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Experimental Criticality Specifications

An Annotated Bibliography Through 1977

Compiled by

Hugh C. Paxton
EXPERIMENTAL CRITICALITY SPECIFICATIONS

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ABSTRACT

Literature references give sources of experimental nuclear criticality data that have relevance to criticality safety. Notes indicate principal fissile materials, diluents, and special geometries, but are not critical specifications.

INTRODUCTION

This compilation gives sources of experimental criticality parameters of systems containing $^{235}$U, $^{238}$U, and $^{239}$Pu. The intent is to cover basic data for criticality safety applications.

A reasonably complete bibliography of criticality data sources appeared in the 1964 publication, "Critical Dimensions of Systems Containing U$^{235}$, Pu$^{238}$, and U$^{239}$," the third item in this report. Since that time, there had been no generally available updating, although individuals have maintained files of the literature. The need for this new compilation became apparent during a comprehensive revision of "The Nuclear Safety Guide."

Not included in this listing are descriptions of computationally complex reactor systems, sub-critical data that do not extrapolate well to criticality, and information from periodic progress reports or ANS Transactions. Results of some early experiments that have been supplanted are included for historical interest.

Abbreviations are illustrated as follows. U(1.4) and U(93) mean uranium containing 1.4 wt% and 93 wt% $^{235}$U. U(nat) means natural uranium as usually encountered. C/U and H/$^{235}$U imply atomic ratios unless specified as volume or mass ratios. Stainless steel is represented by ss.

I. COMPILATIONS


Recapitulation of experimental subcritical and critical data for $^{238}$U and Pu metal and solutions, and $^{235}$U solutions.


Tabulation of nonreactor data with accuracy indexes, mostly solid configurations of $^{235}$U, Pu, $^{238}$U (D$_2$O, phosphate solutions).

Compilation of significant experimental data through 1963, some specifications transformed for uniformity of correlations.


Comprehensive review of experimental criticality data for Pu.


Comprehensive enriched-uranium data, sources for U^{233} and Pu.


Idealized summary of hydrogen-moderated U^{235}, U^{239}Pu, Pu systems; includes steel-water reflector, critical-mass reduction by distributing concentration.

II. SIMPLE UNITS

A. U(≥90)

1. Solutions, Slurries


U(93)O_2(NO_3)_2 solution, 22 to 380 g U/liter, in bare 300- and 800-mm-diam cylinders (incidental to excursion experiments).


U(93.2)O_2F_2 solution, H/^{238}U = 74 to 280, in bare 0.16- or 0.32-cm-wall ss cylinders; agreement with Oak Ridge.


U(93.2)O_2(NO_3)_2 solution, 505 g U/liter, 120.7-cm-square Plexiglas-reflected slab.


U(93)O_2(NO_3)_2 solution, 500 g U/liter, ~120-cm-square slab, bare and Plexiglas reflected.


ALECTO at Saclay: 25- to 42-cm-diam cylinders, ^{239}Pu, ^{235}U, ^{238}U-nitrate solutions, 15 to 18 g Pu/liter, 30 to 300 g ^{239}U/liter, 25 to 250 g ^{235}U/liter, bare, water reflector (see II.D.1 and II.G).

277 g U(90)/liter in 17-cm-diam cylinder with lateral and bottom water reflector, and in bare 24-cm-diam cylinder.


32 to 287 g U(90)/liter as parallelepipeds, bare, water, and water-steel reflected; also U(10), U(5) cylinders (see II.B.1 and II.C.1).


Saclay: solutions at 60 g Pu/liter and ~30 to 100 g ²³⁵U/liter as U(90) in bare 42-cm-diam cylinder and water-reflected 30-cm-diam cylinder, also spaced reflectors, interaction of two 10-cm-diam cylinders with one at 30-cm-diam; Dijon: Pu solution in 50-cm-o.d. by 30-cm-i.d. annulus, interaction of two annuli (see II.D.1 and IV.B).


U(93)O₂ZrO₂-paraffin compacts, H/²³⁵U = 229, parallelepipeds, bare and reflected with polyethylene and ZrO₂-paraffin; 0.0016-in.-thick U(93) foil in Zr and H₂O, range of metal/water, effect of elevated temperature (see II.A.3).


Limiting critical concentration of Pu(NO₃)₄ solution 8.0 g Pu/liter, of U(93)O₂F₂ solution 12.0 g ²³⁸U/liter, from PCTR measurements (see II.D.1).


U(93)O₂F₂ solution, H/²³⁵U = 293, 6-in.-thick by 48-in.-wide slabs.


H/U(93.5) = 198, 220, 248, 300, in 31.5-cm-diam cylinder with 9-cm-thick Fe reflector.


U(93)O₂F₂ solution, H/²³⁸U = 50.4 and 309, in 10- to 30-in.-o.d. annuli with Cd-lined interior filled with water.


U(93)O₂F₂ solution, H/²³⁵U = 44.7 and 51.5, 2.0- to 2.12-in.-thick by 58.5-in.-wide slabs, water reflected.


U(93.2)O₂F₂ solution, H/²³⁵U = 27 to 75; interaction of three and seven 6- and 8-in.-diam cylinders in air and water; individual 6- to 30-in.-diam cylinders and 9-in.-diam sphere, bare, water reflected; 8- to 20-in.-o.d. annuli; also "Y" and "cross," and comparison of furfural, concrete, graphite, firebrick reflectors with water (see IV.A.1).


²³³U and ²³⁵U as uranyl fluoride solutions, H/²³⁵U ~380 and 600, H/²³³U ~240 and 460, 26.4- and 32.0-cm-diam spheres in water (see II.G).

U\(_{(93.2)}\)O\(_4\)(NO\(_3\))\(_2\) solution, H\(^{235}\)U = 1600 to 1800, 36-in.-diam cylinder, bare, and with 8-in.-thick water radially.


U\(_{(93.2)}\)O\(_4\)-H\(_2\)O slurries, w\(^{235}\)U = 90 to 668, 12-in.-diam cylinder in water (hemisphere bottom), critical height vs H/W same as for solution.


U\(_{(93.3)}\)O\(_4\)(NO\(_3\))\(_2\) solution, H\(^{235}\)U = 62 to 733, N\(^{235}\)U = 2.9, 5.4, 7.5, P\(^{239}\)U = 0, 15.8, 53, 8- or 10-in.-diam cylinders with 15-in.-o.d. reflectors of water, UO\(_4\)(NO\(_3\))\(_2\) solution, bismuth subcarbonate, phosphoric acid, and various thicknesses of steel; also 1-in.-diam tubes of P and Bi latticed in bare 15-in.-diam cylinder (as in Pu processes).


U\(_{(93.3)}\)O\(_4\)F\(_2\) solution, H\(^{235}\)U = 32 to 999, 6.5- to 15-in.-diam cylinders, bare, water reflected.

2. Poisoned Solutions


U\(_{(93.2)}\)O\(_4\)(NO\(_3\))\(_2\), 52.2 to 451 g U/liter, in bare 107-cm-diam tank containing 0.26-cm-thick ss plates with 1 wt% B at various spacings.


U\(_{(93.2)}\)O\(_4\)(NO\(_3\))\(_2\) solution, H\(^{235}\)U = 51, in bare 107-cm-diam tank unpoisoned, and containing distributed 0.25-cm-thick plates with 1 wt% B.


U\(_{(92.6)}\)O\(_4\)(NO\(_3\))\(_2\) solution, 63 to 415 g U/liter, critical solution a source for solution-glass exponentials, glass rings from 0.5 to 5.7 wt% B; typical conclusion: k\(_{\text{eff}}\) < 1 if >22 vol% of glass with 4 wt% B.

3. Hydrogenous Compacts, Mixtures


6-cm-diam spheres at C\(^{235}\)U = 7550 in 150-cm-diam cylinder, polyethylene to simulate 0 to 14.4% water, pulsed-neutron measurements give k\(_{\text{eff}}\) = 0.69 to 0.89.


U\(_{(93)}\)F\(_6\)-HF, H/U = 0 to 80, 400-, 450-, 510-, 540-mm-diam spheres, water reflected.


U\(_{(93)}\) slabs, 12.7 by 25.4 cm and 25.4-cm-square, solid and interleaved in thicknesses of 0.12 to 1.4 cm, bare and polyethylene reflected: max. H/U = 5 for U-polyethylene; U-Plexiglas and U-Teflon only 25.4 cm square, unreflected (see II.A.6 and II.A.7).

U(93)-polyethylene, 0.0012-in.-thick U, reflected by ~12-in. Be (min. critical mass 290 g 235U).


U(93)O2-ZrO2-paraffin compacts, H/235U = 229, parallelepipeds, bare and reflected with polyethylene and ZrO2-paraffin; 0.0016-in.-thick U(93) foil in Zr and H2O, range of metal/water, effect of elevated temperature (see II.A.1).


U(93)-ss-graphite at C/235U = 7.8 or 10.7, U(93)-ss-graphite-polyethylene at C/235U = 4.4 to 6.3 and H/235U = 1.0, U(32)-ss-graphite at C/235U = 5.8, U(32)-ss-graphite-polyethylene at C/235U = 6.3 and H/235U = 1.0, Pu-Cu-ss-graphite at C/Pu = 3.0 to 6.0; each in thick U(nat)-ss (see II.A.4, II.B.1, II.B.2, and II.D.3).


BeO-Plexiglas-235U foil cores (15-in.-long by 9.4- to 12.6-in.-diam), H/235U = 229 to 422, Be/235U = 95 to 219, ~12-in.-thick Be inner reflector, 19-in.-thick Plexiglas outer reflector (see II.A.4).


Pseudospheres of 0.5-in.-min compacts approximating U(93)H2C in 8-in. U(nat), Ni, or Ni in U(nat); also LA-1159, May 22, 1950.


C. E.: 0.002-in. U(93.15) foil with polyethylene, B, Al, Zr at H/235U = 25 to 280, B/235U = 0 to 0.27, 14 by 14 by 21-in. core, polyethylene reflector (KAPL 235U-polyethylene-Al assemblies incompletely described).


238U metal in thick U(nat) at 100%, 70%, 50% of full density and 235U enrichment; 239U metal in thick Ni; ~UH4C in thick Ni; better specifications published later; also LA-1251, May 1, 1951 (see II.A.7 and II.B.2).


U(93.4) as ~0.005-in.-thick turnings in water, H/235U = 60, 80, 120, one to six 8- or 10-in.-diam cylinders in water; critical mass ~18% above that of corresponding solution (see IV.A.1).


0.5-in. cubes of U(94.5) and polyethylene to average UH4.5C1.5, pseudosphere in 8-in. U(nat).


1-in. cubic U(95)CF3 and polyethylene parallelepipeds averaging H/235U = 5, 10, 20, thick paraffin reflector.

4. Nonhydrogenous Moderators

0.005- and 0.010-in-thick U foil interleaved with graphite, bare 122-cm cube.


1/8-in.-thick U(93) interleaved with U(O.21), BeO, Al, Be/\(^{238}\)U = 9.6, reflected by 14-in. Fe in 6-in. U(0.21).


0.015-in.-thick 14 wt% U(93.15)-Al interleaved with graphite, C/\(^{238}\)U = 960 to 2.3 x 10\(^{4}\), parallelepipeds, minimal reflection.


U(11)-Al-Fe, U(16)-W-Al-Fe at \(W/\(^{238}\)U = 2.7\), U(21)-W-Al-Fe at \(W/\(^{238}\)U = 4.8\), U(93)-W-Al-Fe at \(W/\(^{238}\)U = 5.9\), U(93)-W-Al-Fe at \(W/\(^{238}\)U = 4.8\) and C/\(^{238}\)U = 0 or 6.8, each in thick Al; U(93)-W-Al-Fe at \(W/\(^{238}\)U = 4.8\) and O/\(^{238}\)U = 0 or 2.0, in various combinations of Al, Al\(_2\)O\(_3\) and BeO (see II.A.6 and II.B.2).


0.05-cm-thick Teflon-U\(_3\)O\(_8\) interleaved with Be, Be/\(^{238}\)U = 1165, 1745, 3481, essentially unreflected.


0.2-in.-thick Pu-Al at Al/Pu = 120, interleaved with graphite, C/\(^{238}\)Pu = 2420 to 14520; also U(93) with graphite, C/\(^{238}\)U = 3490, Al/\(^{238}\)U = 41; buckling to \(\sim 0.3\%\) (see II.D.3).


\(^{238}\)U\(_3\)O\(_6\)-ThO\(_2\)-graphite compacts in graphite, C/\(^{238}\)U = 2775, Th/\(^{238}\)U = 12, graphite reflector.


0.001-, 0.002-in.-thick U(93.2), 0.002-in.-thick Th, mostly bare 48-in.-square by 40- to 52-in.-high cores, C/\(^{238}\)U = 599 and C/Th = 908 (or 0), C/\(^{238}\)U = 1151 and C/Th = 901 (or 0), C/\(^{238}\)U = 2285 and C/Th = 1820 (or 0).


Pu metal spheres, bare, and in U(nat), Fe, C; U(45.5) metal slabs, 11.6-, 16.9-, 22.1-in.-diam, bare, and in U(nat), C, steel, Al; U(92.9)-graphite core at C/Pu = 7.8, 27-cm diam by 38-cm high, U(nat) reflector (see II.B.2 and II.D.4).


U(93)-ss-graphite at C/\(^{238}\)U = 7.8 or 10.7, U(93)-ss-graphite-polyethylene at C/\(^{238}\)U = 4.4 to 6.3 and H/\(^{238}\)U = 1.0, U(32)-ss-graphite at C/\(^{238}\)U = 5.8, U(32)-ss-graphite-polyethylene at C/\(^{238}\)U = 6.3 and H/\(^{238}\)U = 1.0, Pu-Cu-ss-graphite at C/Pu = 3.0 to 6.0; each in thick U(nat)-ss (see II.A.3, II.B.1, II.B.2, and II.D.3).

BeO-Plexiglas-$^{238}\text{U}$ foil cores 15-in. long by 9.4- to 12.6-in. diam, $H/^{238}\text{U} = 229$ to 422, $\text{Be}/^{238}\text{U} = 95$ to 219, $\geq 12$-in.-thick Be inner reflector, 19-in.-thick Plexiglas outer reflector (see II.A.3).


0.001- and 0.002-in.-thick U(93.2) interleaved with BeO, $\text{Be}/^{238}\text{U} = 247$ to 7660, bare parallel-epipeds; also UCRL-5369, Pt I, July 1, 1959.


0.01-in.-thick U(93.4) interleaved with Be, bare 21.0 by 21.0 by 23.3 in. at Be$^{238}\text{U} = 390$, 24.0 by 24.1 by 28.4 in. at Be$^{238}\text{U} = 1560$.


0.001- or 0.002-in.-thick U(93.5) interleaved with graphite, C/U = 991, bare 51 by 51 by 44 in.


0.002- or 0.005-in.-thick U(93.2) interleaved with graphite, pseudocylinders, C/U = 116 to 952 in ~13-cm Be, C/U ~350 in ~20-cm Be.


$\text{UO}_2\text{F}_2$ solution, $D^{238}\text{U} = 34$ to 430, as 13.5- to 18.5-in.-diam spheres in 35-in.-o.d. $\text{D}_2\text{O}$; $D^{238}\text{U} = 230$ to 2080 as bare 25- and 35-in.-diam cylinders.


Interleaved 10.5-in.-diam U(93) and graphite plates in 2-in. graphite, 0.32-, 0.63-, 0.94-in.-thick U, 0-, 0.5-, 1.0-, 2.0-in.-thick graphite.


0.01-in.-thick U(93) interleaved with graphite, C/U = 991, bare 51 by 51 by 44 in.

5. Reflector Moderators


U(93) foil and U(93)-graphite elements in 1-m-diam by 1-m-high cavity in 0.49-m-thick $\text{D}_2\text{O}$, also in 0.39-m-diam by 0.79-m-high cavity in 0.36- to 0.47-m-thick Be.


U(93.2)F$_4$ in 63-cm-diam sphere, 91-cm-i.d., 96.6-cm-thick $\text{D}_2\text{O}$; in shell, only Al, Al-polystyrene-polyethylene, Al-ss.


0.001-in.-thick U(93.2) distributed in 6-ft-diam by 4-ft-long cavity in ~3-ft-thick $\text{D}_2\text{O}$, with variations.


16.2 wt% U(93.2)F$_4$, 55.0% ZrO$_2$, 19.9% NaF-8.8% C-0.25% H$_2$ mixture as 1.25- to 3.75-in. annulus about ~6- to 9-in.-diam Be, reflector ~12-in.-thick Be in 6-ft-thick graphite.
6. Unmoderated Compounds, Mixtures


U(93) slabs, 12.7- by 25.4-cm and 25.4-cm-square, solid and interleaved in thicknesses of 0.12 to 1.4 cm, bare and polyethylene reflected: max. H/U = 5 for U-polyethylene; U-Plexiglas and U-Teflon only 25.4-cm square, unreflected (see II.A.3 and II.A.7).


Recapitulation of data, corrections to homogeneous spheres (see II.B.2).


1.14-cm-diam U(93.2)O2 in 0.05-cm-thick ss, distributed in 26-cm-diam by 31-cm-high core, 7- to 11-cm-thick Be reflector.


Recapitulation of data, corrections to homogeneous spheres (see II.B.2).


4.4 vol% U(93), 50% ss, 4.1% O, 36% Na; 58.9% U(16), 12.7% ss; 80.5% U(9.4), 9.3% ss; 14.9% U(39), 23% Al, 24% ss; 35.1% U(17), 18% Al, 14% ss; 25.2% U(19), 18% C, 17% ss, 36% Na; each in thick 83.3% U(0.23), 7.3% ss; also the ZPR-III data reported by Long et al. (see II.B.2 and II.C.2).
37% C; 30 vol% U(30), 9% ss, 53% C; 10 vol% U(93), 9% ss, 74% C; each in thick U(0.23) with 2% Al, 7% ss (see II.B.2).


14.75-in.-square by 0.105-in.-thick U(93) interleaved in various combinations with 30% Li\textsubscript{2}CO\textsubscript{3}-5% Na\textsubscript{2}CO\textsubscript{3}-65% K\textsubscript{2}CO\textsubscript{3}, solid U(93) plate, both reflected by the same salt.

7. Metal


Benchmark assemblies: bare spheres of U(94), 3\textsuperscript{235}U, Pu-U(93); U(93) spheres in thick U(nat); α-Pu sphere in water; bare cylinders of Av. U(53.3), U(37.5), U(16.0), U(14.1), U(12.3), U(10.9); Av. U(16.2) cylinder in 3-in.-thick U(nat) (see II.B.2, II.D.4, II.F, and II.G).


U(93) slabs, 12.7 by 25.4 cm and 25.4 cm square, solid and interleaved in thicknesses of 0.12 to 1.4 cm, bare and polyethylene reflected: max. H/U = 5 for U-polyethylene; U-Plexiglas and U-Teflon only 25.4 cm square, unreflected (see II.A.3 and II.A.6).


U(93) hemispheres, spherical shells with combinations of air and steel inside and outside.


U(93) spheres, polyethylene in 0-, 4-, 8-, 12-in.-i.d. cavities, immersed in oil.


15- and 21-in.-diam U(93) cylinders, bare, and reflected top and bottom with 2- to 10-in.
polyethylene, 6-in. water, Plexiglas, and paraffin, and 6- to 14-in.-graphite.


U(93.18) sphere in 2.6-in.-thick Al, δ-Pu sphere in 3.1-in.-thick Al (see II.D.4).


5- by 5-in. to 25- by 25-in. U(93) slabs with Plexiglas, Be, graphite reflectors.


15-in.-diam U(93.2) cylinders reflected on one or both ends by multiple layers of two or three of Cu, Fe, Zn, Ni, ss.


5.25-in.-diam U(93.5) cylinders in 0.5- and 1.0-in. Be, graphite, Mg, Ti, steel, Cu, W alloy, U(nat), Ni, Co, Mo, Al₂O₃, Mo₂C, polyethylene; U(93.5) spheres in ~2- and ~4-in. Be, BeO, C, Fe, Ni, Cu, Zn, nickel silver, W alloy, Th, U(nat).


U(93.2) spheres in 17- and 9-cm-thick Pb, 9.88- and 11.17-cm-diam cylinders in 13-cm-thick Pb.


δ-Pu spheres, bare and U(nat) reflector; U(94) spheres, bare and U(nat) reflector; Av. U(53.5), U(37.5), U(29) bare cylinders; Av. U(16.2) cylinder, U reflector (see II.B.2 and II.D.4).


U(93) in 0.88-, 1.28-, 2.14-, 3.65-, 7.98-in.-thick Be.


0.5-, 1.0-in. cubes, 1/8-in.-diam rods of U(94) at various spacings; single water-reflected cube (see III.A.1).


Lady Godiva, a bare metal sphere, better specifications published later; also LA-1614, September 1953.


²₃⁵U metal in thick U(nat) at 100%, 70%, 50% of full density and ²₃⁵U enrichment; ²₃⁵U metal in thick Ni; ~UH₄C in thick Ni; better specifications published later; also LA-1251, May 1, 1951 (see II.A.3 and II.B.2).


1.5-in.-thick circular U(~94) plate in thick paraffin, U(93.9) spheres in 2- to 17-in.-thick graphite.
8. Metal with Solution


U(93.16) metal in solution at ~11, 22, 96 g $^{235}$U/liter; displacements up to ~0.85 half-height.

B. U(10 to 90)

1. Solutions (H$_2$O and D$_2$O), Hydrogenous Mixtures

the Zero-energy Fast Reactor FRO," Fast Critical
Experiments and Their Analysis, Proc. Argonne
Intern. Conf., October 10-13, 1966, Argonne
National Laboratory report ANL-7320, pp. 159-185.

U(20)-ss, U(20)-ss-graphite at C/\textsuperscript{29}U = 4.3,
U(20)-ss-graphite-polyethylene at C/\textsuperscript{29}U = 5.6 and
H/\textsuperscript{28}U = 1.2, each in 35-cm-thick Cu-ss; U(20)-ss in
\~12-cm-thick U(nat) (see II.B.2).

R. C. Lane, "Measurements of the Critical
Parameters of Under-Moderated Uranium-
Hydrogen Mixtures at Intermediate Enrichments," Criticality
177-190.

U(30.14)O\textsubscript{2}-wax, H/\textsuperscript{28}U = 8 to 80, bare, reflectors
of Perspex, polyethylene, beech with and
without Cd, concrete with and without Cd; U(37.67)
metal, reflectors of polyethylene, beech with and
without Cd (see II.B.2).

B. G. Dubovsky, A. V. Kamaev, V. V. Orlov, G.
M. Vladykov, V. N. Gurin, F. M. Kuznetsov, V.
P. Kochergin, I. P. Markelov, G. A. Popov, and
V. J. Swiridenko, "The Critical Parameters of
Aqueous Solutions of UO\textsubscript{2}(NO\textsubscript{3})\textsubscript{2} and Nuclear

32 to 287 g U(90)/liter as parallelepipeds, bare,
water, and water-steel reflected; also U(10), U(5)
cylinders (see II.A.1 and II.C.1).

J. W. Weale, M. H. McTaggart, H. Goodfellow,
and W. J. Paterson, "Operation Experience with
the Zero-Energy Fast Reactor Vera," Exponential

U(93)-ss-graphite at C/\textsuperscript{23}U = 7.8 or 10.7, U(93)-
ss-graphite-polyethylene at C/\textsuperscript{23}U = 4.4 to 6.3 and
H/\textsuperscript{1}H = 1.0, U(32)-ss-graphite at C/\textsuperscript{23}U = 5.8,
U(32)-ss-graphite-polyethylene at C/\textsuperscript{23}U = 6.3 and
H/\textsuperscript{1}H = 1.0, Pu-Cu-ss-graphite at C/Pu = 3.0 to
6.0; each in thick U(nat)-ss (see II.A.3, II.A.4, II.B.2,
and II.D.3).

A. F. Thomas, "Interim Note on Critical Mass
Measurements with 30% Enriched Uranium/
Hydrogen Mixtures at Low H:U Ratios," United
Kingdom Atomic Energy Authority report SNA/
NM/A/13/61 (October 3, 1961).

Near-cubic U(30)O\textsubscript{2}-paraffin, H/\textsuperscript{28}U = 40
(bare), 8.3, 16.5 reflected by Perspex, polyethylene.

J. R. Harrison, M. F. Smith, W. G. Clarke, A.
M. Mills, and J. A. Dyson, "Critical Assemblies
with Heavy Water Solutions of Uranyl Fluoride
(H.A.Z.E.L.), Part II Physics," United Kingdom
Atomic Energy Authority report AERE R/R 2703
(November 1958).

U(45.5)O\textsubscript{2}F\textsubscript{2}-D\textsubscript{2}O solution, 2-ft-diam tank in 18-
in. lateral graphite, D/\textsuperscript{1}H = 1940 to 6720.

W. G. Clarke, C. C. Horton, and M. F. Smith,
"Critical Assemblies of Aqueous Uranyl Fluoride
Solutions, Part I, Experimental Techniques," U-
ited Kingdom Atomic Energy Authority report
AERE R/R 2051 (September 20, 1956).

U(44.6) or \textsuperscript{235}U as UO\textsubscript{2}F\textsubscript{2} solutions, 12-in.-diam
cylinder, bare and thick lateral water reflector,
H/\textsuperscript{1}H or \textsuperscript{235}U = 250 to 850 (see II.G).

C. K. Beck, A. D. Callihan, and R. L. Murray,
"Critical Mass Studies, Part II," Oak Ridge Gaseous

1-in. cubes of 64.8 wt% U(29.8), 31.1% F, 3.3%
C, 0.1% O, 0.7% Al interspersed with 0.5- or 1.0-in.
polyethylene, Av. H/\textsuperscript{1}H = 8 to 224, bare and paraf-
fin reflected; effects of inhomogeneity, shape, core
density.

C. P. Baker and M. G. Holloway, "Critical Mas-
ses of Enriched Uranium Hydrides and Some
Related Measurements," Los Alamos Scientific
Laboratory report IA-618 (February 3, 1947).

U(\~75) H\textsubscript{2}C\textsubscript{2} blocks (0.5-in. min), undiluted
cube or pseudosphere, bare, and in 6- and 12-in.
BeO, 6.5-in. U(nat), 4.5-in. WC, 6.5-in. Fe, also
some cores diluted with polyethylene.

A. H. Snell, "Critical Experiments of Fluorinated
and Hydrogenated Mixtures Containing Enriched
Uranium," Clinton Laboratories report MonP-48
(February 22, 1946).

1-in. cubes of U(24)O\textsubscript{2}C\textsubscript{4}F\textsubscript{4}A\textsubscript{14} inter-
spersed and reflected with polyethylene (6-in. refl) at Av. H/\textsuperscript{1}H = 30.9, 15.1, 11, 7.5.

U(14.7)O$_{30}$ solution at H/U = 632 in 15-liter sphere, 12-in.-thick BeO reflector.


U(14.7)O$_{30}$ solution in 15-liter sphere, 38 g U/liter in 12-in. BeO reflector, 51 g U/liter in graphite.

2. Metal, Nonhydrogenous Mixtures


75.7-cm-diam by 70.1-cm-high core, 0.90 g PuO$_2$/cm$^3$, 6.64 g U(1.8)O$_2$/cm$^3$, 0.05 g Al/cm$^3$, 1.31 g ss/cm$^3$; 57.3-cm-diam by 44.0-cm-high core (two zone), ~1.2 g PuO$_2$/cm$^3$, ~3.6 g UO$_2$/cm$^3$, ~0.5 g C/cm$^3$, ~1.1 g ss/cm$^3$; 72.4-cm-diam by 60.0-cm-high core (two zone), ~0.9 g PuO$_2$/cm$^3$, ~2.8 g UO$_2$/cm$^3$, ~0.3 g Na/cm$^3$, ~1.4 g ss/cm$^3$; 75.2-cm-diam by 60.0-cm-high core (two zone), ~4.3 g (U+UO$_2$)/cm$^3$ [U(30.2)], ~0.06 g C/cm$^3$, ~0.3 g Na/cm$^3$, ~1.5 g ss/cm$^3$; all in 30-cm-thick reflector, 15.8 g U(0.4)/cm$^3$, 0.57 g ss/cm$^3$ (see II.E).


ZPR-6: 6-4000-liter core of U(16.5)O$_2$-Na-ss in ~30-cm-thick U(0.2)-ss. ZPR-6: 7-3100-liter PuO$_2$-U(0.2)O$_2$-Na-ss at U/Pu = 5.7, in 34-cm-thick U(0.2)-ss. ZPR-2,3 with two-zone PuO$_2$-UO$_2$ cores also described (see II.D.3).


Benchmark assemblies: bare spheres of U(94), δ-Pu, $^{238}$U, Pu-U(93), $^{238}$U-U(93); U(93), δ-Pu, $^{238}$U spheres in thick U(nat); δ-Pu sphere in water; bare cylinders of Av. U(53.3), U(37.5), U(16.0), U(14.1), U(12.3), U(10.9); Av. U(16.2) cylinder in 3-in.-thick U(nat) (see II.A.7, II.D.4, II.F, and II.G).


Interleaved 21-in.-diam plates of U(93.3) and U(nat), bare, averaging U(10.9), U(12.3), U(14.1), U(16.0).


U(13)-Na-ss-graphite at C/$^{235}$U = 8.4, in 30-cm-thick U(0.2)-ss.


U(11)-Al-Fe, U(16)-W-Al-Fe at W/$^{235}$U = 2.7, U(21)-W-Al-Fe at W/$^{235}$U = 4.8, U(93)-W-Al-Fe at W/$^{235}$U = 5.9, U(93)-W-Al-Fe at W/$^{235}$U = 4.8 and C/$^{235}$U = 0 or 6.6, each in thick Al; U(93)-W-Al-Fe at W/$^{235}$U = 4.8 and O/$^{235}$U = 0 or 2.0, in various combinations of Al, Al$_2$O$_3$, and BeO (see II.A.4 and II.A.6).


Critical thicknesses of 20-cm-square metal plates reflected by 20-cm-thick concrete and wood, with and without Cd, and polyethylene (also 15-cm and 30-cm square).


4.4 vol% U(93), 50% ss, 4.1% O, 36% Na; 58.9% U(16), 12.7% ss; 80.5% U(9.4), 9.3% ss; 14.9% U(39), 23% Al, 24% ss; 35.1% U(17), 18% Al, 14% ss; 25.2% U(19), 18% C, 17% ss, 36% Na; each in thick U(0.23), 7.3% ss; also the ZPR-III data reported by Long et al. (see II.A.6 and II.C.2).


~10 vol% U(93), 42.8% Al, 9.3% ss, or 74.5% C, 9.3% ss, or 81.0% ss, or 63.6% Na, 18.2% Na; ~80 vol% U(11.9, 9.4, 8.8), 9.3% ss; ~15 vol% U(31.2, 39.5), ~24% Al, 24.6% ss, 14.5 or 7.2% O; 15 vol% U(39), 23.5% Al, 24.5% ss; 15 vol% U(31.2), 25.5% Al, 10.6% C, 24.6% ss; each in thick U(0.23) with 2% Al, 7% ss (see II.A.6 and II.C.2).


Pu metal spheres, bare, and in U(nat), Fe, C; U(45.5) metal slabs, 11.6-, 16.9-, 22.1-in.-diam, bare, and in U(nat), C, steel, Al; U(92.9)-graphite core at \( C^{26}U = 7.8 \), 27-cm-diam by 38-cm-high, U(nat) reflector (see II.A.4 and II.D.4).


~30 vol% U(47), 31% Al, 12% ss; ~50 vol% U(23), 22% Al, 14% ss; 15 vol% U(93), 31% Al, 28% ss; 70 vol% U(17), 19% ss; 81 vol% U(11.5), 9% ss; 60 vol% U(16), 9% ss, 21% C; 45 vol% U(21), 9% ss, 37% C; 30 vol% U(30), 9% ss, 53% C; 10 vol% U(93), 9% ss, 74% C; each in thick U(0.23) with 2% Al, 7% ss (see II.A.6).


δ-Pu spheres, bare and U(nat) reflector; U(94) spheres, bare and U(nat) reflector; Av. U(53.5), U(37.5), U(29) bare cylinders; Av. U(16.2) cylinder, U reflector (see II.A.7 and II.D.4).


Interleaved 15-in.-diam plates of U(93) and U(nat) in 3-in.-thick U(nat).


EBR-II mockup: U(47), Al, ss, parallelepiped in U(depleted), Al, ss.


\( U^{238} \) metal in thick U(nat) at 100%, 70%, 50% of full density and \( U^{238} \) enrichment; \( U^{238} \) metal in thick Ni; ~UH₃C in thick Ni; better specifications published later; also LA-1251, May 1, 1951 (see II.A.3 and II.A.7).


Av. ~35 vol% U(12.8), U(16.7), U(24.2), 10.4% Fe, 30, 15, 0% Al.


10.5-in.-diam plates of U(93.4), 8-mm-thick, and U(nat), 6-mm-thick, interleaved to average U(53.5), U(37.5), U(29).

C. U(<10)

1. Solutions, Hydrogenous Mixtures


\( UO_2F_2 \) solution at 745 to 911 g U/liter, 11-in. 30° intersection, 12.75-in. cross, water reflected.


U(2 or 3)F₃-paraffin compacts, H/\( U^{238} \) from 133 to 972, parallelepipeds bare and reflected with Plexiglas, paraffin, or polyethylene.


PCTR measurements on crystalline U(2.14 or 2.26)\( O_2(NO_3)_2 \) compacts, H/\( U^{238} \) from 3 to 12, give min. critical enrichment 2.10 wt% \( U^{238} \).

U(4.98)O$_2$F$_2$ solution at H/$^{238}$U = 496, bare 39.1-cm-diam cylinder, $h_\infty = 101.7$ cm.


32 to 287 g U(90)/liter as parallelepipeds, bare, water, and water-steel reflected; also U(10), U(5) cylinders (see II.A.1 and II.B.1).


$k_\infty = 1.2$ for 92.1 wt% U(2)F$_2$, 7.9 wt% paraffin, measured in PCTR.

V. I. Neeley, J. A. Berberet, and R. H. Masterson, "k$\infty$ of Three Weight Per Cent U$^{235}$ Enriched UO$_2$ and UO$_2$(NO$_3$)$_2$, Hydrogenous Systems," Hanford Atomic Products Operation report HW-66882 (September 1961).

PCTR gives $k_\infty = 1$ at H/U = 45 for U(3.04)O$_3$, H/U = 31 for U(3.04)O$_4$(NO$_3$)$_2$.


U(1.01), U(1.07), U(1.16) at H/U = 3.5 to 7.5.


$k_\infty = 1.20$ from U(2)F$_2$-paraffin assembly, 1.22 from PCTR.

A. Wattenberg, "Exponential Experiments with D$_2$O and Solutions of UO$_2$F$_2$," Clinton Laboratories report CP-3364 (November 1, 1945).

U(nat)O$_2$F$_2$-D$_2$O (99.8%) solution, 0.024 to 0.35 g UO$_2$F$_2$/liter, min. $m_\infty$(bare) ~3,000 kg U.

2. Metal, Nonhydrogenous Mixtures


Interleaved 15-in.-diam plates of U(93.3) and U(nat), bare, to average U(4.3), U(6.5), U(9.1); indicates $k_\infty = 1$ for U(5.3).


32 to 287 g U(90)/liter as parallelepipeds, bare, water, and water-steel reflected; also U(10), U(5) cylinders (see II.A.1 and II.B.1).


4.4 vol% U(93), 50% ss, 4.1% O, 36% Na; 58.9% U(16), 12.7% ss; 80.5% U(9.4), 9.3% ss; 14.9% U(39), 23% Al, 24% ss; 35.1% U(17), 18% Al, 14% ss; 25.2% U(19), 18% C, 17% ss, 36% Na; each in thick 83.3% U(0.23), 7.3% ss, also the ZPR-III data reported by Long et al. (see II.A.6 and II.B.2).

10 vol% U(93), 42.8% Al, 9.3% ss, or 74.5% C, 9.3% ss, or 81.0% ss, 18.2% Na; ~80 vol% U(11.9, 9.4, 8.8), 9.3% ss; ~24 vol% U(31.2, 39.5), 24.6% ss, 14.5 or 7.2% O; 15 vol% U(39), 23.5% Al, 24.5% ss, 12.5% Al, 10.6% C, 24.6% ss; each in thick U(0.23) with 2% Al, 7% ss (see II.A.6 and II.B.2).


Interleaved 15-in.-diam plates of U(93) and U(nat) in 3-in.-radial U(nat), to average U(0.72), U(4.29), U(5.14), U(6.53), U(9.18); indicates k = 1 for U(5.4).

D. Pu

1. Solutions, Hydrogenous Compacts, Mixtures


PCTR data now lead to minimum critical concentration of 7.2 g 239Pu/liter.


Pu(41% 239Pu) solution, 40 to 140 g Pu/liter, in 61-cm-diam cylinder with partial water reflector.


58 to 412 g Pu (4.6, 18.4, 23.2 wt% 240Pu)/liter, acid molarity from 1.6 to 5.0; 42-in.-square slabs from 3- to 9-in. thick, 0.062-in.-ss wall, internal ss "egg-crate," bare, thick water, 1-in. Plexiglas reflectors.


18.5% 240Pu, parallelepipeds, near-equilateral bare, squat Plexiglas reflected.


Experimental slab data for Pu(NO3)4 solutions at 58, 202, 284 g Pu/liter, adjusted to infinite bare and water-reflected slabs.


Bare and Plexiglas-reflected parallelepipeds, near-equilateral and squat.


Pu(NO3)4 solutions, 24 to 435 g Pu/liter, in 11.5-, 14-, 15.2-in.-diam spheres, water, paraffin, ss, concrete reflectors (one bare), effect of spaced concrete.


ALECTO at Saclay: 25- to 42-cm-diam cylinders, 239Pu-, 235U-, 232U-nitrate solutions, 15 to 18 g Pu/liter, 30 to 300 g 235U/liter, 25 to 250 g 232U/liter, bare, water reflector (see II.A.1 and II.G).


Valduc results: Pu solutions, 20 to 190 g Pu/liter, 30-cm-diam cylinder; 150-cm by 120-cm by 10-cm-thick slab; 50-cm-o.d. by 35-cm-i.d., 50-cm-o.d. by 30-cm-i.d., 50-cm-o.d. by 20-cm-i.d. annuli; two interacting 50-cm-o.d. by 30-cm-i.d. annuli; reflectors various combinations of air, water, with and without Cd (see IV.B).

Plexiglas-reflected shapes from columns to slabs (2.2 and 8.0% 240Pu).


Saclay: solutions at 60 g Pu/liter and ~30 to 100 g 239U/liter as U(90) in bare 42-cm-diam cylinder and water-reflected 30-cm-diam cylinder; also spaced reflectors, interaction of two 10-cm-diam cylinders with one at 30-cm-diam; Dijon: Pu solution in 50-cm-o.d. by 30-cm-i.d. annulus, interaction of two annuli (see II.A.1 and IV.B).


Limiting critical concentration of Pu(NO₃)₄ solution 8.0 g Pu/liter, of U(93)O₂F₂ solution 12.0 g ²³⁵U/liter, from PCTR measurements (see II.A.1).


Pu(NO₃)₄ solutions at 23.5 to 45.5 g Pu/liter, lateral and bottom reflector of thick water.


12.5- or 18.0-in.-diam δ-Pu disks, 0.024- to 0.120-in.-thick, interleaved with Plexiglas at H/Pu = 18 to 94, bare and Plexiglas reflected.


Interleaved 12.5-in.-diam disks of δ-Pu and Plexiglas, 0.632-in-thick Pu, 0.115-in.-thick Plexiglas, bare (other assemblies too subcritical).


Pu sulphate solution ~30 g Pu/liter, 25-cm-diam by 30-cm-high tank in 27.5-cm BeO surrounded by 50-cm graphite.


Pu nitrate solutions at H/Pu = 397, 655, 892, in 30.5-cm-diam tank, lateral water reflector with and without Cd.


485 g ²³⁹Pu as 11.35 liters of Pu(NO₃)₄ solution in glass-Plexiglas containers, subcritical in water, critical with ~2-in. layer of BeO blocks in the water.

2. Poisoned Solutions, Mixtures


Glass rings with 0.5 or 4.0 wt% B, ss rings with 1 wt% B, in solutions from 63 to 412 g Pu/liter.

24-in.-diam water-reflected cylinder, 116 and 363 g Pu/liter, ≤20 g Gad/liter.


30-, 40-mm-o.d. tubes, 30-mm-o.d. rings of 2-, 2.5-mm-thick borosilicate glass, in Pu nitrate solutions at 99 to 356 g Pu/liter.


12.5-in.-diam by 0.058-in.-thick, 18.0-in.-diam by 0.016-in.-thick 8-Pu interleaved with Plexiglas and B-plastic, H/Pu = 13 to 99, B/Pu = 0.021, 0.18, 0.36 (no precision index).

3. Nonhydrogenous Mixtures

P. I. Amundson, E. F. Bennett, S. G. Carpen-

ZPR-6-6:4000-liter core of U(16.5)O₂-Na-ss in ~30-cm-thick U(0.2)-ss. ZPR-6-7:3100-liter PuO₂- U(0.2)O₂-Na-ss at U/Pu = 5.7, in 34-cm-thick U(0.2)-ss. ZPR-2,3 with two-zone PuO₂-UO₂ cores also described (see II.B.2).


~26-, 31-, 41-cm-square slabs of Pu(18%
²⁴⁰Pu)O₂ at H/Pu = 0.04, bare, Plexiglas reflector.


Pu-graphite-Al-ss at C/Pu = 26.7, in thick U(0.22)-ss or thick Pb-ss.


Pu-U(nat)-graphite-Al-ss-Cu-Na or void at C/Pu = 14.5 and U/Pu = 1.6, in thick U(nat)-graphite-ss at C/U = 0.9.


Pu-U(0.21)-graphite-Na-ss at C/Pu = 11.8 and U/Pu = 4.2 in ~12-in.-thick U(0.21)-ss.


Pu-Cu-Ni-graphite at C/Pu = 0, 2.0, 4.0, 8.1, 12.2, 16.2, 24.0, 33, 64, 200, and 400, in thick graphite; U(12)-ss, U(14)-ss-graphite at C²³⁵U = 15.8, Pu-U(nat)-Cu-ss at U/Pu = 8.4, each in thick
U(nat)-ss; also the VERA data reported by Weale et al. (see II.B.2).


0.2-in.-thick Pu-Al at Al/Pu = 120, interleaved with graphite, C/\(^{239}\)Pu = 2420 to 14520; also U(93) with graphite, C/\(^{239}\)U = 3490, Al/\(^{239}\)U = 41; buckling to \(\sim 0.3\%\) (see II.A.4).


U(93)-ss-graphite at C/\(^{238}\)U = 7.8 or 10.7, U(93)-ss-graphite-polyethylene at C/\(^{234}\)U = 4.4 to 6.3 and H/\(^{233}\)U = 1.0, U(32)-ss-graphite at C/\(^{234}\)U = 5.8, U(32)-ss-graphite-polyethylene at C/\(^{234}\)U = 6.3 and H/\(^{233}\)U = 1.0, Pu-Cu-ss-graphite at C/Pu = 3.0 to 6.0; each in thick U(nat)-ss (see II.A.3, II.A.4, II.B.1, and II.B.2).


6-in.-diam \(\delta\)-Pu interleaved with air, steel, Al, Th, U(depleted), in 0-, 2-, 4.5-, 7.5-in.-thick U(nat) or Th.


\~13.25-in.-diam \(\delta\)-Pu, 0.34- to 0.50-in.-thick, interleaved with 14-in.-diam graphite, 1- to 2-in.-thick.

**4. Metal**


12.7-cm-square \(\delta\)-Pu slab, 10.1-cm-thick Plexiglas reflector.


\(\alpha\)-Pu spheres (and hemispheres) in 0- to 5-cm-thick steel with and without oil reflector.


Precision critical specifications for \(\alpha\)-Pu.


Benchmark assemblies: bare spheres of U(94), \(\delta\)-Pu, \(^{233}\)U, Pu-U(93), \(^{233}\)U-U(93); U(93), \(\delta\)-Pu, \(^{233}\)U spheres in thick U(nat); \(\alpha\)-Pu sphere in water; bare cylinders of Av. U(53.3), U(37.5), U(16.0), U(14.1), U(12.3), U(10.9); Av. U(16.2) cylinder in 3-in-thick U(nat) (see II.A.7, II.B.2, II.F, and II.G).


\(\delta\)-Pu sphere in 9.3-cm-thick U(nat).


Pu metal spheres, bare, and in U(nat), Fe, C; U(45.5) metal slabs, 11.6-, 16.9-, 22.1-in.-diam, bare, and in U(nat), C, steel, Al; U(92.9)-graphite core at C/\(^{238}\)U = 7.8, 27-cm-diam by 38-cm-high, U(nat) reflector (see II.A.4 and II.B.2).


U(93.18) sphere in 2.6-in.-thick Al, \(\delta\)-Pu sphere in 3.1-in.-thick Al (see II.A.7).

δ-Pu in 4-in. Plexiglas, 20-in. square, ~7.2-in. square, 5.0-in. square, ~3.89-in. diam, 12.54-in. diam, 2.5 by 2.75 in., 2.75 by 5.0 in., critical heights ±10%.


8.39-kg Pu and 7.60- or 10.01-kg U^{238} in U(93), Be, W alloy, U(nat) (see II.F and II.G).


δ-Pu spheres, bare, in thick U(nat), also LA-2044, October 17, 1956.


2.5- to 5.4-kg spheres in 32.0- to 5.2-cm Be.


δ-Pu spheres, bare and U(nat) reflector; U(94) spheres, bare and U(nat) reflector; Av. U(35.3), U(37.5), U(29) bare cylinders; Av. U(16.2) cylinder, U reflector (see II.A.7 and II.B.2).


δ-phase Pu, 7.4-, 10.8-kg spheres in U(nat), Be, C, Ti; 8.2-, 9.9-, 13.8-cm-diam cylinders in U(nat), Be, C, steel, polyethylene.


U(94) spheres in 0- to 9-in.-thick U(nat), δ-Pu sphere in 4.6-in.-thick U(nat) (see II.A.7).

E. PuO_2-UO_2 Mixtures


75.7-cm-diam by 70.1-cm-high core, 0.90 g PuO_2/cm^3, 6.64 g U(1.8)O_2/cm^3, 0.05 g Al/cm^3, 1.31 g ss/cm^3; 57.3-cm-diam by 44.0-cm-high core (two zone), ~1.2 g PuO_2/cm^3, ~3.6 g UO_2/cm^3, ~0.5 g C/cm^3, ~1.1 g ss/cm^3; 72.4-cm-diam by 60.0-cm-high core (two zone), ~0.9 g PuO_2/cm^3, ~2.8 g UO_2/cm^3, ~0.3 g Na/cm^3, ~1.4 g ss/cm^3; 75.2-cm-diam by 60.0-cm-high core (two zone), ~4.3 g (U + UO_2)/cm^3 [U(30.2)], ~0.06 g C/cm^3, ~0.3 g Na/cm^3, ~1.5 g ss/cm^3; all in 30-cm-thick reflector, 15.8 g U(0.4)/cm^3, 0.57 g ss/cm^3 (see II.B.2).


PuO_2-U(depleted)O_2-polystyrene parallelepipeds, bare, Plexiglas reflected; 29.3 wt% Pu in Pu + U at H/(Pu + U) = 2.8, 15.0% Pu at H/(Pu + U) = 2.86, 8.1% Pu at H/(Pu + U) = 7.3.


61-cm-diam cylinder, ~30 wt% Pu in Pu + U at H/(Pu + U) = 2.8, 15.0% Pu at H/(Pu + U) = 2.86, 8.1% Pu at H/(Pu + U) = 7.3.


Reevaluation of Hanford and AWRE critical specifications; ~30, ~15, ~8 wt% Pu solutions and
hydrogenous solids, 42 to 4800 g (Pu + U)/liter, mostly hydrogenous reflector.


PuO$_2$-UO$_2$-polystyrene, ~15, ~30 wt% Pu in Pu + U, H/(Pu + U) = 2.8, 30.6, Plexiglas reflector, 1/8- to 1-in. Cu or Al, 1/8- or 3/4-in. Cu-Cd (1 wt%).


61-cm-diam cylinder, Pu + U(0.66) solution at ~5 to 7 wt% Pu in Pu + U, H/(Pu + U) ~60 to 80, partial water reflector; PuO$_2$-UO$_2$-polystyrene parallelepiped, 7.6% Pu, H/(Pu + U) = 19.5, Plexiglas reflector.


254-, 306-, 380-, 507-mm-diam cylinders at 330, 32, 18.6, 17.5 g Pu/liter, water reflector.


PuO$_2$-U(0.15)O$_2$-polystyrene parallelepipeds, H/(Pu + U) = 31, 47, 52, polyethylene reflector (some bare), shape variation including slabs.


Homogeneous mixture, H/Pu = 18.6, Pu/U = 0.335, near cube in 20-cm-thick polyethylene.


SCORPIO heated assemblies, 1.2-in.-diam Pu-U rods at 0.25 wt% Pu in Pu + U, latticed in graphite, buckling to ~0.3%.

F. Metallic Pu with U(93)


Benchmark assemblies: bare spheres of U(94), δ-Pu, 233U, Pu-U(93), 233U-U(93); U(93), δ-Pu, 234U spheres in thick U(nat); α-Pu sphere in water; bare cylinders of Av. U(53.3), U(37.5), U(16.0), U(14.1), U(12.3), U(10.9); Av. U(16.2) cylinder in 3-in-thick U(nat) (see II.A.7, II.B.2, II.D.4, and II.G).


2.15-in.-diam α-Pu spheres, 2.3, 4.7, 16.1% 239Pu, in U(93) shell, 19-in.-o.d. U(nat) reflector.


8.39-kg Pu and 7.60- or 10.01-kg 233U in U(93), Be, W alloy, U(nat) (see II.D.4 and II.G).

G. 233U


Benchmark assemblies: bare spheres of U(94), δ-Pu, 233U, Pu-U(93), 233U-U(93); U(93), δ-Pu, 234U spheres in thick U(nat); α-Pu sphere in water; bare cylinders of Av. U(53.3), U(37.5), U(16.0), U(14.1), U(12.3), U(10.9); Av. U(16.2) cylinder in 3-in-thick U(nat) (see II.A.7, II.B.2, II.D.4, and II.F).

ALECTO at Saclay: 25- to 42-cm-diam cylinders, $^{239}\text{Pu}$-, $^{238}\text{U}$-, $^{237}\text{U}$-nitrate solutions, 15 to 18 g Pu/liter, 30 to 300 g $^{238}\text{U}$/liter, 25 to 250 g $^{237}\text{U}$/liter, bare, water reflector (see II.A.1 and II.D.1).


5-region pseudospheres: $^{239}\text{U}$ or $^{238}\text{U}$, Th, C, Al, Fe test region; similar $^{239}\text{Pu}$ buffer; Th decoupler; $^{239}\text{U}$, polyethylene driver; polyethylene reflector.


8.39-kg Pu and 7.60- or 10.01-kg $^{233}\text{U}$ as uranyl fluoride solutions, H/$\text{Pu} = 380$ and 600, H/$\text{U} = 240$ and 460, 26.4- and 32.0-cm-diam spheres in water (see I.I.A.1).

III. MODERATED LATTICES

A. Hydrogenous

1. Enriched U


Lattices of U(62.4)O$_2$BeO fuel pins in water, and in uranyl nitrate solution at 3.7 g $^{238}\text{U}$/liter with and without 0.3 g B/liter (also arrays of elements consisting of 18 pins in square BeO).


$\text{UO}_2$(NO$_3$)$_3$ and $\text{UO}_2$F$_2$ solutions, H/$\text{Pu} = 34$ to 775; 10.4-in.-diam sphere in water, 12.6-in.-diam sphere bare and in water; 12.7- to 30.5-in.-diam cylinders bare and in water or paraffin.


$\text{UO}_2$(NO$_3$)$_3$ and $\text{UO}_2$F$_2$ solutions, H/$\text{Pu}$ bare, water reflector (see II.A.1).


9.9 wt% U(92.2)-Al, lattices of 11.2-cm i.d. by 20.1-cm o.d. by 113-cm long, and 10.1-cm i.d. by 12.3-cm o.d. by 112-cm-long clad with 0.15-cm Al; various pitches to $k_{\text{eff}} = 0.98$ and 0.95, respectively.


Fuel rods: Al-Pu, U(2.3)O$_2$, U(0.16)O$_2$, $^{235}\text{U}$, and U(nat)O$_2$-2 wt% $^{235}\text{U}$, and U(0.16)O$_2$-1.5 wt% $^{235}\text{U}$, and U(nat)O$_2$-2 wt% PuO$_2$ (7.6, 23.5% $^{249}\text{Pu}$) (see III.A.3).


Lattices of various single and double tubes carried to 96% of critical mass.

U(93.15)C,-graphite elements, 0.42 g U/cm³, water-moderated and reflected lattices, some with B,C.


22 Al-clad 0.020-in.-thick U(93.17)-Al (23.8 wt% U) plates, 0.047-in. spacing, in U(92.6)O₃(NO₃)₃ solution at 4.0 g ²³⁵U/liter, also with 0.39 to 1.12 g B/liter.


U(1.01, 2.00, 3.06) rods, 0.175-to 1.66-in. diam.


2- and 3-in.-diam rods, spacings span maximum buckling (Hanford data on 0.175- to 0.925-in.-diam rods included).


Latticed 1.0-cm-diam U(3.1)O₃ rods, H₂O/uranium Vol. ratio = 1.34, clean critical.


U(93.15)C,-graphite elements, C²³⁵U = 90, water-moderated and reflected lattices, spacings span minimum critical mass.


1.015-in.-diam rods containing 5.4 wt% U(93), water-moderated and reflected.


0.44-in.-diam by 66.7-in.-long U(4)O₃ in ss, 480 to 5200 latticed in water containing 0 to 76 mol% D₂O, some with B in solution; 0.26-in.-diam by 62-in.-long U(93)O₂-ThO₂ (Th/²³⁵U = 15) in Al, ~2200 latticed in water containing 60 mol% D₂O; 14- to 50-cm-thick moderator as radial reflector (see III.B).


U(nat), U(0.95), U(1.007), U(1.25), U(-1.44), U(1.6), U(3.06) rods, hollow cylinders [B solutions with 0.925-in.-diam U(1.007) rods] (see III.A.2).


U(1.3, 2.7, 4.0, 4.4)O₂, 0.76- 0.98-, 1.13-, 1.52-cm-diam rods latticed at water/uranium Vol. ratios = 2.2 to 5, some with B solution (a summary of extant data).

48-in.-long by 0.30-in.-diam U(2.7)O₃, 1300 or 1800 latticed; 55-in.-long by 0.30-in.-diam U(4.4)O₃, 750 or 1040 latticed; 795 U(2.7)O₂ rods surrounded by 830 or 1300 U(4.4)O₂ rods; 997 U(2.7)O₂ rods surrounded by 780 or 1188 U(4.4)O₂ rods; thick water reflector.


0.3-in.-diam U(2.7)O₂ rods at water/uranium Vol. ratio = 2.2, 2.9, 3.9.


Elements of U(93.15)-Al plates, 140, 168, 200 g ²³⁵U each, various flooded lattices, Cd effect.


30-in.-long by 3.125-in.-wide by 0.25-in.-thick plates, sets of four spaced 0.625 to 1.125 in.


1-in.-diam U(0.721) and U(0.912) rods in diphenyl (see III.A.2).


BNL: 0.250- or 0.387-in.-diam U(1.027), U(1.143), U(1.299) rods, exponentials; Bettis: 0.38-, 0.60-in.-diam U(1.3), U(1.3)O₂ rods, 0.60-in.-diam U(1.15) rods, criticals; WAPD: 0.300-in.-diam U(2.7)O₃, criticals.


U(1.0), U(1.15), U(1.3) rods, buckling, reflector savings, physics parameters.


0.5-, 1.0-in. cubes, 1/8-in.-diam rods of U(94) at various spacings; single water-reflected cube (see II.A.7).


0.002-in.-thick U(93.2) in 0.011-in.-thick ss, latticed in water, 9.5 to 19.7 vol% metal.


0.600-in.-diam U(1.15, 1.3), 0.387-in.-diam U(1.3) rods, critical lattices.

2. \textsc{U(nat)} rods, $B^2 > 0$ when latticed with air annulus about each rod; BNL: latticed 0.75-in.-diam \textsc{U(1.027)} rods (see III.A.2).


$\text{U(93)}O_2F_x$ solution, 0.5 kg $^{235}\text{U}$/liter, in 1-in.-diam ss tubes, latticed, flat-flux distribution, fur-fural moderator and reflector to simulate high-temperature water.


Supplements K-644 (July 11, 1950) on 1.35-in.-diam by 8-in. \textsc{U(93.3)}-\textsc{Al} P-10 slugs, 41.5 g U each, latticed in water.


1.35-in.-diam (with boss) by 9-in. U(93.2)-92.5\% Al rods, each 47.7 g $^{235}\text{U}$, face-centered lattice in water.


Fuel as of Mon P-357 (August 18, 1947), Al/H$_2$O Vol. ratio 0.65, near-equilateral and slab.

\textbf{M. M. Mann and A. B. Martin,} "Critical Experiments on a Small Reactor of Enriched U$^{235}$ with Al-H$_2$O Moderator and D$_2$O, Be, and H$_2$O Reflectors," Clinton Laboratories report Mon P-357 (August 18, 1947).

UO$_2$F$_x$ solution, 35.6 g $^{235}\text{U}$/liter, in 1- by 1-in.-square Al tubes, Al/H$_2$O Vol. ratio = 0.66 to 0.88, tubes close packed, $\geq$ 50-cm-thick D$_2$O, $\sim$25-cm Be, thick H$_2$O reflectors.

2. \textsc{U(nat)}


1.2-in.-diam \textsc{U(nat)} rods at 1.55-, 1.71-, 1.90-, 2.0-in. pitch, $k_0 < 1$.


1.2-in.-diam rods at 1.8-, 2.0-, 2.2-in. pitch, $B^2 < 0$.

\textbf{R. C. Lloyd,} Summary Listing of Subcritical Measurements of Heterogeneous Water-Uranium Lattices Made at Hanford," Hanford Atomic Products Operation report HW-65562 (June 8, 1960).

\textsc{U(nat)}, U(0.95), U(1.007), U(1.25), U(1.6), U(3.06) rods, hollow cylinders [B solutions with 0.925-in.-diam U(1.007) rods] (see III.A.1).


1-in.-diam U(0.721) and U(0.912) rods in diphenyl (see III.A.1).


ORNL: \textsc{U(nat)} rods, $B^2 > 0$ when latticed with air annulus about each rod; BNL: latticed 0.75-in.-diam \textsc{U(1.027)} rods (see III.A.1).

1.1-in.-diam rod lattice, \( B^2 < 0 \) but more positive than ORNL value.


1.1-in.-diam rods at water/U Vol. ratio = 1.5, \( k_\infty = 0.99 \); ORNL and Swedish (R. Persson) results included.


1.0-, 1.4-in.-diam \( \text{U(nat)} \) rods, \( H_2O/U \) Vol. ratio = 1.56 to 2.10, \( k_\infty = 1.003 \) for 1.4-in.-diam with air annulus about each rod and \( H_2O/U = 1.56 \).

3. Pu


0.5-in.-diam \( \text{PuO}_2,\text{U(nat)}\text{O}_2 \) rods, 25 wt% Pu, latticed in \( \text{Pu} + \text{U} \) solution at 1 to 255 g \( \text{Pu} + \text{U} \)/liter, effect of Gd, directed toward dissolver.


\( \text{U(nat)}\text{O}_2,\text{PuO}_2 \) rods from 1.5 to 4.0 wt% \( \text{PuO}_2 \), \( \text{Al-Pu} \) rods from 1.8 to 5.0 wt% Pu, extrapolations from ~50 to 96% critical size.


Fuel rods: \( \text{Al-Pu},\text{U(2.3)}\text{O}_2,\text{U(0.16)}\text{O}_2 \cdot 1.5 \text{ wt}\% \text{ PuO}_2, \text{and U(nat)}\text{O}_2 \cdot 2 \text{ wt}\% \text{ PuO}_2 \) (7.6, 23.5% \( ^{233}\text{Pu} \)) (see III.A.1).


0.6-in.-diam 10 wt% Pu rods latticed in water, minimum critical number at \( H_2O/(Pu + Al) \) Vol. ratio ~5.5.


0.5-in.-diam Zircaloy-clad Pu(5 wt%)-Al rods, latticed, to 96% of critical number.

4. \( ^{233}\text{U} \)


3% \( ^{233}\text{UO}_2-97\%\text{ThO}_2 \) rods in \( H_2O \) with 0 to 25 g \( H_3BO_3 \)/liter, spans \( B^2 = 0 \) (\( D_2O \) lattices unpoisoned) (see III.B).

B. \( D_2O \)


3% \( ^{233}\text{UO}_2-97\%\text{ThO}_2 \) rods in \( H_2O \) with 0 to 25 g \( H_3BO_3 \)/liter, spans \( B^2 = 0 \) (\( D_2O \) lattices unpoisoned) (see III.A.4).


1.0-in.-diam \( \text{U(nat)} \), 4.5-, 5.0-, 5.5-in. pitch, summary of extant \( B^2 \) data.

One lattice of 0.5-in.-diam rods fills ~16-ft-diam tank uniformly (also clusters).


1-in.-diam U(nat) rods, single-rod lattices range through minimum B


1-in.-diam rods, four single-rod lattices (also clusters).


0.44-in.-diam by 66.7-in.-long U(4)O2 in ss, 480 to 5200 latticed in water containing 0 to 76 mol% D2O, some with B in solution; 0.26-in.-diam by 62-in.-long U(93)O2-ThO2 (Th/232U = 15) in Al, ~2200 latticed in water containing 60 mol% D2O; 14- to 50-cm-thick moderator as radial reflector (see III.A.1).


0.23-in.-diam ThO2-U(~93)O2 rods latticed, Th/232U = 25, 50, exponentials, critical with Th/235U = 25; some fuel clusters.


2.5-cm-diam rods on 12-cm pitch, 200-cm-diam by 210-cm-high bare core.


Extension of Proc. 1st UN Geneva Conf. 5, 239-241 with 3.05-cm-diam rods, also clusters of 1.25-cm-diam metal rods and 1.22- and 1.56-cm-diam oxide rods.


Exponentials with 3.26-, 3.80-cm-diam rods (also tubes) each in 0.25- to 0.30-cm annulus containing H2O or air; some clustered rods.


1-in.-diam U(0.496, 0.720, 0.912) rods; 2-in.-diam U(0.496, 0.720) rods; 0.75-, 1.25-, 1.50-cm-diam U(0.720) rods; ANL results with 1.00-in.-diam U(nat) rods; all in 5-ft-diam tanks.


2.57-, 3.05-cm-diam U(nat) rods latticed in 1-m-diam tank.


2.5-in.-diam tubes of 238U-D2O solution latticed in tank of D2O at average of 2.58, 10.35 g 238U/liter, ~30-, 50-cm-thick D2O reflector.
C. Be or BeO


0.040-in. thick 23.4 wt% U(89.4)-Al in BeO containing 4.3 wt% U(nat) or Th, Be/\textsuperscript{235}U = 1540 to 6500.


0.040-in-thick 23.4 wt% U(89.4)-Al in BeO at Be/\textsuperscript{235}U = 1460, 2930, 5860, 8790.


2.60-, 2.92-, 3.56-cm-diam U(nat) rods in BeO for exponential, some U(l.35) for critical.


U(10)\textsubscript{4}O\textsubscript{6} powder in 0.9- or 1.34-cm-diam tubes latticed in Be, Be/\textsuperscript{238}U = 1777 to 3112, 0- to 15-cm lateral Be-H\textsubscript{2}O reflector; also with H\textsubscript{2}O in core.


63-liter core at Be/\textsuperscript{238}U = 1.7 in thick Be; 85-liter core at Be/\textsuperscript{238}U = 33 in thick Be; 272-liter core at Be/\textsuperscript{238}U = 1.78 in thick Be + void.


U(10)\textsubscript{4}O\textsubscript{6} in ~ 0.13-cm-thick steel-wall annuli latticed in Be, bare, and 15.5-cm lateral Be reflector; effect of water.


0.020-in. \textsuperscript{238}U interleaved with 0.1-, 0.4-, 0.8-in-thick Be, 85-liter core at Be/\textsuperscript{238}U = 45.4, 32.6 (with Fe, Na, Al), reflector of 100-liter Be (with Fe, Al) in 12-in-thick U(nat).

D. Graphite


0.925- to 2.5-in.-diam U(nat) rods spaced in graphite from 4.4 to 15 in.; 1.336-in.-diam U(0.94); 0.925-, 1.66-in.-diam U(1.007); 1.343-in.-diam U(93)-Al; also clustered rods, tubes, rods in tubes.


2.6- to 3.2-cm-diam U(nat) rods, C/U = 57 to 117.


Hanford: 0.925-, 1.175-, 1.36-, 1.66-in.-diam U(nat) rods latticed at C/U = 32 to 199; NAA: 1-in.-diam rods of U(nat), U(0.49), U(0.90).
IV. INTERACTING UNITS

A. Enriched U

1. Solutions, Mixtures

D. W. Magnuson, "Critical Experiments with Enriched Uranium Dioxide," Oak Ridge Y-12 Plant report Y-DR-120 (November 30, 1973). 0.4-, 20-kg U(93)O₂ dry cylinders, 17-kg with alcohol, one- and two-high arrays with polyethylene reflector; maximum reactivity with ~4-cm Plexiglas between units.


Two, three, or four 300-, 256-mm-diam Pu-solution cylinders, 115, 152 g Pu/liter; two 300-mm-diam 238U-solution cylinders at 81, 90, 110 g 238U/liter; also dissimilar cylinders (see IV.A.2).


Recapitulation of data on Oak Ridge arrays: two and three U(93.2) disks on same axis; 5.2-, 10.5-, 15.7-, 20.9-, 26.2-kg U(93.2) metal cylinders, n⁴ arrays (n = 2, 3, 4); 5-liter U(92.6)O₂(NO₃)₂ solution cylinders at H²⁹⁸U = 59, 92, 440, planar and n⁴ arrays (n = 2, 3, 4, 5); 24-cm-diam by 152-cm-high U(4.9)O₂F₂ solution cylinders, planar arrays of 5 to 27 units (see IV.A.2).


Two, three, or four 30-cm-diam U(90)O₂(NO₃)₂ solution cylinders, or 30-cm-square parallelepips, at 71 g U/liter; larger arrays (to 67 units) of 18-cm-diam by 24-cm-high cylinders at 6(?) g U/liter; no reflector.


5-liter U(93)O₂(NO₃)₃ cylinders at 415 g U/liter, arrays up to 125 units bare, 1-in. Plexiglas, 0.5-, to 12-in. paraffin reflectors.


30-cm-diam U(90)O₂(NO₃)₂ solution cylinders at H²⁹⁸U = 260 to 520, bare, graphite reflector.


U(93.2)O₂F₂ solution, H²⁹⁸U = 27 to 75; interaction of three and seven 6- and 8-in.-diam cylinders in air and water; individual 6- to 30-in.-diam cylinders and 9-in.-diam sphere, bare, water reflected; 8- to 20-in.-o.d. annuli; also "Y" and "cross," and comparison of furfural, concrete, graphite, firebrick reflectors with water (see II.A.1).


U(~90)O₂F₂ solution at H²⁹⁸U = 337, interaction of two 3-, 6-in.-thick slabs, three 3-in.-thick slabs, in air or water (slabs 4-ft wide).


U(93.4) as ~0.005-in.-thick turnings in water, H²⁹⁸U = 60, 80, 120, one to six 8- to 10-in.-diam cylinders in water; critical mass ~18% above that of corresponding solution (see II.A.3).

Two 5-, 5.5-, 6-, 8-, 10-, 15-, 20-in.-diam U(93)O,F, solution cylinders, $H^{238}U = 50, 53, 169, 329$, bare and flooded.

2. Metal


10.5-, 15.7-, 20.9-, 26.2-kg cylinders in $n^3$ arrays ($n = 2, 3, 4$), 0- to 15-cm-paraffin reflectors (including 3-sided), effects of Plexiglas, steel between units; also ORNL-TM-868, July 1964.


Eight 21-kg U(93.2) cylinders, 16-in.-thick concrete reflector; bonded vermiculite in arrays with 6-in.-polyethylene reflector.


Recapitulation of data on Oak Ridge arrays, two and three U(93.2) disks on same axis; 5.2-, 10.5-, 15.7-, 20.9-, 26.2-kg U(93.2) metal cylinders, $n^3$ arrays ($n = 2, 3, 4$); 5-liter U(92.6)O$_2$(NO$_2$)$_2$ solution cylinders at $H^{238}U = 59, 92, 440$, planar and $n^3$ arrays ($n = 2, 3, 4, 5$); 24-cm-diam by 152-cm-high U(4.9)O,F$_2$ solution cylinders, planar arrays of 5 to 27 units (see IV.A.1).


1 by 8 by 10-in. U(93) slabs, three-dimensional arrays at 11-, 12-, 15-in. spacing, 1-in.-Plexiglas reflector.

B. Pu


3-, 6-kg $\alpha$-Pu units, planar arrays with polyethylene reflector, $n^3$ arrays ($n = 2, 3, 4$) bare or partially reflected, effect of mock HE moderator; also UCRL-51041, May 10, 1971, and UCRL-50175, December 22, 1966.


Two, three, or four 300-, 256-mm-diam Pu-solution cylinders, 115, 152 g Pu/liter; two 300-mm-diam $^{238}$U-solution cylinders at 81, 90, 110 g $^{235}$U/liter; also dissimilar cylinders (see IV.A.1).


Valduc results: Pu solutions, 20 to 190 g Pu/liter, 30-cm-diam cylinder; 150-cm by 120-cm by 10-cm-thick slab; 50-cm-o.d. by 35-cm-i.d., 50-cm-o.d. by 30-cm-i.d., 50-cm-o.d. by 20-cm-i.d. annuli; two interacting 50-cm-o.d. by 30-cm-i.d. annuli; reflectors various combinations of air, water, with and without Cd (see II.D.1).


Saclay: solutions at 60 g Pu/liter and ~30 to 100 g $^{238}$U/liter as U(90) in bare 42-cm-diam cylinder and water-reflected 30-cm-diam cylinder; also spaced reflectors, interaction of two 10-cm-diam cylinders with one at 30-cm diam; Dijon: Pu solution in 50-cm-o.d. by 30-cm-i.d. annulus, interaction of two annuli (see II.A.1 and II.D.1).

~2 kg δ-Pu buttons, ~2.5-in.-diam, three-dimensional array on concrete (other systems too subcritical).


4.5-in.-i.d. by ~11.5-in.-high $^{233}$UO$_4$(NO$_3$)$_2$ solution bottles, 330 g $^{233}$U/liter, to 4 by 4, 3 by 3 by 2 arrays, bare, Plexiglas reflector, effect of 0- to 2.5-in. Plexiglas between bottles.

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C. $^{233}$U