>54.5 ± 0.3</td>
<td>1.98</td>
</tr>
<tr>
<td>1&quot; normal U in 2&quot; polyethylene, no reflector in inner 6&quot; cyl.</td>
<td>60.8 ± 0.3</td>
<td>2.21</td>
</tr>
</tbody>
</table>
### TABLE V.
CRITICAL PARAMETERS OF ENRICHED $^{235}$U SOLUTIONS IN CYLINDRICAL 60° "Y" AND 90° "CROSS" GEOMETRIES

<table>
<thead>
<tr>
<th>diameter of cylinders (in.)</th>
<th>geometry</th>
<th>H/U$^{235}$ atomic ratio</th>
<th>kg U$^{235}$ per liter</th>
<th>critical height (in.)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>effectively infinite water reflector except at top:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>cross</td>
<td>44.3</td>
<td>0.337</td>
<td>15.6</td>
</tr>
<tr>
<td>5</td>
<td>cross</td>
<td>44.3</td>
<td>0.538</td>
<td>5.75</td>
</tr>
<tr>
<td>5</td>
<td>cross</td>
<td>73.4</td>
<td>0.337</td>
<td>7.8</td>
</tr>
<tr>
<td>5</td>
<td>Y</td>
<td>73.4</td>
<td>0.337</td>
<td>15.6</td>
</tr>
<tr>
<td>no reflector:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Y</td>
<td>73.4</td>
<td>0.337</td>
<td>b</td>
</tr>
<tr>
<td>5</td>
<td>cross</td>
<td>73.4</td>
<td>0.337</td>
<td>b</td>
</tr>
<tr>
<td>7.5</td>
<td>cross</td>
<td>44.3</td>
<td>0.538</td>
<td>b</td>
</tr>
<tr>
<td>7.5</td>
<td>cross</td>
<td>72.4</td>
<td>0.342</td>
<td>b</td>
</tr>
</tbody>
</table>

$^a$ Above the intersection of the center lines.

$^b$ Extrapolation of the reciprocal source-neutron multiplication curve from an observation taken at least 36 cm above the intersection of the center lines indicates that this vessel will not be critical at any height.
CRITICAL SLAB THICKNESS

Fig. 31.
CRITICAL SLAB THICKNESS
IN AN INFINITE SYSTEM

Fig. 32.

11.6 g $^{235}$U per liter

Oralloy (90°) Slabs

<table>
<thead>
<tr>
<th>Curve</th>
<th>Slab Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10&quot; x 16&quot;</td>
</tr>
<tr>
<td>B</td>
<td>16&quot; x 20&quot;</td>
</tr>
<tr>
<td>C</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

Tamper: Uranyl Fluoride Solution

$U^{235}$ Concentration in g/liter

Critical Slab Thickness in Inches
2) Close-packed array of 17 porcelain filter boats (4" diam.) containing 3-1/2"-deep Oy (∼ 93) peroxide at H/U235 ∼ 18; reflected on 3 sides by thick water and concrete. (56)

3) Slab on concrete floor, made up of 23 - 2-3/4" x 2-3/4" x 3-3/4"-deep units of (Oy ∼ 93)308 containing water such that H/U235 = 12 (705 gm U235 per unit in milk carton). (56)

4a) Oy (∼ 93)-metal slab 8" x 8-1/2" x 1-3/32"-thick, reflected by 6"-thick salt eutectic consisting of 55 w/o K2CO3 and 45 w/o Li2CO3. (16" x 17" x 1-3/32" slab also subcritical but at high multiplication). (56)

4b) Stack of four 8" x 8-1/2" x 1-3/2"-thick Oy-metal slabs separated by 2"-thick layers of the salt of 4a), essentially unreflected. Data also exist for Oy (∼ 93) sheet distributed in 65 w/o K2CO3, 30 w/o Li2CO3 and 5 w/o Na2CO3. (57)

5) Four 30" x 6'-high cylinders of condensed Oy (2%)F6 at H/U235 ∼ 4, in contact, water reflected. (58)

INTERACTING UNITS

Three-dimensional arrays

Critical data for cubic lattices of fissionable metal units are summarized in Figure 34, where the ordinate is critical capacity of the array in terms of number of bare, spherical critical masses of the material, and the abscissa is volume-fraction F of the lattice that is occupied by the unit. (59) (Consistent densities of units are used for determining coordinates.) Though data do not exist for cubic lattices of nearly equilateral solution units, information about clusters of solution cylinders or slabs can be forced into the form of Figure 34 by confining attention to roughly equilateral lattices (1/2 ≤ h/d ≤ 2). The data of Figure 35 represent this sort
CUBIC LATTICES OF HIGHLY-ENRICHED U METAL

Critical lattice capacity - spherical "cris"

- 20 kg Oy SPHERES, CONCRETE-REFLECTED LATTICE
- 20 kg Oy SPHERES, UNREFLECTED LATTICE
- 32 kg Oy SPHERES, CONCRETE-REFLECTED LATTICE
- 32 kg Oy SPHERES, PARTIALLY REFLECTED LATTICE
- 24.5 kg Oy SLABS, 1" x 8" x 10" LUCITE ABOUT LATTICE
- 30 kg ASSEMBLAGES OF ~5kg Oy PIECES ($\rho_{eff} \approx 40\%$) PARTIALLY-REFLECTED LATTICE

F - Fraction of lattice occupied by units

Fig. 34.
FIG. 35

APPROXIMATELY CUBIC ARRAYS
OF U-235 SOLUTIONS
Unreflected lattices

- LIMITING SLOPE

3 - 3" THICK x 47.5" WIDE
SOLUTION SLABS, H/U²³⁵=337,
(1/2 ≤ LATTICE h/d ≤ 2)

X 7 - 6" DIA. SOLUTION CYLINDERS,
H/U²³⁵=44 (1/2 ≤ LATT. h/d ≤ 2)

○ 8" DIA. SOL. CYLS. (CLUSTERS OF 3,7)
H/U²³⁵=44, LATT. h/d=0.625

○ 8" DIA. SOL. CYLS. (CLUSTERS OF 3,7)
H/U²³⁵=309, LATT. h/d=1.00

○ 9 1/2" DIA. SOL. CYLS. (CLUSTERS OF 3,4,7)
H/U²³⁵=297, LATT. h/d=0.60

F - Fraction of lattice occupied by units

R9-N2-446
of compromise for 3-3" slabs and 7-6" diam. cylinders. (5,20,21,59)

In the cases of 8"-diam. and 9-1/2" diam. cylinders, where data exist for clusters of different numbers, shape is preserved (assuming lattice extrapolation lengths equal to one-half of the surface-to-surface separation of units).

Each slope, -s, of Figures 34 and 35 corresponds to a density exponent if the lattice is thought of as a single low-density unit. Figure 36 is a correlation of s with quantity of reflector about the lattice and reactivity (fraction critical) of an individual unit.

It has been observed that 1"-thick plexiglas between all pairs of 1" x 8" x 10" Oy (-93)-metal units decreases the critical number in a cubic lattice by the factor ~ 5. (60)

**Linear and planar arrays**

Figure 37 gives cross-multiplication data for linear and two-dimensional arrays of Oy (-93)-metal units. It suggests that interactions for large linear or planar arrays can be predicted from measurements on a few units, provided 1-1/Mx is an undistorted measure of reactivity. (59)

The influence of spacing on interaction between various numbers of bare in-plane solution cylinders is shown in Figure 38.

**Pairs of water-immersed units**

Figure 39 gives a measure of interaction between pairs of units immersed in water vs. separation of units. Whereas 4"-thick water effectively isolates small spheres, about 8" is required for long cylinders and large slabs that are face to face. (5,6,20,21,61)

**Effects of incidental reflectors**

Figure 40 shows the critical height of a 9"-diameter U^{235} solution as a function of distance from a concrete slab. (5) Effects of carbon
1. Equivalent 20 kg solid Oy spheres
2. Equiv. 32 kg solid Oy spheres
3. 24.5 kg solid Oy slabs, 1"x 8"x 10"
4. 30 kg assemblages of ~5 kg Oy pieces
   \( (p_{\text{eff}} \sim 40\%)\)
5. 6" dia. solution cylinders, \(H/U^{235} = 4.4\)
6. 8" dia. solution clys., \(H/U^{235} = 4.4\)
7. 8" dia. solution cylinders, \(H/U^{235} = 309\)
8. 9½" dia. solution clys., \(H/U^{235} = 297\)
9. 3-3" thick solution slabs, \(H/U^{235} = 337\)

(Oy = highly-enriched uranium)

Data from J.T. THOMAS and C.L. SCHUSKE are included

---

Fig. 36. - 56 -
LINEAR AND PLANAR ARRAYS OF ~ 32 kg Oy SPHERES
Centered 8" above concrete floor in room with concrete walls

<table>
<thead>
<tr>
<th>CENTER-CENTER SPACING</th>
<th>NORMALIZING FACTOR FOR 1 - 1/Mx</th>
</tr>
</thead>
<tbody>
<tr>
<td>16&quot;, PLANAR</td>
<td>1.16</td>
</tr>
<tr>
<td>20&quot;, PLANAR</td>
<td>1.54</td>
</tr>
<tr>
<td>25&quot;, PLANAR(o)</td>
<td>2.78</td>
</tr>
<tr>
<td>30&quot;, PLANAR</td>
<td>3.60</td>
</tr>
<tr>
<td>16&quot;, LINEAR, ROOM CENTER</td>
<td>1.32</td>
</tr>
<tr>
<td>16&quot;, LINEAR, 8&quot; FROM WALL</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Fig. 37.
INTERACTION WITHIN IN-PLANE ARRAY OF UNREFLECTED $G^+$-DIAMETER $O_{(95)}C_2F_2$
SOLUTION CYLINDERS $H/n^2\pi=44.8$

$1/2(n^2\pi) = \frac{1}{2} \cdot \frac{\pi}{n^2}$

(volume of one cylinder in the critical array, $\frac{1}{2} n^2 \pi$ spherical critical volume)

$\Theta (h_n=15.8^\circ)$
$\Theta (h_n=16.5^\circ)$

$\Theta (h_n=16.8^\circ)$
$\Theta (h_n=16.9^\circ)$
$\Theta (h_n=31^\circ)$
$\Theta (h_n=36^\circ)$
$\Theta (h_n=32^\circ)$
$\Theta (h_n=26.3^\circ)$
$\Theta (h_n=26.9^\circ)$

0.25" axis-to-axis spacing

1/4" axis-to-axis spacing

interaction as fraction of equivalent sphere critical volume

number of units

Fig. 38. - 58 -
INTERACTION BETWEEN WATER-FLOODED PAIRS
OF FISSIONABLE UNITS (maximum areas face)

\( * \sim 20 \text{kg } \text{O}_4(95.5) \text{- metal spheres} \)

\( \bigcirc \ -6' \text{ diam } \text{O}_4\text{O}_2\text{F}_2 \text{- solution cylinder, } H/U^{\text{c}} = 44.3 \)

\( \bigcirc \ -3' \text{- thick } \times 46' \text{- wide } \text{O}_4\text{O}_2\text{F}_2 \text{- solution slab, } H/U^{\text{c}} = 56.1 \)

(interaction \( E \sim 1 \sim 16 \text{ keV}, \text{where } V_S \text{ is equivalent-sphere volume of a unit, } V_S \text{ is corresponding spherical critical volume} \))
Critical Mass as a Function of the Distance Between a 9-in.-dia Stainless Steel Cylinder Containing an Enriched U$^{235}$ Solution and a 6-in.-thick Concrete Wall.
and firebrick as reflectors on the base of a 20"-diameter U\textsuperscript{235} solution cylinder are given by Figures 41 and 42.

The influence of a concrete wall about 8-1/2" from a vertical plane array of Oy-metal units appears in Figure 43 as a function of concrete thickness. Figure 44 shows the degree to which a concrete wall of various thicknesses isolates plane arrays of the Oy units 8-1/2" from each side of the wall. The ordinate is ratio of multiplication of the two arrays, with wall between, to that of a single array.
Critical Mass as a Function of the Thickness of Carbon on the Bottom of a 20-in.-dia Aluminum Cylinder Containing an Enriched $^{235}\text{U}$ Solution.
Critical Mass as a Function of the Thickness of Carbon and Firebrick on the Bottom of a 20-in.-dia Aluminum Cylinder Containing an Enriched $U^{235}$ Solution.
Fig. 44.

MULTIPLICATION RATIO OF ARRAYS

$3 \times 3$ - Unit Plane Arrays

\[
d = (17 + T) \text{ inches}
\]

$\Delta - S = 16^\circ$

Concrete Tamper

$\frac{M_{\text{double}}}{M_{\text{single}}}$

Concrete Thickness $T$ in inches

Legend:

- $O - S = 16^\circ$
- $\Delta - S = 24^\circ$
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51. H. R. Ralston, UCRL-5610, June 1959 (Classified).


58. A. D. Callihan, A Test of Neutron Multiplication by Slightly Enriched Uranium, Part II, ORNL-1698, March 1954.

