

**Minimum Critical Masses at the
Portsmouth Gaseous Diffusion Plant**

June 1994

by

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Under Contract 400183

to

MARTIN MARIETTA UTILITY SERVICES, INC.

**PORTSMOUTH GASEOUS DIFFUSION PLANT
P.O. Box 628 Piketon, Ohio 45661**

Under Contract USECHQ-93-C-0001

to the

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TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
2.0 SAFE MASS	2
3.0 CRITICAL MASS	5
4.0 COMPARISON TO OTHER DATA	7
5.0 SAFETY FACTOR	10
6.0 CONCLUSIONS	12
REFERENCES	13
APPENDIX A	14

LIST OF TABLES

Table 1. Data Used for Safe-Mass Curve Fit	3
Table 2. Data Used for Critical-Mass Curve Fit	5
Table 3. Data Points Used for Comparison	8
Table A-1. Calculated Safe and Critical Masses	15

LIST OF FIGURES

Figure 1. Safe Mass Fit to GAT-225 Data	4
Figure 2. Critical Mass Fit to ORNL/TM-12292 Data	6
Figure 3. Comparison to Data Tabulated Safe and Critical Masses	9
Figure 4. Safety Factor Ratio of Critical to Safe Mass	11

1.0 INTRODUCTION

This report presents a tabulation of safe masses and minimum critical masses for uranium (U). These minimum critical mass and safe mass tables were obtained by interpolating between the values reported in the literature to obtain values as a function of enrichment within the 1.5 percent to 100 percent range. Equivalent mass values for uranium-235 (U^{235}), uranium hexafluoride (UF_6), and uranyl fluoride (UO_2F_2) have been generated from the safe mass and minimum critical masses for uranium.

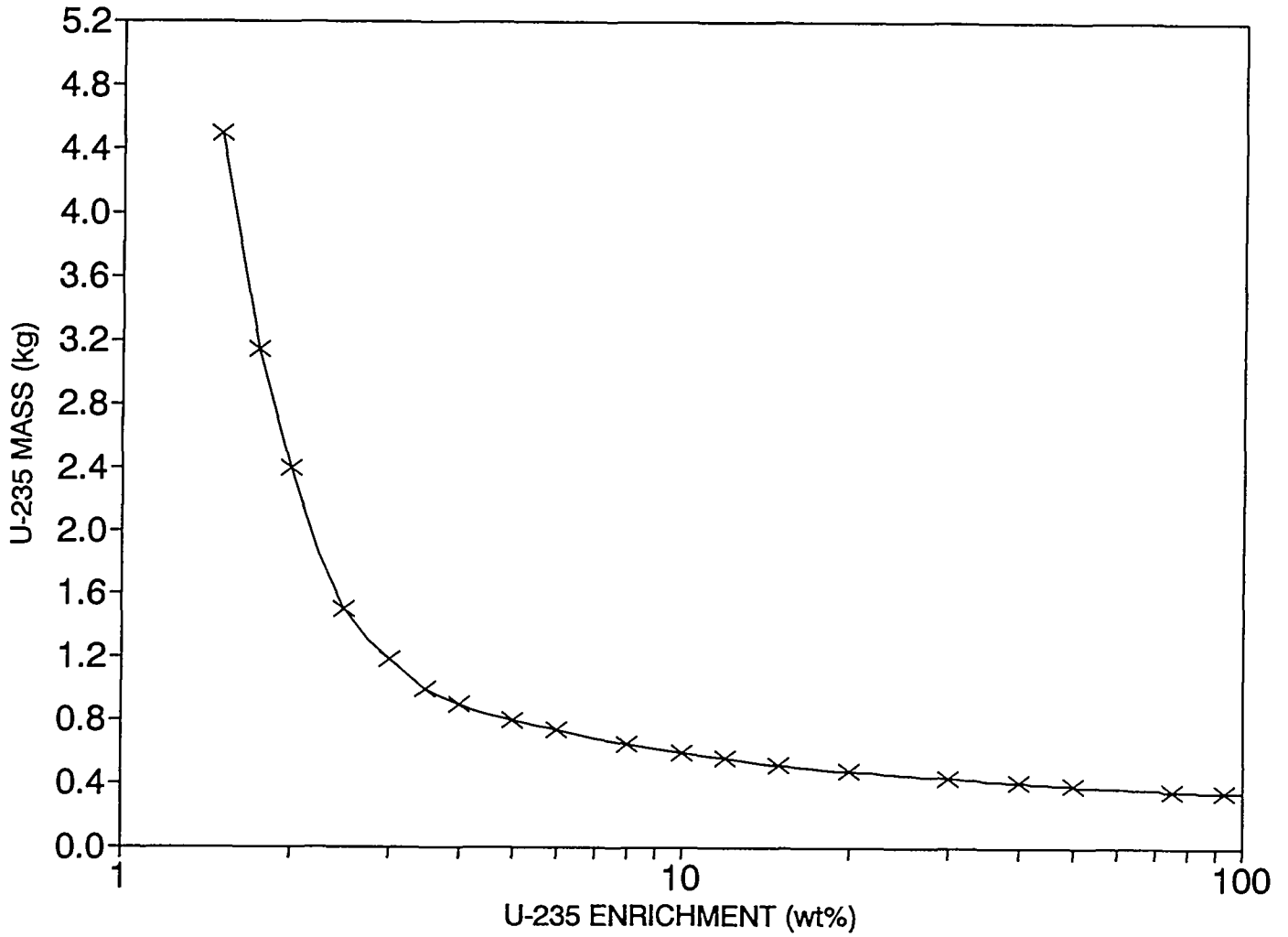
2.0 SAFE MASS

The safe mass tables were derived from the safe mass values historically used at the Portsmouth Gaseous Diffusion Plant, which are delineated in GAT-225 (Reference 1). These data points, which are shown in Table 1, were used to develop an equation for safe mass of U^{235} as a function of enrichment over the range of 1.5 to 93 percent.

The curve that results from the equation is shown in Figure 1. The safe mass value at 93 percent is 350 grams, which is equal to the safe mass limit given in the GAT-225 for 100 percent enriched uranium. Consequently, as shown in Figure 1, the safe mass in the of range 93 to 100 percent enrichment is assumed to be a constant value of 350 grams. Using the safe masses of U^{235} for each enrichment, the safe masses of uranium were calculated based on the relative atomic weights. The calculations assume the uranium consisted entirely of U^{235} and U^{238} (i.e., the percentage of U^{234} was assumed to be negligible). The safe masses of UF_6 and UO_2F_2 were then calculated based on their relative molecular weights. Detailed results for uranium, U^{235} , UF_6 , and UO_2F_2 are shown in Appendix A.

Table 1. Data Used for Safe-Mass Curve Fit

U^{235} (wt %)	Safe Mass (grams) Reference: GAT-225, Table I
1.5	4500
1.75	3150
2	2400
2.5	1500
3	1180
3.5	1000
4	900
5	800
6	740
8	650
10	600
12	560
15	520
20	480
30	440
40	410
50	390
75	360
93	350



**Figure 1. Safe Mass
Fit to GAT-225 Data**

3.0 CRITICAL MASS

The data used to develop the curve-fit equation for critical masses were derived from Table B.2 of ORNL/TM-12292 (Reference 2). These data represent the critical mass at an H/X of 500 for uranyl fluoride-water (UO₂F₂-H₂O) systems in fully-water-reflected spherical geometry determined using the SCALE 4.0 package. GAT-225 specifies an H/X of 500 if mass is the parameter of nuclear safety control. ORNL/TM-12292 indicates that an H/X of 500 results in a near-minimum predicted critical mass. These data points, which are shown in Table 2, were used to develop an equation for critical mass of U²³⁵ as a function of enrichment over the range of 1.5 to 100 percent. The lowest enrichment used to determine the curve was 1.4 percent. However, for consistency with safe mass data, Appendix A presents results for enrichments of 1.5 percent and higher. The curve that results from the equation is shown in Figure 2.

Table 2. Data Used for Critical-Mass Curve Fit

U ²³⁵ (wt %)	Critical Mass (grams U ²³⁵) Reference: ORNL/TM-12292, Table B.2
1.4	23773
1.7	9881
2	6264
3	3077
4	2221
5	1851
7	1505
10	1275
20	1021
50	852
10	775

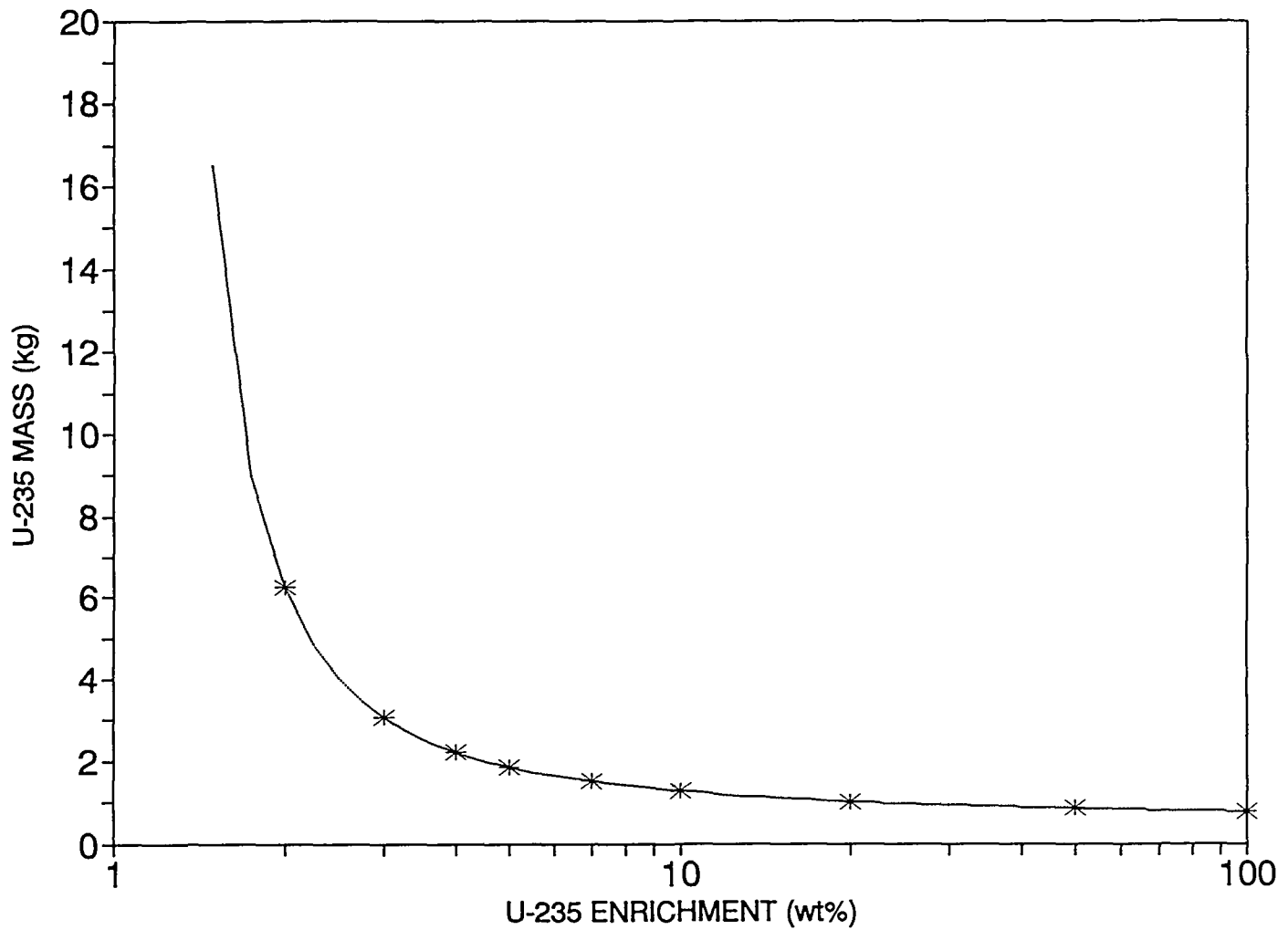


Figure 2. Critical Mass
Fit to ORNL/TM-12292 Data

4.0 COMPARISON TO OTHER DATA

The resulting safe and critical mass curves were compared to available data from ANSI/ANS-8.1, LA-10860, and ARH-600 (References 3, 4, and 5). The sources of the data points are given in Table 3, and the data points are included in Figure 3.

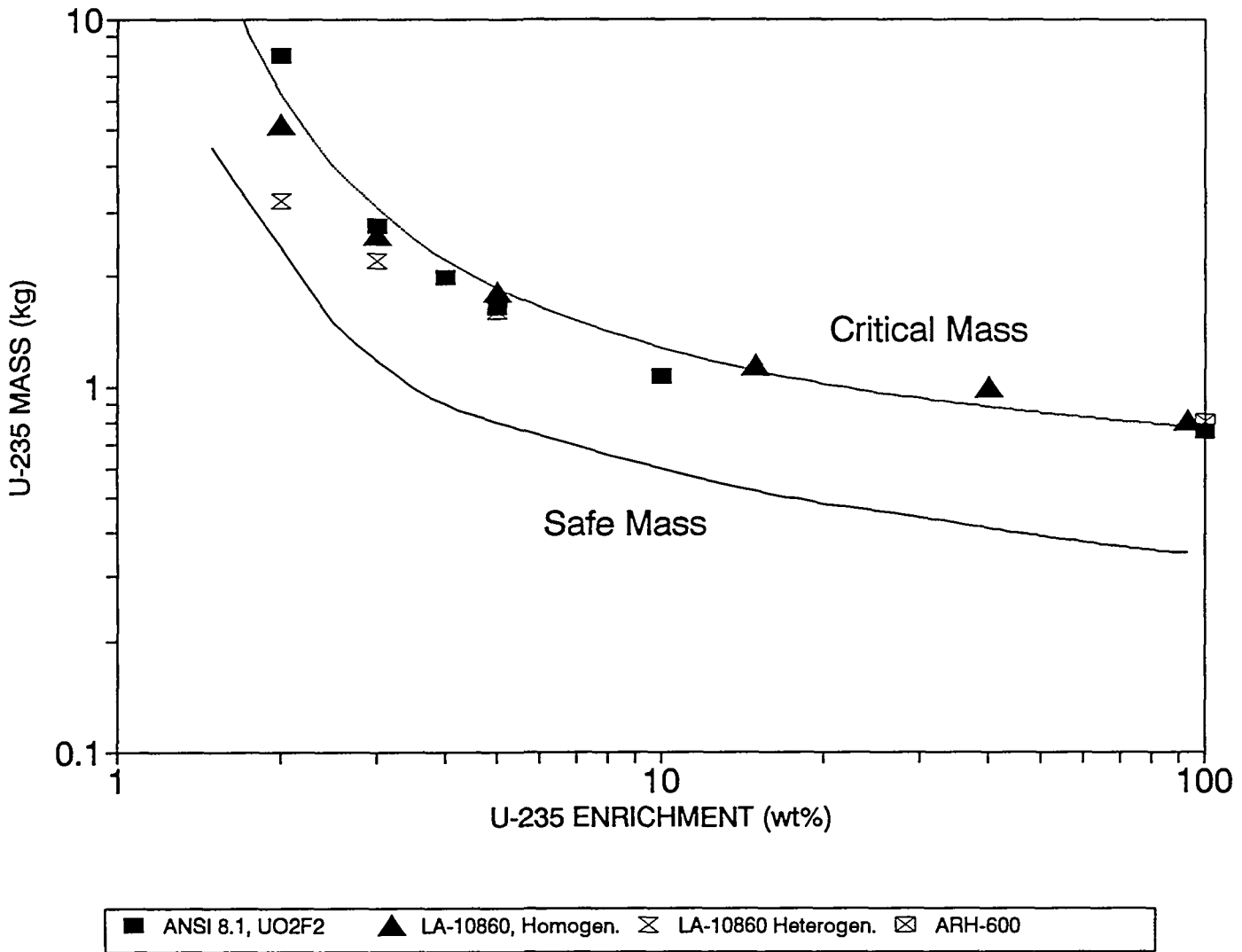
Figure 3 shows that the calculated safe values are conservative with respect to the other data over the full range of enrichments. The estimated critical masses are also conservative with respect to the data for homogeneous critical systems from LA-10860 and ARH-600 for enrichments above 5 percent.

At enrichments less than or equal to 5 percent, the LA-10860 data points for homogeneous critical system, (which are estimated from Figure 22 of LA-10860) are slightly less than the values derived from the ORNL/TM-12292 calculated data. The LA-10860 data point for low-enriched heterogeneous critical systems (see Figure 22 of LA-10860) are less than that predicted for a homogeneous system. The subcritical limits for aqueous solutions of UO_2F_2 from ANSI/ANS-8.1 (see Tables 1 and 6 of ANSI/ANS-8.1) are less than the estimate of the critical mass determined by the curve fit between 2 and 5 percent. The ANSI/ANS-8.1 data represent a subcritical limit and were determined considering the calculational uncertainties.

Overall, the tabulated values are comparable to the data presented in other references at enrichments above 5 percent. There are, however, significant differences between the estimated critical masses reported in the various sources at low enrichments. The differences reflect calculational uncertainties and different modeling assumptions.

Table 3. Data Points Used for Comparison

U^{235} (wt%)	Critical Mass U^{235} (kg)	Reference
2	3.2	LA-10860, Figure 22, Heterogeneous water-reflected data point, minimum critical mass
2	5.2	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
3	2.2	LA-10860, Figure 22, Heterogeneous water-reflected data point, minimum critical mass
3	2.6	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
5	1.6	LA-10860, Figure 22, Heterogeneous water-reflected data point, minimum critical mass
5	1.8	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
15	1.15	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
40	1.00	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
93	0.814	LA-10860, Figure 22, Homogeneous water- reflected data point, minimum critical mass
100	0.806	ARH-600, Figure III.B.6(100)-2, minimum critical mass
2	8.00	ANSI/ANS-8.1, Table 6, subcritical limit for aqueous solutions of UO_2F_2
3	2.75	ANSI/ANS-8.1, Table 6, subcritical limit for aqueous solutions of UO_2F_2
4	1.98	ANSI/ANS-8.1, Table 6, subcritical limit for aqueous solutions of UO_2F_2
5	1.64	ANSI/ANS-8.1, Table 6, subcritical limit for aqueous solutions of UO_2F_2
10	1.07	ANSI/ANS-8.1, Table 6, subcritical limit for aqueous solutions of UO_2F_2
100	0.76	ANSI/ANS-8.1, Table 1, subcritical limit for aqueous solutions of UO_2F_2



**Figure 3. Comparison to Data
Tabulated Safe and Critical Masses**

5.0 SAFETY FACTOR

Historically, the gaseous diffusion plants have incorporated a factor of safety with minimum critical masses to generate "safe" masses. In order to account for errors in double batching or to reduce the potential for criticality as a result from errors in conversion from metric mass units (kilograms) to more conventional units of weight (pounds), the safe mass was taken as 43.5 percent of the critical value. This percentage equates to a safety factor of 2.3.

Figure 4 presents the calculated safety factor over the enrichment range of interest, 1.5 to 100 percent. The safety factor is calculated as the ratio of the estimated critical mass to the estimated safe mass at each enrichment. Figure 4 shows that the safety factors vary from 2.1 to 2.3 for enrichments in the range of 5 to 100 percent. These values are comparable to the safety factor of 2.3 that was used to develop the safe masses in GAT-225. However, the safety factors are somewhat larger at lower enrichments (as much as 3.7 at 1.5 percent enrichment).

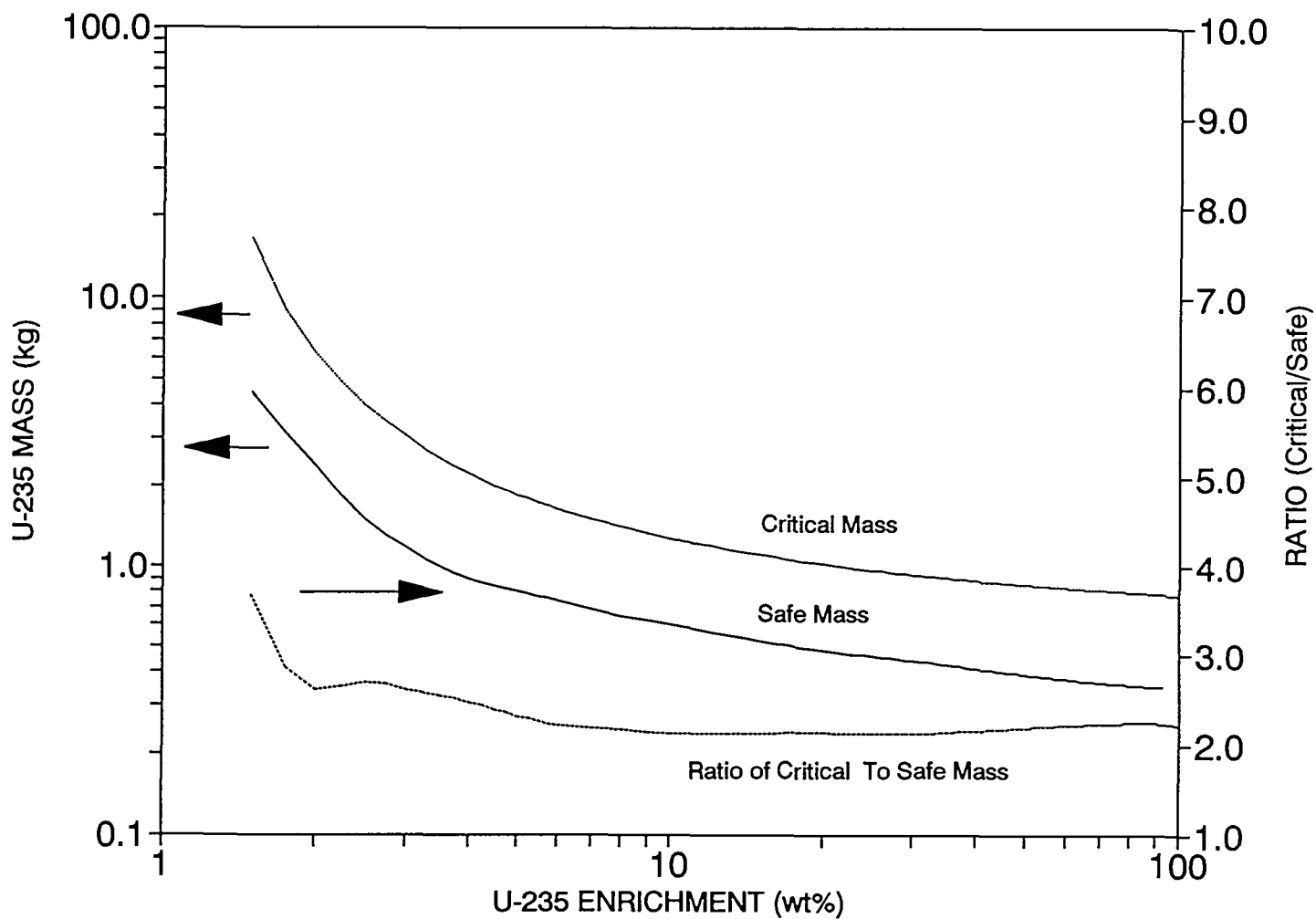


Figure 4. Safety Factor
Ratio of Critical to Safe Mass

6.0 CONCLUSIONS

The safe mass values are an interpolation of the GAT-225 safe mass parameters. The tabulated values can be used over the full range of enrichment for criticality safety analysis calculations.

The tabulated critical mass values represent an estimate of the mass required for a system that is exactly critical with the assumptions of an H/X of 500 and fully-water-reflected spherical geometry. The tabulated values are based on recent calculations using the SCALE package. The tabulated values are comparable to the data presented in other references at enrichments above 5 percent. There are, however, significant differences between the values for critical masses reported in the literature at lower enrichments.

The tabulated critical mass values do not incorporate a safety factor and do not represent a conservative estimate of the minimum critical mass. The tabulated critical masses are often useful in performing risk assessments. However, all criticality safety analyses should incorporate a safety factor, and limiting conditions should be based on safe parameters.

REFERENCES

1. GAT-225, Revision 4, Feuerbacher, J.L., "Nuclear Criticality Safety Guide for the Portsmouth Gaseous Diffusion Plant," Portsmouth Gaseous Diffusion Plant, March 1981.
2. ORNL/TM-12292, Jordan, W.C., Turner, J.C., "Estimated Critical Conditions for $\text{UO}_2\text{F}_2\text{-H}_2\text{O}$ Systems in Fully Water-Reflected Spherical Geometry", Oak Ridge National Laboratory, December 1992.
3. ANSI/ANS-8.1, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors", American Nuclear Society, 1983.
4. LA-10860-MS, Paxton, H.C., and Pruvost, N.L., "Critical Dimensions of Systems Containing U^{235} , Pu-239, and U-233 - 1986 Revision", Los Alamos National Laboratory, July 1987.
5. ARH-600, Carter, R.D., et al, "Criticality Handbook", volume II, Atlantic Richfield Hanford Company, March 1976.
6. K-1019, Revision 5, Henry, H.F., et al, "Criticality Data and Nuclear Safety Guide Applicable to The Oak Ridge Gaseous Diffusion Plant", Oak Ridge Gaseous Diffusion Plant, May 1959.

APPENDIX A

**CALCULATED RESULTS
SAFE AND CRITICAL MASSES
FOR U²³⁵, URANIUM,
UF₆, AND UO₂F₂**

Table A-1. Calculated Safe and Critical Masses

U^{235} (wt%)	Safe Mass (kg)				Critical Mass (kg)			
	U^{235}	Uranium	UF ₆	UO ₂ F ₂	U^{235}	Uranium	UF ₆	UO ₂ F ₂
1.5	4.500	300.000	443.682	388.228	16.508	1100.561	1627.663	1424.227
1.75	3.150	180.000	266.212	232.938	8.981	513.187	758.980	664.116
2	2.400	120.000	177.476	155.293	6.264	313.200	463.213	405.315
2.25	1.851	82.254	121.653	106.447	4.870	216.432	320.100	280.090
2.5	1.500	60.000	88.740	77.648	4.028	161.139	238.325	208.535
2.75	1.306	47.483	70.228	61.449	3.472	126.272	186.758	163.413
3	1.180	39.333	58.175	50.903	3.077	102.567	151.699	132.736
3.25	1.079	33.198	49.101	42.963	2.779	85.517	126.483	110.672
3.5	1.000	28.571	42.259	36.976	2.549	72.819	107.704	94.241
3.75	0.943	25.135	37.177	32.529	2.367	63.113	93.348	81.679
4	0.900	22.500	33.280	29.119	2.221	55.525	82.127	71.860
4.25	0.867	20.401	30.175	26.403	2.103	49.475	73.179	64.030
4.5	0.841	18.681	27.631	24.177	2.005	44.550	65.895	57.657
4.75	0.819	17.237	25.496	22.308	1.922	40.465	59.853	52.370
5	0.800	16.000	23.666	20.708	1.851	37.020	54.758	47.912
5.25	0.783	14.921	22.071	19.312	1.789	34.075	50.403	44.101
5.5	0.768	13.966	20.659	18.076	1.734	31.531	46.641	40.809
5.75	0.754	13.110	19.392	16.968	1.686	29.314	43.362	37.940
6	0.740	12.333	18.244	15.963	1.642	27.367	40.482	35.420
7	0.689	9.845	14.563	12.742	1.505	21.500	31.804	27.827
8	0.650	8.125	12.020	10.516	1.407	17.587	26.017	22.763
9	0.623	6.917	10.233	8.953	1.333	14.811	21.911	19.170
10	0.600	6.000	8.877	7.766	1.275	12.750	18.863	16.504
11	0.579	5.262	7.785	6.811	1.228	11.166	16.520	14.454
12	0.560	4.667	6.905	6.041	1.190	9.914	14.668	12.833
13	0.544	4.188	6.197	5.421	1.157	8.902	13.172	11.524
14	0.531	3.795	5.616	4.913	1.130	8.068	11.938	10.445
15	0.520	3.467	5.130	4.488	1.106	7.371	10.907	9.542
16	0.510	3.187	4.717	4.126	1.085	6.779	10.031	8.776
17	0.501	2.947	4.362	3.816	1.066	6.271	9.280	8.119
18	0.493	2.740	4.055	3.547	1.049	5.830	8.628	7.548
19	0.486	2.559	3.787	3.313	1.035	5.445	8.058	7.050

U^{235} (wt%)	Safe Mass (kg)				Critical Mass (kg)			
	U^{235}	Uranium	UF ₆	UO ₂ F ₂	U^{235}	Uranium	UF ₆	UO ₂ F ₂
20	0.480	2.400	3.552	3.107	1.021	5.105	7.556	6.610
21	0.475	2.260	3.345	2.926	1.009	4.803	7.109	6.219
22	0.470	2.135	3.160	2.765	0.997	4.533	6.710	5.870
23	0.465	2.023	2.995	2.620	0.987	4.291	6.352	5.556
24	0.461	1.922	2.845	2.489	0.977	4.072	6.028	5.273
25	0.457	1.830	2.708	2.369	0.968	3.873	5.734	5.016
26	0.454	1.745	2.584	2.260	0.960	3.692	5.466	4.782
27	0.450	1.667	2.469	2.159	0.952	3.527	5.222	4.568
28	0.447	1.596	2.362	2.066	0.945	3.375	4.997	4.371
29	0.443	1.529	2.264	1.980	0.938	3.235	4.790	4.190
30	0.440	1.467	2.172	1.900	0.932	3.106	4.599	4.023
31	0.437	1.409	2.086	1.824	0.926	2.986	4.422	3.868
32	0.433	1.354	2.005	1.754	0.920	2.875	4.257	3.724
33	0.430	1.303	1.930	1.688	0.915	2.772	4.104	3.590
34	0.427	1.256	1.859	1.626	0.909	2.675	3.961	3.465
35	0.424	1.211	1.793	1.568	0.905	2.585	3.828	3.348
36	0.421	1.169	1.731	1.514	0.900	2.500	3.702	3.238
37	0.418	1.130	1.673	1.463	0.896	2.420	3.585	3.135
38	0.415	1.093	1.618	1.415	0.891	2.345	3.474	3.038
39	0.413	1.058	1.567	1.370	0.887	2.275	3.370	2.947
40	0.410	1.025	1.518	1.328	0.883	2.208	3.271	2.861
41	0.408	0.994	1.473	1.288	0.880	2.146	3.178	2.780
42	0.405	0.965	1.430	1.250	0.876	2.086	3.090	2.703
43	0.403	0.938	1.389	1.215	0.873	2.030	3.007	2.630
44	0.401	0.912	1.350	1.181	0.869	1.976	2.927	2.560
45	0.399	0.887	1.314	1.149	0.866	1.925	2.852	2.494
46	0.397	0.863	1.279	1.119	0.863	1.877	2.780	2.431
47	0.395	0.841	1.246	1.090	0.860	1.830	2.712	2.372
48	0.393	0.820	1.215	1.062	0.857	1.786	2.647	2.315
49	0.392	0.799	1.185	1.036	0.855	1.744	2.585	2.260
50	0.390	0.780	1.156	1.011	0.852	1.704	2.525	2.208
51	0.388	0.761	1.128	0.987	0.849	1.666	2.468	2.158
52	0.387	0.744	1.102	0.964	0.847	1.629	2.414	2.111
53	0.385	0.727	1.077	0.942	0.845	1.593	2.362	2.065

Final Report

June 1994

Minimum Critical Masses for Uranium at the
Portsmouth Gaseous Diffusion Plant

Page 16

U^{235} (wt%)	Safe Mass (kg)				Critical Mass (kg)			
	U^{235}	Uranium	UF_6	UO_2F_2	U^{235}	Uranium	UF_6	UO_2F_2
54	0.384	0.710	1.053	0.921	0.842	1.560	2.312	2.021
55	0.382	0.695	1.030	0.900	0.840	1.527	2.263	1.979
56	0.381	0.680	1.008	0.881	0.838	1.496	2.217	1.939
57	0.379	0.665	0.986	0.862	0.836	1.466	2.173	1.900
58	0.378	0.651	0.966	0.844	0.833	1.437	2.130	1.863
59	0.377	0.638	0.946	0.827	0.831	1.409	2.089	1.827
60	0.375	0.625	0.927	0.811	0.829	1.382	2.049	1.792
61	0.374	0.613	0.909	0.795	0.827	1.356	2.011	1.758
62	0.373	0.601	0.891	0.779	0.826	1.332	1.974	1.726
63	0.372	0.590	0.874	0.765	0.824	1.307	1.939	1.695
64	0.370	0.579	0.858	0.750	0.822	1.284	1.904	1.665
65	0.369	0.568	0.842	0.737	0.820	1.262	1.871	1.636
66	0.368	0.558	0.827	0.723	0.818	1.240	1.839	1.608
67	0.367	0.548	0.813	0.711	0.817	1.219	1.808	1.581
68	0.366	0.538	0.799	0.698	0.815	1.199	1.778	1.554
69	0.365	0.529	0.785	0.686	0.813	1.179	1.748	1.529
70	0.364	0.520	0.772	0.675	0.812	1.160	1.720	1.504
71	0.363	0.512	0.759	0.664	0.810	1.141	1.693	1.480
72	0.362	0.503	0.747	0.653	0.809	1.123	1.666	1.457
73	0.362	0.495	0.735	0.642	0.807	1.106	1.640	1.434
74	0.361	0.488	0.723	0.632	0.806	1.089	1.615	1.412
75	0.360	0.480	0.712	0.622	0.804	1.073	1.591	1.391
76	0.359	0.473	0.701	0.613	0.803	1.057	1.567	1.370
77	0.358	0.466	0.691	0.604	0.802	1.041	1.545	1.350
78	0.358	0.459	0.681	0.595	0.800	1.026	1.522	1.331
79	0.357	0.452	0.671	0.586	0.799	1.011	1.500	1.312
80	0.356	0.446	0.661	0.578	0.798	0.997	1.479	1.293
81	0.356	0.439	0.652	0.570	0.796	0.983	1.459	1.275
82	0.355	0.433	0.643	0.562	0.795	0.970	1.439	1.258
83	0.355	0.427	0.634	0.554	0.794	0.956	1.419	1.241
84	0.354	0.422	0.626	0.547	0.793	0.944	1.400	1.224
85	0.354	0.416	0.617	0.540	0.791	0.931	1.382	1.208
86	0.353	0.410	0.609	0.533	0.790	0.919	1.364	1.192
87	0.353	0.405	0.601	0.526	0.789	0.907	1.346	1.176

Final Report

June 1994

Minimum Critical Masses for Uranium at the
Portsmouth Gaseous Diffusion Plant

Page 17

U^{236} (wt%)	Safe Mass (kg)				Critical Mass (kg)			
	U^{236}	Uranium	UF_6	UO_2F_2	U^{236}	Uranium	UF_6	UO_2F_2
88	0.352	0.400	0.594	0.519	0.788	0.895	1.329	1.161
89	0.352	0.395	0.586	0.513	0.787	0.884	1.312	1.147
90	0.351	0.390	0.579	0.506	0.786	0.873	1.296	1.132
91	0.351	0.385	0.572	0.500	0.784	0.862	1.280	1.118
92	0.350	0.381	0.565	0.494	0.783	0.851	1.264	1.105
93	0.350	0.376	0.559	0.488	0.782	0.841	1.249	1.091
94	0.350	0.372	0.553	0.483	0.781	0.831	1.234	1.078
95	0.350	0.368	0.547	0.478	0.780	0.821	1.219	1.066
96	0.350	0.365	0.541	0.473	0.779	0.812	1.205	1.053
97	0.350	0.361	0.536	0.468	0.778	0.802	1.191	1.041
98	0.350	0.357	0.530	0.463	0.777	0.793	1.177	1.029
99	0.350	0.354	0.525	0.459	0.776	0.784	1.164	1.017
100	0.350	0.350	0.520	0.454	0.775	0.775	1.151	1.006

Final Report

June 1994

*Minimum Critical Masses for Uranium at the
Portsmouth Gaseous Diffusion Plant*

Page 18
