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NUCLEAR SAFETY OF THE TEN-WELL INSERT FOR THE SRP FUEL ELEMENT DISSOLVER

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PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION UNDER CONTRACT AT(07-2)-1

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ABSTRACT

Mass limits are developed and presented for safe dissolution of fissile materials in the Ten-Well Insert, an improved device for limiting the configuration of fuel in SRP dissolvers. This insert permits high-capacity dissolution of SRP fuels, offsite fuels, and scrap fissile materials with adequate margins of nuclear safety. Limits were developed by calculating the safe (subcritical) mass per well as a function of the concentration of fissile material in the dissolver solution. Safe mass values were then selected for use as well-loading limits so as to ensure subcriticality throughout the dissolution.

Well-loading limits are presented for uranium metal, uranium-aluminum alloy, U_3O_8-aluminum cermet, plutonium-aluminum alloy, and uranium-plutonium-aluminum alloy. With these limits, the maximum k_{eff} is 0.95.

Nuclear safety is maintained in process operations by:

1. Conforming to well-loading limits calculated from the safe mass values.

2. Conforming to dissolver-loading limits established prior to this work and applicable to the SRP dissolver in use.

3. Maintaining the concentration of fissile material in solution below 4.0 g/l.

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NUCLEAR SAFETY OF THE TEN-WELL INSERT FOR THE SRP FUEL ELEMENT DISSOLVER

INTRODUCTION

Nuclear Safety Considerations

For large-scale chemical processing of fissile material, criticality must be avoided by a substantial margin. In general, subcritical conditions may be ensured by concentration control, batch size (mass) limitations, or by designing equipment of geometrically favorable configuration.[1] Combinations of these techniques provide the redundancy of control necessary to protect against accidental violation of operating limits through procedural or calculational errors.

At the Savannah River Plant (SRP), nuclear safety in chemical processing must be maintained by control of concentration and batch size because the vessels are not of critically-safe dimensions. Nuclear safety analyses are made for each process step before processing may begin, usually on the "worst case" basis, i.e., detailed calculations are made to ensure that no foreseeable combination of conditions can lead to criticality in the process.

In the design and operation of SRP process fuel dissolvers, nuclear safety is ensured by control of fissile material configuration, by mass limits, and by concentration control.[1] A safe configuration of irradiated nuclear fuel elements is achieved by placing the fuel elements in a device within the dissolver, called an insert. The fuel is confined within this insert during dissolution. Safe concentration and batch size limits are significantly increased by confining the undissolved fuel in this manner, so that dissolver throughput is enhanced. Also, residual undissolved fuel is more readily detectable.

This report describes the derivation of the special nuclear safety limits for one of these configuration-limiting devices, the Ten-Well Insert. This insert contains ten separate cylindrical wells for charging irradiated fuel elements to SRP dissolvers. The nuclear safety limits were selected to maximize dissolver throughput while conforming to accepted standards of nuclear safety.

Dissolution of Fuel Elements

Details of the dissolution of aluminum-clad enriched uranium fuels at SRP are reported elsewhere.[2] In general, packaged fuel elements are loaded into an insert within a process dissolver (Figure 1) where the elements are dissolved in a boiling solution of nitric acid containing mercuric nitrate as a catalyst. Most such fuels are dissolved at SRP in a rectangular insert that provides some separation of the fuel packages (Figure 2a). The SRP fuels are packaged (bundled) in a slab configuration, one element thick (Figure 2b). The rectangular insert can receive up to four fuel bundles.

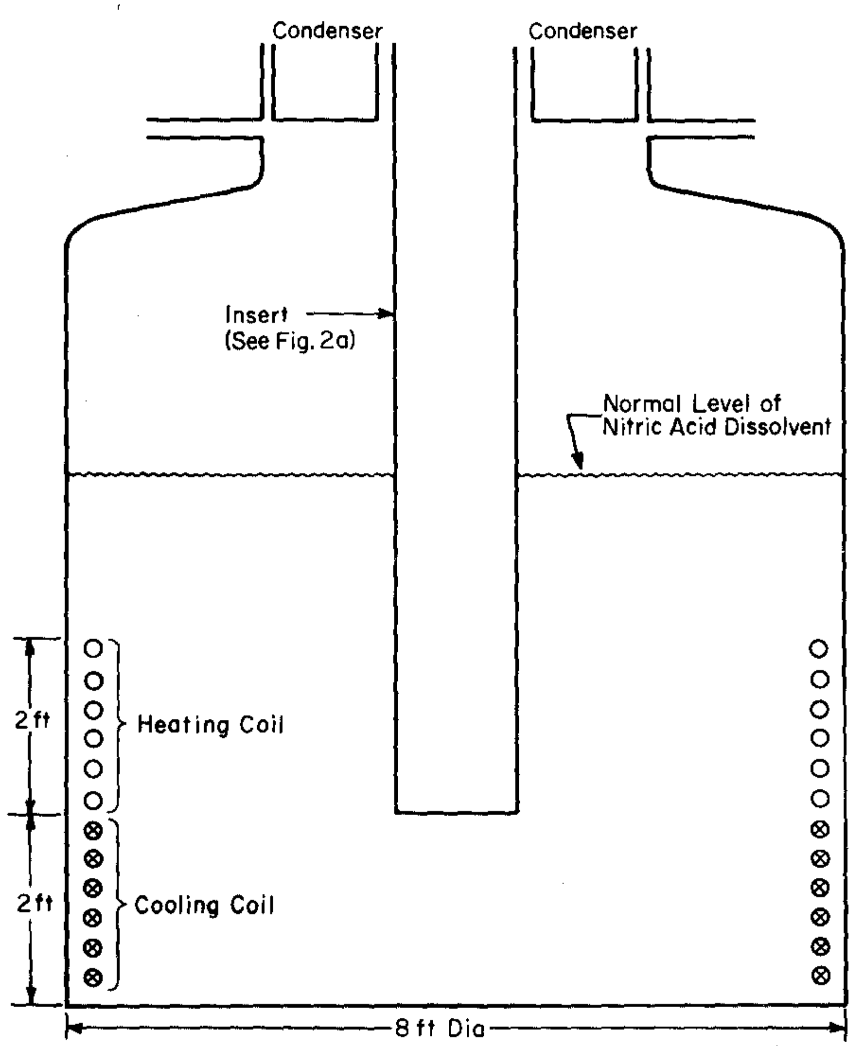
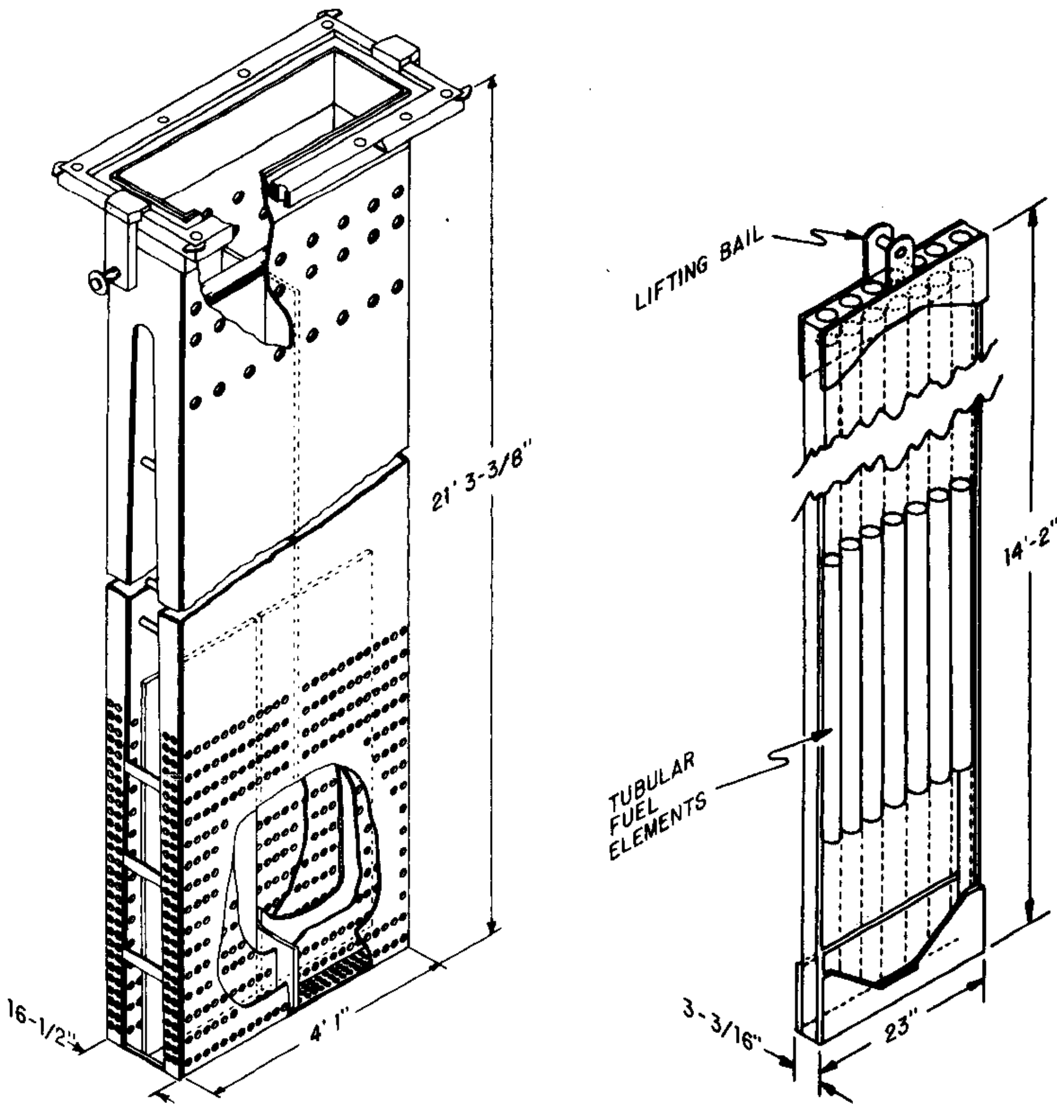


FIGURE 1. Schematic of SRP Dissolver



a. Insert for 4 SRP Enriched Uranium Bundles.

b. SRP Enriched Uranium Fuel Element Bundle.

FIGURE 2. Dissolver Insert and Fuel Element Bundle for SRP Enriched Uranium Fuel Elements

A special multi-well insert, the Ten-Well Insert that is the subject of this report, was designed and constructed for dissolving fuel elements from the Piqua Reactor, because the Piqua fuel elements were too large to fit into existing rectangular SRP dissolver inserts. The Ten-Well Insert was also designed for dissolving various other offsite fuels, such as the Materials Test Reactor (MTR) fuels. For many such fuels, the configuration of the Ten-Well Insert reduces the dependence on administrative controls without reducing the margins of safety.

The Ten-Well Insert (Figure 3) is a 2 x 5 array of 18-foot-deep cylindrical wells. Each well is 5.5 inches in inner diameter, and is constructed of 304L stainless steel, perforated to permit circulation of the dissolvent. Measurement of small volumes of fuel fragments is facilitated by a 6 x 2.5-inch-inner diameter extension (foot) on the bottom end of each well. A typical package of fuel elements for charging to one of the ten wells is shown in Figure 4. For the Ten-Well Insert, the design parameters of greatest importance to nuclear safety calculations are the spacing of the wells and the dimensions of each cylindrical well.

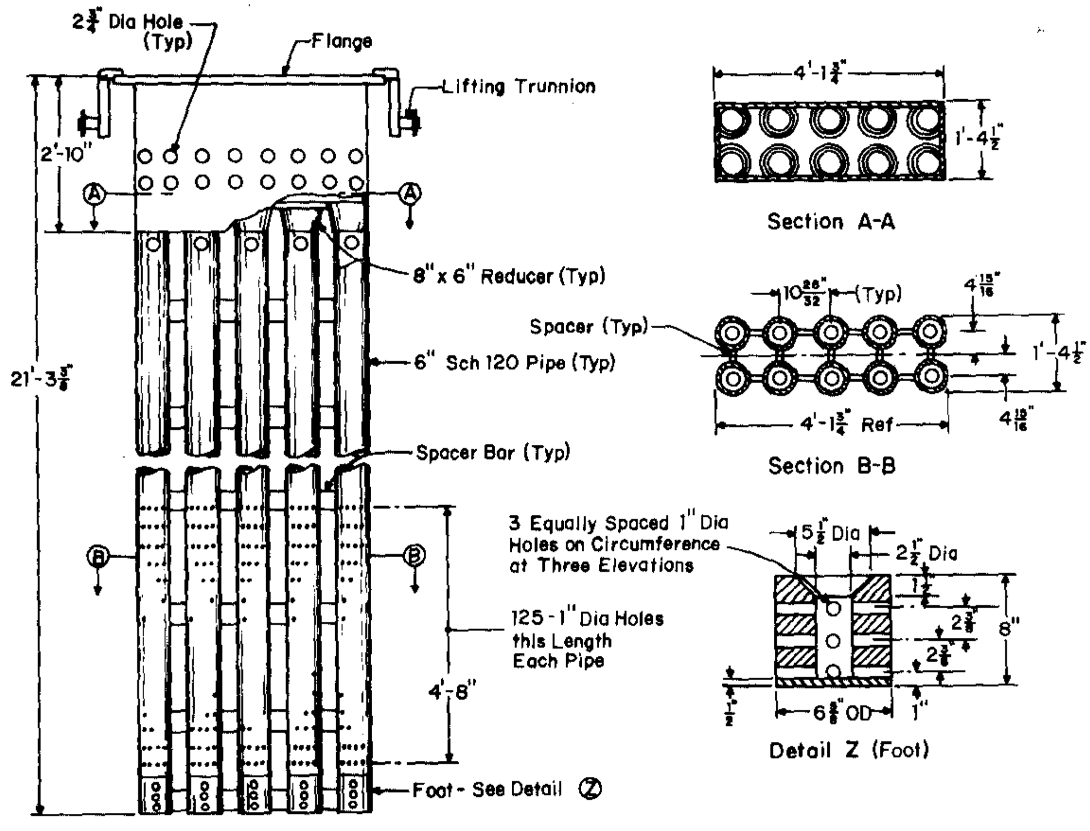


FIGURE 3. Ten-Well Insert

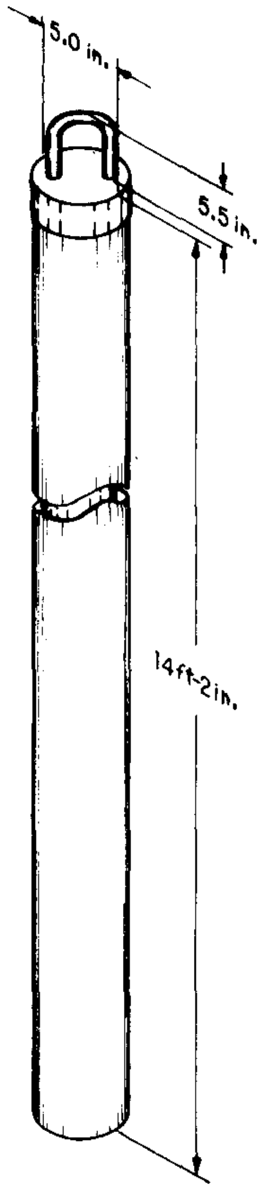


FIGURE 4. General-Purpose Fuel Element Bundle for Ten-Well Insert

Computer calculations, with well-established neutron multiplication codes, determined safe mass-concentration values in spaced cylindrical geometry. Graphical analysis of the results determined limits for dissolver loading that were safe throughout the dissolution. The computer calculations used two codes that have been extensively correlated with experimental measurements: the Multigroup Buckling Code (MGBS)[3] and the Two-Group Analytical Code (TGAN).[3] A Monte Carlo code, KENO,[4] corroborated the results obtained from MGBS and TGAN.

SAFE MASS CALCULATIONS

Mass Limits for the Dissolver Vessel

Mass limits for fissile material (see Glossary) in fuel or in solution were established previously for each of the two SRP dissolvers. An overall dissolver limit is imposed to limit the total quantity of fissile material present in the vessel in any form. This dissolver mass limit, called the "pot limit," (see Glossary) maintains a safe concentration of fissile material in the dissolver in any case of accidental overevaporation of its contents. This pot limit applies to the dissolver regardless of which of the several SRP inserts is in use.

Solution volume could be appreciably reduced by evaporation if the condenser cooling water supply were lost and the dissolver solution continued to boil. This situation would normally not occur because instrument interlocks should shut off the steam supply to the dissolver coils and because several indications of an abnormal situation should be observed. The dissolver operator would be alerted by high off-gas temperature, decreasing solution level, and increasing specific gravity of the solution. Should overevaporation occur in spite of these safeguards, the dissolver design prevents evaporation below a fixed volume. Dissolver steam service is connected only to the upper coils, the bottoms of the coils are about 24 inches above the bottom of the dissolver (Figure 1). Evaporation ceases when the solution level is below the upper coils, at which time 4400 liters would remain in the large SRP dissolver, and 2200 liters would remain in the smaller SRP dissolver.

The subcritical concentrations of fissile material on which the pot limits are based are those approved by the American National Standards Institute (ANSI).[5] These limits and the pot limits for the two SRP chemical dissolvers are given in Table 1. For mixtures of plutonium and uranium, the concept of "equivalent ^{239}Pu" simplifies calculation and application of pot limits for materials of various uranium-to-plutonium weight ratios (U/Pu):

$$\text{Equivalent } ^{239}\text{Pu} = {}^{239}\text{Pu} + {}^{241}\text{Pu} + 0.625\ {}^{235}\text{U}$$

This definition is conservative where $^{240}\text{Pu} \gtrsim 1.2\ ^{241}\text{Pu}$. The maximum equivalent ^{239}Pu concentration allowed at SRP is 6.75 g/l in lieu of an approved ANSI limit[5] or a measured subcritical concentration limit.

Scoping Calculations for Multi-Well Insert Designs

Safe mass values (see Glossary) for fissile material in the wells of the Ten-Well Insert were derived in two phases. First, scoping calculations were made to establish the optimum number of wells for the available space in the dissolver opening and to demonstrate that charging limits for the wells would be compatible with fuels scheduled for processing at SRP. These calculations considered only enriched uranium (93% ^{235}U) in the form of uranium-aluminum alloy.

The second phase involved calculation of safe mass values for other fuel forms, such as plutonium alloys, over a wider range of fissile material concentrations, both in the fuel and in the solution.

The wells must be contained within a rectangular space that could not exceed 42 x 126 cm (16-1/2 x 49-3/4 inches), the limiting dimensions of the dissolver opening. Because mass limits increase with increasing distance between wells, the wells were set as far apart as possible within the limiting rectangle. Scoping calculations, described below, were then made for arrays of wells whose nominal outer diameters were tangent to the edges of the limiting rectangle. Each well was to be constructed of 6-inch-diameter, Schedule 120, 304L stainless-steel pipe. To allow for pipe tolerances and process corrosion of the walls of the pipe, the nominal inner diameter (5.501 inches) for the pipe was increased by 0.635 cm (1/4 inch), and the nominal outer diameter (6.625 inches) was decreased by the same amount. The resulting dimensions (Table 2) were used for scoping calculations. Scoping calculations were then repeated for wells 0.635 cm (1/4 inch) closer together in both directions to allow for fabrication tolerances.

The scoping calculations established that a 2 x 5 rectangular array of ten wells would meet SRP process requirements and would simplify dissolver-charging limits for many offsite fuels processed at SRP, including the Piqua fuel. The safe mass values, summarized in Table 3, show that no well limit (see Glossary) will be required for fuels containing as much as 25% uranium in the U-Al alloy. Because most MTR fuels contain less than 25% uranium in the U-Al alloy and because dissolution of MTR fuel elements (assemblies) results in solutions containing less than 4 g U/l, Table 3 imposes no limit on the number of these fuel assemblies charged to the insert. Consequently, the amount of such fuel charged would be limited by other considerations, such as aluminum solubility, rather than by nuclear safety limits.

The Multigroup Buckling Code (MGBS)[3] was used to calculate two-group parameters[6] for a series of metal-to-water volume ratios

TABLE 1

Maximum Fissile Material Limits in SRP Dissolvers

Fissile Element	*Subcritical Concentration Limit, g/l*	*Mass Limit, kg*[b] *Small Dissolver*	*Large Dissolver*
^{235}U	11.5	25.3	50.6
^{239}Pu	7.0	15.4	30.8
Equivalent ^{239}Pu[a]	6.75	14.8	29.7

a. Equivalent $^{239}Pu = {}^{239}Pu + {}^{241}Pu + 0.625\ {}^{235}U$ where $^{240}Pu > 1.2\ {}^{241}Pu$.

b. Mass Limit

Small SRP Dissolver: (2200 liters) • (ANSI subcritical concentration limit)

Large SRP Dissolver: (4400 liters) • (ANSI subcritical concentration limit)

TABLE 2

Limiting Dimensions for a Ten-Well Insert

	Each Well	*Array* *2 × 4*	*2 × 5*
Maximum Inner Radius, cm (in.)	7.3 (2-7/8)	-	-
Minimum Wall Thickness, cm (in.)	0.79 (5/16)	-	-
Minimum Bottom Plate Thickness, cm (in.)	0.64 (1/4)	-	-
Maximum Open Area, %	15.0	-	-
Nominal Center-to-Center Spacing:[a]			
Width, cm (in.)	-	25.08 (9-7/8)	25.08 (9-7/8)
Length, cm (in.)	-	36.52 (14-3/8)	27.39 (10-3/4)

a. Maximum consistent with the allowed rectangle.

TABLE 3

Safe Mass Values for a 2 x 5 Array of Wells Containing ^{235}U Solutions

U in Solution, g/l	*Well Spacing →*	*Safe Mass of ^{235}U per Well, kg* *40 wt % U* *Nominal*	*-1/4 inch*	*35 wt % U* *Nominal*	*-1/4 inch*	*30 wt % U* *Nominal*	*-1/4 inch*	*25 wt % U* *Nominal*	*-1/4 inch*
0		∞	6.98	∞	∞	∞	∞	∞	∞
2		3.30	2.74	7.44	4.43	∞	∞	∞	∞
4		2.02	1.79	2.57	2.21	4.65	3.42	∞	∞

and alloy compositions. Typical material bucklings[6] (B^2_m) and migration areas[6] (M^2) for various alloys are given in Table 4. Two-group parameters were also obtained for the well wall, for water, and for dilute uranium solutions. Fuels were represented in the wells by homogeneous mixtures of UO_2, aluminum, and water. The mathematical treatment is conservative because the presence of nitric acid (a neutron absorber) was ignored. Uranium was assumed to be enriched to 93% ^{235}U. Alloy composition was varied from 20% uranium - 80% aluminum to 40% uranium - 60% aluminum in steps of 5% (Table 4).

The two-group parameters from MGBS were then used with the Two-Group Analytical Code (TGAN)[3] to calculate extrapolation distances[6] for insert wells. TGAN is a one-dimensional code and cannot be used to calculate a finite array of cylindrical wells. However, TGAN can be used for a finite array of slabs where the cylindrical wells are treated as square wells having the same cross-section and wall thickness. To calculate the average extrapolation distance of a squared well in one dimension, the lines of wells perpendicular to that dimension were represented as infinite slabs.

Replacing cylindrical wells with square wells is slightly non-conservative. Comparison calculations for 40% alloy in single square and cylindrical wells of the same cross-section show that the square wells are less reactive by 0.005 k_{eff} in water and up to 0.02 k_{eff} in 4 g U/1 solution. However, data correlating critical experiments and calculations with MGBS-TGAN for ^{235}U in water[3] show that the calculations give k_{eff} values of at least 1.04 for a critical sphere at the $H/^{235}U$ atom ratios for which the minimum well masses occurred ($H/^{235}U$ = 90 to 130). Safe limits corresponding to k_{eff} = 0.95 for the squared-well calculations are therefore considered to have a margin of safety of at least 0.07.*

With data obtained from MGBS and TGAN, the mass of uranium was calculated as a function of k_{eff} for each metal-to-water ratio.[7] The results were graphed, and the minimum masses were found from a cross plot of mass vs. metal-to-water ratio at constant k_{eff}. These minima (Table 3) gave a calculated k_{eff} of 0.95 and represent a mass that is safe in each of the ten wells of the insert regardless of the metal-to-water ratio.

Other well configurations were examined with KENO, a Monte Carlo code,[4] to determine the conservatism in the MGBS-TGAN results. These configurations were scaled to fit the rectangular

* 1.04 - 0.02 - 0.95

TABLE 4

Material Buckling (B^2m) and Migration Areas (M^2) for Homogeneous U-Al Alloy-Water Mixtures

Metal/Water	*20 wt % U*		*25 wt % U*		*30 wt % U*		*35 wt % U*		*40 wt % U*	
Volume Fraction	B^2m	M^2	B^2m	M^2	B^2m	M^2	B^2m	M^2	B^2m	M^2
0.30	0.021088	41.11	0.020738	40.06	0.021064	39.06	0.020764	39.29	-	-
0.25	0.021578	38.27	0.022360	37.40	0.022848	36.58	0.023158	35.79	0.023348	35.02
0.20	0.022573	35.83	0.023688	35.10	0.024421	34.47	0.024916	33.77	0.025244	33.14
0.18	0.022782	34.98	0.024068	34.27	-	-	0.025529	33.04	0.025937	32.46
0.16	0.022823	34.18	0.024317	33.51	0.025328	32.91	0.026052	32.36	0.026560	31.88
0.14	0.022634	33.46	0.024373	32.81	0.025570	32.25	0.026441	31.73	0.027072	31.24
0.12	0.022106	32.82	0.024147	32.19	0.025578	31.65	0.026628	31.16	0.027417	30.70
0.10	0.021078	32.30	0.023478	31.66	0.025215	31.13	0.026505	30.66	0.027484	30.23
0.08	0.019267	31.92	0.022138	31.26	0.024246	30.73	0.025852	30.27	0.027101	29.65
0.06	0.016146	31.78	0.019574	31.07	0.022182	30.51	0.024220	30.04	0.025849	29.62

space of the dissolver. A 2 x 6 well-array resulted in inconveniently small mass limits, even in water. Although a 2 x 4 array resulted in larger mass limits than a 2 x 5 array, the physical dimensions of the anticipated fuels precluded taking full advantage of these larger limits. Consequently, the 2 x 5 array design (the Ten-Well Insert) was chosen because it permits the maximum dissolving capacity with an adequate margin of safety.

KENO calculations demonstrated sufficient conservatism in the basic MGBS-TGAN results: KENO yielded k_{eff} values at least 0.05 below the MGBS-TGAN values for solution concentrations as high as 4 g U/l.

Safe Mass Calculations for the Ten-Well Insert

After the Ten-Well Insert was constructed on the basis of the scoping calculations, safe mass per well limits were calculated for uranium metal, U-Al alloys, and U_3O_8-Al cermets (Table 5); for Pu-Al alloys (Table 6); and for U-Pu-Al alloys (Tables 7 and 8). These more-detailed calculations used the same methods and codes discussed above for the scoping calculations, but covered a full range of compositions.

Assumptions

Safe mass values per well were calculated for bulk solution concentrations from 0 to 4 grams of fissile material per liter. Fissile material is defined as ^{235}U + ^{239}Pu + ^{241}Pu (see Glossary). Uranium was assumed to be enriched to 93.5% ^{235}U. It was also assumed that $^{240}Pu \geqslant 1.2\ ^{241}Pu$. Composition and density data are given in Table 9. As in the scoping calculations, the distance between well centers was 1/4 inch less than the design value.

In the scoping calculations, all ten wells were assumed to contain fuel. Other charging arrangements were calculated because well limits increase if the space between charged wells is increased by leaving some wells empty. With the second and fourth pairs of wells empty, three isolated pairs of wells are produced. With one well of each of these isolated pairs empty, there are three isolated wells (Figure 5).

Based on previous experimental results, a cermet was assumed to dissolve in the same manner as the metal alloys.[7] Other specific assumptions were:

1. The entire charge is in the form of declad fragments, which may have any packing density.

TABLE 5

Safe Masses for Uranium Metal, U-Al Alloys, and U_3O_8-Al Cermets

Concentration, ^{235}U g/l	*Safe Mass ^{235}U, kg/Well*[a,b] *U Metal*	*50 wt % U*	*45 wt % U*	*40 wt % U*	*35 wt % U*	*30 wt % U*
All Wells, 2 × 5 Array						
0	1.29	2.09	2.46	3.25	7.10	∞
1	1.18	1.77	2.00	2.42	3.50	∞
2	1.08	1.53	1.68	1.95	2.45	4.37
3	1.00	1.33	1.44	1.60	1.92	2.67
4	0.93	1.17	1.26	1.37	1.57	1.98
Isolated Pair, 1 × 2 Array						
0	1.63	3.85	6.75	∞	∞	∞
1	1.50	3.00	4.10	13.0	∞	∞
2	1.39	2.47	3.10	4.80	∞	∞
3	1.29	2.08	2.45	3.30	7.50	∞
4	1.19	1.80	2.05	2.50	3.85	∞
Isolated Well						
0	2.08	∞	∞	∞	∞	∞
1	1.92	14.0	∞	∞	∞	∞
2	1.78	5.90	∞	∞	∞	∞
3	1.65	4.10	7.85	∞	∞	∞
4	1.52	3.22	4.60	∞	∞	∞

a. May be used for uranium containing not more than 1 wt % plutonium.

b. Interpolation is permitted where there are sufficient points to establish a curve.

TABLE 6

Safe Masses for Pu-Al Alloys

Concentration, ^{239}Pu equiv. g/l	*Safe Mass ^{239}Pu Equivalent, kg/Well*[a,b]					
	50 wt % Pu	*45 wt % Pu*	*40 wt % Pu*	*35 wt % Pu*	*30 wt % Pu*	*25 wt % Pu*
<u>All Wells, 2 × 5 Array</u>						
0	1.56	1.70	1.98	2.65	5.10	∞
1	1.16	1.24	1.36	1.67	2.00	3.05
2	0.91	0.95	1.02	1.12	1.28	1.52
3	0.74	0.76	0.79	0.85	0.93	1.04
4	0.61	0.63	0.65	0.68	0.72	0.77
<u>Isolated Pairs, 1 × 2 Array</u>						
0	2.90	3.90	8.35	∞	∞	∞
1	2.00	2.31	3.02	7.00	∞	∞
2	1.50	1.65	1.92	2.45	4.70	
3	1.18	1.26	1.39	1.61	2.10	4.00
4	0.95	1.02	1.10	1.21	1.40	1.72
<u>Isolated Wells</u>						
0	∿12.0	∞	∞	∞	∞	∞
1	4.85	∿15.0	∞	∞	∞	∞
2	2.98	4.10	9.70	∞	∞	∞
3	2.10	2.40	2.99	5.30	∞	∞
4	1.57	1.75	2.08	2.90	6.65	∞

a. ^{239}Pu equivalent = ^{239}Pu + ^{241}Pu; ^{240}Pu ⩾1.2 × ^{241}Pu.

TABLE 7

Safe Masses for U-Pu-Al Alloys with U/Pu of 1.0

Fissile Material Conc., g/l	*Safe Mass Fissile Material, kg/Well*[a,b] *50 wt % U + Pu*	*45 wt % U + Pu*	*40 wt % U + Pu*	*35 wt % U + Pu*	*30 wt % U + Pu*	*25 wt % U + Pu*
All Wells, 2 × 5 Array						
0	1.94	2.24	2.84	5.00	∞	∞
1	1.45	1.61	1.85	2.40	4.33	∞
2	1.15	1.23	1.35	1.56	2.00	3.50
3	0.94	1.00	1.06	1.18	1.36	1.72
4	0.78	0.82	0.85	0.92	1.00	1.15
Isolated Pairs, 1 × 2 Array						
0	4.40	∿10.0	∞	∞	∞	∞
1	2.80	4.00	8.15	∞	∞	∞
2	2.07	2.39	3.25	7.20	∞	∞
3	1.57	1.70	1.98	2.83	11.50	∞
4	1.27	1.38	1.54	1.89	2.67	∞
Isolated Wells						
0	∞	∞	∞	∞	∞	∞
1	∞	∞	∞	∞	∞	∞
2	5.90	∞	∞	∞	∞	∞
3	3.45	7.0	∞	∞	∞	∞
4	2.41	3.05	4.65	∞	∞	∞

a. Fissile material = $^{235}U + ^{239}Pu + ^{241}Pu$; $^{240}Pu \geq 1.2 \times ^{241}Pu$.

b. Wt ratio U/Pu = 1.0.

TABLE 8

Safe Masses for U-Pu-Al Alloys with U/Pu of 3.0

Fissile Material Conc., g/l	Safe Mass Fissile Material, kg/Well[a,b] 50 wt % U + Pu	45 wt % U + Pu	40 wt % U + Pu	35 wt % U + Pu	30 wt % U + Pu	25 wt % U + Pu
All Wells, 2 × 5 Array						
0	2.15	2.55	3.40	∿7.5	∞	∞
1	1.67	1.90	2.24	3.35	∿15.0	∞
2	1.37	1.48	1.66	2.02	3.00	∞
3	1.12	1.20	1.32	1.52	1.87	2.85
4	0.95	0.99	1.06	1.17	1.36	1.77
Isolated Pairs, 1 × 2 Array						
0	4.94	∞	∞	∞	∞	∞
1	3.25	5.00	∞	∞	∞	∞
2	2.42	3.03	4.60	∞	∞	∞
3	1.90	2.20	2.82	5.00	∞	∞
4	1.57	1.76	2.05	2.85	6.80	∞
Isolated Wells						
0	∞	∞	∞	∞	∞	∞
1	∞	∞	∞	∞	∞	∞
2	8.70	∞	∞	∞	∞	∞
3	4.45	∞	∞	∞	∞	∞
4	3.06	∿5.7	∿20.0	∞	∞	∞

a. Fissile material = $^{235}U + ^{239}Pu + ^{241}Pu$; $^{240}Pu \geqslant 1.2 \times ^{241}Pu$.

b. Wt ratio U/Pu = 3.0.

TABLE 9

Composition and Density of Fissile Materials

Fissile Material[a,b]	*Composition, wt %*	*Density, g/cm*^{3}
U Metal	93.5 ^{235}U-6.5 ^{238}U	18.8
U-Al Alloy	50 U	4.514
	45 U	4.230
	40 U	3.979
	35 U	3.757
	30 U	3.558
U-Pu-Al Alloy		
U/Pu = 1.0	25 U-25 Pu	5.046
	20 U-20 Pu	4.261
	15 U-15 Pu	3.686
U/Pu = 3.0	37.5 U-12.5 Pu	4.644
	30 U-10 Pu	4.045
	22.5 U-7.5 Pu	3.597
Pu-Al Alloy	50 Pu	4.752
	45 Pu	4.417
	40 Pu	4.125
	35 Pu	3.870
	30 Pu	3.644
	25 Pu	3.444
U_3O_8-Al Cermet[c]	50 U	4.505
	45 U	4.223
	40 U	3.974
	35 U	3.752
	30 U	3.555

a. All U is 93.5 wt % ^{235}U-6.5 wt % ^{238}U.

b. All Pu is 100 ^{239}Pu; ρ(Pu) = 19.6 g/cm^3.

c. 50 wt % U, not 50 wt % U_3O_8; $\rho(U_3O_8)$ = 8.39 g/cm^3.

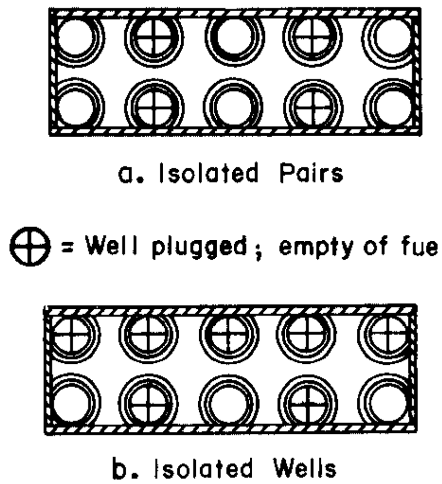


FIGURE 5. Alternative Charging Arrangements for Bundles in the Ten-Well Insert

2. The dissolver contains water or, if several charges were co-dissolved, the dissolver would contain ^{235}U at a concentration determined by assuming all previous charges had dissolved completely.

3. Solution depth is sufficient to immerse completely the entire column of fragments at the worst (most reactive) density.

4. Residual fragments from preceding dissolutions are at the bottom of the well. They may have any packing density but will not expand once compacted.

5. The mass of fissile material in the form of fragments outside the insert is insignificant.

6. Fissile material and aluminum in the fuel core dissolve at the same rate.

The dissolving model based on the above assumptions differs from the model previously used for tubular fuels in the rectangular insert.[7] The older model had to be modified to reflect a fundamental difference in the way tubular elements and plate-type (MTR) fuels dissolve. MTR fuel plates are held together by an aluminum supporting structure which may dissolve before any chemical attack on uranium begins. The freed fuel plates are then able to fall randomly into any array allowed by the insert.

The entire charge is then conservatively assumed to collapse as a random array of small alloy fragments that assumes the geometry and dimensions of the bottom of the insert. (Assumption 1 is even more conservative for tubular fuel elements, which do not lose their shapes or collapse until the core material becomes very thin.[2,7]) A random array of small fragments at the bottom of the insert is more reactive than any combination of plates, tubes, and fragments. The conservatism inherent in these assumptions permits the limits to be applied also to scrap materials of undefined shapes, such as pieces of fuel elements cut for postirradiation examination.

Results

Calculated safe mass limits for U-Al alloys and U_3O_8-Al cermets are compared in Table 10; these safe masses are virtually identical for a given weight percent of total uranium in the fuel. Table 10 also compares slightly nonconservative calculations, in which concentrations were determined from the metallic alloy where the uranium was treated as UO_2 in the homogenized fuel regions (as done for the scoping calculations). The difference in k_{eff} is only 0.002 to 0.003.

TABLE 10

Comparison of Safe-Mass Limits for Alloy and Cermets[a]

	Safe Mass ^{235}U, *kg/Well*					
Fuel:	*U-Al, U as Metal*[b]		*U_3O_8-Al*		*U-Al, U as UO_2*[c]	
Array:	*1 × 2*	*2 × 5*	*1 × 2*	*2 × 5*	*1 × 2*	*2 × 5*
^{235}U g/l:						
0	3.99	2.11	3.85	2.09	4.65	2.24
1	3.05	1.77	3.00	1.77	3.38	1.86
2	2.51	1.55	2.47	1.53	2.70	1.60
3	2.10	1.34	2.08	1.33	2.20	1.37
4	1.82	1.18	1.80	1.17	1.90	1.21

a. Uranium is assumed to be 50 wt % of the fuel for the scoping calculations.

b. Uranium treated as metal in fuel region calculation.

c. Uranium treated as UO_2 in fuel region calculation.

For U-Pu-Al alloys, the safe mass limits per well are given in Tables 7 and 8. The values and bulk solution concentrations are given in terms of fissile content.

NECESSITY FOR ADDITIONAL RESTRICTIONS

To maintain nuclear safety during dissolution of fuel in dissolver inserts, the quantities of fuel to be dissolved must conform to the individual well limits and to the total pot limit, and the combination of undissolved and dissolved fissile material must remain subcritical throughout the dissolution. Safe mass values in water (0 g/l in the tables) calculated for the Ten-Well Insert (Tables 5 through 8), are not directly applicable as well-charging limits because some combinations of undissolved fuel and dissolved fuel are more reactive. Thus, a safe charge may become unsafe as dissolution proceeds. For example, as indicated by the upper operating line in Figure 6, a 6-kg ^{235}U mass in a well could become unsafe soon after core dissolution begins in a run that would normally terminate safely at a concentration of 4 g ^{235}U/l. This effect is caused by the rapid drop in the safe mass values as the ^{235}U concentration increases. Another problem in deriving process limits from the safe mass values is that some safe mass values exceed the dissolver pot limits.

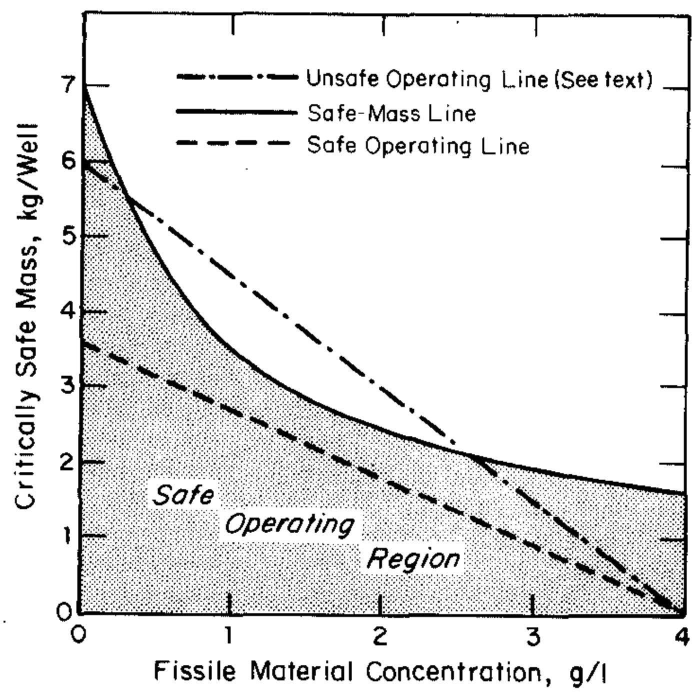


FIGURE 6. Safe Mass Diagram for Dissolving 35 wt % U - 65 wt % Al in the Ten-Well Insert

CRITERIA FOR ACTUAL WELL LIMITS

To establish well limits that are safe for actual dissolution in the Ten-Well Insert, the following criteria were applied, as appropriate:

1. *A maximum concentration of 4.0 g of ^{235}U + ^{239}Pu + ^{241}Pu per liter is imposed at all times during the dissolution.* This 4.0 g/l value is the highest concentration of fissile material considered in the safe mass calculations; higher concentrations are beyond the scope of any available safety analysis. This concentration limit was applied to establish all of the limits for the Ten-Well Insert (Tables 11 through 14).

2. *The safe (subcritical) mass value for 1 g of fissile material per liter of solution is conservatively specified as the well limit for solutions containing 0.1 g/l or less.* The effect of this mass limit and the 4 g/l concentration limit above is to decrease the charge size, so that the operating line will not reach the unsafe region. For example, the lower operating line in Figure 6 describes dissolution under these limits; that is, a well is charged with 3.5 kg of ^{235}U* which is dissolved to yield a solution increasing in ^{235}U concentration from 0.1 to 4.0 g/l. The mass in the well will always remain below the safe mass values (Figure 6). The 0.1-g/l concentration allows for the carryover of solution "heels" from one dissolution to the fresh acid charge of the next. In operation, the concentration of fissile material is never assumed to be zero.

3. *Where the above criteria were inadequate to ensure nuclear safety, an additional restriction is imposed, requiring that no more than some fraction of the pot limit may be contained in any well.* For example, in the case of 30% U-Al alloy in ten wells, no more than one-fourth of the pot limit (Table 1) is allowed in any well (25.3 x 1/4 = 6.32 kg ^{235}U). For the case illustrated in Figure 7, this charge is safe in either dissolver throughout the dissolution. In other cases, a larger fraction of the pot limit may be allowed in a well. For example, as shown in Figure 8, 1/2 of the small dissolver pot limit for equivalent ^{239}Pu (14.8 x 1/2 = 7.40 kg ^{235}U + ^{239}Pu + ^{241}Pu) would be a safe charge to a solution containing $\leq$0.1 g(^{235}U + ^{239}Pu + ^{241}Pu)/l in either dissolver, as long as the final concentration did not exceed 4.0 g/l. Thus, for this criterion, 1/2, 1/3, 1/4, etc., of the appropriate pot limit were considered successively until safety was ensured throughout dissolution.

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* The maximum safe mass value for 35% U-Al alloy fuel in a 1.0 g ^{235}U/l solution (see Table 5).

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To determine from a well limit the number of assemblies of a specific fuel that are permitted in a well, the mass of fissile material in each assembly must be known.

Pot Limit: The critically safe mass of solid and dissolved fissile material in the dissolver (pot). The pot limit is determined by multiplying the subcritical concentration limit (Table 1) for the fissile material in solution by the minimum solution volume attainable in the dissolver. The dissolver pot limit maintains a safe concentration of fissile mateial in the dissolver in the event of accidental overevaporation of its contents.

Fissile Material: In this report, the mass of fissile material in a solid is the sum of the weights of ^{235}U, ^{239}Pu, and ^{241}Pu in the solid. The concentration of fissile material in a solution is the sum of the concentrations of ^{235}U, ^{239}Pu, and ^{241}Pu in the solution.

Finally, it should be noted that a well limit includes the entire fissile content of solid material in a well; i.e., any residual fragments from a previous charge plus the freshly charged material. Where the material charged has a high wt % uranium or plutonium content and a high ^{235}U enrichment, the well limits prohibit dissolution of successive charges in the Ten-Well Insert. This is because the smallest measurable quantity of residual fragments in the well (e.g., about 7 kg of uranium metal) could be larger than the largest well limit (1.92 kg of ^{235}U, Table 11). However, the limits for $\leqslant$100 wt % uranium provide complete limits should the need arise to process U-Al alloy containing over 50 wt % uranium at low ^{235}U enrichments.

GLOSSARY

Safe mass value: A mass of solid fissile material that is safe in a well of the Ten-Well Insert when the concentration of fissile material in the solution surrounding the solid mass is no greater than a specified value. Such a mass is safe because it is subcritical by an adequate margin, i.e., the effective neutron multiplication factor (k_{eff}) is no greater than 0.95, as long as it is separated from another fissile mass by the distance between the insert wells. The relationship between safe mass and solution concentration may not be linear, so one safe mass value is often inadequate as an operating limit for a dissolver where the solid mass continuously decreases and the solution concentration continuously increases.

Well limit: A mass of solid fissile material that can be loaded into a well of the Ten-Well Insert and dissolved safely, provided that the terminal concentration of fissile material in solution is no greater than a specified value. Such a mass is safe because it can be loaded and dissolved without exceeding either a safe mass of solid fissile material or the specific concentration of fissile material in the solution for which that solid mass is safe. To select a well limit the following must be known:

1. The U/Pu weight ratio in the solid phase.

2. The concentration of uranium and/or plutonium in the solid phase, e.g., the weight percent uranium in the U-Al alloy of a fuel assembly.

3. The number of wells of the Ten-Well Insert that will be charged with fissile material.

4. The *initial* concentration of fissile material in the dissolver solution (carry-over from previous dissolution).

TABLE 14

Well Limits for U-Pu-Al Alloys with U/Pu >3.0[a]

Wells Charged	*Init. Conc. Fissile Material, g/l*[b]	*Maximum Fissile Material Concentration, kg/well* <25 wt % Pu+U	<30 wt % Pu+U	<35 wt % Pu+U	<40 wt % Pu+U	<45 wt % Pu+U	<50 wt % Pu+U
Any or All Wells	0 to 0.1	7.40[c]	4.93[d]	3.35	2.24	1.90	1.67
	>0.1, <4.0	1.77	1.36	1.17	1.06	0.99	0.95
Isolated Pairs	0 to 0.1	*e*	*e*	12.6[f]	6.32[f]	4.10[f]	3.00[f]
	>0.1, <4.0	*e*	6.80	2.85	2.05	1.76	1.57
Isolated Wells	0 to 0.1	*e*	*e*	*e*	*e*	12.6[f]	6.32[f]
	>0.1, <4.0	*e*	*e*	*e*	20.0	4.60[f]	3.06

a. Ratio: 3.0 ≤ U/Pu <100.

b. Fissile Material = $^{235}U + ^{239}Pu + ^{241}Pu$; where $^{240}Pu \geq 1.2\ ^{241}Pu$.

c. Based on the criteria discussed in the text; 1/2 of the pot limit for equivalent ^{239}Pu in the small dissolver.

d. Based on the criteria discussed in the test, 1/3 of the pot limit for equivalent ^{239}Pu in the small dissolver.

e. See Table 11, Footnote *a*.

f. As discussed in the text, this limit has been reduced to be compatible with limits in Table 11, so as to apply to materials with U/Pu weight ratios between 3.0 and 100.

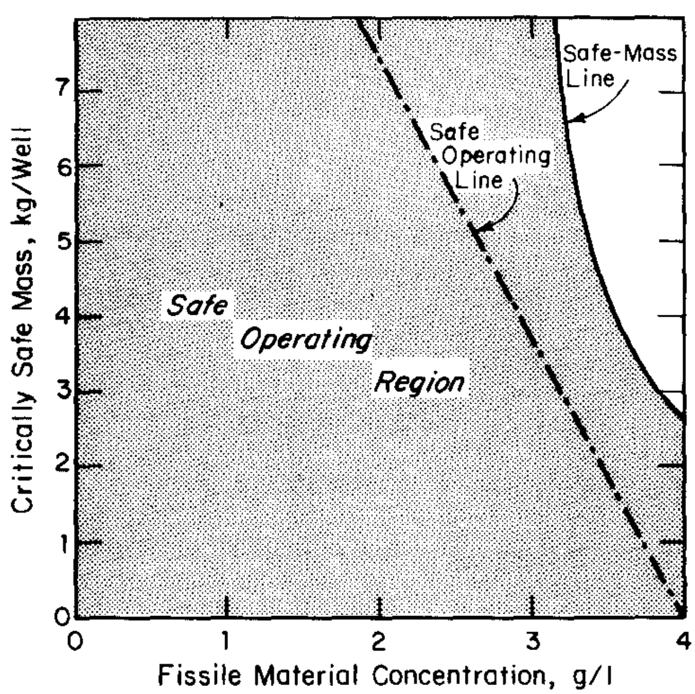

FIGURE 9. Safe Mass Diagram for Dissolving 15 wt % U - 15 wt % Pu - 70 wt % Al Alloy in the Ten-Well Insert (Isolated Pairs Configuration)

TABLE 12

Well Limits for Pu-Al Alloys[a]

Wells Charged	Initial Conc. Fissile Material, g/l[b]	Maximum Fissile Material Concentration, kg/well <25 wt % Pu+U	<30 wt % Pu+U	<35 wt % Pu+U	<40 wt % Pu+U	<45 wt % Pu+U	<50 wt % Pu+U
Any or All Wells	0 to 0.1	3.00	2.00	1.67	1.36	1.24	1.16
	>0.1, <4.0	0.77	0.72	0.68	0.65	0.63	0.61
Isolated Pairs	0 to 0.1	14.8[c]	7.40[d]	3.70[e]	3.02	2.31	2.00
	>0.1, <4.0	1.72	1.40	1.21	1.10	1.02	0.95
Isolated Wells	0 to 0.1	*f*	*f*	14.8[c]	7.40[d]	7.40[d]	4.85
	>0.1, <4.0	*f*	6.65	2.90	2.08	1.75	1.57

a. Ratio: $0 \leqslant U/Pu < 1.0$.

b. Fissile material = $^{235}U + {}^{239}Pu + {}^{241}Pu$; where $^{240}Pu \geqslant 1.2\ {}^{241}Pu$.

c. Based on the criteria discussed in the text; 1/2 of the pot limit for equivalent ^{239}Pu in the large dissolver.

d. Based on the criteria discussed in the text; 1/2 of the pot limit for equivalent ^{239}Pu in the small dissolver.

e. Based on the criteria discussed in the text; 1/4 of the pot limit for equivalent ^{239}Pu in the small dissolver.

f. See Table 11, Footnote *a*.

TABLE 13

Well Limits for U-Pu-Al Alloys with U/Pu <3.0[a]

Wells Charged	Init. Conc. Fissile Material, g/l[b]	Maximum Fissile Material Concentration, kg/well <25 wt % U+Pu	<30 wt % U+Pu	<35 wt % U+Pu	<40 wt % U+Pu	<45 wt % U+Pu	<50 wt % U+Pu
Any or All Wells	0 to 0.1	4.93[c]	3.70[d]	2.40	1.85	1.61	1.45
	>0.1, <4.0	1.15	1.00	0.92	0.85	0.82	0.78
Isolated Pairs	0 to 0.1	*e*	*e*	7.40[f]	4.93[c]	4.00	2.80
	>0.1, <4.0	*e*	2.67	1.89	1.54	1.38	1.27
Isolated Wells	0 to 0.1	*e*	*e*	*e*	*e*	14.8[g]	7.40[f]
	>0.1, <4.0	*e*	*e*	*e*	4.65	3.05	2.41

a. Ratio: $1.0 \leqslant U/Pu < 3.0$.

b. Fissile Material = $^{235}U + {}^{239}Pu + {}^{241}Pu$; where $^{240}Pu \geqslant 1.2\ {}^{241}Pu$.

c. Based on the criteria discussed in the text; 1/3 of the pot limit for equivalent ^{239}Pu in the small dissolver.

d. Based on the criteria discussed in the text; 1/4 of the pot limit for equivalent ^{239}Pu in the small dissolver.

e. See Table 11, Footnote *a*.

f. Based on the criteria discussed in the text, 1/2 of the pot limit for equivalent ^{239}Pu in the small dissolver.

g. Based on the criteria discussed in the text, 1/2 of the pot limit for equivalent ^{239}Pu in the large dissolver.

Successive Charges

Occasionally, more than one charge of fuel assemblies with very small ^{235}U contents have been dissolved in a single batch of dissolvent (successive charges) to obtain a ^{235}U concentration adequate for subsequent chemical processing. Conservative well limits for these successive charging operations were derived by imposing the safe mass value in 4 g/l solution as the limit for any charge added to solutions containing >0.1 g/l. As before, the maximum concentration limit of 4.0 g/l and the pot limit apply at all times.

Plutonium Alloy Charges

Safe mass values for plutonium-containing alloys were calculated only for three specific cases: Pu-Al alloy (Table 12), U-Pu-Al alloy with a U/Pu weight ratio of 1.0 (Table 13), and U-Pu-Al alloy with a U/Pu weight ratio of 3.0 (Table 14). Thus, well limits for materials with U/Pu weight ratios other than those calculated had to be established. Safe mass values generally become smaller as the U/Pu ratio decreases, but this is not true in every case. Where it is true, the well limits over a range of U/Pu ratios are the safe mass values at the lower end of the range.

As indicated in Table 14 (Footnote *f*), however, a few safe mass values for U-Pu-Al alloys at U/Pu ratios of 3.0 are larger than those for U-Al alloy (U/Pu $\geq$100). Consequently, the values for U-Al alloys were conservatively imposed as the well limits for these cases in the range 3.0 $\leq$U/Pu <100. For example, in Figure 9, the entire pot limit for the small dissolver for equivalent ^{239}Pu (14.8 kg) would be safe (<4.0 g/l) to dissolve in one well in either dissolver. Similarly, Figure 9 also shows that the entire pot limit for the large dissolver, 29.7 kg, would be safe in one well in the large dissolver. A few cases where the entire pot limit for the large dissolver is not safe in one well are designated in Table 12 by Footnote *c* and in Table 13 by Footnote *g*. Finally, those limits in Tables 11 through 14 where Criterion 3 above was applied are designated by fractional pot limits (see Footnotes). In summary, the smaller safe mass value was always used at the well limit.

Miscellaneous Considerations

The scoping calculations determined safe mass values for 25 wt % uranium as U-Al alloy in 3.72 g ^{235}U/l solution, but the later calculation for 4 g ^{235}U/l did not include values for 25 wt % uranium. Consequently, one well limit in Table 11 (Footnote *b*) is based on 3.72 g ^{235}U/l, instead of 4 g ^{235}U/l.

One or another of these criteria are applied for different cases. A mass of 6.32 kg at 0.1 g/l (from Criterion 3) is safe for the case in Figure 7, but would be unsafe for the case in Figure 6 unless the volume of dissolvent were large enough to yield a final concentration less than 2 g/l. On the other hand, in the case shown in Figure 7, an infinite mass is safe in a well at 1 g/l, so Criterion 2 above does not provide a useful limit.

OPERATIONAL CHARACTERISTICS OF THE TEN-WELL INSERT

Uranium Charges

Well Limits

The well limits in Table 11 were formulated from the above criteria and from the safe mass values for each set of conditions in Table 5. In those cases in Table 11 not marked by footnotes, the appropriate safe mass value *is* the well limit. Where well limits are denoted by Footnote *a*, the safe mass values are so large that the well charge is limited only by the appropriate pot limit (Table 1) and the 4.0 g/l concentration limit.

TABLE 11

Well Limits for U-Al Alloys and U_3O_8-Al Cermets

Wells Charged	*Initial Conc. ^{235}U, g/l*	*Maximum Fissile Material Concentration, kg/well* *<25 wt % U*	*<30 wt % U*	*<35 wt % U*	*<40 wt % U*	*<45 wt % U*	*<50 wt % U*	*100 wt % U*
Any or All Wells	0 to 0.1	*a*	6.32[c]	3.50	2.42	2.00	1.77	1.18
	>0.1,<4.0	*b*	1.98	1.57	1.37	1.26	1.17	0.93
Isolated Pairs[e]	0 to 0.1	*a*	*a*	12.6[d]	6.32[c]	4.10	3.00	1.50
	<0.1,<4.0	*a*	*a*	3.85	2.50	2.05	1.80	1.19
Isolated Wells[f]	0 to 0.1	*a*	*a*	*a*	*a*	12.6[d]	6.32[c]	1.92
	>0.1,<4.0	*a*	*a*	*a*	*a*	4.60	3.22	1.52

a. There is no well limit for this set of conditions, so long as the total mass of fissile material in the dissolver is less than the appropriate pot limit and the concentration of fissile material in solution does not exceed 4.0 g/l at any time.

b. There is no well limit for this set of conditions, so long as the total mass of fissile material in the dissolver is less than the appropriate pot limit and the concentration of ^{235}U in solution does not exceed 3.72 g/l at any time.

c. Based on the criteria discussed in the text; 1/4 of the pot limit for ^{235}U in the small dissolver.

d. Based on the criteria discussed in the text; 1/2 of the pot limit for ^{235}U in the small dissolver.

e. The term Isolated Pairs means that the second and fourth pairs of wells contain no measurable fissile material and are plugged.

f. The term Isolated Wells means that no two adjacent or diagonally adjacent wells contain measurable fissile material; unused wells are plugged.

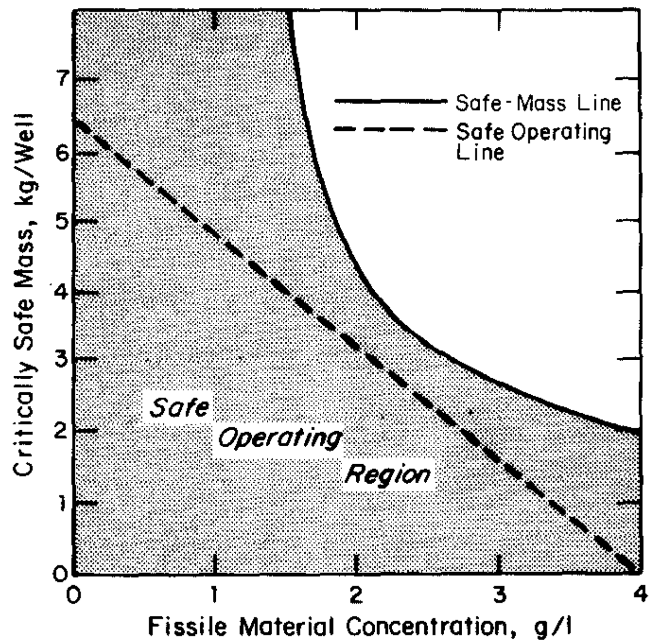

FIGURE 7. Safe Mass Diagram for Dissolving 30 wt % U - 70 wt % Al in the Ten-Well Insert

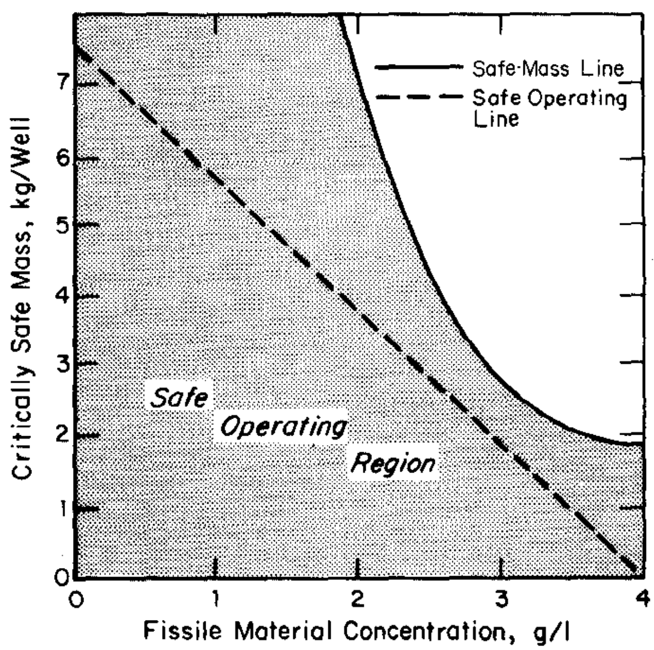

FIGURE 8. Safe Mass Diagram for Dissolving 17.5 wt % U - 17.5 wt % Pu - 65 wt % Al Alloy in the Ten-Well Insert (Isolated Pairs Configuration)