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**Review of PGDP Assessment of
Criticality Safety Problems in
Increasing Product Assay
to 5 wt % ^{235}U**

L. M. Petrie
J. C. Turner
G. B. Stewart

COMPUTING AND TELECOMMUNICATIONS DIVISION

at
Oak Ridge National Laboratory
Post Office Box X
Oak Ridge, Tennessee 37830

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**L. M. Petrie
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ABSTRACT

Paducah Gaseous Diffusion Plant (PGDP) performed an evaluation of the PGDP facilities to determine the feasibility of increasing product assay from 2.0 wt % to 5.0 wt % ^{235}U and to determine the impact of this increase on plant criticality safety; their conclusions are reported in KY-710. This report critiques the methods used and conclusions reached in KY-710.

INTRODUCTION

In August 1983 the Paducah Gaseous Diffusion Plant (PGDP) asked the Nuclear Engineering Applications Department, Computing and Telecommunications Division, to review a report, KY-710, on the criticality safety considerations of increasing the product assay from 2.0 wt % to 5.0 wt % ^{235}U . Computer analyses were to be used to verify that appropriate criteria had been applied in arriving at the conclusions presented in the report and to analyze the suggested modifications for achieving criticality safety in the Paducah operations. The analyses are summarized in Appendix A.

The report being reviewed, KY-710, noted that it did not constitute formal nuclear safety approval of the proposed methods of modification. Likewise, this review is for the purpose of providing guidance in long-range planning and does not constitute a formal safety approval of the individual process systems. Responsibility for the formal approval remains in the PGDP organization.

This review is organized as comments on the corresponding sections of KY-710. For completeness some tables from KY-710 have been copied and included; other sections of KY-710 have been liberally paraphrased to give a background or explanation for the corresponding comments.

BASIC CRITERIA FOR DETERMINING NUCLEAR SAFETY

KY-710 set forth the following seven criteria for determining nuclear safety:

1. Uranium hexafluoride in the gaseous phase, as encountered at temperatures, pressures, and compositions typical of a diffusion cascade, cannot sustain a nuclear chain reaction. Gaseous UF_6 is, therefore, always nuclearly safe regardless of whether the assay is 2 wt % or 5 wt % ^{235}U .
2. Uranium enriched to not greater than 5.0 wt % ^{235}U cannot sustain a nuclear chain reaction in the absence of moderating atoms such as hydrogen (H/U ratio ≤ 0.33).
3. At 5%, the minimum theoretical critical mass is approximately 81 lb of uranium (120 lb of UF_6). At 2%, the minimum critical mass is more than six times larger - 506 lb of uranium (748 lb of UF_6).
 - a. For criticality safety purposes if double-batching* is not possible, the safe mass is set at 90% of the minimum critical mass (safety factor - 1.25). This corresponds to 65 lb of uranium enriched to 5 wt % ^{235}U .
 - b. If double-batching is not precluded, the safe mass for 5% enrichment would be 35.3 lb, allowing a safety factor of 2.3. This safety factor would allow for two containers to be combined and still be nuclearly safe.
4. Table 1 summarizes the safe geometries at both 2 wt % and 5 wt % ^{235}U . Because geometry control requires no administrative controls to be effective, it is the most positive form of nuclear safety control; implementation of this method should be considered wherever possible.

Table 1. Safe geometric values

Geometry	2%	5%	Safety Factor
a. Infinite slab depth (in.)	8.7	5.0	1.05
b. Infinite cylinder diameter (in.)	16.0	10.25	1.05
c. Volume (gal)	25.1	7.1	1.1

5. At any uranium enrichment, the safe concentration of ^{235}U in a water solution is 5 grams per liter with a safety factor of 1.9. For 5% assay, this corresponds to a concentration of 100 grams of uranium per liter. At 2%, the safe concentration is 250 grams of uranium per liter of solution.
6. It is impossible for uranium enriched to less than 1 wt % ^{235}U to become critical under accident conditions.
7. Spacing considerations for containers are based upon a total solid angle of interaction equal to 1 steradian for safe geometry containers. For safe masses, the permissible total solid angle of interaction is equal to 2.5 steradians. In general, the spacing provided for the 2% system will be adequate for 5% systems when the control used to maintain criticality safety is the same.

These are standard, commonly accepted criteria in use in the nuclear industry. An eighth criterion could be added requiring a system analysis using a validated computer code and cross sections to show the system is subcritical. The margin of subcriticality needed to be safe using this criteria depends on the validation results of the code and cross sections.

*Double-batching refers to the possibility of accidentally doubling the mass of uranium in one container (e.g., two half-full, 55-gal drums are combined).

NUCLEAR SAFETY CONSIDERATIONS IN CASCADE EQUIPMENT

Criterion 1 states that all cascade equipment which processes only gaseous phase UF_6 is always nuclearly safe under normal operating conditions regardless of whether the assay is 2 wt % or 5 wt % ^{235}U . This review was requested by PGDP to address this point; and certainly at normal operating conditions, i.e., UF_6 in the gaseous phase, Criterion 1 is both applicable and valid.

For abnormal conditions, as long as the level of internal moderation is limited, both Criterion 2 and a computer analysis show the equipment will still be safe. However, if sufficient moderation is introduced into the equipment during an accident and, if sufficient UF_6 has also accumulated in the same location due to freeze-out, then these criteria are no longer applicable. At optimum moderation, the geometric configuration is such that several hundred pounds of UF_6 are required before the safe geometry criterion is violated.

Surge Drums

To be nuclearly safe by Criterion 1 the surge drums must be operated at a temperature and pressure combination which does not allow the stored UF_6 to condense. If condensed UF_6 is to be stored, regardless of the assay of the uranium, three parameters must be controlled: the weight of the condensing UF_6 ; the pressure in the drum, to maintain structural integrity; and the hydrogen content, to preclude the availability of a moderator (Criterion 2).

For safe condensation the weight limitation of 4.5% enrichment is satisfactory based on the current limitation of product cylinders. However, due to the discrete sizes of the cylinders, KY-710 includes a large weight differential (from 15,000 down to 5,000 lb) in going from 4.5 to 5.0 wt % enrichment. If the 5,000-lb limit at 5% causes no operational problems, it is surely conservative. If necessary, the 15,000-lb limit could probably be justified at 5% as well as at 4.5%.

Overall, the surge drum analysis presented in KY-710 appears quite conservative.

Uranium Hexafluoride Freezer/Sublimer

The freezer/sublimer system has already been evaluated and approved as critically safe for enrichments up to 5 wt % ^{235}U . An overview of this system is given here, but a more detailed study is given in KY-710.

The purpose of the UF_6 freezer/sublimer is to reestablish stable cascade operating conditions in the event of a disturbance causing an excess of uranium. This system consists of a shell which encloses a lattice of finned tubes containing water-cooled refrigerant-114. With this design, excess UF_6 from the cascade can be either frozen around the tubes in the shell side of the vessel or sublimed to the gaseous state for gradual return to the cascade. One safety feature of the freezer/sublimer maintains appropriate temperatures and pressures to assure that HF present in the cascade stream cannot condense as the UF_6 freezes out, thus eliminating HF as a source of moderation. Other safety designs monitor differential pressure to protect against the leakage of water into the R-114 loop, allowing moderation of uranium in the shell side of the vessel. If, in spite of these safety features, full density water does enter the tube side of the freezer/sublimer, accidental criticality is still not possible if the assay of the UF_6 being processed is below 2.35%.

Product Cylinders

Product cylinders of four different sizes were reviewed in KY-710. The 14-ton and 10-ton cylinders are both nuclearly safe for storage of uranium with 4.5% assay. The 2½-ton cylinders and MD-cylinders can safely store uranium enriched to 5%. National Standard, ANSI N14.1 1982, covers the limitations on the 48-in.-diameter product cylinders at 4.5% enrichment.

Spacing Considerations for Storage of Product Cylinders

The present spacing regulations requiring a 1-ft, edge-to-edge separation of cylinders should be sufficient with the 4.5% and 5% product cylinders. No further restrictions are anticipated.

Accumulators

The product accumulator resembles a 10-ton product cylinder and has a storage capacity of 21,000 lbs. The KY-710 analysis conservatively concluded that this accumulator would be nuclearly safe up to 4.5% ²³⁵U but would need to be replaced if the assay were increased to 5 wt % ²³⁵U. Since accumulators are not transport containers and are not restricted by a national standard, a careful analysis of these accumulators should show them safe at 5% provided the moderation control of Criterion 2 is met. See Appendix A for further discussion of this point.

The side withdrawal accumulator, 4300-lb capacity, would be safe at 5% enrichment with moderation control for the 2½-ton cylinder applied.

UF₆/R-114 Separator System

In a previous analysis the UF₆/R-114 separator system was found nuclearly safe at assays not greater than 2 wt % ²³⁵U. Based on this analysis, PGDP decided that the separator system will be restricted to assays of less than 2%. If it becomes necessary to use this system for processing uranium at greater assays, a smaller diameter vessel will have to be designed and evaluated.

Sodium Fluoride Traps

None of the six sodium fluoride traps currently in use at PGDP are nuclearly safe for assays of 5%. The two traps located in C-335 are used to trap residual UF₆ from the UF₆/R-114 separator system. As long as the UF₆/R-114 separator is restricted to assays of less than 2%, these traps will not require modification. Should the UF₆/R-114 separator be modified to handle larger assays, these two traps will need to be modified also.

The other four traps, located in C-310, are used in conjunction with the cylinder "burp" stations and must handle 5% assay material. Analysis of these traps (see Appendix A) shows they are not subcritical unless moderation control can be implemented. Since reducing the trap's volume to limit the amount of UF₆ which may be trapped out is probably not feasible, these traps will need to be replaced.

Alumina Traps

The following table reproduced from KY-710 presents safe values for various size alumina traps based on different criteria.

Table 2. Safe values for various size alumina traps

Diameter (in.)	Volume (ft ³)	Mass of U Trapped (lb)	Safe Assay by Geometry (wt % ²³⁵ U)	Safe Assay by Mass (wt % ²³⁵ U)
10.25*	NR**	NR**	5.00	NA
12.00	1.7	64	3.50	5.00
15.00	3.7	137	2.25	3.25
18.00	8.0	298	1.65	2.15
24.00	13.2	490	1.25	1.80

*This size trap is not currently present in the cascade. It is listed for comparison - should Method 1 of the preceding discussion be chosen.

**No restriction.

Computer analysis indicates that the safe assay by mass results are somewhat conservative. For instance, the 15-in. trap will be safe with 4% (rather than the 3.25% given in the table) assay material under the conditions of the safe assay by mass. See Figure A.2 in Appendix A.

When deciding whether to use the "safe assay by geometry" or the "safe assay by mass" method to determine criticality safety, a word of caution is in order. If the "safe by mass" method is chosen, strict administrative controls will be necessary to ensure that no more than the proper amount of trapping material is present.

Magnesium Fluoride Traps

There are two magnesium fluoride traps in C-310 which will need to be nuclearly safe for assays up to 5 wt % ²³⁵U. As the current traps do not meet this requirement, the conclusion of KY-710 that these traps need to be modified or replaced is correct.

Pump Oil Separators

The analysis and table (see below) presented in KY-710 for the pump oil separators provide an adequate basis for deciding which separators are safe and which need to be replaced when the final plant assay is 5%. However, the assessment indicates that hydrocarbon oil can accumulate a maximum of 4.5 lb of UF₆ (3.04 lb U) per gallon of oil. This uranium concentration is less than the optimum value for 5% material. Thus, this maximum possible value is more dilute and on the overmoderated side of the optimum. Hence, the safe masses listed in the table for a given assay could be increased while increasing the safe oil volume proportionately.

Table 3. Safe volumes for oil separators

Assay (wt % ²³⁵ U)	Safe Mass* (lb of U)	Safe Oil Volume (gal)
1.00	NR**	NR**
2.00	405	133
3.00	162	53
3.5	122	40
4.00	95	31
5.00	65	21

*Double-hatching precluded.

**No restriction.

C-310 Scale Pits

The C-310 scale pits have close-off valves which will shut the drain line to the cylinder when a leak is detected, and a system to close the cylinder valve upon UF_6 detection is scheduled for installation. Additionally, the use of water on any enriched uranium release is administratively controlled, and criticality at assays below 5% is not possible in the absence of a moderator. The KY-710 analysis of the C-310 scale pits is both correct and adequate in its conclusion that this combination of safety features virtually nullifies the potential for criticality.

Storage of Contaminated Waste

Two options for nuclearly safe storage of contaminated wastes are presented in KY-710. One option is to purchase special containers with an inner diameter of no more than 10 in.; the second option is to use 5-gallon buckets. As long as strict rules governing the spacing between columns of storage containers are followed, either option is both safe and feasible.

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NUCLEAR SAFETY CONSIDERATIONS IN DECONTAMINATION AND RECOVERY EQUIPMENT

Located in C-400, the decontamination and recovery facilities handle equipment from all areas of the plant; they are, therefore, required to be nuclearly safe for the top assay which may be encountered - 5 wt % ^{235}U .

The following systems within the decontamination and recovery facility possess a potential for criticality: the spray booth and associated storage tanks, the small parts hand decontamination table, the contaminated solution acidifying and storage tanks, the uranium precipitation system, and the cylinder wash facility. Each of these systems is addressed separately.

Spray Booth and Associated Storage Tanks

With the exception of the storage tanks, all parts of the spray booth were found to be safe for decontaminating equipment exposed to 5 wt % ^{235}U . The alternatives for the storage tanks are to replace them with tanks that meet the geometry specifications of Criterion 4b or to make the current tanks nuclearly safe at higher assays by adding fixed neutron absorbers, such as Raschig rings. An evaluation using the KENO computer code showed the solution tanks to be safe at assays of 5 wt % when poisoned with Raschig rings. See Appendix A for a discussion on this point.

Small Parts Hand Decontamination Table

The decontamination table is used for manually cleaning small parts which cannot be cleaned effectively in the spray booth. The conclusion of the KY-710 report that lowering the overflow level from 8.5 in. to 5 in. would make this table safe for 5% assays is correct and adequate.

Contaminated Solution Acidifying and Storage Tanks

The contaminated solution acidifying and storage tanks operate as two units of six tanks each - five for storage and one for acidifying. All twelve tanks need to be nuclearly safe to handle assays at 5 wt %. The alternatives are to replace all twelve tanks with 10.25-in. maximum diameter tanks or to use Raschig poison rings as neutron absorbers in the present tanks. A computer analysis was performed to verify that the addition of Raschig rings to the present tanks would make them nuclearly safe. See Appendix A.

Uranium Precipitation System

The uranium precipitation system is not nuclearly safe for uranium enriched to 5 wt % ^{235}U . Either of the two alternatives presented in KY-710, isotopic dilution to less than 1% or replacement of the system, would be a valid solution.

Cylinder Wash Facility

To prevent accidental criticality in the cylinder wash facility would require a combination of the following:

1. The drain pan would need overflow holes drilled at the 5-in. level.
2. The 16-in.-diameter storage tanks would need to be replaced with 10-in.-diameter tanks or would need the addition of neutron absorbers.
3. At 5% enrichment the cylinder heel weight would have to be limited to a maximum of 35 lbs. Because of the difficulty of accurately determining heel weights, additional safeguards (either limiting the amount of wash solution in the cylinder or using a borated wash solution which has neutron absorbers) would be required.

NUCLEAR SAFETY CONSIDERATIONS IN THE C-360 SAMPLING COMPLEX

The C-360 sampling complex works with liquid UF_6 , some of which is at product assay. Therefore, the whole facility must be safe at 5%. The equipment requiring evaluation are the autoclaves, the various tanks, the traps, the scale and elevator, and the oil interceptors. Modifications necessary to ensure nuclear safety of each piece are considered individually.

Autoclaves

Moderation control is the key to criticality safety for the autoclaves which are used for heating 10- and 14-ton cylinders of 4.5% and 2½-ton cylinders of 5% material. Normally, cylinder pressure is greater than the pressure of the autoclave; therefore, should a breach occur, UF_6 would be released into the interior of the autoclave but moderation could not enter the cylinder. A UF_6 detector is located in the autoclave, and when a leak is detected the following occur automatically.

1. The steam supply valve to the autoclave shuts.
2. The steam condensate drain line is rerouted to holding tanks.
3. If the autoclave becomes overpressured during the liquefaction mode, a rupture disk relieves the pressure so that UF_6 containment is maintained.

Given these features, the limitations on the autoclaves are essentially the limitations of the product cylinders brought into the autoclave. Consequently, the autoclave will be safe at 4.5% with the 10- and 14-ton cylinders and at 5% with the 2½-ton cylinders.

Various Tanks

The sampling and transfer facility has three sets of tanks. The surge tanks and the pressure relief tanks are currently safe for 5 wt % ^{235}U ; KY-710 details the rationale for this conclusion. However, the 16-in.-diameter holding tanks will need to be replaced with 10-in.-diameter holding tanks; or, the 16-in.-diameter tanks can be made safely subcritical with the addition of Raschig rings.

Alumina and Cold Traps

The alumina and cold traps are used in parallel with the surge evacuation tanks to achieve a better vacuum. Their diameters (less than 7 in. for the cold trap and less than 8 in. for the alumina) make both traps geometrically safe for 5% assay.

Scale and Elevator Pits

The four pits in C-360 which must be nuclearly safe are the first-floor scale pit, the basement scale pit, the hoist pit, and the elevator pit. Table 4, reproduced from KY-710, shows the minimum quantities of uranium and water necessary for criticality in each.

The possibility of accumulating the quantity of uranium necessary for criticality as a result of a gaseous UF_6 release is very remote. KY-710 lists seven separate considerations which add to the nuclear safety of the pits. However, should further assurance of nuclear safety be required, Raschig rings can be placed in the pits as neutron absorbers.

Table 4. Minimum quantities required for criticality in C-360 pits

Pit	Volume* (ft³)	Uranium (lb)	Water (gal)
First-floor scale	26.9	2,436	110
Basement scale	48.7	4,396	200
Hoist	49.8	4,511	204
Elevator	66.7	6,042	274

*5-in. critical slab length.

Oil Interceptors

All floor drain lines in C-360 pass through two oil interceptors. When a release is detected in the building, valves in the influent lines automatically close. Should the valves malfunction, the first-floor separator would require 340 lb of uranium to mix homogeneously with water before it was moderated to the correct degree for criticality. The other would require 115 lb.

CRITICALITY ALARM SYSTEM

Based on the directive of DOE Manual Chapter 0530, Nuclear Criticality Safety, additional radiation alarms will probably need to be located in areas processing high assays.

CONCLUSIONS

KY-710 presents a comprehensive evaluation of all of Paducah plant facilities with respect to nuclear safety during operation at a product assay of 5 wt % ^{235}U . Computer analyses were performed to verify the conclusions of the PGDP review. Below is a listing of the involved Paducah systems (reproduced from KY-710) organized into groups of nuclearly safe, need administrative controls, need modifications, and need to be replaced. At the end of each group are final comments on this review.

Nuclearly Safe As Now Exist

All equipment in which UF_6 is in gaseous phase (e.g., converters, compressors)

Surge drums up to 4.5%

10- and 14-ton product cylinders up to 4.5%

2½-ton and MD cylinders

Product accumulators up to 4.5%

Side withdrawal accumulators

C-310 scale pits

Uranium hexafluoride freezer/sublimator

Spray booth (except solution storage tanks)

C-360 autoclaves

C-360 scale and elevator pits

C-360 oil interceptors

C-360 surge and pressure relief tanks

Uranium precipitators (using isotopic dilution)

The KY-710 analyses for the surge drums and product accumulators were conservative. Computer analysis shows both to be nuclearly safe up to 5% as they now exist.

Nuclearly Safe With Additional Administrative Controls

Surge drums

$\text{UF}_6/\text{R-114}$ separator and associated NaF traps (restricted to 2%)

Alumina traps (some may be safe, depending on cascade gradient)

Pump oil separator (some may be safe, depending on cascade gradient)

Depending on the cascade gradient, some of the alumina traps and oil pump separators may need to be replaced.

Nuclearly Safe With Modifications To Existing Equipment

C-310 sodium fluoride traps (possible)

Magnesium fluoride traps (possible)

Storage of contaminated waste

Spray booth solution storage tanks (addition of neutron absorbers)

Small parts hand decontamination table

Acidifying and storage tanks (addition of neutron absorbers)

Cylinder wash facility

Criticality alarm system

C-360 steam condensate tanks (addition of neutron absorbers)

To be safe, the C-310 sodium fluoride traps and the magnesium fluoride traps will need to be replaced.

Nuclearly Safe Only If Replaced With New Equipment

Product accumulators (to enable handling 4.5% to 5% assay)

C-310 sodium fluoride traps (probable)

Magnesium fluoride traps (probable)

Handling of contaminated traps (need safe diameter storage containers)

Finally, calculations of the 10-ton product accumulators show that with the required moderation control they are essentially as safe at 5% as at 4.5% assay.

APPENDIX A
SUMMARY OF SUPPORTING ANALYSES

APPENDIX A

SUMMARY OF SUPPORTING ANALYSES

As a starting point for later use in the study, the optimum concentration of UO_2F_2 solutions for enrichments varying from 3 wt % ^{235}U to 5.5 wt % ^{235}U were determined. Using these concentrations, k_{eff} as a function of cylinder radius for the different enrichments was calculated. These calculations were compared against standard criticality safety criteria and found to be compatible. The data generated from this study are given in Table A.1 and displayed in Figure A.1.

Next, using the criteria given in KY-710 that the maximum weight of UF_6 absorbed on alumina is equal to the weight of the alumina, optimum concentrations of UO_2F_2 solutions with alumina were determined, and maximum k_{eff} 's for some of the alumina traps were determined as a function of enrichment. These calculations were done by fixing the amount of U in the trap, but allowing the distribution to change by varying the concentration. The remainder of the trap was then filled with an alumina-water mixture, and the trap was fully reflected. The results of this study are displayed in Figure A.2 and indicate that the values used in Table 2 of KY-710 are conservative and could be relaxed somewhat if needed.

A study of the 10-ton product accumulator was performed next. Since this piece of equipment is similar to a 10-ton shipping cylinder which is approved for 4.5 wt % assay, this study was done at both 4.5% and 5%. The results are displayed in Figure A.3. The first value on the figure (at $\text{H}_2\text{O}/\text{U} < 0.1$) corresponds to assuming 0.5% impurity by weight, all HF. The middle point corresponds to assuming the 0.5% is all H_2O , and the last point is the moderation limit specified in criterion 2. The calculation represents a 10-ton spherical mass fully reflected by water. As can be seen from the figure, k_{eff} increases by about 0.025 in going from 4.5 to 5 wt % ^{235}U . Since the safety margin for this system is so large, this increase is not significant.

In order to study the NaF burp traps at 5 wt %, the optimum concentration of UO_2F_2 and NaF was determined, assuming 2 lbs of UF_6 per lb of NaF. These results are displayed in Figure A.4. Using this concentration, a 16-in.-diameter burp trap was analyzed including the monel heat transfer plates. The k_{eff} calculated was 1.031 ± 0.003 . Unless the moderation can be controlled, these traps will need to be replaced.

Finally, the effect of adding Raschig rings to an optimally moderated solution was checked. Although only the single geometric configuration was considered, the k infinity for the system was so far subcritical (0.225) that any reasonable arrangement of Raschig rings will make any of the solution tanks subcritical. The system studied corresponded to a close-packed, square pitched lattice of rings, so that about one-third the volume was occupied by glass.

Table A.1 Paducah UO_2F_2 Solution Study

3.0 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 2050 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P3X1	3000	1.28646	X3B1	15.7	0.952626
P3X2	2500	1.31504	X3B2	20.0	1.04305
P3X3	2000	1.32379	X3B3	18.0	1.00561
P3X4	1500	1.30249	X3B4	13.0	0.873691
P3X5	2100	1.32398			
P3X6	2150	1.32367			
P3X7	2050	1.32402			

3.25 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 2000 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P3P25X1	2000	1.34529	X325B1	18.0	1.02405
P3P25X2	2100	1.34483	X325B2	17.0	1.00270
P3P25X3	1900	1.34469	X325B3	16.0	0.978297
P3P25X4	1800	1.34282	X325B4	14.0	0.923228
P3P25X5	2050	1.34519	X325B5	13.5	0.907419

3.50 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1950 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P3P50X1	2000	1.36430	X350B1	13.0	0.906689
P3P50X2	1900	1.36434	X350B2	14.0	0.938840
P3P50X3	2100	1.36320	X350B3	15.0	0.968270
P3P50X4	1800	1.36316	X350B4	16.0	0.994753
P3P50X5	1950	1.36445			

Table A.1 (continued)

3.75 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1900 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P3P75X1	2000	1.38120	X375B1	15.5	0.997216
P3P75X2	1900	1.38182	X375B2	14.5	0.969079
P3P75X3	1800	1.38129	"	13.5	0.937593
P3P75X4	2100	1.37953	"	12.5	0.903234
P3P75X5	1975	1.38145			

4.0 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1850 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P4X1	2000	1.39631	X4B1	12.0	0.897497
P4X2	1900	1.39748	X4B2	13.0	0.934125
P4X3	1800	1.39754	X4B3	14.0	0.967038
P4X4	1850	1.39766	X4B4	15.0	0.996827
P4X5	1750	1.39712			

4.25 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1800 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P4P25X1	2000	1.40992	X425B1	14.5	0.995270
P4P25X2	1900	1.41160	X425B2	13.5	0.963371
P4P25X3	1800	1.41219	X425B3	12.5	0.928434
P4P25X4	1700	1.41158	"	11.5	0.889422
P4P25X5	1825	1.41215			

Table A.1 (continued)

0.50 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1750 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P4P50X	2000	1.42223	X450B1	11.0	0.879445
P4P50X2	1900	1.42437	"	12.0	0.920530
P4P50X3	1800	1.42546	X450B2	13.0	0.957606
P4P50X4	1700	1.42540	X450B3	14.0	0.991094
P4P50X5	1750	1.42558			

4.75 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1700 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P4P75X1	2000	1.43342	X475B1	13.75	0.994239
P4P75X2	1900	1.43598	X475B2	12.75	0.959643
P4P75X3	1800	1.43754	X475B3	11.75	0.921115
P4P75X4	1700	1.43797	X475B4	11.00	0.889450
P4P75X5	1650	1.43772			

5.0 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1675 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P5X1	1900	1.44658	X5B1	10.75	0.827733
P5X2	1800	1.44856	X5B2	11.75	0.930455
P5X3	1700	1.44947	X5B3	12.75	0.969052
P5X4	1600	1.44912	X5B4	13.75	1.00364
P5X5	1650	1.44945			
P5X6	1675	1.44950			

Table A.1 (continued)

5.25 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1650 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P5P25X1	1800	1.45867	X525X1	13.50	1.00491
P5P25X2	1700	1.46002	X525X2	12.50	0.969062
P5P25X3	1600	1.46014	X525X3	11.50	0.929092
P5P25X4	1650	1.46023	X525X4	10.75	0.896336
P5P25X5	1550	1.45969			

5.50 % ENRICHED

INFHOMMEDIUM CSAS1X			INFINITE CYLINDER XSDRNPM - 1600 GU/L		
CASE	GU/L	LAMBDA	CASE	RADIUS	LAMBDA
P5P50X1	1750	1.46900	X550X1	10.50	0.892905
P5P50X2	1700	1.46973	X550X2	11.25	0.926734
P5P50X3	1650	1.47016	X550X3	12.25	0.967752
P5P50X4	1600	1.47029	X550X4	13.25	1.00465
P5P50X5	1550	1.47007

Fig. A.1 Paducah UO_2F_2 Solution Cylinders

Fig. A.2 UO_2F_2 in Al_2O_3 Traps (Fully Reflected)

Fig. A.3 Product Accumulators (Fully Reflected) 4.5% vs 5.0%

Fig. A.4 Optimum U Concentration for NaF Burp Traps

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