LA-12659-MS

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Minimum Critical Mass Analytical Studies

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Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Edited by Gerry Edwards, Group IS-1
Photocomposition by Randi Bagley, Group IS-1

LA-12659-MS

UC-714
Issued: October 1993

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Rene G. Sanchez

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

MINIMUM CRITICAL MASS ANALYTICAL STUDIES

by

Rene G. Sanchez

ABSTRACT

Analytical studies have confirmed that the minimum critical mass for ^{235}U in a critical reactor assembly moderated with high-density polyethylene and surrounded by a thick-beryllium reflector is on the order of 275 g. Similar studies have also shown that the minimum critical masses for ^{233}U and alpha-phase ^{239}Pu in the same type of critical assembly and surrounded by a thick-beryllium reflector are on the order of 185 g and 190 g, respectively.

I. INTRODUCTION

Because of the recent interest in performing experiments to determine the minimum critical mass for plutonium and uranium systems at room temperature, an analytical study has been completed, with the help of the Monte Carlo neutron photon (MCNP) transport computer code, to define minimum critical mass parameters for these systems. The study indicates that for an optimum moderator and reflector, the minimum critical mass for a ^{235}U system is on the order of 275 g and occurs at a $H/^{235}U$ ratio of 331. This result agrees with the experimental value of "...250 to 300 grams..." reported by Jarvis and Mills [1-3] in 1967. In addition, this study also shows that the minimum critical mass for ^{233}U and alpha phase ^{239}Pu in a hydrogen-moderated core with a thick beryllium reflector is on the order of 185 g and 190 g, respectively, and occurs at $H/^{233}U$ ratio of 337 and $H/^{239}Pu$ ratio of 543.

II. URANIUM AND PLUTONIUM SYSTEMS

To minimize the mass needed to maintain an effective multiplication factor, k_{eff}, of 1, it is important to recognize that neutron conservation (namely, the reduction of all losses not associated with the fission process) is essential to the solution of the problem. Because ^{233}U, ^{235}U, and ^{239}Pu have large fission cross sections at thermal energies (see Table I), an optimum hydrogenous quasi-homogeneous core with a thick reflector should reduce the critical mass to its lowest level for these systems.

In this study, several quasi-homogeneous configurations were examined, using the MCNP-4X-C computer code and the continuous energy cross-section data. For each case, a total of one-hundred-thousand source histories was run with the help of MCNP computer transport code. The majority of the configurations studied consisted of stacked high-density 0.635-cm (0.25 in.)-thick polyethylene plates and fissile foils made of 93% ^{235}U, 98% ^{233}U, and 95% alpha phase ^{239}Pu (see Table II). Foils of the same isotopic composition were separated by one, two, or more layers of polyethylene plates. The hydrogenous core was then surrounded by a 33.02-cm (13 in.)-thick beryllium reflector (Figs. 1 and 2). Computer models were then developed using foils of different thicknesses and surface areas. The results indicate that the optimum thickness for the foils is 0.003048 cm (0.0012 in.), with a width of 15.24 cm (6 in.) and length of 15.5575 cm (6.125 in.). Table III shows the results of these studies.

Table I. Thermal (0.0253 eV) cross-section data for fissile nuclide.[a]

Material	σ_a	σ_t	α	η	ν
^{233}U	578.8	531.1	0.0899	2.287	2.492
^{235}U	680.8	582.2	0.169	2.068	2.418
^{239}Pu	1011.3	742.5	0.362	2.108	2.871

[a] Reference 4.

Table II. Isotopic composition of foils.*

Material	^{233}U	^{234}U	^{235}U	^{238}U	^{239}Pu	^{240}Pu
^{235}U Foils	—	1.000%	93.499%	5.501%	—	—
^{233}U Foils	98.45%	0.94%	0.02%	0.590%	—	—
^{239}Pu Foils	—	—	—	—	95.00%	5.00%

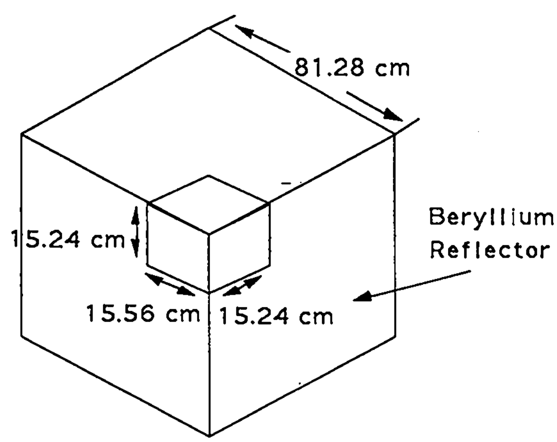


Fig. 1. Beryllium reflector and cubical fuel-cell cavity.

* It is probably impossible to conduct an experiment with very thin plutonium foils. However, they were calculated as foils to preserve the comparison with ^{235}U and ^{233}U.

Table III. Data for a hydrogenous core in a thick-beryllium reflector.

^{235}U Foil Dimensions (in.)

Cubical Geometry	Weight of Core Moderator Material (g)	Total ^{235}U Mass (g)	Atomic Ratio $H/^{235}U$	k_{eff}
9 x 9 x 0.003	1439.87	278.9	173	0.878 ± 0.0033
9 x 9 x 0.003	1762.85	278.9	212	0.894 ± 0.0034
9 x 9 x 0.003	2408.81	278.9	289	0.913 ± 0.0038
9 x 9 x 0.003	4183.15	278.9	502	0.856 ± 0.0028
6 x 6 x 0.003	1418.33	278.9	170	0.942 ± 0.0037
6 x 6 x 0.003	1994.22	278.9	240	0.950 ± 0.0039
6 x 6 x 0.003	2495.72	278.9	300	0.964 ± 0.0036
6 x 6 x 0.003	2710.13	278.9	326	0.949 ± 0.0034
6 x 6.125 x 0.0012	2749.00	278.49	331	1.020 ± 0.0026
6 x 6.125 x 0.0012	2893.68	278.49	348	1.020 ± 0.0036
6 x 6.120 x 0.0012	2604.34	277.44	314	1.019 ± 0.0022
Spherical Geometry Radius = 8.82 cm	2746.63	279.30	329	1.017 ± 0.0021

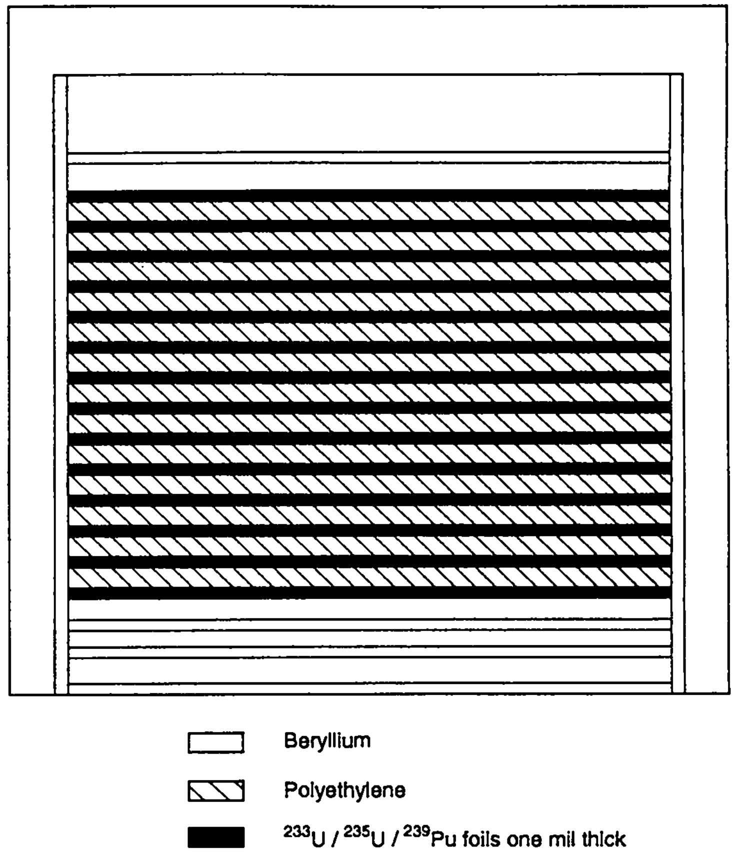
^{233}U Foil Dimensions (in.)

Cubical Geometry	Weight of Core Moderator Material (g)	Total ^{233}U Mass (g)	Atomic Ratio $H/^{233}U$	k_{eff}
6 x 6.125 x 0.0012	1735.50	185.54	311	0.995 ± 0.0027
6 x 6.125 x 0.0012	1880.89	185.54	337	0.999 ± 0.0026
6 x 6.125 x 0.0012	1953.24	185.54	350	0.996 ± 0.0027
6 x 6.125 x 0.0012	2025.58	185.54	362	0.996 ± 0.0026
6 x 6.125 x 0.0012	2170.97	185.54	389	0.991 ± 0.0022
6 x 6.125 x 0.0012	2243.32	185.54	402	0.988 ± 0.0030
6 x 6.125 x 0.0012	2388.72	185.54	428	0.979 ± 0.0027

^{239}Pu Foil Dimensions (in.)

Cubical Geometry	Weight of Core Moderator Material (g)	Total ^{239}Pu Mass (g)	Atomic Ratio $H/^{239}Pu$	k_{eff}
6 x 6.125 x 0.00123	1880.89	195.82	441	0.992 ± 0.0032
6 x 6.125 x 0.00123	2896.52	195.05	506	0.982 ± 0.0020
6 x 6.125 x 0.0012	3038.37	190.60	543	0.998 ± 0.0024
6 x 6.125 x 0.0012	3919.00	190.60	701	0.981 ± 0.0020

Fig. 2. Arrangement of $^{233}U/^{235}U/^{239}Pu$ foils and polyethylene plates inside a beryllium reflector.



For the case of ^{235}U, the effect of a spherical geometry (Fig. 3) vs a cubical geometry was investigated. The results showed that for the same mass and $H/^{235}U$ ratio, the effective multiplication factor, k_{eff}, is about the same for both geometries. This effect can be explained when we consider that reflected neutrons will have higher probability of interacting with the ^{235}U foils in a cubical geometry (larger area) as opposed to a spherical geometry. Results obtained confirm those published in Ref. 5; Table III shows these results.

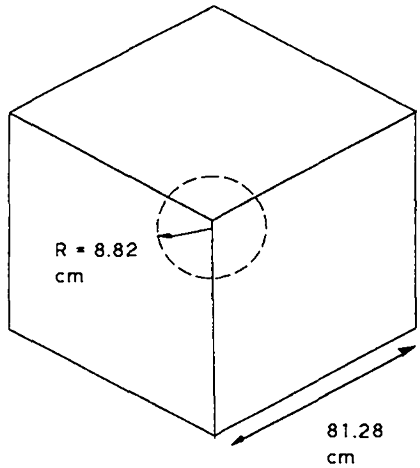


Fig. 3. Beryllium reflector and spherical fuel-cell cavity.

III. CONCLUSIONS

These analytical studies have confirmed that the minimum critical mass for ^{235}U in a hydrogenous core with a thick-beryllium reflector agrees with the experimental value of 250 to 300 g. The studies have also shown that the minimum critical mass for ^{233}U and alpha-phase ^{239}Pu in a hydrogen-moderated core with a thick-beryllium reflector is on the order of 185 g and 190 g, respectively.

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