ENGINEERING CHANGE NOTICE

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2. ECN Category (mark one) Supplemental ☐ Direct Revision ☒ Change ECN ☐ Temporary ☐ Standby ☐ Supersedeure ☐ Cancel/Void ☐	3. Originator's Name, Organization, MSIN, and Telephone No. David G. Erickson, Nuclear Analysis and Characterization, HO-32, 376-4146		4. USQ Required? ☐ Yes ☒ No	5. Date 6/07/96
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13a. Description of Change The revision of this document incorporates analyses for a new style of cartridge filters. The new filters are of a new style, in a different configuration. The original analysis, which is still valid, is included as an appendix.				
14a. Justification (mark one) Criteria Change ☐ Design Improvement ☐ Environmental ☐ Facility Deactivation ☐ As-Found ☐ Facilitate Const ☐ Const. Error/Omission ☐ Design Error/Omission ☐				
14b. Justification Details Criticality safety evaluation of the K Basin filter cartridge assemblies.				
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15. Design Verification Required

☐ Yes
☒ No

16. Cost Impact

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 Savings ☐ \$

CONSTRUCTION

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17. Schedule Impact (days)

 Improvement ☐
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18. Change Impact Review: Indicate the related documents (other than the engineering documents identified on Side 1) that will be affected by the change described in Block 12. Enter the affected document number in Block 19.

SDD/DD	☐	Seismic/Stress Analysis	☐	Tank Calibration Manual	☐
Functional Design Criteria	☐	Stress/Design Report	☐	Health Physics Procedure	☐
Operating Specification	☐	Interface Control Drawing	☐	Spare Multiple Unit Listing	☐
Criticality Specification	☐	Calibration Procedure	☐	Test Procedures/Specification	☐
Conceptual Design Report	☐	Installation Procedure	☐	Component Index	☐
Equipment Spec.	☐	Maintenance Procedure	☐	ASME Coded Item	☐
Const. Spec.	☐	Engineering Procedure	☐	Human Factor Consideration	☐
Procurement Spec.	☐	Operating Instruction	☐	Computer Software	☐
Vendor Information	☐	Operating Procedure	☐	Electric Circuit Schedule	☐
OM Manual	☐	Operational Safety Requirement	☐	ICRS Procedure	☐
FSAR/SAR	☐	IEFD Drawing	☐	Process Control Manual/Plan	☐
Safety Equipment List	☐	Cell Arrangement Drawing	☐	Process Flow Chart	☐
Radiation Work Permit	☐	Essential Material Specification	☐	Purchase Requisition	☐
Environmental Impact Statement	☐	Fac. Proc. Samp. Schedule	☐	Tickler File	☐
Environmental Report	☐	Inspection Plan	☐		☐
Environmental Permit	☐	Inventory Adjustment Request	☐		☐

19. Other Affected Documents: (NOTE: Documents listed below will not be revised by this ECN.) Signatures below indicate that the signing organization has been notified of other affected documents listed below.

Document Number/Revision

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OPERATIONS AND ENGINEERING

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ADDITIONAL

CRITICALITY SAFETY EVALUATION REPORT FOR K BASIN FILTER CARTRIDGES

David G. Erickson

Westinghouse Hanford Company, Richland, WA 99352

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Abstract: A criticality safety evaluation of the K Basin filter cartridge assemblies was completed to support operations without a criticality alarm system. The results show that for normal operation, the cartridge assembly is far below the safety limit of $k_{eff} = 0.95$.

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ABSTRACT

A criticality safety evaluation of the new style K Basin filter cartridge assemblies has been completed to support operations without a criticality alarm system. The results show that for normal operation, the filter cartridge assembly is far below the safety limit of $k_{\text{eff}} = 0.95$, which is applied to plutonium systems at the Hanford Site.

During normal operating conditions, uranium, plutonium, fission and corrosion products in suspension are continually accumulating in the filter cartridge medium. Currently, filter cartridge assemblies are scheduled to be replaced at six month intervals in the K East Basin, and at one year intervals in the K West Basin. According to available plutonium concentration data for K East Basin and data for the U/Pu ratio, and even given the conservative assumption that the presence of fission and corrosion products is ignored, the safety limit of $k_{\text{eff}} = 0.95$ cannot be exceeded in the cartridge filters.

For off-normal scenarios, it would require at least two unlikely, independent, and concurrent events to take place before the $k_{\text{eff}} = 0.95$ limit is exceeded. Contingencies considered include failure to replace the filter cartridge assemblies at the scheduled time resulting in additional buildup of fissionable material, the loss of geometry control from the filter cartridge assembly breaking apart and releasing the individual filter cartridges into an optimal configuration, and a lower than normal U/Pu ratio of 10 which is much less than measured data for K East Basin. Extensive measurements in the sand filter backwash pit and plutonium production information give average U/Pu ratios of close to 400.

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CRITICALITY SAFETY EVALUATION REPORT FOR
K BASIN FILTER CARTRIDGES

1.0 INTRODUCTION

A nuclear criticality analysis has been performed for the new style filter cartridge cage assemblies used in the Hanford Site K East (KE) and K West (KW) Basins. The old style filter cartridge assemblies may still be used, and the analyses of those filters has been included as Appendix D at the end of this report. Each new filter cartridge cage assembly holds 7 filter cartridges arranged in a cluster configuration. The filter cartridge cage assembly removes particulates from the basin water by trapping materials in the polypropylene fiber of the filter cartridges. Previous administrative limits were designed to prevent plutonium buildup beyond 225 g in each filter cartridge assembly.

Normal and off-normal operation was analyzed by performing explicit calculations of the filter cartridge assembly cluster geometry using the MCNP code. Data were obtained for an average uranium and plutonium concentration typical of the center-of-basin in KE Basin (Appendix C). These data, along with the flow rate through the filter cartridge assembly, allowed for the estimation of the fissionable material buildup inside the filter assembly with time. Several off-normal contingencies were analyzed, including buildup of fissionable material beyond the planned replacement period, loss of geometry control within the filter assembly, and lower-than-expected U/Pu ratios. The filter cartridge assemblies are scheduled to be replaced at six month intervals in the KE basin and at 12 month intervals in the KW basin. The filters may be changed out earlier than scheduled if the measured pressure drop across the filters becomes too large indicating that the filters are full.

All calculations performed using the data obtained for the KE Basin are conservatively bounding for the KW Basin. Historical center-of-basin water sample data from the KW Basin show that the uranium and plutonium concentrations are usually more than two orders of magnitude less than the center-of-basin water sample data from the KE Basin. The effect of this much lower concentration would greatly increase the time necessary to fill up the cartridge filters.

2.0 DESCRIPTION OF SYSTEM AND FACILITY

The filter cartridge cage assembly contains 7 filter cartridges with 6 filters placed in a ring around the central filter. Each filter cartridge is 58.74 cm (23.13 in.) long, and is made of pleated polypropylene media within a perforated 304 stainless steel housing. The inner diameter of the filter is 9.53 cm (3.75 in.) The outer diameter of the filter is 14.92 cm (5.875 in.) A sketch of an assembled filter cartridge is shown in Figure 1. The filters are assembled into cartridges by placing them between two plates connected by a tie rod. These cartridges are then placed into holes in the upper cage plate. A sketch of the filter cartridge arrangement in the cage assembly is shown in Figure 2. The diameter of the filter cartridge assembly is 66.04 cm (26 in.) There are two filter cartridge assemblies in the basin and

Figure 1. Sketch of Filter Cartridge Assembly Showing Top and Side Views.

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Figure 2. Sketch of the Filter Cartridge Arrangement in the Cage Assembly.

water flows through the assembly in operation at 107,880 L/hr (28,500 gal/hr). The water flows into the top of the cartridge cage assembly, down into the center of the filter media, then flows radially out from each filter. The filter cartridge cage assemblies are located near the bottom of the basin floor in the K Basins. The two filter cartridge cage assemblies are separated by a sufficient amount of water to provide neutronic isolation, approximately 51 cm (20 in.) A layout of the K Basins showing the location of the filter cartridge assemblies is shown in Figure 3.

3.0 REQUIREMENTS DOCUMENTATION

There are no unique requirements applicable to this evaluation.

4.0 METHODOLOGY

The MCNP Monte Carlo Neutron and Photon transport program is widely used and accepted throughout the nuclear industry (Briesmeister and Hendricks 1990, Carter 1994, LANL 1986). MCNP-4.2 which uses continuous energy group ENDF/B-V cross sections was used for this analysis. This code is configuration controlled on the workstations of the SECC (Carter 1994). Any changes or modifications are verified with a standard set of test problems that meet quality assurance requirements. Calculations were performed on a WHC SGI¹ workstation in the Science and Engineering Computational Center.

The use of MCNP for analyzing N Reactor fuel has been extensively validated by comparing calculated neutron multiplication constants to experimental results (Erickson and Wilcox 1989, Schwinkendorf 1991, and Wittekind 1991). It has also been tested extensively with experimental data from homogeneous low-enriched uranium oxide-water systems. The code consistently reproduced the measured data. The computed results are within the uncertainties of the experimental points. The low-enriched uranium oxide-water validation is found in *K Basin Criticality Evaluation for irradiated Fuel Canisters in Sludge*, WHC-SD-NR-CSER-001 (Wittekind 1992).

5.0 DISCUSSION OF CONTINGENCIES

Off-normal scenarios considered in this criticality safety evaluation include failure to replace the filter cartridge assembly when required to do so (resulting in an ever-increasing loading of fissionable material), the loss of geometry in the filter cartridge assembly (resulting in optimal geometry of the sludge in the cartridge filter cage), and lower-than-expected values for U/Pu. The loss of fission and corrosion products was assumed for all scenarios analyzed.

The maximum credible amount of sludge material to accumulate inside the filter cartridge medium was assumed to be a "thick paste" of 4.0 g/cm³ heavy metal oxide solution, in which the heavy metal was composed of both 0.95-wt% ²³⁵U in uranium and 12-wt% ²⁴⁰Pu in plutonium. The U/Pu ratio was assumed to equal 400 for normal conditions, and U/Pu = 10 was used in the contingency

¹ SGI is a trademark of Silicon Graphics, Inc.

Figure 3. Layout of K Basins Showing Cartridge Filter Location.

002 00

analyses; U/Pu = 10 is lower than any U/Pu data available for KE Basin, so this is considered a bounding case. Extensive chemical analysis of K Basin sludge samples has established that U/Pu = 400 is a best-estimate (Rice 1993, Rice 1994, and Welsh 1994.) This value is also consistent with reactor production calculations (Hedengren 1987). The nominal time required for this amount of buildup (4.0 g/cm³ of mixed uranium plutonium oxide completely filling the filter medium) was determined to be just under one year at U/Pu = 400.

6.0 EVALUATION AND RESULTS

6.1 NORMAL CONDITIONS

The filter cartridge is a particulate removal system very similar to the sand filter. It will remove particles of uranium oxide, plutonium oxide, fission products, and corrosion products. These materials will be trapped by the polypropylene filter and accumulate there. In the sand filter the sand is periodically cleaned by a back wash, and the collected particulates are washed into the sand filter backwash pit. Extensive characterization of the sludge in the backwash pit has taken place, detailed chemical and isotopic analyses have been performed, and the sludge's composition is well known (Rice 1993, Rice 1994, and Welsh 1994.) The filter cartridge should be removing sludge with a similar composition from the water. Therefore as the filter cartridge becomes loaded, it will have material in it very similar to the sludge found in the backwash pit.

Under normal operation the filter cartridges will collect sludge consisting of fission and corrosion products and uranium and plutonium oxides in a ratio of U/Pu = 400. Calculations have shown that at these U/Pu ratios, with fission products and corrosion products present, the filter cartridge cage cannot be made critical under any conditions irrespective of whether the uranium enrichment is 0.95- or 1.25-wt% ²³⁵U (Erickson 1994b).

If a very conservative assumption is made that the fission products and corrosion products disappear and we are left only with a uranium and plutonium oxide system in the filter cartridge, the system will still not be made critical. In other words, the k_{eff} will be less than 0.95 for typical conditions of moderation and material loadings. The highest k_{eff} calculated for an off-normal 1.4-year accumulation of uranium and plutonium, which completely fills the filter media and interior volume, is equal to 0.664. This conclusion is true for KE Basin and very conservative for the KW Basin. Therefore, normal operation of filter cartridges in water and in dry storage will be substantially subcritical and will not exceed $k_{eff} = 0.95$.

The calculations for normal conditions assume that uranium and plutonium loading builds up in the filter until the time the filter is replaced. This entire filter media volume was assumed to be filled with a sludge material, actually a thick paste, composed of 4.0 g/cm³ oxide. This oxide consists of UO₂ plus PuO₂, according to a given U/Pu ratio. A U/Pu ratio equal to 400 is thought to represent the greatest amount of fissionable material that can be considered as credible inside the filter cartridges during normal operation. Furthermore the calculations assumed that there are no fission products, iron, or other corrosion products present in the system. This conservative assumption resulted in significantly higher calculated neutron multiplication than would otherwise be the case.

Average values for plutonium concentration (5.5×10^{-7} g/L, appropriate for center-of-basin, Appendix C), a best estimate U/Pu ratio, and the flow rate through the filter cartridge assembly (107,880 L/hr) were used to calculate the accumulation rate of heavy metal oxide. Given the rate of plutonium accumulation (520 g/yr), it is possible to find (assuming 100% filter efficiency) the time required for this maximum amount of material to accumulate. Assuming that U/Pu = 400, the time required for 4.0 g/cm³ of heavy metal oxide sludge to accumulate in the filter media is approximately 0.82 years.

The results in Table 1 are based on normal operating conditions for the KE and KW Basins, assuming the same uranium and plutonium concentrations. Historical center-of-basin water sample data from the KW Basin show that the uranium and plutonium concentrations are usually more than two orders of magnitude less than the center-of-basin water sample data from the KE Basin. The results in Table 1 clearly show that when the best-estimate U/Pu value of 400 is assumed, there is no danger from a criticality, even if the filter cartridge assembly is not replaced at the scheduled time, which would be a violation of procedures. Even assuming that the uranium enrichment is equal to 1.25 wt% (which would be the case in the KW Basin), the k_{eff} remains below 0.60.

Table 1. MCNP k_{eff} Results for Normal Sludge Accumulation (U/Pu = 400).

Case Name	Description	$k_{eff} \pm 2\sigma$
CF001A	²³⁵ U=0.95%, filters filled with sludge, ~0.82 years.	0.526 $\pm$ 0.003
CF011A	²³⁵ U=1.25%, filters filled with sludge, ~0.82 years.	0.579 $\pm$ 0.004

6.2 OFF-NORMAL CONDITIONS

For off-normal conditions the following contingency sequences were considered:

- Inadvertent material buildup
- Changes in the U/Pu ratio
- Collapse of the filter cartridge assembly geometry, with the resulting change in moderation.

It was conservatively assumed that there were no fission or corrosion products in the filter cartridges.

6.2.1 Material Buildup

The first off-normal contingency analyzed was failure to replace the filter cartridge at the scheduled time intervals of 6 month and 12 months for KE and KW Basins respectively. Table 2 shows the results if the filters are left in place until the filter media and interior volume is full. Using the values discussed previously for accumulation rate, this will take about 1.4 years for the KE Basin without a reduction in efficiency. With the much lower concentrations of uranium and plutonium found in the KW Basin, this may take

decades. If the U/Pu ratio remains at 400, extended operation will increase k_{eff} above the normal values, but not significantly.

Table 2. MCNP k_{eff} Results for Off-normal Sludge Accumulation (U/Pu = 400).

Case Name	Description	$k_{eff} \pm 2\sigma$
CF021B	$^{235}\text{U}=0.95\%$, filter full of sludge, ~1.4 years without changeout.	0.615 ± 0.004
CF031B	$^{235}\text{U}=1.25\%$, filter full of sludge, ~1.4 years without changeout.	0.664 ± 0.004

6.2.2 Material Segregation

The second off-normal contingency analyzed was for a U/Pu ratio less than the best-estimate value of 400. Measured data show a large spread in U/Pu values, but little confidence is given to this data because of the level of uncertainty in the measurements. Nevertheless a value of U/Pu = 10 was selected as a bounding case for the uranium loss scenario. Table 1 was redone for U/Pu = 10 and the results are reported in Table 3. At this U/Pu ratio and using the typical plutonium concentration in the basin water, filter cartridges are still subcritical if they are not changed out at the scheduled times of 6 months and 12 months for KE and KW respectively.

In this scenario the plutonium is held constant when the U/Pu is changed in the model because higher confidence is given to the measured plutonium data than to the measured uranium data. With this assumption the time required to fill the filter media volume with 4.0 g/cm^3 material is approximately 36 times longer or about 30 years (because there is 40 times less uranium in solution but the same concentration of plutonium.)

Table 3. MCNP k_{eff} Results for Off-normal Sludge Composition Accumulation.

Case Name	Description	$k_{eff} \pm 2\sigma$
CF002A	$^{235}\text{U}=0.95\%$, U:Pu = 10	0.922 ± 0.005
CF012A	$^{235}\text{U}=1.25\%$, U:Pu = 10	0.923 ± 0.005

6.2.3 Loss of Intact Geometry

The third contingency considered was the collapse of a filter cartridge assembly. It is conceivable that one or more tie rods could break, in which case geometry control would be lost. For this contingency, it was assumed that all seven tie rods broke, releasing all of the sludge entrained in the filters. Full density water reflection is assumed. This would be the case if the filter assembly were to come apart while still under water (e.g., while being raised out of the basin during replacement) Cases for both U:Pu=400 and U:Pu=10 are given. The 27.30 cm hemisphere case is if this were to occur when just the filter media volume is full. The 32.50 cm case includes the interior filter volume full of material as well. The final case given (CF105) includes at least three contingencies: failure to replace the filter cartridge

assembly on time, an unrealistically low value of U/Pu, and the breakage of the filter assembly. However, the system is still safely subcritical.

Table 4. MCNP k_{eff} Results for Off-normal Sludge Accumulation.. Loss of Geometry Control

Case Name	Description	$k_{eff} \pm 2\sigma$
CF122	27.30 cm Hemisphere, U:Pu=400, ^{235}U =0.95%, ~0.82 year accumulation.	0.730 ± 0.004
CF121	32.50 cm Hemisphere, U:Pu=400, ^{235}U =0.95%, ~1.4 year accumulation.	0.796 ± 0.005
CF112	27.30 cm Hemisphere, U:Pu=400, ^{235}U =1.25%, ~0.82 year accumulation.	0.781 ± 0.004
CF111	32.50 cm Hemisphere, U:Pu=400, ^{235}U =1.25%, ~1.4 year accumulation.	0.847 ± 0.004
CF105	27.30 cm Hemisphere, U:Pu=10, ^{235}U =1.25%, ~30 year accumulation.	0.940 ± 0.005

More than two contingencies have to occur to reach a $k_{eff} = 0.95$. In all the scenarios analyzed, the requirement for double contingency was not violated. No credible contingencies were identified where a single occurrence could violate criticality safety.

7.0 DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS

The one administratively controlled limit applicable to this evaluation is that the filter cartridge assembly be replaced on time, which according to the present schedule, is six months for KE Basin and one year for KW Basin.

8.0 SUMMARY AND CONCLUSIONS

The *Nuclear Criticality Safety Manual*, WHC-CM-4-29, Section 5, states that:

"Criticality alarm systems (CAS) and criticality detection systems shall be installed as follows:

- (1) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3 and the probability of criticality is greater than 1×10^{-6} per year (as documented in a DOE approved SAR), a CAS meeting ANSI/ANS-8.3 shall be provided to cover occupied areas in which the expected dose exceeds 12 rads in free air, where a CAS is defined to include a criticality accident detection device and a personnel evacuation alarm.
- (2) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3 and the probability of criticality is greater than 1×10^{-6} per year, (as documented in a DOE-

approved SAR), but there are no occupied areas in which the expected dose exceeds 12 rads in free air, a criticality detection system shall be provided; where a criticality detection system is defined to be an appropriate criticality accident detection device but without an immediate evacuation alarm. The criticality accident detection system response time should be sufficient to allow for appropriate process-related mitigation and recovery actions. While an immediate evacuation alarm is not required under these circumstances, evacuation shall be implemented (i.e., evacuation notification or delayed alarm) if potential doses to occupational workers could be effectively limited by such actions.

- (3) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3, but a criticality accident is determined to be impossible due to the physical form of the fissionable material, or the probability of occurrence is determined to be less than 1×10^{-6} per year (as documented in a DOE-approved SAR), neither a CAS nor a criticality detection system is required. In addition, neither a CAS nor a criticality detection system is required to be installed underwater when fissionable material is handled or stored beneath water shielding that is adequate to protect personnel; however, a means to detect fission product gases or other volatile fission products should be provided in occupied areas immediately adjacent to such underwater storage areas, except for fuel systems where no fission products are likely to be released. Also, neither a CAS nor a criticality detection system are required for fissionable material during shipment of fissionable material packaged in approved shipping containers, or fissionable material packaged in approved shipping containers awaiting transport provided no other operation involving fissionable material not so packaged is permitted on the dock or in the shipment area.
- (4) The decision to install a criticality detection system rather than a CAS, and the decision that neither a CAS nor a criticality detection system is necessary, must be justified based upon a documented DOE-approved safety analysis."

The basis for not requiring a criticality alarm system for the filter cartridge operation is that a nuclear criticality is not possible "due to the physical form of fissionable material," from criteria #3 above. All analyses of normal and unlikely contingencies show the cartridge filters are adequately subcritical.

The filter cartridge cage assembly is a filter for particulate matter in basin water, similar to the sand filter. The particulates that will be trapped include corrosion and fission products, uranium and plutonium oxides, and other particulates. The presence of corrosion and fission products in the filter cartridge assembly during normal operation in water and subsequent dry storage was shown to make criticality impossible under any conditions. The filter cartridge assemblies are scheduled to be replaced at six month intervals in the KE basin and at 12 month intervals in the KW basin. The filters may be changed out earlier than scheduled if the measured pressure drop across the filters becomes too large indicating that the filters are full. Filter geometry limits the total material that can be accumulated in a filter. The analysis has shown that even over filled, the cartridge filters

are adequately subcritical. The form of the fissile material in the geometry of the cartridge filters make criticality impossible.

For off-normal analyses, a number of contingencies were evaluated. The contingencies considered included failure to replace the filter cartridge assemblies at the scheduled time resulting in additional buildup of fissionable material with a maximum $k_{\text{eff}} = 0.664$, concentrations of plutonium at U/Pu ratios less than measured data for K East Basin with a maximum $k_{\text{eff}} = 0.923$ for a U/Pu ratio of 10, and the loss of geometry control from the filter cartridge assembly breaking apart and releasing the individual filter cartridges into an optimal configuration with a maximum $k_{\text{eff}} = 0.847$ with a normal U/Pu ratio. In all accident scenarios identified, no single contingency was found that would exceed the $k_{\text{eff}} = 0.95$ limit, therefore in all identified cases, a single contingency was insufficient to create a critical system. In addition, conservatism in the analysis would increase the margin of subcriticality. Two of the more important conservatisms are the absence of all fission and corrosion products and using a low U/Pu ratio.

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APPENDIX A
INDEPENDENT REVIEW

CHECKLIST FOR INDEPENDENT REVIEW

Document Reviewed: Criticality Safety Evaluation Report for K Basin Filter CartridgesAuthor: D. G. EricksonYes No N/A

- ☒ ☐ ☐ Problem completely defined.
- ☒ ☐ ☐ Necessary assumptions explicitly stated and supported.
- ☒ ☐ ☐ Computer codes and data files documented.
- ☒ ☐ ☐ Data checked for consistency with original source information as applicable.
- ☒ ☐ ☐ Mathematical derivations checked including dimensional consistency of results.
- ☒ ☐ ☐ Models appropriate and used within range of validity or use outside range of established validity justified.
- ☒ ☐ ☐ Hand calculations checked for errors.
- ☒ ☐ ☐ Code run streams correct and consistent with analysis documentation.
- ☒ ☐ ☐ Code output consistent with input and with results reported in analysis documentation.
- ☒ ☐ ☐ Acceptability limits on analytical results applicable and supported. Limits checked against sources.
- ☒ ☐ ☐ Safety margins consistent with good engineering practices.
- ☒ ☐ ☐ Conclusions consistent with analytical results and applicable limits.
- ☒ ☐ ☐ Results and conclusions address all points required in the problem statement.
- ☒ ☐ ☐ Have all reasonable accidents been considered?
- ☐ ☒ ☒ Has low density water (steam) been evaluated as a moderator?
- ☒ ☐ ☐ Is the fuel and other hardware composition correct?
- ☒ ☐ ☐ Are the cases considered conservative? Too conservative?
- ☒ ☐ ☐ Do the computer models adequately reflect the actual geometry? Have cross sectional cuts of the geometry been made and do they show the desired geometry?
- ☐ ☐ ☒ Has the analysis been reviewed by Safety? This may not be required in a preliminary design.
- ☒ ☐ ☐ Has the reviewer completed the Criticality Safety Course for Managers and Engineers?
- Date completed June 5, 1996

Reviewed by: Edward M. MillerDate June 5, 1996

NOTE: Any hand calculations, notes, or summaries generated as part of this review should be signed, dated, and attached to this checklist. Materials should be labeled and recorded so that it is intelligible to a technically-qualified third party.

APPENDIX B
ALL MCNP INPUT FILES

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Case CF001A. This case models the seven cartridge filters with a U:Pu ratio of 400 and the ^{235}U enrichment is 0.95%. The filter media volume is completely full with 4.0 g/cm^3 sludge.

message:

CF001a - Cartridge Filter U:Pu=400, H:U=6.366, U235=0.95%, no ends

c	m	x	-x	y	-y	z	-z	r	-r	u=	imp:n=		
1	3	-1.00	-2	19	-18						\$	CF 1 bottom	
2	3	-1.00	-1	18	-16						\$	CF 1 inside	
3	1	-4.	-2	1	18						\$	CF 1 sludge	
4	3	-1.00	-2	16	-15						\$	CF 1 top	
5	3	-1.00	-4	19	-18						\$	CF 2 bottom	
6	3	-1.00	-3	18	-16						\$	CF 2 inside	
7	1	-4.	-4	3	18						\$	CF 2 sludge	
8	3	-1.00	-4	16	-15						\$	CF 2 top	
9	3	-1.00	-6	19	-18						\$	CF 3 bottom	
10	3	-1.00	-5	18	-16						\$	CF 3 inside	
11	1	-4.	-6	5	18						\$	CF 3 sludge	
12	3	-1.00	-6	16	-15						\$	CF 3 top	
13	3	-1.00	-8	19	-18						\$	CF 4 bottom	
14	3	-1.00	-7	18	-16						\$	CF 4 inside	
15	1	-4.	-8	7	18						\$	CF 4 sludge	
16	3	-1.00	-8	16	-15						\$	CF 4 top	
17	3	-1.00	-10	19	-18						\$	CF 5 bottom	
18	3	-1.00	-9	18	-16						\$	CF 5 inside	
19	1	-4.	-10	9	18						\$	CF 5 sludge	
20	3	-1.00	-10	16	-15						\$	CF 5 top	
21	3	-1.00	-12	19	-18						\$	CF 6 bottom	
22	3	-1.00	-11	18	-16						\$	CF 6 inside	
23	1	-4.	-12	11	18						\$	CF 6 sludge	
24	3	-1.00	-12	16	-15						\$	CF 6 top	
25	3	-1.00	-14	19	-18						\$	CF 7 bottom	
26	3	-1.00	-13	18	-16						\$	CF 7 inside	
27	1	-4.	-14	13	18						\$	CF 7 sludge	
28	3	-1.00	-14	16	-15						\$	CF 7 top	
29	3	-1.0	-22	-15	19	2	4	6	8	10	12	14	\$ Water surrounding CFs
30	3	-1.0	-22	-19	20								\$ Water below (inside)
31	3	-1.00	-23	-22	-15	20							\$ Cage wall
32	3	-1.00	-23	-20	21								\$ Cage bottom
33	3	-1.0	-24	-25	15								\$ Water above cage
34	3	-1.0	-24	-23	-15	21							\$ Water around cage
35	3	-1.0	-24	-21	26								\$ Water below cage
36	0		24	25	-26								\$ Outside Everything
1	c/z	4.7625									\$	CF 1 inner surface (center)	
2	c/z	7.4613									\$	CF 1 outer surface	
3	c/z	0.000	20.955	4.7625							\$	CF 2 inner surface	
4	c/z	0.000	20.955	7.4613							\$	CF 2 outer surface	
5	c/z	18.1476	10.4775	4.7625							\$	CF 3 inner surface	
6	c/z	18.1476	10.4775	7.4613							\$	CF 3 outer surface	
7	c/z	18.1476	10.4775	4.7625							\$	CF 4 inner surface	
8	c/z	18.1476	10.4775	7.4613							\$	CF 4 outer surface	
9	c/z	0.000	20.955	4.7625							\$	CF 5 inner surface	
10	c/z	0.000	20.955	7.4613							\$	CF 5 outer surface	
11	c/z	-18.1476	10.4775	4.7625							\$	CF 6 inner surface	
12	c/z	-18.1476	10.4775	7.4613							\$	CF 6 outer surface	
13	c/z												

```

mode n
imp:n 1 34r 0
m1 1001.50c -1.94102E-02 $H Sludge
    8016.50c -2.53095E-01 $O
    92235.50c -6.89389E-03 $U235
    92238.50c -7.18779E-01 $U238
    94239.55c -1.60319E-03 $Pu239
    94240.50c -2.18617E-04 $Pu240
mt1 lwtr.01t $ Hydrogen in water 300
m2 6000.50c -0.0004 $C stainless steel 304 (8.03 g/cc)
    14000.50c -0.0100 $Si
    24000.50c -0.1900 $Cr
    25055.50c -0.0200 $Mn
    26000.55c -0.6871 $Fe
    28000.50c -0.0925 $Ni
m3 1001.50c 2 $H H2O
    8016.50c 1 $O
mt3 lwtr.01t $ Hydrogen in water 300
kcode 1000 0.5 5 50
ksrc 0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
    0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
    18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
    18.1476 -10.4775 15.0 18.1476 -10.4775 45.0 18.1476 -10.4775 70.0
    0.0000 -20.9550 15.0 0.0000 -20.9550 45.0 0.0000 -20.9550 70.0
    -18.1476 -10.4775 15.0 -18.1476 -10.4775 45.0 -18.1476 -10.4775 70.0
    -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
totnu
print
ctme 60

```

Case CF011A. This case models the seven cartridge filters with a U:Pu ratio of 400 and the ^{235}U enrichment is 1.25%. The filter media volume is completely full with 4.0 g/cm³ sludge.

message:

CF011a - Cartridge Filter U:Pu=400, H:U=6.366, U=1.25%, no ends

```

c
c m x -x y -y z -z r -r u= imp:n= $
1 3 -1.00 -2 19 -18 $ CF 1 bottom
2 3 -1.00 -1 18 -16 $ CF 1 inside
3 1 -4 -2 1 18 -16 $ CF 1 sludge
4 3 -1.00 -2 16 -15 $ CF 1 top
5 3 -1.00 -4 19 -18 $ CF 2 bottom
6 3 -1.00 -3 18 -16 $ CF 2 inside
7 1 -4 -4 3 18 -16 $ CF 2 sludge
8 3 -1.00 -4 16 -15 $ CF 2 top
9 3 -1.00 -6 19 -18 $ CF 3 bottom
10 3 -1.00 -5 18 -16 $ CF 3 inside
11 1 -4 -6 5 18 -16 $ CF 3 sludge
12 3 -1.00 -6 16 -15 $ CF 3 top
13 3 -1.00 -8 19 -18 $ CF 4 bottom
14 3 -1.00 -7 18 -16 $ CF 4 inside
15 1 -4 -8 7 18 -16 $ CF 4 sludge
16 3 -1.00 -8 16 -15 $ CF 4 top
17 3 -1.00 -10 19 -18 $ CF 5 bottom
18 3 -1.00 -9 18 -16 $ CF 5 inside
19 1 -4 -10 9 18 -16 $ CF 5 sludge
20 3 -1.00 -10 16 -15 $ CF 5 top
21 3 -1.00 -12 19 -18 $ CF 6 bottom
22 3 -1.00 -11 18 -16 $ CF 6 inside
23 1 -4 -12 11 18 -16 $ CF 6 sludge
24 3 -1.00 -12 16 -15 $ CF 6 top
25 3 -1.00 -14 19 -18 $ CF 7 bottom
26 3 -1.00 -13 18 -16 $ CF 7 inside
27 1 -4 -14 13 18 -16 $ CF 7 sludge
28 3 -1.00 -14 16 -15 $ CF 7 top
29 3 -1.0 -22 -15 19 2 4 6 8 10 12 14 $ Water surrounding Cfs
30 3 -1.0 -22 -19 20 $ Water below (inside)
31 3 -1.00 -23 22 -15 20 $ Cage wall

```

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32	3	-1.00	-23	-20	21		\$ Cage bottom
33	3	-1.0	-24	-25	15		\$ Water above cage
34	3	-1.0	-24	23	-15	21	\$ Water around cage
35	3	-1.0	-24	-21	26		\$ Water below cage
36	0		24	25	-26		\$ Outside Everything

1	c/z	4.7625					\$ CF 1 inner surface (center)
2	c/z	7.4613					\$ CF 1 outer surface
3	c/z	0.000	20.955	4.7625			\$ CF 2 inner surface
4	c/z	0.000	20.955	7.4613			\$ CF 2 outer surface
5	c/z	18.1476	10.4775	4.7625			\$ CF 3 inner surface
6	c/z	18.1476	10.4775	7.4613			\$ CF 3 outer surface
7	c/z	18.1476	-10.4775	4.7625			\$ CF 4 inner surface
8	c/z	18.1476	-10.4775	7.4613			\$ CF 4 outer surface
9	c/z	0.000	-20.955	4.7625			\$ CF 5 inner surface
10	c/z	0.000	-20.955	7.4613			\$ CF 5 outer surface
11	c/z	-18.1476	-10.4775	4.7625			\$ CF 6 inner surface
12	c/z	-18.1476	-10.4775	7.4613			\$ CF 6 outer surface
13	c/z	-18.1476	10.4775	4.7625			\$ CF 7 inner surface
14	c/z	-18.1476	10.4775	7.4613			\$ CF 7 outer surface
15	p/z	72.3900					\$ Top of filter (outside)
16	p/z	71.1200					\$ Top of filter (inside)
17	p/z	22.3825					\$ Sludge level (if needed)
18	p/z	12.3825					\$ Bottom of filter (inside)
19	p/z	11.4300					\$ Bottom of filter (outside)
20	p/z	0.6350					\$ Cage bottom (inside)
21	p/z	0.0000					\$ Cage bottom (outside)
22	c/z	32.385					\$ Cage (inside)
23	c/z	33.020					\$ Cage (outside)
24	c/z	65.000					\$ water surrounding cage
25	p/z	105.000					\$ water above cage
26	p/z	-31.000					\$ water below cage

```

mode      n
imp:n 1 34r 0
m1        1001.50c -1.94102E-02 $H Sludge
          8016.50c -2.53095E-01 $O
          92235.50c -9.07091E-03 $U235
          92238.50c -7.16602E-01 $U238
          94239.55c -1.60319E-03 $Pu239
          94240.50c -2.18617E-04 $Pu240
mt1        lwtr.01t $ Hydrogen in water 300
m2         6000.50c -0.0004 $ C stainless steel 304 (8.03 g/cc)
          14000.50c -0.0100 $ Si
          24000.50c -0.1900 $ Cr
          25055.50c -0.0200 $ Mn
          26000.55c -0.6871 $ Fe
          28000.50c -0.0925 $ Ni
m3         1001.50c 2 $ H H2O
          8016.50c 1 $ O
mt3        lwtr.01t $ Hydrogen in water 300
kcode     1000 0.5 5 100
ksrc      0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
          0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
          18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
          18.1476 -10.4775 15.0 18.1476 -10.4775 45.0 18.1476 -10.4775 70.0
          0.0000 -20.9550 15.0 0.0000 -20.9550 45.0 0.0000 -20.9550 70.0
          -18.1476 -10.4775 15.0 -18.1476 -10.4775 45.0 -18.1476 -10.4775 70.0
          -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
totnu
print
ctme 60

```


Case CF021B. This case models the seven cartridge filters with a U:Pu ratio of 400 and the ^{235}U enrichment is 0.95%. The filter media volume is completely full with 4.0 g/cm³ sludge, as is the volume inside the filter.

message:

CF021b - Cartridge Filter U:Pu=400, H:U=6.366, U235=0.95%, no ends, full sludge

c	m	x	-x	y	-y	z	-z	r	-r	u	imp:n	\$	
1	3	-1.00	-2	19	-18							\$ CF 1 bottom	
2	1	-4.00	-1	18	-17							\$ CF 1 sludge inside	
3	3	-1.00	-1	17	-16							\$ CF 1 inside	
4	1	-4	-2	1	18	-16						\$ CF 1 sludge	
5	3	-1.00	-2	16	-15							\$ CF 1 top	
6	3	-1.00	-4	19	-18							\$ CF 2 bottom	
7	1	-4.00	-3	18	-17							\$ CF 1 sludge inside	
8	3	-1.00	-3	17	-16							\$ CF 1 inside	
9	1	-4	-4	3	18	-16						\$ CF 2 sludge	
10	3	-1.00	-4	16	-15							\$ CF 2 top	
11	3	-1.00	-6	19	-18							\$ CF 3 bottom	
12	1	-4.00	-5	18	-17							\$ CF 1 sludge inside	
13	3	-1.00	-5	17	-16							\$ CF 1 inside	
14	1	-4	-6	5	18	-16						\$ CF 3 sludge	
15	3	-1.00	-6	16	-15							\$ CF 3 top	
16	3	-1.00	-8	19	-18							\$ CF 4 bottom	
17	1	-4.00	-7	18	-17							\$ CF 1 sludge inside	
18	3	-1.00	-7	17	-16							\$ CF 1 inside	
19	1	-4	-8	7	18	-16						\$ CF 4 sludge	
20	3	-1.00	-8	16	-15							\$ CF 4 top	
21	3	-1.00	-10	19	-18							\$ CF 5 bottom	
22	1	-4.00	-9	18	-17							\$ CF 1 sludge inside	
23	3	-1.00	-9	17	-16							\$ CF 1 inside	
24	1	-4	-10	9	18	-16						\$ CF 5 sludge	
25	3	-1.00	-10	16	-15							\$ CF 5 top	
26	3	-1.00	-12	19	-18							\$ CF 6 bottom	
27	1	-1.00	-11	18	-17							\$ CF 1 sludge inside	
28	3	-1.00	-11	17	-16							\$ CF 1 inside	
29	1	-4	-12	11	18	-16						\$ CF 6 sludge	
30	3	-1.00	-12	16	-15							\$ CF 6 top	
31	3	-1.00	-14	19	-18							\$ CF 7 bottom	
32	1	-4.00	-13	18	-17							\$ CF 1 sludge inside	
33	3	-1.00	-13	17	-16							\$ CF 1 inside	
34	1	-4	-14	13	18	-16						\$ CF 7 sludge	
35	3	-1.00	-14	16	-15							\$ CF 7 top	
36	3	-1.0	-22	-15	19	2	4	6	8	10	12	14	\$ Water surrounding CFs
37	3	-1.0	-22	-19	20								\$ Water below (inside)
38	3	-1.00	-23	22	-15	20							\$ Cage wall
39	3	-1.00	-23	-20	21								\$ Cage bottom
40	3	-1.0	-24	-25	15								\$ Water above cage
41	3	-1.0	-24	23	-15	21							\$ Water around cage
42	3	-1.0	-24	-21	26								\$ Water below cage
43	0		24	25	-26								\$ Outside Everything
1	cz	4.7625											\$ CF 1 inner surface (center)
2	cz	7.4613											\$ CF 1 outer surface
3	c/z	0.000	20.955	4.7625									\$ CF 2 inner surface
4	c/z	0.000	20.955	7.4613									\$ CF 2 outer surface
5	c/z	18.1476	10.4775	4.7625									\$ CF 3 inner surface
6	c/z	18.1476	10.4775	7.4613									\$ CF 3 outer surface
7	c/z	18.1476	-10.4775	4.7625									\$ CF 4 inner surface
8	c/z	18.1476	-10.4775	7.4613									\$ CF 4 outer surface
9	c/z	0.000	-20.955	4.7625									\$ CF 5 inner surface
10	c/z	0.000	-20.955	7.4613									\$ CF 5 outer surface
11	c/z	-18.1476	-10.4775	4.7625									\$ CF 6 inner surface
12	c/z	-18.1476	-10.4775	7.4613									\$ CF 6 outer surface
13	c/z	-18.1476	10.4775	4.7625									\$ CF 7 inner surface
14	c/z	-18.1476	10.4775	7.4613									\$ CF 7 outer surface
15	pz	72.3900											\$ Top of filter (outside)
16	pz	71.1200											\$ Top of filter (inside)
17	pz	71.1200											\$ Sludge level (if needed)
18	pz	12.3825											\$ Bottom of filter (inside)
19	pz	11.4300											\$ Bottom of filter (outside)
20	pz	0.6350											\$ Cage bottom (inside)

```

21 pz      0.0000          $ Cage bottom (outside)
22 cz      32.385         $ Cage (inside)
23 cz      33.020         $ Cage (outside)
24 cz      65.000         $ water surrounding cage
25 pz      105.000        $ water above cage
26 pz      -31.000        $ water below cage

mode n
imp:n 1 41r 0
m1      1001.50c -1.94102E-02 $H          Sludge
        8016.50c -2.53095E-01 $O
        92235.50c -6.89389E-03 $U235
        92238.50c -7.18779E-01 $U238
        94239.55c -1.60319E-03 $Pu239
        94240.50c -2.18617E-04 $Pu240
mt1      lwtr.01t          $ Hydrogen in water 300
m2      6000.50c -0.0004     $ C          stainless steel 304 (8.03 g/cc)
        14000.50c -0.0100    $ Si
        24000.50c -0.1900    $ Cr
        25055.50c -0.0200    $ Mn
        26000.55c -0.6871    $ Fe
        28000.50c -0.0925    $ Ni
m3      1001.50c 2          $ H          H2O
        8016.50c 1          $ O
mt3      lwtr.01t          $ Hydrogen in water 300
kcode 1000 0.5 5 100
ksrc 0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
      0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
      18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
      18.1476 -10.4775 15.0 18.1476 -10.4775 45.0 18.1476 -10.4775 70.0
      0.0000 -20.9550 15.0 0.0000 -20.9550 45.0 0.0000 -20.9550 70.0
      -18.1476 -10.4775 15.0 -18.1476 -10.4775 45.0 -18.1476 -10.4775 70.0
      -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0

totnu
print
ctme 60

```

Case CF031B. This case models the seven cartridge filters with a U:Pu ratio of 400 and the ²³⁵U enrichment is 1.25%. The filter media volume is completely full with 4.0 g/cm³ sludge, as is the volume inside the filter.

message:

CF031b - Cartridge Filter U:Pu=400, H:U=6.366, U235=1.25%, no ends, full sludge

```

c
c m x -x y -y z -z r -r u= imp:n= $
1 3 -1.00 -2 19 -18 $ CF 1 bottom
2 1 -4.00 -1 18 -17 $ CF 1 sludge inside
3 3 -1.00 -1 17 -16 $ CF 1 inside
4 1 -4 -2 1 18 -16 $ CF 1 sludge
5 3 -1.00 -2 16 -15 $ CF 1 top
6 3 -1.00 -4 19 -18 $ CF 2 bottom
7 1 -4.00 -3 18 -17 $ CF 1 sludge inside
8 3 -1.00 -3 17 -16 $ CF 1 inside
9 1 -4 -4 3 18 -16 $ CF 2 sludge
10 3 -1.00 -4 16 -15 $ CF 2 top
11 3 -1.00 -6 19 -18 $ CF 3 bottom
12 1 -4.00 -5 18 -17 $ CF 1 sludge inside
13 3 -1.00 -5 17 -16 $ CF 1 inside
14 1 -4 -6 5 18 -16 $ CF 3 sludge
15 3 -1.00 -6 16 -15 $ CF 3 top
16 3 -1.00 -8 19 -18 $ CF 4 bottom
17 1 -4.00 -7 18 -17 $ CF 1 sludge inside
18 3 -1.00 -7 17 -16 $ CF 1 inside
19 1 -4 -8 7 18 -16 $ CF 4 sludge
20 3 -1.00 -8 16 -15 $ CF 4 top
21 3 -1.00 -10 19 -18 $ CF 5 bottom
22 1 -4.00 -9 18 -17 $ CF 1 sludge inside
23 3 -1.00 -9 17 -16 $ CF 1 inside
24 1 -4 -10 9 18 -16 $ CF 5 sludge
25 3 -1.00 -10 16 -15 $ CF 5 top
26 3 -1.00 -12 19 -18 $ CF 6 bottom

```

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27	1	-1.00	-11	18	-17												\$ CF 1 sludge inside
28	3	-1.00	-11	17	-16												\$ CF 1 inside
29	1	-4.	-12	11	18	-16											\$ CF 6 sludge
30	3	-1.00	-12	16	-15												\$ CF 6 top
31	3	-1.00	-14	19	-18												\$ CF 7 bottom
32	1	-4.00	-13	18	-17												\$ CF 1 sludge inside
33	3	-1.00	-13	17	-16												\$ CF 1 inside
34	1	-4.	-14	13	18	-16											\$ CF 7 sludge
35	3	-1.00	-14	16	-15												\$ CF 7 top
36	3	-1.0	-22	-15	19		2	4	6	8	10	12	14				\$ Water surrounding CFs
37	3	-1.0	-22	-19	20												\$ Water below (inside)
38	3	-1.00	-23	22	-15	20											\$ Cage wall
39	3	-1.00	-23	-20	21												\$ Cage bottom
40	3	-1.0	-24	-25	15												\$ Water above cage
41	3	-1.0	-24	23	-15	21											\$ Water around cage
42	3	-1.0	-24	-21	26												\$ Water below cage
43	0		24	25	-26												\$ Outside Everything

1	cz	4.7625															\$ CF 1 inner surface (center)
2	cz	7.4613															\$ CF 1 outer surface
3	c/z	0.000	20.955	4.7625													\$ CF 2 inner surface
4	c/z	0.000	20.955	7.4613													\$ CF 2 outer surface
5	c/z	18.1476	10.4775	4.7625													\$ CF 3 inner surface
6	c/z	18.1476	10.4775	7.4613													\$ CF 3 outer surface
7	c/z	18.1476	-10.4775	4.7625													\$ CF 4 inner surface
8	c/z	18.1476	-10.4775	7.4613													\$ CF 4 outer surface
9	c/z	0.000	-20.955	4.7625													\$ CF 5 inner surface
10	c/z	0.000	-20.955	7.4613													\$ CF 5 outer surface
11	c/z	-18.1476	-10.4775	4.7625													\$ CF 6 inner surface
12	c/z	-18.1476	-10.4775	7.4613													\$ CF 6 outer surface
13	c/z	-18.1476	10.4775	4.7625													\$ CF 7 inner surface
14	c/z	-18.1476	10.4775	7.4613													\$ CF 7 outer surface
15	pz	72.3900															\$ Top of filter (outside)
16	pz	71.1200															\$ Top of filter (inside)
17	pz	71.1199															\$ Sludge level (if needed)
18	pz	12.3825															\$ Bottom of filter (inside)
19	pz	11.4300															\$ Bottom of filter (outside)
20	pz	0.6350															\$ Cage bottom (inside)
21	pz	0.0000															\$ Cage bottom (outside)
22	cz	32.385															\$ Cage (inside)
23	cz	33.020															\$ Cage (outside)
24	cz	65.000															\$ water surrounding cage
25	pz	105.000															\$ water above cage
26	pz	-31.000															\$ water below cage

```

mode n
imp:n 1 41r 0
m1 1001.50c -1.94102E-02 $H Sludge
    8016.50c -2.53095E-01 $O
    92235.50c -9.07091E-03 $U235
    92238.50c -7.16602E-01 $U238
    94239.55c -1.60319E-03 $Pu239
    94240.50c -2.18617E-04 $Pu240
mt1 lwtr.01t $ Hydrogen in water 300
m2 6000.50c -0.0004 $C stainless steel 304 (8.03 g/cc)
    14000.50c -0.0100 $Si
    24000.50c -0.1900 $Cr
    25055.50c -0.0200 $Mn
    26000.55c -0.6871 $Fe
    28000.50c -0.0925 $Ni
m3 1001.50c 2 $H H2O
    8016.50c 1 $O
mt3 lwtr.01t $ Hydrogen in water 300
kcode 1000 0.5 5 100
ksrc 0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
    0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
    18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
    18.1476 -10.4775 15.0 18.1476 -10.4775 45.0 18.1476 -10.4775 70.0
    0.0000 -20.9550 15.0 0.0000 -20.9550 45.0 0.0000 -20.9550 70.0
    -18.1476 -10.4775 15.0 -18.1476 -10.4775 45.0 -18.1476 -10.4775 70.0
    -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
totnu
print
ctme 60

```

Case CF002A. This case models the seven cartridge filters with a U:Pu ratio of 10 and the ^{235}U enrichment is 0.95%. The filter media volume is completely full with 4.0 g/cm³ sludge.

message:

CF002a - Cartridge Filter U:Pu=10, H:U=7.005, U235=0.95%, no ends

c	m	x	-x	y	-y	z	-z	r	-r	u	imp:n	\$	
1	3	-1.00	-2	19	-18							\$ CF 1 bottom	
2	3	-1.00	-1	18	-16							\$ CF 1 inside	
3	1	-4.	-2	1	18	-16						\$ CF 1 sludge	
4	3	-1.00	-2	16	-15							\$ CF 1 top	
5	3	-1.00	-4	19	-18							\$ CF 2 bottom	
6	3	-1.00	-3	18	-16							\$ CF 2 inside	
7	1	-4.	-4	3	18	-16						\$ CF 2 sludge	
8	3	-1.00	-4	16	-15							\$ CF 2 top	
9	3	-1.00	-6	19	-18							\$ CF 3 bottom	
10	3	-1.00	-5	18	-16							\$ CF 3 inside	
11	1	-4.	-6	5	18	-16						\$ CF 3 sludge	
12	3	-1.00	-6	16	-15							\$ CF 3 top	
13	3	-1.00	-8	19	-18							\$ CF 4 bottom	
14	3	-1.00	-7	18	-16							\$ CF 4 inside	
15	1	-4.	-8	7	18	-16						\$ CF 4 sludge	
16	3	-1.00	-8	16	-15							\$ CF 4 top	
17	3	-1.00	-10	19	-18							\$ CF 5 bottom	
18	3	-1.00	-9	18	-16							\$ CF 5 inside	
19	1	-4.	-10	9	18	-16						\$ CF 5 sludge	
20	3	-1.00	-10	16	-15							\$ CF 5 top	
21	3	-1.00	-12	19	-18							\$ CF 6 bottom	
22	3	-1.00	-11	18	-16							\$ CF 6 inside	
23	1	-4.	-12	11	18	-16						\$ CF 6 sludge	
24	3	-1.00	-12	16	-15							\$ CF 6 top	
25	3	-1.00	-14	19	-18							\$ CF 7 bottom	
26	3	-1.00	-13	18	-16							\$ CF 7 inside	
27	1	-4.	-14	13	18	-16						\$ CF 7 sludge	
28	3	-1.00	-14	16	-15							\$ CF 7 top	
29	3	-1.0	-22	-15	19	2	4	6	8	10	12	14	\$ Water surrounding CFS
30	3	-1.0	-22	-19	20								\$ Water below (inside)
31	3	-1.00	-23	-22	-15	20							\$ Cage wall
32	3	-1.00	-23	-20	21								\$ Cage bottom
33	3	-1.0	-24	-25	15								\$ Water above cage
34	3	-1.0	-24	-23	-15	21							\$ Water around cage
35	3	-1.0	-24	-21	26								\$ Water below cage
36	0		24	25	-26								\$ Outside Everything

```

mode n
imp:n 1 34r 0
m1 1001.50c -1.94505E-02 $H
    8016.50c -2.53342E-01 $O
    92235.50c -6.27803E-03 $U235
    92238.50c -6.54567E-01 $U238
    94239.55c -5.83987E-02 $Pu239
    94240.50c -7.96346E-03 $Pu240
mt1 lwtr.01t $ Hydrogen in water 300
m2 6000.50c -0.0004 $ C stainless steel 304 (8.03 g/cc)
    14000.50c -0.0100 $ Si
    24000.50c -0.1900 $ Cr
    25055.50c -0.0200 $ Mn
    26000.55c -0.6871 $ Fe
    28000.50c -0.0925 $ Ni
m3 1001.50c 2 $ H H2O
    8016.50c 1 $ O
mt3 lwtr.01t $ Hydrogen in water 300
kcode 1000 0.5 5 100
ksrc 0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
    0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
    18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
    18.1476 -10.4775 15.0 18.1476 -10.4775 45.0 18.1476 -10.4775 70.0
    0.0000 -20.9550 15.0 0.0000 -20.9550 45.0 0.0000 -20.9550 70.0
    -18.1476 -10.4775 15.0 -18.1476 -10.4775 45.0 -18.1476 -10.4775 70.0
    -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
totnu
print
ctme 60

```

Case CF012A. This case models the seven cartridge filters with a U:Pu ratio of 10 and the ²³⁵U enrichment is 1.25%. The filter media volume is completely full with 4.0 g/cm³ sludge.

message:

CF012a - Cartridge Filter U:Pu=10, H:U=7.005, U=1.25%, no ends

```

c
c m x -x y -y z -z r -r u= imp:n= $
1 3 -1.00 -2 19 -18 $ CF 1 bottom
2 3 -1.00 -1 18 -16 $ CF 1 inside
3 1 -4 -2 1 18 -16 $ CF 1 sludge
4 3 -1.00 -2 16 -15 $ CF 1 top
5 3 -1.00 -4 19 -18 $ CF 2 bottom
6 3 -1.00 -3 18 -16 $ CF 2 inside
7 1 -4 -4 3 18 -16 $ CF 2 sludge
8 3 -1.00 -4 16 -15 $ CF 2 top
9 3 -1.00 -6 19 -18 $ CF 3 bottom
10 3 -1.00 -5 18 -16 $ CF 3 inside
11 1 -4 -6 5 18 -16 $ CF 3 sludge
12 3 -1.00 -6 16 -15 $ CF 3 top
13 3 -1.00 -8 19 -18 $ CF 4 bottom
14 3 -1.00 -7 18 -16 $ CF 4 inside
15 1 -4 -8 7 18 -16 $ CF 4 sludge
16 3 -1.00 -8 16 -15 $ CF 4 top
17 3 -1.00 -10 19 -18 $ CF 5 bottom
18 3 -1.00 -9 18 -16 $ CF 5 inside
19 1 -4 -10 9 18 -16 $ CF 5 sludge
20 3 -1.00 -10 16 -15 $ CF 5 top
21 3 -1.00 -12 19 -18 $ CF 6 bottom
22 3 -1.00 -11 18 -16 $ CF 6 inside
23 1 -4 -12 11 18 -16 $ CF 6 sludge
24 3 -1.00 -12 16 -15 $ CF 6 top
25 3 -1.00 -14 19 -18 $ CF 7 bottom
26 3 -1.00 -13 18 -16 $ CF 7 inside
27 1 -4 -14 13 18 -16 $ CF 7 sludge
28 3 -1.00 -14 16 -15 $ CF 7 top
29 3 -1.0 -22 -15 19 2 4 6 8 10 12 14 $ Water surrounding Cfs
30 3 -1.0 -22 -19 20 $ Water below (inside)
31 3 -1.00 -23 22 -15 20 $ Cage wall

```

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32	3	-1.00	-23	-20	21		\$ Cage bottom
33	3	-1.0	-24	-25	15		\$ Water above cage
34	3	-1.0	-24	23	-15	21	\$ Water around cage
35	3	-1.0	-24	-21	26		\$ Water below cage
36	0		24:	25:	-26		\$ Outside Everything

1	c/z	4.7625					\$ CF 1 inner surface (center)
2	c/z	7.4613					\$ CF 1 outer surface
3	c/z	0.000	20.955	4.7625			\$ CF 2 inner surface
4	c/z	0.000	20.955	7.4613			\$ CF 2 outer surface
5	c/z	18.1476	10.4775	4.7625			\$ CF 3 inner surface
6	c/z	18.1476	10.4775	7.4613			\$ CF 3 outer surface
7	c/z	18.1476	-10.4775	4.7625			\$ CF 4 inner surface
8	c/z	18.1476	-10.4775	7.4613			\$ CF 4 outer surface
9	c/z	0.000	-20.955	4.7625			\$ CF 5 inner surface
10	c/z	0.000	-20.955	7.4613			\$ CF 5 outer surface
11	c/z	-18.1476	-10.4775	4.7625			\$ CF 6 inner surface
12	c/z	-18.1476	-10.4775	7.4613			\$ CF 6 outer surface
13	c/z	-18.1476	10.4775	4.7625			\$ CF 7 inner surface
14	c/z	-18.1476	10.4775	7.4613			\$ CF 7 outer surface
15	p/z	72.3900					\$ Top of filter (outside)
16	p/z	71.1200					\$ Top of filter (inside)
17	p/z	22.3825					\$ Sludge level (if needed)
18	p/z	12.3825					\$ Bottom of filter (inside)
19	p/z	11.4300					\$ Bottom of filter (outside)
20	p/z	0.6350					\$ Cage bottom (inside)
21	p/z	0.0000					\$ Cage bottom (outside)
22	c/z	32.385					\$ Cage (inside)
23	c/z	33.020					\$ Cage (outside)
24	c/z	65.000					\$ water surrounding cage
25	p/z	105.000					\$ water above cage
26	p/z	-31.000					\$ water below cage

```

mode      n
imp:n     1 34r 0
m1        1001.50c -1.94505E-02 $H      Sludge
          8016.50c -2.53342E-01 $O
          92235.50c -8.26056E-03 $U235
          92238.50c -6.52584E-01 $U238
          94239.55c -5.83987E-02 $Pu239
          94240.50c -7.96346E-03 $Pu240
mt1        lwtr.01t $ Hydrogen in water 300
m2         6000.50c -0.0004 $ C      stainless steel 304 (8.03 g/cc)
          14000.50c -0.0100 $ Si
          24000.50c -0.1900 $ Cr
          25055.50c -0.0200 $ Mn
          26000.55c -0.6871 $ Fe
          28000.50c -0.0925 $ Ni
m3         1001.50c 2 $ H      H2O
          8016.50c 1 $ O
mt3        lwtr.01t $ Hydrogen in water 300
kcode     1000 0.5 5 100
ksrc      0.0000 0.0000 15.0 0.0000 0.0000 45.0 0.0000 0.0000 70.0
          0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
          18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
          18.1476 10.4775 15.0 18.1476 10.4775 45.0 18.1476 10.4775 70.0
          0.0000 20.9550 15.0 0.0000 20.9550 45.0 0.0000 20.9550 70.0
          -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
          -18.1476 10.4775 15.0 -18.1476 10.4775 45.0 -18.1476 10.4775 70.0
totnu
print
ctme 60

```

Case CF122 This case models a 27.3 cm hemisphere of 4.0 g/cm³ sludge with a U:Pu ratio of 400 and the ²³⁵U enrichment is 0.95%.

message:

```
CF122 - 27.30 cm Hemisphere, U:Pu=400, H:U=6.366, U235=0.95%

c
c  m  dens      geom      $Comment
1  1  -4.000     -1  2      imp:n=1 $ sludge hemi
2  2  -1.000     -1  -2      imp:n=1 $ water hemi refl
3  2  -1.00      1  -3      imp:n=1 $ water reflector
4  0              3      imp:n=0 $ outside everything

1  so  27.30      $sphere for sludge
2  pz   0.00      $plane for hemi
3  so  72.50      $sphere for reflector

mode  n
m1    1001.50c   -1.94102E-02  $H      Sludge
      8016.50c   -2.53095E-01  $O
      92235.50c  -6.89389E-03    $U235
      92238.50c  -7.18779E-01    $U238
      94239.55c  -1.60319E-03    $Pu239
      94240.50c  -2.18617E-04    $Pu240

mt1    lwtr.01t      $ Hydrogen in water 300
m2     1001.50c      2      $ H      H2O
      8016.50c      1      $ O
mt2     lwtr.01t      $ Hydrogen in water 300
kcode  1000  1.0  5  100
ksrc   0.0  0.0  10.0  0.0  0.0  20.0
       10.0  0.0  10.0  -10.0  0.0  10.0
       0.0  10.0  10.0  0.0 -10.0  10.0

totnu
print
ctme
```

Case CF121 This case models a 32.5 cm hemisphere of 4.0 g/cm³ sludge with a U:Pu ratio of 400 and the ²³⁵U enrichment is 0.95%.

message:

```
CF121 - 32.50 cm Hemisphere, U:Pu=400, H:U=6.366, U235=0.95%

c
c  m  dens      geom      $Comment
1  1  -4.000     -1  2      imp:n=1 $ sludge hemi
2  2  -1.000     -1  -2      imp:n=1 $ water hemi refl
3  2  -1.00      1  -3      imp:n=1 $ water reflector
4  0              3      imp:n=0 $ outside everything

1  so  32.50      $sphere for sludge
2  pz   0.00      $plane for hemi
3  so  72.50      $sphere for reflector

mode  n
m1    1001.50c   -1.94102E-02  $H      Sludge
      8016.50c   -2.53095E-01  $O
      92235.50c  -6.89389E-03    $U235
      92238.50c  -7.18779E-01    $U238
      94239.55c  -1.60319E-03    $Pu239
      94240.50c  -2.18617E-04    $Pu240

mt1    lwtr.01t      $ Hydrogen in water 300
m2     1001.50c      2      $ H      H2O
      8016.50c      1      $ O
mt2     lwtr.01t      $ Hydrogen in water 300
kcode  1000  1.0  5  100
ksrc   0.0  0.0  10.0  0.0  0.0  20.0
       10.0  0.0  10.0  -10.0  0.0  10.0
       0.0  10.0  10.0  0.0 -10.0  10.0

totnu
print
ctme
```

Case CF112 This case models a 27.3 cm hemisphere of 4.0 g/cm³ sludge with a U:Pu ratio of 400 and the ²³⁵U enrichment is 1.25%.

message:

```
CF112 - 27.30 cm Hemisphere, U:Pu=400, H:U=6.366, U235=1.25%
c
c      m  dens      geom      $Comment
1 1 -4.000      -1 2      imp:n=1 $ sludge hemi
2 2 -1.000      -1 -2      imp:n=1 $ water hemi refl
3 2 -1.00      1 -3      imp:n=1 $ water reflector
4 0      3      imp:n=0 $ outside everything

1 so 27.30      $sphere for sludge
2 pz 0.00      $plane for hemi
3 so 72.50      $sphere for reflector

mode n
m1 1001.50c -1.94102E-02 $H Sludge
    8016.50c -2.53095E-01 $O
    92235.50c -9.07091E-03 $U235
    92238.50c -7.16602E-01 $U238
    94239.55c -1.60319E-03 $Pu239
    94240.50c -2.18617E-04 $Pu240
mt1 lwtr.01t      $ Hydrogen in water 300
m2 1001.50c 2      $ H H2O
    8016.50c 1      $ O
mt2 lwtr.01t      $ Hydrogen in water 300
kcode 1000 1.0 5 100
ksrc 0.0 0.0 10.0 0.0 0.0 20.0
     10.0 0.0 10.0 -10.0 0.0 10.0
     0.0 10.0 10.0 0.0 -10.0 10.0

totnu
print
ctme
```

Case CF111 This case models a 32.5 cm hemisphere of 4.0 g/cm³ sludge with a U:Pu ratio of 400 and the ²³⁵U enrichment is 1.25%.

message:

```
CF111 - 32.50 cm Hemisphere, U:Pu=400, H:U=6.366, U235=1.25%
c
c      m  dens      geom      $Comment
1 1 -4.000      -1 2      imp:n=1 $ sludge hemi
2 2 -1.000      -1 -2      imp:n=1 $ water hemi refl
3 2 -1.00      1 -3      imp:n=1 $ water reflector
4 0      3      imp:n=0 $ outside everything

1 so 32.50      $sphere for sludge
2 pz 0.00      $plane for hemi
3 so 72.50      $sphere for reflector

mode n
m1 1001.50c -1.94102E-02 $H Sludge
    8016.50c -2.53095E-01 $O
    92235.50c -9.07091E-03 $U235
    92238.50c -7.16602E-01 $U238
    94239.55c -1.60319E-03 $Pu239
    94240.50c -2.18617E-04 $Pu240
mt1 lwtr.01t      $ Hydrogen in water 300
m2 1001.50c 2      $ H H2O
    8016.50c 1      $ O
mt2 lwtr.01t      $ Hydrogen in water 300
kcode 1000 1.0 5 100
ksrc 0.0 0.0 10.0 0.0 0.0 20.0
     10.0 0.0 10.0 -10.0 0.0 10.0
     0.0 10.0 10.0 0.0 -10.0 10.0

totnu
print
ctme
```


Case CF105 This case models a 27.3 cm hemisphere of 4.0 g/cm³ sludge with a U:Pu ratio of 10 and the ²³⁵U enrichment is 1.25%.

message:

CF105 - 27.30 cm Hemisphere, U:Pu=10, H:U=7.005, U235=1.25%

c	m	dens	geom	\$Comment
1	1	-4.000	-1 2	imp:n=1 \$ Sludge hemi
2	2	-1.000	-1 -2	imp:n=1 \$ water hemi refl
3	2	-1.00	1 -3	imp:n=1 \$ water reflector
4	0		3	imp:n=0 \$ outside everything
1	so	27.30		\$sphere for sludge
2	pz	0.00		\$plane for hemi
3	so	67.30		\$sphere for reflector

mode	n			
mt1	1001.50c	-1.94505E-02	\$H	Sludge
	8016.50c	-2.53342E-01	\$O	
	92235.50c	-8.26056E-03	\$U235	
	92238.50c	-6.52584E-01	\$U238	
	94239.55c	-5.83987E-02	\$Pu239	
	94240.50c	-7.96346E-03	\$Pu240	
mt1	lwtr.01t		\$	Hydrogen in water 300
mt2	1001.50c	2	\$ H	H2O
	8016.50c	1	\$ O	
mt2	lwtr.01t		\$	Hydrogen in water 300
kcode	1000	1.0	5	50
ksrc	0.0	0.0	10.0	0.0 0.0 20.0
	10.0	0.0	10.0	-10.0 0.0 10.0
	0.0	10.0	10.0	0.0 -10.0 10.0
totnu				
print				
ctme				

APPENDIX C
BASIN URANIUM AND PLUTONIUM CONCENTRATION DATA

KE Center-of-basin uranium and plutonium concentration data. This data came from personal communications with M. A. Green of the Spent Nuclear Fuel Division. The following list is a compilation of KE sample point #10 data, and is from sample analysis done by the 222S Labs. The plutonium g/L column assumes 12wt% ^{240}Pu in its conversion from $\mu\text{Ci/L}$ to g/L.

Date	U g/L	Pu-239/240 µCi/L	Pu-238 µCi/L	Pu g/L
05-Jan-94	2.870E-05	8.420E-03	0.00129	1.029E-07
12-Jan-94	4.320E-05	2.660E-02	0.00460	3.250E-07
19-Jan-94	3.330E-05	1.140E-02	0.00211	1.735E-07
26-Jan-94	4.410E-05	3.140E-02	0.00571	3.837E-07
02-Feb-94	3.640E-05	2.020E-02	0.00385	2.469E-07
09-Feb-94	3.590E-05	1.710E-02	0.00257	2.089E-07
16-Feb-94	6.580E-05	4.290E-02	0.00366	3.042E-07
23-Feb-94	4.460E-05	2.320E-02	0.00345	2.835E-07
02-Mar-94	2.340E-05	2.010E-02	0.00302	2.456E-07
09-Mar-94	5.410E-05	2.950E-03	0.00347	3.622E-08
16-Mar-94	3.860E-05	1.780E-02	0.00265	2.175E-07
23-Mar-94	6.830E-05	2.140E-02	0.00325	2.615E-07
30-Mar-94	3.740E-05	2.200E-02	0.00336	2.686E-07
06-Apr-94	4.570E-05	1.880E-02	0.00279	2.297E-07
13-Apr-94	1.900E-07	1.320E-02	0.00180	1.613E-07
20-Apr-94	3.070E-05	1.480E-02	0.00237	1.808E-07
27-Apr-94	2.760E-05	1.470E-02	0.00100	1.795E-07
03-May-94	2.260E-05	1.160E-02	0.00181	1.417E-07
11-May-94	3.550E-05	1.560E-02	0.00238	1.906E-07
18-May-94	8.419E-06	1.370E-02	0.00198	1.588E-07
25-May-94	3.490E-05	1.070E-02	0.00151	1.307E-07
01-Jun-94	3.050E-04	1.350E-02	0.00195	1.649E-07
08-Jun-94	3.670E-05	1.160E-02	0.00179	1.417E-07
14-Jun-94	3.350E-05	1.220E-02	0.00171	1.491E-07
22-Jun-94	1.270E-04	1.520E-02	0.00234	1.857E-07
29-Jun-94	1.930E-05	9.160E-03	0.00142	1.119E-07
06-Jul-94	3.480E-05	9.360E-03	0.00142	1.144E-07
13-Jul-94	3.900E-05	9.950E-03	0.00152	1.216E-07
20-Jul-94	1.930E-05	9.860E-03	0.00158	1.205E-07
27-Jul-94	3.300E-05	9.090E-03	0.00146	1.111E-07
03-Aug-94	3.070E-05	6.680E-03	0.00148	1.183E-07
10-Aug-94	5.410E-05	1.840E-02	0.00299	2.248E-07
17-Aug-94	4.030E-05	1.980E-02	0.00309	2.419E-07
24-Aug-94	4.980E-05	2.070E-02	0.00310	2.529E-07
31-Aug-94	4.050E-05	2.080E-02	0.00319	2.541E-07
07-Sep-94	2.390E-05	4.430E-03	0.00289	5.426E-08
14-Sep-94	2.920E-05	1.710E-02	0.00262	2.089E-07
21-Sep-94	3.430E-05	1.300E-02	0.00190	1.588E-07
28-Sep-94	2.750E-05	1.190E-02	0.00182	1.454E-07
05-Oct-94	8.440E-06	1.990E-02	0.00321	2.432E-07
12-Oct-94	1.900E-05	1.340E-02	0.00215	1.637E-07
19-Oct-94	8.690E-06	7.880E-03	0.00124	9.628E-08
26-Oct-94	1.700E-05	8.830E-03	0.00135	1.079E-07
02-Nov-94	1.270E-05	1.400E-02	0.00201	1.711E-07
09-Nov-94	2.180E-05	1.030E-02	0.00158	1.259E-07
16-Nov-94	2.160E-05	2.50E-03	0.00136	1.130E-07

Date	U g/L	Pu-239/240 $\mu\text{Ci/L}$	Pu-238 $\mu\text{Ci/L}$	Pu g/L
23-Nov-94	9.280E-05	4.200E-02	0.00293	5.130E-07
30-Nov-94	2.470E-05	9.460E-03	0.00150	1.156E-07
07-Dec-94	7.910E-06	5.150E-03	0.00759	6.332E-08
14-Dec-94	2.480E-04	4.510E-02	0.00553	5.610E-07
21-Dec-94	2.360E-04	3.610E-02	0.00976	4.413E-07
28-Dec-94	1.210E-04	3.000E-02	0.00456	3.666E-07
04-Jan-95	8.590E-05	7.700E-02	0.00404	3.299E-07
11-Jan-95	9.300E-05	2.730E-02	0.00382	3.357E-07
18-Jan-95	1.180E-04	3.490E-02	0.00540	4.264E-07
25-Jan-95	6.340E-05	4.010E-02	0.00678	4.900E-07
01-Feb-95	7.750E-05	1.950E-02	0.00318	2.483E-07
08-Feb-95	5.320E-05	0.020E-02	0.00301	2.368E-07
15-Feb-95	4.410E-05	2.810E-02	0.00416	3.433E-07
22-Feb-95	2.170E-05	8.800E-02	0.00444	3.421E-07
01-Mar-95	3.250E-05	2.780E-02	0.00437	3.397E-07
08-Mar-95	4.220E-05	2.340E-02	0.00399	2.859E-07
15-Mar-95	4.620E-05	2.620E-02	0.00408	3.201E-07
22-Mar-95	6.000E-05	3.080E-02	0.00505	3.764E-07
29-Mar-95	7.770E-05	3.340E-02	0.00530	4.081E-07
05-Apr-95	4.840E-05	2.950E-02	0.00481	3.605E-07
12-Apr-95	4.150E-04	3.270E-02	0.00520	3.996E-07
19-Apr-95	1.140E-04	3.020E-02	0.00481	3.690E-07
26-Apr-95	3.540E-04	2.820E-02	0.00456	3.446E-07
03-May-95	5.460E-04	3.700E-02	0.00560	4.521E-07
10-May-95	4.190E-04	2.690E-02	0.00462	3.287E-07
17-May-95	5.520E-04	1.190E-02	0.00995	1.459E-07
24-May-95	1.020E-03	6.520E-03		7.961E-08
31-May-95	1.200E-03	5.640E-03	0.00085	6.891E-08
07-Jun-95	1.190E-03	8.330E-03		1.017E-07
14-Jun-95	1.520E-03	9.450E-03		1.154E-07
21-Jun-95	1.040E-03	1.080E-02		1.319E-07
28-Jun-95	7.020E-04	1.790E-02		2.186E-07
05-Jul-95	4.410E-04	1.100E-02		1.343E-07
12-Jul-95	3.260E-04	1.190E-02		1.453E-07
19-Jul-95	1.940E-04	1.300E-02		1.587E-07
26-Jul-95	1.930E-04	1.330E-02		1.624E-07
02-Aug-95	1.630E-04	1.680E-02		2.051E-07
09-Aug-95	3.860E-04	2.600E-03		3.175E-08
15-Aug-95	1.400E-05	1.180E-02	0.00210	1.442E-07
22-Aug-95	2.980E-04	1.710E-02		2.088E-07
29-Aug-95	2.760E-04	1.330E-02	0.00240	1.625E-07
05-Sep-95	1.710E-04	1.140E-02		1.392E-07
Avg	1.697E-04	1.811E-02	0.00326	2.213E-07
Max	1.520E-03	4.510E-02	0.00995	5.512E-07

APPENDIX D

**WHC-SD-SNF-CSER-002 Rev. 0
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RELEASE AUTHORIZATION	
Document Number:	WHC-SD-SNF-CSER-002, Revision 0
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<p>This document was reviewed following the procedures described in WHC-CM-3-4 and is:</p> <p>APPROVED FOR PUBLIC RELEASE</p>	
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ABSTRACT

A criticality safety evaluation of the K Basin filter cartridge assemblies has been completed to support operations without a criticality alarm system. The results show that for normal operation, the filter cartridge assembly is far below the safety limit of $k_{\text{eff}} = 0.95$, which is applied to plutonium systems at the Hanford Site.

During normal operating conditions, uranium, plutonium, and fission and corrosion products in solution are continually accumulating in the available void spaces inside the filter cartridge medium. Currently, filter cartridge assemblies are scheduled to be replaced at six month intervals in KE Basin, and at one year intervals in KW Basin. According to available plutonium concentration data for KE Basin and data for the U/Pu ratio, it will take many times the six-month replacement time for sufficient fissionable material accumulation to take place to exceed the safety limit of $k_{\text{eff}} = 0.95$, especially given the conservative assumption that the presence of fission and corrosion products is ignored. Accumulation of sludge with a composition typical of that measured in the sand filter backwash pit will not lead to a $k_{\text{eff}} = 0.95$ value.

For off-normal scenarios, it would require at least two unlikely, independent, and concurrent events to take place before the $k_{\text{eff}} = 0.95$ limit was exceeded. Contingencies considered include failure to replace the filter cartridge assemblies at the scheduled time resulting in additional buildup of fissionable material, the loss of geometry control from the filter cartridge assembly breaking apart and releasing the individual filter cartridges into an optimal configuration, and concentrations of plutonium at U/Pu ratios less than measured data for KE Basin, typically close to 400 according to extensive measurements in the sand filter backwash pit and plutonium production information.

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CRITICALITY SAFETY EVALUATION REPORT FOR
K BASIN FILTER CARTRIDGES

1.0 INTRODUCTION

A nuclear criticality analysis has been performed for filter cartridge cage assemblies used in the Hanford Site KE and KW Basins. Each filter cartridge assembly holds 88 filter cartridges arranged in a cluster configuration. The filter cartridge cage assembly removes particulates from the basin water by trapping materials in the polypropylene fiber of the filter cartridges. The previous administrative limit was designed to prevent plutonium buildup beyond 225 g in each filter cartridge assembly.

Normal operation was analyzed by performing explicit calculations of the filter cartridge assembly cluster geometry using the W-PIJ module of the British WIMS-E code (Gubbins et al. 1982). Data were obtained for an average uranium and plutonium concentration typical of the center-of-basin in KE Basin. These data, along with the flow rate through the filter cartridge assembly, allowed for the estimation of the fissionable material buildup inside the filter assembly with time. Several off-normal contingencies were analyzed, including buildup of fissionable material beyond the planned replacement period, loss of geometry control within the filter assembly, and lower-than-expected U/Pu ratios. The effects of reduced density moderation were also calculated, a condition which would occur as the filter cartridge assembly is raised out of the basin during replacement and placed in dry storage. Additional calculations evaluating criticality physics trends are discussed in Appendix A.

2.0 DESCRIPTION OF SYSTEM AND FACILITY

The filter cartridge cage assembly contains 88 filter cartridges placed in concentric rings. Each filter cartridge is 76.2 cm (30 in.) long, and is made of a polypropylene fiber wound around a hollow, 304 stainless steel core. The stainless steel core wall is 0.028 cm (0.011 in.) thick, and has an outer diameter of 2.7041 cm (1.0646 in.). The outer diameter of the filter cartridge is 6.35 cm (2.5 in.). The internal arrangement of filter cartridges inside the cage assembly is shown in Figure 1. The filter cartridges are held in place by two end plates, pulled together with tie rods. The diameter of the filter cartridge assembly is 76.2 cm (30 in.). There are two filter cartridge assemblies in the basin and water flows through the assembly in operation at 107,880 L/hr (28,500 gal/hr). The filter cartridge cage assemblies are located near the bottom of the basin floor in the K Basins. The two filter cartridge cage assemblies are separated by a sufficient amount of water to provide neutronic isolation, approximately 51 cm (20 in.). A layout of the K Basins showing the location of the filter cartridge assemblies is shown in Figure 2.

3.0 REQUIREMENTS DOCUMENTATION

There are no unique requirements applicable to this evaluation.

**Figure 1. Cross Sectional Layout of Filter Cartridges
Inside Filter Cartridge Cage Assembly.**

Figure 2. 105K Primary Recirculation System.

4.0 METHODOLOGY

The criticality analysis used the WIMS-E computer code (Gubbins et al. 1982), a commercially licensed software system from the British ANSWERS organization. It is a collection of neutron transport and utility programs designed to execute and communicate using a common set of interfaces. The nuclear cross section data library accessed by WIMS-E is the '1986' WIMS library (Halsall, et al. 1986). WIMS-E is licensed for use at the Hanford Site on several different HP workstations. Westinghouse Hanford currently executes WIMS-E on any one of several HP735 workstations at the 3200 George Washington Way building. The shell script that executes WIMS-E is located in the home directory of the Hanford Site WIMS-E code custodian.

As a commercially licensed software product, WIMS-E has been extensively benchmarked and validated against a large set of test problems supplied by the British. In addition to this set of test problems, WIMS-E has been thoroughly validated against low-enriched uranium metal and plutonium systems such as those at the Hanford Site. WIMS-E has been validated against uranium and plutonium solutions (Schwinkendorf 1992b), N Reactor MKIA tube-in-tube fuel assemblies and uranium rods of various enrichments and diameters (Schwinkendorf 1992a), and uranium metal billets (Erickson 1991). WIMS-E has been shown to conservatively predict criticality in a highly consistent manner. The two-dimensional WIMS-E module W-PIJ was used at Hanford previously to calculate core reactivity for the 300 Area Neutron Radiography Facility (Schwinkendorf 1990). W-PIJ was used to model the explicit, full core loading arrangement of the reactor in (r,0) geometry, using integral transport theory. The core geometry was arranged in concentric rings. With an axial leakage buckling correction and an outer albedo normalized to initial startup data, this model successfully predicted the shutdown margin for a proposed new loading.

The GOLF computer code (Schwinkendorf 1994) was used to calculate finite hemisphere dimensions for $k_{eff} = 0.95$ and $k_{eff} = 1.0$ masses for the contingency analysis in which the filter cartridge assembly breaks apart and the individual filter cartridges come together into an optimum geometry. The GOLF code is a one-dimensional neutron diffusion theory program used at the Hanford Site in the past for the calculation of minimum critical and safe masses in various geometries. GOLF may use either two- or four-group, lattice-averaged, macroscopic cross sections generated by WIMS-E.

5.0 DISCUSSION OF CONTINGENCIES

Off-normal scenarios considered in this criticality safety evaluation include failure to replace the filter cartridge assembly when required to do so (resulting in an ever-increasing loading of fissionable material), the loss of geometry in the filter cartridge assembly (resulting in optimal spacing of the filter cartridges within the assembly), and lower-than-expected values for U/Pu. The loss of fission and corrosion products was assumed for all scenarios analyzed.

The maximum credible amount of sludge material to accumulate inside the filter cartridge medium was assumed to be a "thick paste" of 4.0 g/cm³ heavy metal oxide solution, in which the heavy metal was composed of both 0.95-wt% ²³⁵U in uranium and 12-wt% ²⁴⁰Pu in plutonium. The U/Pu ratio was assumed to equal 400 for normal conditions, and U/Pu = 10 was used in the contingency analyses; U/Pu = 10 is lower than any U/Pu data available for KE Basin, so this is considered a bounding case. Extensive chemical analysis of K Basin sludge samples has established that U/Pu = 400 is a best-estimate (see Appendix B). This value is also consistent with reactor production calculations. The nominal time required for this amount of buildup (4.0 g/cm³ of mixed uranium plutonium oxide in the available void spaces inside the filter medium) was determined to be just over two years at U/Pu = 400.

As fissionable material builds up inside the filter cartridge assembly, the amount of water moderator required for maximum reactivity will shift to maintain the optimum. At the maximum credible plutonium loading analyzed (4.0 g/cm³ of oxide), the system is undermoderated with full density moderation.

6.0 EVALUATION AND RESULTS

6.1 NORMAL CONDITIONS

The filter cartridge is a particulate removal system very similar to the sand filter. It will remove particles of uranium oxide, plutonium oxide, fission products, and corrosion products. These materials will be trapped by the polypropylene fiber and accumulate there. In the sand filter the sand is periodically cleaned by a back wash, and the collected particulates are washed into the sand filter backwash pit. Extensive characterization of the sludge in the backwash pit has taken place, detailed chemical and isotopic analyses have been performed, and the sludge's composition is well known. The filter cartridge should be removing the same type of sludge from the water. Therefore as the filter cartridge becomes loaded, it will have sludge in it very similar to that found in the backwash pit.

Under normal operation the filter cartridges will collect sludge consisting of fission and corrosion products and uranium and plutonium oxides in a ratio of U/Pu = 400. Calculations have shown that at these U/Pu ratios, with fission products and corrosion products present, the filter cartridge cage cannot be made critical under any conditions irrespective of whether the uranium enrichment is 0.95- or 1.25-wt% ²³⁵U (Erickson 1994a, 1994b).

If a very conservative assumption is made that the fission products and corrosion products disappear and we are left only with a uranium and plutonium oxide system in the filter cartridge, the system still cannot be made critical with any amount of plutonium present. In other words, the k_{eff} will be less than 0.95 for typical conditions of moderation and material loadings. The highest k_{eff} calculated for a 10-year accumulation of uranium and plutonium is equal to 0.813. This conclusion is true for both KE and KW Basins. Therefore, normal operation of filter cartridges in water and in dry storage will be substantially subcritical and will not exceed $k_{eff} = 0.95$.

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The first calculations for normal conditions assume that uranium and plutonium loading builds up in the filter's void spaces until the time the filter is replaced. The "void fraction," or volume fraction inside the filter cartridge medium that is available for water intrusion and material uptake, can be estimated by subtracting the smear density to solid density ratio from one, or $(1 - 0.2445/.9) = 0.7283$.

This void fraction was assumed to be filled with a sludge material, actually a thick paste, composed of 4.0 g/cm^3 oxide. This oxide consists of UO_2 plus PuO_2 , according to a given U/Pu ratio. A U/Pu ratio equal to 400 is thought to represent the greatest amount of fissionable material that can be considered as credible inside the filter cartridges during normal operation. Furthermore the calculations assumed that there are no fission products, iron, or other corrosion products present in the system. This conservative assumption resulted in significantly higher calculated neutron multiplication than would otherwise be the case.

Average values for plutonium concentration ($5.5 \times 10^{-7} \text{ g/L}$, appropriate for center-of-basin), a best estimate U/Pu ratio, and the flow rate through the filter cartridge assembly ($107,880 \text{ L/hr}$) were used to calculate the accumulation rate of heavy metal oxide. Given the rate of plutonium accumulation (520 g/yr), it is possible to find (assuming 100% filter efficiency) the time required for this maximum amount of material to accumulate. Assuming that $\text{U/Pu} = 400$, the time required for 4.0 g/cm^3 of heavy metal oxide sludge to accumulate is approximately 2.1 years. The plutonium is held constant when the U/Pu is changed in the model because higher confidence is given to the measured plutonium data than to the measured uranium data. In the next section on contingency analysis, $\text{U/Pu} = 10$ is considered, in which case the time required to fill the filter medium with 4.0 g/cm^3 material is approximately 40 times longer (because there is 40 times less uranium in solution.) The results in Table 1 are based on an infinite array of filter cartridge assemblies (an albedo boundary condition of 1.00 was imposed on the outer surface of a 20 cm water reflector around the filter cartridge assembly), but only a single layer high; an axial leakage correction appropriate for a cylinder 76.2 cm (30 in.) high was used. At high U/Pu ratios the neutron multiplication factor shows some sensitivity to uranium enrichment. To model a single cage assembly, the middle row in Table 1 was redone using an outer boundary albedo equal to zero. With 20 cm of water reflector, the infinite-array system is essentially decoupled. These results are in the last row in Table 1. There are two entries in the last column of Table 1. The first entry is for both moderator and reflector density equal to 0.01 g/cm^3 . This models the filter cartridge assembly after it is initially pulled out of the basin. The second entry is for moderator density equal to 0.01 g/cm^3 , but 20 cm of full density water reflection is placed around the filter assembly. This models the filter cartridge assembly in dry storage, but fully reflected.

Table 1. WIMS-E W-PIJ k_{eff} Results for Maximum Sludge Accumulation
(U/Pu = 400, Time = 2.1 Years without Replacement).

²³⁵ U enrichment	Albedo	Full density moderator	Moderator density = 0.01 g/cm ³	
			Reflector density = 0.01 g/cm ³	Full density reflection
1.25	1.0	0.813028	0.213715	0.226095
0.95	1.0	0.735925	0.193586	0.205021
0.95	0.0	0.726024	0.192760	0.198250

The results in Table 1 clearly show that when the best-estimate U/Pu value of 400 is assumed, there is no danger from a criticality, even if the filter cartridge assembly is not replaced after two years of continuous operation, which would be a gross violation of procedures. Even assuming that the uranium enrichment is equal to 1.25 wt% (which would not be the case in the KE Basin), the k_{eff} remains well below 0.90. It is also apparent from the second entry in the last column that full density reflection around the drained filter cartridge assembly does provide some additional moderation to boost the k_{eff} , but not to a significant degree. This effect will also be shown in the next section, where this table is repeated for the contingency in which U/Pu = 10.

The results in Table 1 are appropriate for filter cartridges that have not been replaced in two years. Reduced accumulation calculations were performed to find k_{eff} as a function of time before replacement. As fissionable material builds up, it makes sense that the amount of water moderation required for an optimum reactivity configuration would also shift, so interspersed moderation calculations were performed as a function of time before replacement. All of these time-dependent calculations assumed a boundary albedo equal to zero. Figure 3 illustrates the k_{eff} versus time for full density as well as several reduced-density cases. The U/Pu ratio for these results was equal to 400.

For the U/Pu = 400 scenario, there is so little fissile material in the filter cartridge assembly that full density moderation is not optimum. It is difficult to see in Figure 3 that this is the case because the variation in k_{eff} due to moderator variation is small compared to the scale of the graph. However, Figure 4 illustrates the variation in k_{eff} as a function of interspersed moderator density for two points in time, which correspond to metal oxide concentrations equal to 0.5 and 1.0 g/cm³ in the available void space in the filter cartridge medium. The highest value shown in Figure 3 corresponds to the bottom row in Table 1 (U/Pu = 400, k_{eff} = 0.726). These curves would increase so that the maximum k_{eff} would reach 0.736 for an infinite array of filter cartridge assemblies (hexagonal lattice spacing equal to 118 cm (44 in.) center-to-center). If the assumed uranium enrichment is increased to 1.25 wt%, this maximum would increase to 0.813, which is still substantially below the k_{eff} safety limit of 0.95, and would require over two years of continuous operation.

Figure 3. k -effective vs Time
($U/Pu = 400$, $U-235 = 0.95$ wt%).

Figure 4. k -eff vs Water Density
($U/Pu = 400$, $U-235 = 0.95$ wt%).

Normal operation is considered to be continuous operation out to the scheduled replacement time, which is six months for KE Basin. Assuming that the U/Pu is equal to 400, Figure 3 shows that the k_{eff} of a single cartridge assembly, fully water reflected, is less than 0.34 when replaced on schedule at the end of six months of continuous operation. Sample WIMS-E input files may be found in Appendix C.

6.2 OFF-NORMAL CONDITIONS

For off-normal conditions the following contingency sequences were considered:

- Inadvertent material buildup
- Changes in the U/Pu ratio
- Collapse of the filter cartridge assembly geometry, with the resulting change in moderation.

It was assumed that there were no fission or corrosion products in the filter cartridges. This is considered to be the first contingency.

6.2.1 Material Buildup

The first off-normal contingency analyzed was failure to replace the filter cartridge at the scheduled time interval of six months. If the U/Pu ratio remains at 400, extended operation will increase k_{eff} significantly, as shown in Figure 3, but even after two years of continuous operation, the continued accumulation of fissionable material never drives the k_{eff} of the filter cartridge assembly beyond 0.80. Inadvertent material buildup without a change in the U/Pu ratio will not exceed $k_{eff} = 0.95$ for collapse of geometry or loss of moderation. If plutonium buildup at 520 g/yr occurs (because basin personnel neglect to replace the filter cartridge assembly on schedule) with a concurrent loss of uranium (i.e., the U/Pu ratio is equal to 10), the k_{eff} will approach 0.95 after ten years. Double contingency does not result in a k_{eff} greater than 0.95.

6.2.2 Material Segregation

The second off-normal contingency analyzed was for a U/Pu ratio less than the best-estimate value of 400. Measured data show a large spread in U/Pu values, but little confidence is given to this data because of the level of uncertainty in the measurements. Nevertheless a value of U/Pu = 10 was selected as a bounding case for the uranium loss scenario. Table 1 was redone for U/Pu = 10 and the results are reported in Table 2. At this U/Pu ratio and a typical plutonium concentration in the basin water, filter cartridge assemblies would go critical before the 78 years (4.0 g/cm^3 in filter body) assumed in Table 2.

These calculations were also performed as a function of time. Figure 5 shows k_{eff} as a function of time for U/Pu = 10. The highest reactivity is achieved with full density moderation. Because of the steep rate of increase in k_{eff} with time, increased resolution was given to the time out to 1.5 years, shown with an expanded scale in Figure 6. Each curve in Figure 6 is plotted for optimum moderation, the optimum moderator density increasing as fissionable material accumulates; each point represents the maximum for that amount of accumulated material (as interspersed moderator density was varied). Figure 5 shows that even with U/Pu = 10, it would take nearly twelve years of operation before a criticality could take place, which is nearly 24 times the scheduled replacement interval. The results in Figure 6 show that with U/Pu equal to 400, k_{eff} is less than 0.36 at the time of replacement, and k_{eff} is less than 0.54 at one year of operation.

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The additional curves in Figure 6 illustrate behavior for intermediate values of U/Pu. The curves for both U/Pu = 200 and U/Pu = 400 terminate where the heavy metal oxide has reached 4.0 g/cm³. The rate of rise for U/Pu = 400 is steeper because total heavy metal is accumulating faster (plutonium concentration is held constant). However, the higher plutonium content of the U/Pu = 200 heavy metal oxide mixture results in a higher k_{eff} when 4.0 g/cm³ is finally reached, although this occurs later in time. The final point plotted for U/Pu = 100 is when the metal oxide content is equal to 3.0 g/cm³. The final points plotted for the U/Pu = 10 and U/Pu = 25 curves are for 0.5 g/cm³ and 1.0 g/cm³ heavy metal oxide, respectively.

Table 2. WIMS-E W-PIJ k_{eff} Results for Maximum Sludge Accumulation (U/Pu = 10, Time = 78 Years without Replacement).

²³⁵ U enrichment	Albedo	Full density moderator	Moderator density = 0.01 g/cm ³	
			Reflector density = 0.01 g/cm ³	Full density reflection
1.25	1.0	1.232345	0.365224	0.379434
0.95	1.0	1.229298	0.363638	0.377833
0.95	0.0	1.214307	0.363321	0.368335

It takes more than two contingencies to reach a $k_{eff} = 0.95$.

Figure 5. k -effective vs Time
(U/Pu = 10, U-235 = 0.95 wt%).

Figure 6. k -effective vs Time
(Optimal Moderation with Time).

6.2.3 Loss of Intact Geometry

The third contingency considered was the collapse of a filter cartridge assembly. It is conceivable that the tie rods could break during the replacement procedure, in which case all geometry control would be lost. In this scenario, optimum spacing must be assumed. In Figure 7, the lattice k_u of filter cartridges is plotted as a function of time, out to 9.7 years without replacement. The U/Pu ratio is the most conservative, U/Pu = 10, and full density moderation is assumed. This would be the case if the filter assembly were to come apart while still under water (e.g., while being raised out of the basin during replacement). Figure 7 shows that if the filter cartridge assembly comes apart while still under water, $k_u = 0.95$ will not be exceeded as long as the collapse occurs before four years of continuous operation. The k_u at 3.9 years (equivalent to 0.2 g/cm³ heavy metal oxide sludge in the void spaces inside the filter medium) is equal to 0.938 when the filter cartridges are brought into a close-packed arrangement (hexagonal touching). Further accumulation of fissionable material could then produce a k_u greater than 0.95 when brought into optimum spacing, but the finite amount of material would be correspondingly large, depending on how close k_u is to $k_{eff} = 0.95$. The point is that for the k_u of the close-packed lattice to exceed 0.95 shortly after four years, the U/Pu must equal 10 and loss of geometry control must occur. These two contingencies (the cartridge filter assembly breaking apart and a value of U/Pu less than any measured) could occur and k_u still could be below 0.95. If the filter cartridge is not replaced on schedule and is left in operation for over four years, which would be an additional contingency, then k_u could exceed 0.95 for the compacted lattice. Additional fissionable material buildup beyond four years would be required for k_u to exceed 0.95 by a sufficient margin for the k_{eff} to attain 0.95 (e.g., for a hemispherical pile of 88 filter cartridges). At this point, there would be at least three contingencies: failure to replace the filter cartridge assembly on time, an unrealistically low value of U/Pu, and the breakage of the filter assembly.

Figure 7. k -infinity vs Spacing
(U/Pu Atomic Ratio = 10).

Figure 7 illustrates k_{∞} values as fissionable material accumulates. The minimum spacing shown corresponds to touching in a close-packed hexagonal array. Beyond four years, the k_{∞} value may exceed 1.0, but the k_{eff} for a finite array will be smaller. Two-group lattice cross sections were extracted from the WIMS-E results and input to GOLF, a neutron diffusion code, which calculated the radius required for a fully-water-reflected hemisphere to attain either $k_{eff} = 0.95$ or $k_{eff} = 1.0$. The lattice spacing for all the GOLF calculations was for the most reactive, a hexagonal close-packed array.

Figure 8 shows the number of filter cartridges that would be required to attain a given k_{eff} as fissionable material buildup continues, if they were to come together into an optimum configuration in a fully water reflected hemispherical pile. It would take 6.2 years to gain sufficient reactivity for a single filter cartridge assembly (containing 88 individual filters) to reach a k_{eff} equal to 0.95 if it came apart and had the individual filter cartridges rearranged into an optimum lattice geometry forming a fully reflected hemispherical pile. It would take over seven years of continuous operation for this pile of 88 filter cartridges to attain a k_{eff} equal to 1.00.

More than two contingencies have to occur to reach a $k_{eff} = 0.95$. In all the scenarios analyzed, the requirement for double contingency was not violated.

Figure 8. Number of Filters
(Hemispherical Geometry, U/Pu = 10).

7.0 DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS

The one administratively controlled limit applicable to this evaluation is that the filter cartridge assembly be replaced on time, which according to the present schedule, is six months for KE Basin and one year for KW Basin.

8.0 SUMMARY AND CONCLUSIONS

The *Nuclear Criticality Safety Manual*, WHC-CM-4-29, Section 5, states that:

"Criticality alarm systems (CAS) and criticality detection systems shall be installed as follows:

- (1) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3 and the probability of criticality is greater than 1×10^{-6} per year (as documented in a DOE approved SAR), a CAS meeting ANSI/ANS-8.3 shall be provided to cover occupied areas in which the expected dose exceeds 12 rads in free air, where a CAS is defined to include a criticality accident detection device and a personnel evacuation alarm.
- (2) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3 and the probability of criticality is greater than 1×10^{-6} per year, (as documented in a DOE-approved SAR), but there are no occupied areas in which the expected dose exceeds 12 rads in free air, a criticality detection system shall be provided; where a criticality detection system is defined to be an

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appropriate criticality accident detection device but without an immediate evacuation alarm. The criticality accident detection system response time should be sufficient to allow for appropriate process-related mitigation and recovery actions. While an immediate evacuation alarm is not required under these circumstances, evacuation shall be implemented (i.e., evacuation notification or delayed alarm) if potential doses to occupational workers could be effectively limited by such actions.

- (3) In those cases where the mass of fissionable material exceeds the limits established in paragraph 4.2.1 of ANSI/ANS-8.3, but a criticality accident is determined to be impossible due to the physical form of the fissionable material, or the probability of occurrence is determined to be less than 1×10^{-6} per year (as documented in a DOE-approved SAR), neither a CAS nor a criticality detection system is required. In addition, neither a CAS nor a criticality detection system is required to be installed underwater when fissionable material is handled or stored beneath water shielding that is adequate to protect personnel; however, a means to detect fission product gases or other volatile fission products should be provided in occupied areas immediately adjacent to such underwater storage areas, except for fuel systems where no fission products are likely to be released. Also, neither a CAS nor a criticality detection system are required for fissionable material during shipment of fissionable material packaged in approved shipping containers, or fissionable material packaged in approved shipping containers awaiting transport provided no other operation involving fissionable material not so packaged is permitted on the dock or in the shipment area.
- (4) The decision to install a criticality detection system rather than a CAS, and the decision that neither a CAS nor a criticality detection system is necessary, must be justified based upon a documented DOE-approved safety analysis."

The basis for not requiring a criticality alarm system for the filter cartridge operation is that nuclear criticality is not credible during the operation and dry storage of the filter cartridges, "due to the physical form of fissionable material."

The filter cartridge cage assembly is a filter for particulate matter in basin water, similar to the sand filter. The particulates that will be trapped include corrosion and fission products, uranium and plutonium oxides, and other particulates. The presence of corrosion and fission products in the filter cartridge assembly during normal operation in water and subsequent dry storage will assure subcriticality by a very significant margin.

For off-normal analyses, a number of contingencies were evaluated. In all accident scenarios, more than two contingencies were required to exceed the $k_{eff} = 0.95$ limit. Two of the more important contingencies were the absence of all fission and corrosion products from the filter and the reduction in the U/Pu ratio. To reach $k_{eff} = 0.95$, even for multiple contingencies, continuous operation without replacement of the filter cartridge assembly is required beyond the expected life of the facility, which is another eight years.

9.0 REFERENCES

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APPENDIX A
ADDITIONAL SUPPORTING CALCULATIONAL RESULTS

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ADDITIONAL SUPPORTING CALCULATIONAL RESULTS

In addition to calculations reported in the main document, other calculations were performed in an attempt to better understand the physical trends of the filter cartridge assembly system. These calculations were mostly infinite lattice calculations. The first set of these calculations investigated the effect of uranium enrichment and U/Pu ratio, when the amount of plutonium present in the system was held constant at the previous administrative limit of 225 g per filter cartridge assembly.

The uranium to plutonium ratio (U/Pu) was assumed to vary between 10 and 25, and the uranium enrichment was varied between 0.88-wt% ²³⁵U and 1.25-wt% ²³⁵U. The uranium enrichment was found to be a minor factor compared to the U/Pu ratio. The temperature reactivity effect was shown to be negative for an increase in filter cartridge temperature. Compaction (or relocation) of the individual filter cartridges within the filter cartridge assembly had a positive reactivity effect; k_{∞} calculations showed that the optimum spacing for filter cartridges is less than the as-manufactured spacing when they contain the limiting concentration of plutonium. Additional amounts of plutonium (up to several times the previous administrative limit) and interspersed moderation effects were also investigated.

A.1 OPTIMUM SPACING

The average spacing of the filter cartridges inside the filter cartridge assembly may be defined by dividing the cross sectional area of the cage by 88, the number of filter cartridges. This yields the average area per lattice cell. Solving for the cylindricized cell radius yields 4.0 cm. Lattice transport calculations using the British WIMS-E computer code (Gubbins et al. 1982) were performed for a range of lattice spacings in full density water. The results indicate that the filter cartridges are overmoderated in the as-built configuration for the limiting plutonium concentration of 225 g. These calculations were performed for two values of assumed U/Pu ratio. Figure A.1 illustrates the variation in calculated k_{∞} as lattice spacing is changed for U/Pu = 10 and 25, and for uranium enrichment of 1.25-wt%. The higher U/Pu ratio represents a larger quantity of heavy metal because the total amount of plutonium was held constant. The higher total ²³⁵U content in the higher U/Pu mixture increases k_{∞} slightly. Figure A.2 shows the same results for uranium enrichment equal to 1.15-wt% ²³⁵U, and Figure A.3 contains the results for 0.88-wt% ²³⁵U.

A.2 INTERSPERSED MODERATION

The effects of interspersed moderation were investigated in two ways. First, reducing water density between filter cartridges simulates the immediate effect of removing the filter cartridge cage from the basin water, draining the outside water. This trend is shown in Figure A.4. If water now drains from the region inside the filter cartridge (with water density equal to 0.01 g/cm³ outside the filter cartridge), the result is a monotonic increase in k_{∞} with reduced water density, as shown in Figure A.5. In both Figures A.4 and A.5, the polypropylene filter material is assumed to be either wet (saturated with water) or dry. Lattice k_{∞} is increased when water density either inside or outside the filter cartridge is reduced.

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Figure A.1. k -infinity vs Spacing
(Filter Cartridge, U-235 = 1.25 wt%). Figure A.2. k -infinity vs Spacing
(Filter Cartridge, U-235 = 1.15 wt%).

Figure A.3. k -infinity vs Spacing
(Filter Cartridge, U-235 = 0.88 wt%).

Figure A.4. k -infinity vs H2O Density
(Full Density Water Inside Filter).

Figure A.5. k -infinity vs H₂O Density
(Outer Water Density = 0.01 g/cc).

The spacing assumed for the above calculations was typical of the average spacing inside the as-built filter cartridge cage assembly. If the lattice spacing variation is now carried out with low-density interspersed moderation, the result is as shown in Figure A.6, which is the same as Figure A.1 but with a new curve added. The drained case assumes that $U/Pu = 10$ and that the moderator density is equal to 0.01 g/cm³. These figures seem to imply that optimum moderation is achieved with as little water in the system as possible, which would suggest that any amount of water added is more of a poison than a moderator. This appears to be inconsistent with the known effects of adding water to a dry system; however, water is not the only moderator in this system. The polypropylene filter medium is composed of the repeating polymeric unit $[\text{CH}_2\text{CHCH}_2]_n$, and this much hydrogen and carbon, taken together with the small concentration of plutonium present, constitutes an overmoderated system.

A.3 STAINLESS STEEL CORE/TEMPERATURE EFFECTS

The filter cartridges contain a central 304 stainless steel core, which supports the geometry of the filter cartridge and prevents it from collapsing under the pressure of the inward, radially directed flow. Stainless steel is known to be a good neutron absorber. The difference in lattice k_0 (calculated both with and without the stainless steel core present) was found to be 54 mk.

The Doppler effect for this system was also calculated and found to be negative. Lattice k_0 is plotted as a function of fissile material temperature for $U/Pu = 100$ in Figure A.7. This Doppler effect will tend to become stronger (increasingly negative) for higher U/Pu ratios, as this increases the amount of resonance absorption per fissile atom.

Figure A.6. k -infinity vs Spacing
(Full Density Moderation vs. Drained).

Figure A.7. k -infinity vs Temperature
Lattice Spacing = 7.62 cm (3.0 inch).

A.4 EFFECT OF GREATER PLUTONIUM LOADING

If the filter cartridges are not replaced, fissionable material will continue to accumulate. Criticality is eventually possible given a high enough plutonium loading in the filter cartridges and no accumulation of fission or corrosion products. This series of calculations included variation in both spacing and reduced density moderation for a series of assumed plutonium loadings in the cage assembly. First, to be conservative, the only heavy metal assumed to be present was pure ^{239}Pu . Figure A.8 illustrates k_{∞} as a function of lattice spacing for full density moderation and for a set of elevated plutonium loadings. Figure A.9 presents the same results but for a reduced moderator density of 0.01 g/cm^3 . For full-density moderation, the system is still slightly overmoderated for higher plutonium loadings, even up to three times the allowable limit. With 750 g of plutonium in the cage assembly, the system is still subcritical. The k_{∞} increases with either reduced water density or with compaction of filter cartridges to smaller spacings. A reduced water density equal to 0.01 g/cm^3 was assumed to model the humid environment immediately after the water is drained; this is the "low-density" moderated case. With water present to only 0.01 g/cm^3 , k_{∞} is increased dramatically, as shown in Figure A.9, and the trend with reduced spacing is still somewhat positive. A plutonium loading of just over 500 g results in a k_{∞} equal to 1.0 for the as-built lattice spacing inside the cage assembly.

W-PIJ calculations were performed for the 750 g plutonium loading. W-PIJ is a two-dimensional (r,θ) module of WIMS-E that solves the neutron transport equations using integral transport theory (Anderson 1973). The first W-PIJ calculation assumed a drained configuration (moderator density equal to 0.01 g/cm^3), no axial neutron leakage, and an outer surface albedo equal to 1.0. The outer boundary was set to 58.1 cm, which corresponds to a hexagonal lattice spacing of 110.7 cm (43.6 in.), center-to-center, between filter cartridge assemblies. This is, therefore, still an infinite lattice calculation, but the repeating unit is now an entire filter cartridge assembly. The result was $k_{\infty} = 1.132$. When the outer boundary albedo was changed to zero, k_{∞} became k_{eff} , and the value was reduced to 0.210 (this is k_{∞} for an infinitely long, single filter cartridge assembly.) When the plutonium in the model (pure ^{239}Pu) was replaced with plutonium that contains 12-wt% ^{240}Pu , the k_{∞} was reduced to 0.188. When a finite buckling correction was added, thus treating axial neutron leakage for a single filter cartridge assembly, k_{eff} was reduced further, down to 0.014. To model a single-stacked array of filter cartridge assemblies, the boundary albedo was again increased to 1.0, and the result was $k_{\text{eff}} = 0.015$. The primary reason these k_{eff} results are so much lower than the k_{∞} results is because of the low moderator density, 0.01 g/cm^3 . Diffusion coefficients do not enter into the calculation of k_{∞} , but they become very important in the calculation of k_{eff} because of their large numeric values. Loosely packed lattices with little or no water moderation will have very large neutron mean-free-paths and hence high neutron leakage.

Figure A.8. k -infinity vs Spacing
(Full Density Moderation). Figure A.9. k -infinity vs Spacing
(Low Density Moderation = 0.01 g/cc).

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Assuming an average plutonium concentration equal to 5.5×10^{-7} g/L, the calculated accumulation of plutonium in the filter cartridge assembly is equal to 520 g in one year. With the U/Pu = 10 contingency, as depicted in Figure 5 of Section 6.2 of the main document, the plutonium accumulation rate of 0.52 kg/yr drives the filter cartridge to critical at about twelve years, or when 6 kg of plutonium have accumulated in the filter cartridge assembly.

When the filter cartridge assembly is pulled out of the basin, it will drain immediately from the outside, then from inside the filter cartridges. Figures A.10 and A.11 show the k_{eff} as the water density decreases. Figures A.10 and A.11 show that reducing the water density exhibits monotonic behavior. In other words, there is no maximum in k_{eff} part way through draining. Figure A.10 shows the increase in k_{eff} as the moderator density is reduced in the space surrounding the filter cartridges (i.e., the outside water), and Figure A.11 shows k_{eff} increase as the moderator density is decreased inside the filter cartridges (i.e., inside the iron core). Figures A.10 and A.11 contain lattice k_{eff} results and do not include the effects of finite system neutron leakage; these effects become very strong in reduced moderator density systems because of the higher neutron mean-free-paths. These effects are treated in explicit detail in the cluster calculation results contained in Figures 3 through 6 in the main document. Finite system results do indicate a maximum in k_{eff} part way through the draining process because neutron leakage overwhelms the problem as neutron mean-free-paths become large.

A.5 REFERENCES

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Figure A.10. k -inf vs Water Density
(Full Density Moderation Inside). Figure A.11. k -inf vs Water Density
(Outer Moderator Density = 0.01 g/cc).

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APPENDIX B

**URANIUM AND PLUTONIUM ANALYTICAL CHEMISTRY
RESULTS COMPARED TO ORIGEN2 CALCULATIONS**

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Hanford Company

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Internal
Memo

From: Technology Support Programs
Phone: 6-8175 HO-38
Date: June 9, 1993
Subject: URANIUM AND PLUTONIUM ANALYTICAL CHEMISTRY RESULTS COMPARED TO
ORIGEN2 CALCULATIONS

To: H. Toffer HO-38

cc: D. G. Erickson HO-38
WDW-File/LB 9316

Reference: D. C. Hedengren and H. J. Goldberg, "ORIGEN2 Predictions of N Reactor Fuel Actinide Composition," SD-CP-TI-105, June 24, 1987.

The question of consistency of the uranium and plutonium chemical analyses with computer calculations is considered.

To recapitulate, the PNL isotopic analyses for uranium and plutonium were:

²³⁴ U	0.0074565 wt% U
²³⁵ U	0.6938084 wt% U
²³⁶ U	0.0788619 wt% U
²³⁸ U	99.2198732 wt% U

²³⁸ Pu	0.0745658 wt% Pu
²³⁹ Pu	86.0096250 wt% Pu
²⁴⁰ Pu	12.5987204 wt% Pu
²⁴¹ Pu	1.1008806 wt% Pu
²⁴² Pu	0.2162082 wt% Pu

The PNL ratio of uranium to plutonium is computed to be 228, as computed in the appendix. The WHC ratio of uranium to plutonium is computed to be 480, as computed in the appendix.

One ORIGEN2 calculation (Reference, page C15) for MKIV fuel at 12 wt% ²⁴⁰Pu has these isotopic quantities for U, Pu and ²⁴¹Am at 10 years decay.

²³⁴ U	65.18	g/MTIHM	0.00655 wt% U
²³⁵ U	7036.	g/MTIHM	0.70712 wt% U
²³⁶ U	813.9	g/MTIHM	0.08180 wt% U
²³⁸ U	987,100	g/MTIHM	99.20456 wt% U
²³⁸ Pu	2.816	g/MTIHM	0.13588 wt% Pu
²³⁹ Pu	1768.	g/MTIHM	85.31810 wt% Pu
²⁴⁰ Pu	253.3	g/MTIHM	12.22241 wt% Pu
²⁴¹ Pu	42.99	g/MTIHM	2.07438 wt% Pu
²⁴² Pu	5.316	g/MTIHM	0.25651 wt% Pu
U/Pu ratio			480
²⁴¹ Am	26.97	g/MTIHM	

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CONCLUSION

Analytical chemistry values for uranium and plutonium are consistent with the isotopic composition of MkIV fuel irradiated to 12 wt% ^{240}Pu exposure with 20 years decay. There are no noteworthy differences with this conclusion.

The ORIGEN2 composition calculations for 12 wt% ^{240}Pu exposure are consistent with 480-490 U/Pu ratio, which is closer to the WHC analytical results.

DISCUSSION

Uranium isotopic composition depends on the assumed original composition. The reference calculation assumed ^{234}U 7 ppm, ^{235}U 0.947 wt%, ^{238}U 400 ppm, and ^{238}U balance. The average ^{234}U could easily be 7 ppm or 8 ppm, there is not that much difference. The analytical chemistry results are consistent with ORIGEN2 calculations and assumptions for the ^{234}U original composition. The analytical chemistry results for ^{235}U indicate the fuel exposure, which is approximately the exposure of 12 wt% ^{240}Pu . The calculated ^{236}U value depends strongly on the assumed input ^{235}U composition. The actual ^{236}U composition was about 297 ppm for a long time, then it rose in the early 1980's up to about 560 ppm when N Reactor was shut down. The analytical chemistry results, indicating a ^{236}U 350 ppm original composition, are consistent with ORIGEN2 calculations and assumptions for the ^{236}U original composition.

The ORIGEN2 ^{238}Pu composition depends on the assumed original ^{238}U . The ORIGEN2 ^{238}Pu calculation has a deficiency in the way the ORIGEN2 library was created and ORIGEN2 may be twice as high in the calculation of the reaction $^{238}\text{U}(n,2n)^{237}\text{U}(\beta^-, t_{1/2}=6.75 \text{ days})^{237}\text{Np}$ because of the way that the ORIGEN2 library was created. The ORIGEN2 library began with the 33,000 MWD/MT PWR reactor neutron cross sections, then adjusted the neutron cross sections with WIMS-D that does not include the (n,2n) cross sections. The PWR neutron spectrum is harder than N Reactor's neutron spectrum so the (n,2n) reactions would be too high, by about twice as much. The ^{237}Np is mentioned because that is the precursor in the formation of ^{238}Pu , and ORIGEN2 calculations of too much ^{237}Np means that ORIGEN2 also calculates too much ^{238}Pu . The analytical chemistry results for ^{238}Pu are consistent with ORIGEN2 calculation limitations and assumptions for the ^{236}U original composition.

The ^{239}Pu , ^{240}Pu and ^{242}Pu composition indicate the fuel exposure, which is reasonable close the approximately 12 wt% ^{240}Pu fuel exposure in the analytical chemistry results.

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The ^{241}Pu and ^{241}Am results simply indicate the decay time since irradiation. The ^{241}Pu ($\beta, t_{1/2} = 14.4 \text{ years}$) ^{241}Am decay continues after reactor discharge. This indicates the chemical analysis is averaged from fuel that is about twenty years since reactor discharge. Details of the fuel age since reactor discharge calculation are included in the appendix. This calculation depends on consistency between the ($^{239}\text{Pu} + ^{240}\text{Pu}$) activity and the ^{241}Am activity measurements and the availability of the plutonium isotopic composition.

Warren D. Wittekind, Principal Engineer
Technology Support Programs

kls

Attachments

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APPENDIX

CALCULATION OF URANIUM QUANTITY FROM PNL ANALYSIS

Dry Solid Phase

265 mg/g $\pm$ 4%; calculated σ = 265 mg/g $\times$ 0.04 = 10.60 mg/g
 277 mg/g $\pm$ 4%; calculated σ = 277 mg/g $\times$ 0.04 = 11.08 mg/g
 271 mg/g $\pm$ 4%; calculated σ = 271 mg/g $\times$ 0.04 = 10.84 mg/g
 203 mg/g $\pm$ 5%; calculated σ = 203 mg/g $\times$ 0.05 = 10.15 mg/g
 209 mg/g $\pm$ 5%; calculated σ = 209 mg/g $\times$ 0.05 = 10.45 mg/g

Equation:

$$\bar{X} = \left(\sum_{i=1,5} (X_i / (\sigma_i)^2) \right) / \left(\sum_{i=1,5} (1 / (\sigma_i)^2) \right)$$

Calculation:

$$\frac{265 / (10.60)^2 + 277 / (11.08)^2 + 271 / (10.84)^2 + 203 / (10.15)^2 + 209 / (10.45)^2}{1 / (10.60)^2 + 1 / (11.08)^2 + 1 / (10.84)^2 + 1 / (10.15)^2 + 1 / (10.45)^2} = 243.3 \text{ mg/g}$$

URANIUM QUANTITY FROM WHC ANALYSIS

Status report for E 9325 H&RWC 0344WQL TIME: 5/20/93 9:37 stated:

U = 2.57000E-01 g/g = 257 mg/g

CALCULATION OF TOTAL PLUTONIUM FROM PNL (^{239}Pu + ^{240}Pu) $\mu\text{Ci/g}$

Situation:

- 1) The (^{239}Pu + ^{240}Pu) activity in $\mu\text{Ci/g}$ of sample is known.
- 2) The plutonium isotopic composition (mass %) is also known.
- 3) The (^{238}Pu) activity in $\mu\text{Ci/g}$ of sample could be known also.

Analytical Chemistry Results (PNL of 21 May 1993):

- 1) 90.5 $\mu\text{Ci/g}$ of sample is activity of (^{239}Pu + ^{240}Pu).
- 2)

^{238}Pu	0.0745658	mass%
^{239}Pu	86.0096250	mass%
^{240}Pu	12.5987204	mass%
^{241}Pu	1.1008806	mass%
^{242}Pu	0.2162082	mass%
- 3) 13.8 $\mu\text{Ci/g}$ of sample is activity of (^{238}Pu).

Additional Necessary Information:

N_A Avogadro's Number 6.022045 $\times 10^{23}$ atoms/gram-mole (6.022045E+23)
 μCi Definition 1 μCi = 3.7×10^4 dis/s (3.7E+4)

Isotope	AW(Atomic Weight)	$t_{1/2}$ (half-life) yr
^{238}Pu	238.049555	87.7
^{239}Pu	239.052157	24,100
^{240}Pu	240.053808	6,560

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CALCULATION OF TOTAL AMERICIUM-241 FROM PNL ^{241}Am $\mu\text{Ci/g}$

Situation:

- 1) The ^{241}Am activity in $\mu\text{Ci/g}$ of sample is known.

Analytical Chemistry Results (PNL of 21 May 1993):

- 1) 62.5 $\mu\text{Ci/g}$ of sample is activity of ^{241}Am

Additional Necessary Information:

$$\begin{array}{ll} N_A \text{ Avogadro's Number} & 6.022045 \times 10^{23} \text{ atoms/gram-mole (6.022045E+23)} \\ \mu\text{Ci Definition} & 1 \mu\text{Ci} = 3.7 \times 10^4 \text{ dis/s (3.7E+4)} \end{array}$$

Isotope ^{241}Am	AW(Atomic Weight) 241.056823	$t_{1/2}$ (half-life) yr 432.7
------------------------------	---------------------------------	-----------------------------------

Calculation:

$$(^{241}\text{Am grams}) \times (\text{atoms/gram}) \times (\mu\text{Curies/atom}) = ^{241}\text{Am } \mu\text{Ci/g Pu}$$

Example for ^{241}Am :

$$\begin{aligned} & 1 \text{ g } ^{241}\text{Am} \times \frac{6.022045\text{E}+23 \text{ atoms/g-mole}}{241.056823 \text{ g } ^{241}\text{Am/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{432.7 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \mu\text{Ci } ^{241}\text{Am}}{3.7\text{E}+4 \text{ dis/s}} \\ & = 3.427\text{E}+6 \mu\text{Ci } ^{241}\text{Am/g } ^{241}\text{Am} \\ & 62.5 \mu\text{Ci}(^{241}\text{Am})/\text{g sample} / 3.427\text{E}+6 \mu\text{Ci}(^{241}\text{Am})/\text{g } ^{241}\text{Am} = 1.82\text{E}-5 \text{ g } ^{241}\text{Am/g sample} \\ & \therefore \text{final U/}^{241}\text{Am ratio from PNL analysis is} \\ & \text{U/Pu} = (251.6 \text{ mg U/g}) / (1.82\text{E}-5 \text{ g } ^{241}\text{Am/g}) = 13,800 \end{aligned}$$

CALCULATION OF TOTAL AMERICIUM-241 FROM WHC ^{241}Am $\mu\text{Ci/g}$

Situation:

- 1) The ^{241}Am activity in $\mu\text{Ci/g}$ of sample is known.

Analytical Chemistry Results (WHC of 20 May 1993):

- 1) 49.1 $\mu\text{Ci/g}$ of sample is activity of ^{241}Am

Calculation

$$49.1 \mu\text{Ci}(^{241}\text{Am})/\text{g sample} / 3.427\text{E}+6 \mu\text{Ci}(^{241}\text{Am})/\text{g } ^{241}\text{Am} = 1.43\text{E}-5 \text{ g } ^{241}\text{Am/g sample}$$

The final $\text{U/}^{241}\text{Am}$ ratio from WHC analysis is

$$\text{U/}^{241}\text{Am} = (257. \text{ mg U/g}) / (1.43\text{E}-5 \text{ g } ^{241}\text{Am/g}) = 18,000$$

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CALCULATION OF FUEL AGE AND DISCHARGE DATE FROM ^{241}Am AND ^{241}Pu QUANTITIES

Assumption: All ^{241}Am results from $^{241}\text{Pu}(\beta^-, t_{1/2}=14.4 \text{ years})^{241}\text{Am}$.

Test calculation using ORIGEN2 computed isotopic composition with 10 years decay.

$$\text{Equation: } N(t=T) = N(t=0) * \exp(-(\ln(2)/14.4) * T)$$

$$\text{Calculation: } 42.99 = (42.99 + 26.97) * \exp(-(\ln(2)/14.4) * T)$$

$$\ln(42.99 / (42.99 + 26.97)) = -(\ln(2)/14.4) * T$$

$$T = 10.1164 \text{ years.}$$

This puts day 0 at 42.5 days back into the irradiation cycle, not exactly the day of reactor discharge, but close enough when working with analytical chemistry results and their uncertainty.

CALCULATION OF FUEL AGE AND DISCHARGE DATE FROM PNL ^{241}Am AND ^{241}Pu QUANTITIES

Calculation:

$$^{241}\text{Pu} = 0.011008806 \text{ } ^{241}\text{Pu}/\text{Pu} * 1.102 \text{ mg Pu/g sample} = 1.213\text{E-}5 \text{ g } ^{241}\text{Pu/g sample}$$

$$^{241}\text{Am} = 1.82\text{E-}5 \text{ g } ^{241}\text{Am/g sample}$$

$$1.213\text{E-}5 \text{ g } ^{241}\text{Pu} = (1.213\text{E-}5 \text{ g } ^{241}\text{Pu} + 1.82\text{E-}5 \text{ g } ^{241}\text{Am}) * \exp(-(\ln(2)/14.4) * T)$$

$$\ln(1.213\text{E-}5 \text{ g } ^{241}\text{Pu} / (1.213\text{E-}5 \text{ g } ^{241}\text{Pu} + 1.82\text{E-}5 \text{ g } ^{241}\text{Am})) = -(\ln(2)/14.4) * T$$

$$T = 19.03918964 \text{ years.}$$

This means 19 years ago, or $1993.5 - 19 = 1974.5$. This corresponds to HAPO date 10871 (July 1, 1974), an average key number for 105 KE basin.

CALCULATION OF FUEL AGE AND DISCHARGE DATE FROM WHC ^{241}Am AND ^{241}Pu QUANTITIES

Calculation:

$$^{241}\text{Pu} = 0.011008806 \text{ } ^{241}\text{Pu}/\text{Pu} * 5.289\text{E-}4 \text{ g Pu/g sample} = 5.82\text{E-}6 \text{ g } ^{241}\text{Pu/g sample}$$

$$^{241}\text{Am} = 1.43\text{E-}5 \text{ g } ^{241}\text{Am/g sample}$$

$$5.82\text{E-}6 \text{ g } ^{241}\text{Pu} = (5.82\text{E-}6 \text{ g } ^{241}\text{Pu} + 1.43\text{E-}5 \text{ g } ^{241}\text{Am}) * \exp(-(\ln(2)/14.4) * T)$$

$$\ln(5.82\text{E-}6 \text{ g } ^{241}\text{Pu} / (5.82\text{E-}6 \text{ g } ^{241}\text{Pu} + 1.43\text{E-}5 \text{ g } ^{241}\text{Am})) = -(\ln(2)/14.4) * T$$

$$T = 25.7628786 \text{ years.}$$

This means 25.5 years ago, or $1993.5 - 25.5 = 1968$. This corresponds to HAPO date 08498 (January 1, 1968), older than the oldest discharge key number for 105 KE basin.

Calculation:

$$\begin{aligned} & \left(\frac{^{239}\text{Pu grams}}{^{239}\text{Pu grams}} \right) \times \left(\frac{\text{atoms/gram}}{\text{atoms/gram}} \right) \times \left(\frac{\mu\text{Curies/atom}}{\mu\text{Curies/atom}} \right) = \frac{^{239}\text{Pu } \mu\text{Ci/g Pu}}{^{239}\text{Pu } \mu\text{Ci/g Pu}} \\ & \left(\frac{^{240}\text{Pu grams}}{^{240}\text{Pu grams}} \right) \times \left(\frac{\text{atoms/gram}}{\text{atoms/gram}} \right) \times \left(\frac{\mu\text{Curies/atom}}{\mu\text{Curies/atom}} \right) = \frac{^{240}\text{Pu } \mu\text{Ci/g Pu}}{^{240}\text{Pu } \mu\text{Ci/g Pu}} \end{aligned}$$

Example for $^{239}\text{Pu} + ^{240}\text{Pu}$:

$$\frac{.860096250 \text{ g } ^{239}\text{Pu}}{1 \text{ g Pu}} \times \frac{6.022045 \times 10^{23} \text{ atoms/g-mole}}{239.052157 \text{ g } ^{239}\text{Pu/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{24,100 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \mu\text{Ci } ^{239}\text{Pu}}{3.7 \times 10^4 \text{ dis/s}}$$

$$= 5.337 \times 10^4 \mu\text{Ci } ^{239}\text{Pu/g Pu}$$

$$\frac{.125987204 \text{ g } ^{240}\text{Pu}}{1 \text{ g Pu}} \times \frac{6.022045 \times 10^{23} \text{ atoms/g-mole}}{240.053808 \text{ g } ^{240}\text{Pu/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{6,560 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \mu\text{Ci } ^{240}\text{Pu}}{3.7 \times 10^4 \text{ dis/s}}$$

$$= 2.860 \times 10^4 \mu\text{Ci } ^{240}\text{Pu/g Pu}$$

$$5.337 \times 10^4 \mu\text{Ci } ^{239}\text{Pu/g Pu} + 2.860 \times 10^4 \mu\text{Ci } ^{240}\text{Pu/g Pu} = 8.197 \times 10^4 \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g Pu}$$

$$90.5 \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g sample} / 8.197 \times 10^4 \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g Pu} = 1.104 \times 10^{-3} \text{ gPu/g sample}$$

Example for ^{238}Pu :

$$\frac{.000745658 \text{ g } ^{238}\text{Pu}}{1 \text{ g Pu}} \times \frac{6.022045 \times 10^{23} \text{ atoms/g-mole}}{238.049555 \text{ g } ^{238}\text{Pu/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{87.7 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \mu\text{Ci } ^{238}\text{Pu}}{3.7 \times 10^4 \text{ dis/s}}$$

$$= 1.277 \times 10^4 \mu\text{Ci } ^{238}\text{Pu/g Pu}$$

$$13.8 \mu\text{Ci } (^{238}\text{Pu})/\text{g sample} / 1.277 \times 10^4 \mu\text{Ci } (^{238}\text{Pu})/\text{g Pu} = 1.081 \times 10^{-3} \text{ gPu/g sample}$$

The weighted average of these two results is calculated next.

$$\frac{1.104 \times 10^{-3} \text{ Pu g/g } (.05)^2 + 1.081 \times 10^{-3} \text{ Pu g/g } (.17)^2}{1/ (.05)^2 + 1/ (.17)^2} = 1.102 \text{ Pu mg/g}$$

The final U/Pu ratio from PNL analysis is

$$\text{U/Pu} = (251.6 \text{ mg U/g}) / (1.102 \text{ mg Pu/g}) = 228$$

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CALCULATION OF TOTAL PLUTONIUM FROM WHC (^{239}Pu + ^{240}Pu) $\mu\text{Ci/g}$

Situation:

- 1) The (^{239}Pu + ^{240}Pu) activity in $\mu\text{Ci/g}$ of sample is known.
- 2) The plutonium isotopic composition (mass %) is also known.

Analytical Chemistry Results (WHC of 20 May 1993):

- 1) .5x(44.1 + 42.6) $\mu\text{Ci/g}$ of sample is activity of (^{239}Pu + ^{240}Pu).

Analytical Chemistry Results (PNL of 21 May 1993):

2) ^{238}Pu	0.0745658	mass%
^{239}Pu	86.0096250	mass%
^{240}Pu	12.5987204	mass%
^{241}Pu	1.1008806	mass%
^{242}Pu	0.2162082	mass%

Additional Necessary Information:

N_A Avogadro's Number	6.022045×10^{23} atoms/gram-mole	(6.022045E+23)
μCi Definition	1 μCi = 3.7×10^4 dis/s	(3.7E+4)

Isotope	AW(Atomic Weight)	$t_{1/2}$ (half-life) yr
^{239}Pu	239.052157	24,100
^{240}Pu	240.053808	6,560

Calculation:

$$\begin{aligned} & \left(\frac{^{239}\text{Pu grams}}{^{240}\text{Pu grams}} \right) \times \left(\frac{\text{atoms/gram}}{\text{atoms/gram}} \right) \times \left(\frac{\mu\text{Curies/atom}}{\mu\text{Curies/atom}} \right) = \frac{^{239}\text{Pu } \mu\text{Ci/g Pu}}{^{240}\text{Pu } \mu\text{Ci/g Pu}} \\ & \left(\frac{^{239}\text{Pu } \mu\text{Ci/g Pu} + ^{240}\text{Pu } \mu\text{Ci/g Pu}}{^{239}\text{Pu } \mu\text{Ci/g Pu} + ^{240}\text{Pu } \mu\text{Ci/g Pu}} \right) = \frac{^{239}\text{Pu } \mu\text{Ci/g Pu}}{^{239}\text{Pu } \mu\text{Ci/g Pu} + ^{240}\text{Pu } \mu\text{Ci/g Pu}} \end{aligned}$$

Example for ^{239}Pu + ^{240}Pu :

$$\frac{.860096250 \text{ g } ^{239}\text{Pu}}{1 \text{ g Pu}} \times \frac{6.022045\text{E}+23 \text{ atoms/g-mole}}{239.052157 \text{ g } ^{239}\text{Pu/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{24,100 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \text{ } \mu\text{Ci } ^{239}\text{Pu}}{3.7\text{E}+4 \text{ dis/s}}$$

$$= 5.337\text{E}+4 \text{ } \mu\text{Ci } ^{239}\text{Pu/g Pu}$$

$$\frac{.125987204 \text{ g } ^{240}\text{Pu}}{1 \text{ g Pu}} \times \frac{6.022045\text{E}+23 \text{ atoms/g-mole}}{240.053808 \text{ g } ^{240}\text{Pu/g-mole}} \times \frac{\ln(2) \text{ dis/s/atom}}{6,560 \times 365.25 \times 24 \times 60 \times 60} \times \frac{1 \text{ } \mu\text{Ci } ^{240}\text{Pu}}{3.7\text{E}+4 \text{ dis/s}}$$

$$= 2.860\text{E}+4 \text{ } \mu\text{Ci } ^{240}\text{Pu/g Pu}$$

$$5.337\text{E}+4 \text{ } \mu\text{Ci } ^{239}\text{Pu/g Pu} + 2.860\text{E}+4 \text{ } \mu\text{Ci } ^{240}\text{Pu/g Pu} = 8.197\text{E}+4 \text{ } \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g Pu}$$

$$43.35 \text{ } \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g sample} / 8.197\text{E}+4 \text{ } \mu\text{Ci } (^{239}\text{Pu} + ^{240}\text{Pu})/\text{g Pu} = 5.289\text{E}-4 \text{ gPu/g sample}$$

The final U/Pu ratio from WHC analysis is

$$\text{U/Pu} = (257. \text{ mg U/g}) / (5.289 \text{ mg Pu/g}) = 480$$

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APPENDIX C

SAMPLE INPUT FILES FOR WINS-E LATTICE AND CLUSTER CALCULATIONS

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The following is a listing of the WIMS-E input file that was used to generate the k_{eff} as a function of reduced lattice spacing for sludge accumulation at six months. These results are found in Figure 7.

```

*****
* ... COMPOSITION BY SCHWINKENDORF ...
* U/PU          = 10
* U ENRICHMENT  = 0.947 WTX
* OXIDE CONC    = 0.20 G/CC
* WATER DENSITY = 1.00 G/CC
*****
NCYCLE 1 14
WHEAD 1
NMESH 27
NREGION 4
NRMATERIAL 4
ENDP
PRINT 0
CENT
MESH 8 1 8 10
* OXIDE CONC = 0.20 G/CC
MATERIAL 1 1.10522 296.0 1 2235 0.09999 8238 10.45747
                                         6239 0.93355 1240 0.12730
                                         6016 59.01803 2012 18.94217 3001 10.42149
MATERIAL 2 8.030 296.0 2 9056 100.
MATERIAL 3 1.000 296.0 3 3001 11.1 6016 88.9
MATERIAL 4 1.000 296.0 3 3001 11.1 6016 88.9
ANNULUS 1 1.324 3
ANNULUS 2 1.352 2
ANNULUS 3 3.175 1
QUAL 1 1
ANNULUS 4 3.50 4
QUAL 1 2
ANNULUS 4 4.00 4
QUAL 1 3
ANNULUS 4 4.50 4
QUAL 1 4
ANNULUS 4 5.00 4
QUAL 1 5
ANNULUS 4 5.50 4
QUAL 1 6
ANNULUS 4 6.00 4
QUAL 1 7
ANNULUS 4 6.50 4
QUAL 1 8
ANNULUS 4 7.00 4
QUAL 1 9
ANNULUS 4 7.50 4
QUAL 1 10
ANNULUS 4 8.00 4
QUAL 1 11
ANNULUS 4 8.50 4
QUAL 1 12
ANNULUS 4 9.00 4
QUAL 1 13
ANNULUS 4 9.50 4
QUAL 1 14
ANNULUS 4 10.00 4
BEGIN
*
* PRES CALCULATION
*
WPRES 1 2
GROUPS 15 27
NUCLIDE 2235 296.
NUCLIDE 8238 296.
NUCLIDE 6239 296.
PRINT 0
BEGIN

```

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```
*
* PERSEUS CALCULATIONS
*
```

```
WTHES      2
PRINT      0
BEGIN
*
WRES       2 3
GROUPS    15 27
NUCLIDE   2235 296.
NUCLIDE   8238 296.
NUCLIDE   6239 296.
PRINT      0
BEGIN
*
```

```
* PERSEUS CALCULATIONS
*
```

```
WTHES      3
PRINT      0
BEGIN
*
WPIP       3
PRINT      0
TOLER      1.0E-5
OMEGA      1.25
BEGIN
FINISH
STOP
```

The following WIMS-E input file was used to generate the cluster k_{eff} as a function of time before replacement for full density moderation and U/Pu equal to 400, as shown in Figure 3.

```
*****
* FILTER CARTRIDGE W-PIJ CALCULATION OF 88 FILTERS ...
* ... GEOMETRY BY PARRA ...
* ... COMPOSITION BY SCHWINKENDORF ...
* U/PU      = 400
* U ENRICHMENT = 0.947 WTX
* OXIDE CONC  = 0.50 - 4.00 G/CC, IN STEPS OF 0.50 G/CC
* WATER DENSITY = 1.00 G/CC
*****
NCYCLE 1 8
WHEAD 1
NMESH 27
NREGION 4
NMATERIAL 4
ENDP
PRINT 0
CENT
MESH 8 1 8 10
QUAL 3 1 * OXIDE CONC = 0.50 G/CC
MATERIAL 1 1.30379 296.0 1 2235 0.23260 8238 24.32637
6239 0.05429 1240 0.00740
6016 50.65891 2012 16.05715 3001 8.66328
QUAL 3 2 * OXIDE CONC = 1.00 G/CC
MATERIAL 1 1.63475 296.0 1 2235 0.37102 8238 38.80285
6239 0.08660 1240 0.01181
6016 41.23925 2012 12.80634 3001 6.68215
QUAL 3 3 * OXIDE CONC = 1.50 G/CC
MATERIAL 1 1.96571 296.0 1 2235 0.46282 8238 48.40462
6239 0.10805 1240 0.01473
6016 34.99150 2012 10.65018 3001 5.36813
QUAL 3 4 * OXIDE CONC = 2.00 G/CC
MATERIAL 1 2.29667 296.0 1 2235 0.52817 8238 55.23907
6239 0.12328 1240 0.01681
6016 30.54440 2012 9.11544 3001 4.43282
QUAL 3 5 * OXIDE CONC = 2.50 G/CC
MATERIAL 1 2.62763 296.0 1 2235 0.57706 8238 60.35188
6239 0.13469 1240 0.01837
6016 27.21757 2012 7.96732 3001 3.73312
```

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```

QUAL 3 6 * OXIDE CONC = 3.00 G/CC
MATERIAL 1 2.95859 296.0 1 2235 0.61501 8238 64.32080
        6239 0.14355 1240 0.01957
        6016 24.63504 2012 7.07606 3001 3.18997
QUAL 3 7 * OXIDE CONC = 3.50 G/CC
MATERIAL 1 3.28955 296.0 1 2235 0.64532 8238 67.49111
        6239 0.19062 1240 0.02054
        6016 22.57216 2012 6.36414 3001 2.75611
QUAL 3 8 * OXIDE CONC = 4.00 G/CC
MATERIAL 1 3.62051 296.0 1 2235 0.67009 8238 70.08180
        6239 0.15441 1240 0.02133
        6016 20.88643 2012 5.78238 3001 2.40157
MATERIAL 2 8.030 296.0 2 9056 100.
MATERIAL 3 1.000 296.0 3 3001 11.1 6016 88.9
MATERIAL 4 1.000 296.0 3 3001 11.1 6016 88.9
ANNULUS 1 1.324 3
ANNULUS 2 1.352 2
ANNULUS 3 3.175 1
ANNULUS 4 3.99378 4
BEGIN
*
* PRES CALCULATION
*
UPRES 1 2
GROUPS 15 27
NUCLIDE 2235 296.
NUCLIDE 8238 296.
NUCLIDE 6239 296.
PRINT 0
BEGIN
*
* PERSEUS CALCULATIONS
*
UTRES 2
PRINT 0
BEGIN
*
URES 2 3
GROUPS 15 27
NUCLIDE 2235 296.
NUCLIDE 8238 296.
NUCLIDE 6239 296.
PRINT 0
BEGIN
*
* PERSEUS CALCULATIONS
*
UTRES 3
PRINT 0
BEGIN
*
WPIP 3
PRINT 0
TOLER 1.0E-5
OMEGA 1.25
BEGIN
*
* COLLAPSING TO 18 GROUPS TO DO CLUSTER PIJ
*
WCOND 3 4
GROUP 18
ENDP
PART 2 5 10 14 23 24 26 27 36 39 45 48 53 56 60 63 66 69
BEGIN
*
* PIJ CALCULATIONS FOR FUEL STORAGE CANISTER
*
WPIJ 4
CELLOIM 260 11 1 1 1 1
ROODIM 88 82 3 1
CONTROL 1 163 97 1 0 3
ENDP
CENT
ADEG

```

WHC-SD-SNF-CSER-002 Rev. 0

```

PRINT 1
ANNULUS -1 1.324 3 *WATER INSIDE FIRST FUEL
ANNULUS -2 1.352 2 *CLAD
ANNULUS -3 3.175 1 *FIRST FUEL RING
ANNULUS -4 3.429 3 *WATER
ANNULUS -5 10.287 3 *SECOND FUEL RING
ANNULUS -6 17.145 3 *THIRD FUEL RING
ANNULUS -7 24.003 3 *FOURTH FUEL RING
ANNULUS -8 30.861 3 *FIFTH FUEL RING
ANNULUS -9 37.719 3 *SIXTH FUEL RING
ANNULUS -10 38.100 3 *WATER
ANNULUS -11 58.100 4 *OUTSIDE WATER REFLECTOR
SURFACE 0.0
ARRAY 1 1 6 6.858 0 *SECOND RING: 6 PINS
RODSUB 1 1 1.324 3 *INNER WATER
RODSUB 1 2 1.352 2 *CLAD
RODSUB 1 3 3.175 1 *FUEL
ARRAY 2 1 1 13.716 14 *THIRD RING: #1 PIN
RODSUB 2 1 1.324 3 *INNER WATER
RODSUB 2 2 1.352 2 *CLAD
RODSUB 2 3 3.175 1 *FUEL
ARRAY 3 1 1 13.716 44 *THIRD RING: #2 PIN
RODSUB 3 1 1.324 3 *INNER WATER
RODSUB 3 2 1.352 2 *CLAD
RODSUB 3 3 3.175 1 *FUEL
ARRAY 4 1 1 13.716 73 *THIRD RING: #3 PIN
RODSUB 4 1 1.324 3 *INNER WATER
RODSUB 4 2 1.352 2 *CLAD
RODSUB 4 3 3.175 1 *FUEL
ARRAY 5 1 1 13.716 101 *THIRD RING: #4 PIN
RODSUB 5 1 1.324 3 *INNER WATER
RODSUB 5 2 1.352 2 *CLAD
RODSUB 5 3 3.175 1 *FUEL
ARRAY 6 1 1 13.716 130 *THIRD RING: #5 PIN
RODSUB 6 1 1.324 3 *INNER WATER
RODSUB 6 2 1.352 2 *CLAD
RODSUB 6 3 3.175 1 *FUEL
ARRAY 7 1 1 13.716 160 *THIRD RING: #6 PIN
RODSUB 7 1 1.324 3 *INNER WATER
RODSUB 7 2 1.352 2 *CLAD
RODSUB 7 3 3.175 1 *FUEL
ARRAY 8 1 1 13.716 200 *THIRD RING: #7 PIN
RODSUB 8 1 1.324 3 *INNER WATER
RODSUB 8 2 1.352 2 *CLAD
RODSUB 8 3 3.175 1 *FUEL
ARRAY 9 1 1 13.716 230 *THIRD RING: #8 PIN
RODSUB 9 1 1.324 3 *INNER WATER
RODSUB 9 2 1.352 2 *CLAD
RODSUB 9 3 3.175 1 *FUEL
ARRAY 10 1 1 13.716 259 *THIRD RING: #9 PIN
RODSUB 10 1 1.324 3 *INNER WATER
RODSUB 10 2 1.352 2 *CLAD
RODSUB 10 3 3.175 1 *FUEL
ARRAY 11 1 1 13.716 287 *THIRD RING: #10 PIN
RODSUB 11 1 1.324 3 *INNER WATER
RODSUB 11 2 1.352 2 *CLAD
RODSUB 11 3 3.175 1 *FUEL
ARRAY 12 1 1 13.716 316 *THIRD RING: #11 PIN
RODSUB 12 1 1.324 3 *INNER WATER
RODSUB 12 2 1.352 2 *CLAD
RODSUB 12 3 3.175 1 *FUEL
ARRAY 13 1 1 13.716 345 *THIRD RING: #12 PIN
RODSUB 13 1 1.324 3 *INNER WATER
RODSUB 13 2 1.352 2 *CLAD
RODSUB 13 3 3.175 1 *FUEL
ARRAY 14 1 1 20.574 9 *FOURTH RING: #1 PIN
RODSUB 14 1 1.324 3 *INNER WATER
RODSUB 14 2 1.352 2 *CLAD
RODSUB 14 3 3.175 1 *FUEL
ARRAY 15 1 1 20.574 29 *FOURTH RING: #2 PIN
RODSUB 15 1 1.324 3 *INNER WATER
RODSUB 15 2 1.352 2 *CLAD
RODSUB 15 3 3.175 1 *FUEL

```

ARRAY 16 1 1	20.574	48	*FOURTH RING: #3 PIN
RODSUB 16 1	1.324	3	*INNER WATER
RODSUB 16 2	1.352	2	*CLAD
RODSUB 16 3	3.175	1	*FUEL
ARRAY 17 1 1	20.574	67	*FOURTH RING: #4 PIN
RODSUB 17 1	1.324	3	*INNER WATER
RODSUB 17 2	1.352	2	*CLAD
RODSUB 17 3	3.175	1	*FUEL
ARRAY 18 1 1	20.574	86	*FOURTH RING: #5 PIN
RODSUB 18 1	1.324	3	*INNER WATER
RODSUB 18 2	1.352	2	*CLAD
RODSUB 18 3	3.175	1	*FUEL
ARRAY 19 1 1	20.574	105	*FOURTH RING: #6 PIN
RODSUB 19 1	1.324	3	*INNER WATER
RODSUB 19 2	1.352	2	*CLAD
RODSUB 19 3	3.175	1	*FUEL
ARRAY 20 1 1	20.574	124	*FOURTH RING: #7 PIN
RODSUB 20 1	1.324	3	*INNER WATER
RODSUB 20 2	1.352	2	*CLAD
RODSUB 20 3	3.175	1	*FUEL
ARRAY 21 1 1	20.574	143	*FOURTH RING: #8 PIN
RODSUB 21 1	1.324	3	*INNER WATER
RODSUB 21 2	1.352	2	*CLAD
RODSUB 21 3	3.175	1	*FUEL
ARRAY 22 1 1	20.574	163	*FOURTH RING: #9 PIN
RODSUB 22 1	1.324	3	*INNER WATER
RODSUB 22 2	1.352	2	*CLAD
RODSUB 22 3	3.175	1	*FUEL
ARRAY 23 1 1	20.574	197	*FOURTH RING: #10 PIN
RODSUB 23 1	1.324	3	*INNER WATER
RODSUB 23 2	1.352	2	*CLAD
RODSUB 23 3	3.175	1	*FUEL
ARRAY 24 1 1	20.574	217	*FOURTH RING: #11 PIN
RODSUB 24 1	1.324	3	*INNER WATER
RODSUB 24 2	1.352	2	*CLAD
RODSUB 24 3	3.175	1	*FUEL
ARRAY 25 1 1	20.574	236	*FOURTH RING: #12 PIN
RODSUB 25 1	1.324	3	*INNER WATER
RODSUB 25 2	1.352	2	*CLAD
RODSUB 25 3	3.175	1	*FUEL
ARRAY 26 1 1	20.574	255	*FOURTH RING: #13 PIN
RODSUB 26 1	1.324	3	*INNER WATER
RODSUB 26 2	1.352	2	*CLAD
RODSUB 26 3	3.175	1	*FUEL
ARRAY 27 1 1	20.574	274	*FOURTH RING: #14 PIN
RODSUB 27 1	1.324	3	*INNER WATER
RODSUB 27 2	1.352	2	*CLAD
RODSUB 27 3	3.175	1	*FUEL
ARRAY 28 1 1	20.574	293	*FOURTH RING: #15 PIN
RODSUB 28 1	1.324	3	*INNER WATER
RODSUB 28 2	1.352	2	*CLAD
RODSUB 28 3	3.175	1	*FUEL
ARRAY 29 1 1	20.574	312	*FOURTH RING: #16 PIN
RODSUB 29 1	1.324	3	*INNER WATER
RODSUB 29 2	1.352	2	*CLAD
RODSUB 29 3	3.175	1	*FUEL
ARRAY 30 1 1	20.574	331	*FOURTH RING: #17 PIN
RODSUB 30 1	1.324	3	*INNER WATER
RODSUB 30 2	1.352	2	*CLAD
RODSUB 30 3	3.175	1	*FUEL
ARRAY 31 1 1	20.574	351	*FOURTH RING: #18 PIN
RODSUB 31 1	1.324	3	*INNER WATER
RODSUB 31 2	1.352	2	*CLAD
RODSUB 31 3	3.175	1	*FUEL
ARRAY 32 1 1	27.432	14	*FIFTH RING: #1 PIN
RODSUB 32 1	1.324	3	*INNER WATER
RODSUB 32 2	1.352	2	*CLAD
RODSUB 32 3	3.175	1	*FUEL
ARRAY 33 1 1	27.432	29	*FIFTH RING: #2 PIN
RODSUB 33 1	1.324	3	*INNER WATER
RODSUB 33 2	1.352	2	*CLAD
RODSUB 33 3	3.175	1	*FUEL

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ARRAY 34 1 1	27.432	43	*FIFTH RING: #3 PIN
RODSUB 34 1	1.324	3	*INNER WATER
RODSUB 34 2	1.352	2	*CLAD
RODSUB 34 3	3.175	1	*FUEL
ARRAY 35 1 1	27.432	57	*FIFTH RING: #4 PIN
RODSUB 35 1	1.324	3	*INNER WATER
RODSUB 35 2	1.352	2	*CLAD
RODSUB 35 3	3.175	1	*FUEL
ARRAY 36 1 1	27.432	72	*FIFTH RING: #5 PIN
RODSUB 36 1	1.324	3	*INNER WATER
RODSUB 36 2	1.352	2	*CLAD
RODSUB 36 3	3.175	1	*FUEL
ARRAY 37 1 1	27.432	86	*FIFTH RING: #6 PIN
RODSUB 37 1	1.324	3	*INNER WATER
RODSUB 37 2	1.352	2	*CLAD
RODSUB 37 3	3.175	1	*FUEL
ARRAY 38 1 1	27.432	100	*FIFTH RING: #7 PIN
RODSUB 38 1	1.324	3	*INNER WATER
RODSUB 38 2	1.352	2	*CLAD
RODSUB 38 3	3.175	1	*FUEL
ARRAY 39 1 1	27.432	115	*FIFTH RING: #8 PIN
RODSUB 39 1	1.324	3	*INNER WATER
RODSUB 39 2	1.352	2	*CLAD
RODSUB 39 3	3.175	1	*FUEL
ARRAY 40 1 1	27.432	129	*FIFTH RING: #9 PIN
RODSUB 40 1	1.324	3	*INNER WATER
RODSUB 40 2	1.352	2	*CLAD
RODSUB 40 3	3.175	1	*FUEL
ARRAY 41 1 1	27.432	143	*FIFTH RING: #10 PIN
RODSUB 41 1	1.324	3	*INNER WATER
RODSUB 41 2	1.352	2	*CLAD
RODSUB 41 3	3.175	1	*FUEL
ARRAY 42 1 1	27.432	158	*FIFTH RING: #11 PIN
RODSUB 42 1	1.324	3	*INNER WATER
RODSUB 42 2	1.352	2	*CLAD
RODSUB 42 3	3.175	1	*FUEL
ARRAY 43 1 1	27.432	202	*FIFTH RING: #12 PIN
RODSUB 43 1	1.324	3	*INNER WATER
RODSUB 43 2	1.352	2	*CLAD
RODSUB 43 3	3.175	1	*FUEL
ARRAY 44 1 1	27.432	217	*FIFTH RING: #13 PIN
RODSUB 44 1	1.324	3	*INNER WATER
RODSUB 44 2	1.352	2	*CLAD
RODSUB 44 3	3.175	1	*FUEL
ARRAY 45 1 1	27.432	231	*FIFTH RING: #14 PIN
RODSUB 45 1	1.324	3	*INNER WATER
RODSUB 45 2	1.352	2	*CLAD
RODSUB 45 3	3.175	1	*FUEL
ARRAY 46 1 1	27.432	245	*FIFTH RING: #15 PIN
RODSUB 46 1	1.324	3	*INNER WATER
RODSUB 46 2	1.352	2	*CLAD
RODSUB 46 3	3.175	1	*FUEL
ARRAY 47 1 1	27.432	260	*FIFTH RING: #16 PIN
RODSUB 47 1	1.324	3	*INNER WATER
RODSUB 47 2	1.352	2	*CLAD
RODSUB 47 3	3.175	1	*FUEL
ARRAY 48 1 1	27.432	274	*FIFTH RING: #17 PIN
RODSUB 48 1	1.324	3	*INNER WATER
RODSUB 48 2	1.352	2	*CLAD
RODSUB 48 3	3.175	1	*FUEL
ARRAY 49 1 1	27.432	288	*FIFTH RING: #18 PIN
RODSUB 49 1	1.324	3	*INNER WATER
RODSUB 49 2	1.352	2	*CLAD
RODSUB 49 3	3.175	1	*FUEL
ARRAY 50 1 1	27.432	303	*FIFTH RING: #19 PIN
RODSUB 50 1	1.324	3	*INNER WATER
RODSUB 50 2	1.352	2	*CLAD
RODSUB 50 3	3.175	1	*FUEL
ARRAY 51 1 1	27.432	317	*FIFTH RING: #20 PIN
RODSUB 51 1	1.324	3	*INNER WATER
RODSUB 51 2	1.352	2	*CLAD
RODSUB 51 3	3.175	1	*FUEL

ARRAY	52	1	27.432	331	*FIFTH RING: #21 PIN
RODSUB	52	1	1.324	3	*INNER WATER
RODSUB	52	2	1.352	2	*CLAD
RODSUB	52	3	3.175	1	*FUEL
ARRAY	53	1	27.432	346	*FIFTH RING: #22 PIN
RODSUB	53	1	1.324	3	*INNER WATER
RODSUB	53	2	1.352	2	*CLAD
RODSUB	53	3	3.175	1	*FUEL
ARRAY	54	1	27.432	360	*FIFTH RING: #23 PIN
RODSUB	54	1	1.324	3	*INNER WATER
RODSUB	54	2	1.352	2	*CLAD
RODSUB	54	3	3.175	1	*FUEL
ARRAY	55	1	34.290	6	*SIXTH RING: #1 PIN
RODSUB	55	1	1.324	3	*INNER WATER
RODSUB	55	2	1.352	2	*CLAD
RODSUB	55	3	3.175	1	*FUEL
ARRAY	56	1	34.290	18	*SIXTH RING: #2 PIN
RODSUB	56	1	1.324	3	*INNER WATER
RODSUB	56	2	1.352	2	*CLAD
RODSUB	56	3	3.175	1	*FUEL
ARRAY	57	1	34.290	29	*SIXTH RING: #3 PIN
RODSUB	57	1	1.324	3	*INNER WATER
RODSUB	57	2	1.352	2	*CLAD
RODSUB	57	3	3.175	1	*FUEL
ARRAY	58	1	34.290	40	*SIXTH RING: #4 PIN
RODSUB	58	1	1.324	3	*INNER WATER
RODSUB	58	2	1.352	2	*CLAD
RODSUB	58	3	3.175	1	*FUEL
ARRAY	59	1	34.290	52	*SIXTH RING: #5 PIN
RODSUB	59	1	1.324	3	*INNER WATER
RODSUB	59	2	1.352	2	*CLAD
RODSUB	59	3	3.175	1	*FUEL
ARRAY	60	1	34.290	63	*SIXTH RING: #6 PIN
RODSUB	60	1	1.324	3	*INNER WATER
RODSUB	60	2	1.352	2	*CLAD
RODSUB	60	3	3.175	1	*FUEL
ARRAY	61	1	34.290	74	*SIXTH RING: #7 PIN
RODSUB	61	1	1.324	3	*INNER WATER
RODSUB	61	2	1.352	2	*CLAD
RODSUB	61	3	3.175	1	*FUEL
ARRAY	62	1	34.290	86	*SIXTH RING: #8 PIN
RODSUB	62	1	1.324	3	*INNER WATER
RODSUB	62	2	1.352	2	*CLAD
RODSUB	62	3	3.175	1	*FUEL
ARRAY	63	1	34.290	97	*SIXTH RING: #9 PIN
RODSUB	63	1	1.324	3	*INNER WATER
RODSUB	63	2	1.352	2	*CLAD
RODSUB	63	3	3.175	1	*FUEL
ARRAY	64	1	34.290	109	*SIXTH RING: #10 PIN
RODSUB	64	1	1.324	3	*INNER WATER
RODSUB	64	2	1.352	2	*CLAD
RODSUB	64	3	3.175	1	*FUEL
ARRAY	65	1	34.290	121	*SIXTH RING: #11 PIN
RODSUB	65	1	1.324	3	*INNER WATER
RODSUB	65	2	1.352	2	*CLAD
RODSUB	65	3	3.175	1	*FUEL
ARRAY	66	1	34.290	132	*SIXTH RING: #12 PIN
RODSUB	66	1	1.324	3	*INNER WATER
RODSUB	66	2	1.352	2	*CLAD
RODSUB	66	3	3.175	1	*FUEL
ARRAY	67	1	34.290	144	*SIXTH RING: #13 PIN
RODSUB	67	1	1.324	3	*INNER WATER
RODSUB	67	2	1.352	2	*CLAD
RODSUB	67	3	3.175	1	*FUEL
ARRAY	68	1	34.290	155	*SIXTH RING: #14 PIN
RODSUB	68	1	1.324	3	*INNER WATER
RODSUB	68	2	1.352	2	*CLAD
RODSUB	68	3	3.175	1	*FUEL
ARRAY	69	1	34.290	205	*SIXTH RING: #15 PIN
RODSUB	69	1	1.324	3	*INNER WATER
RODSUB	69	2	1.352	2	*CLAD
RODSUB	69	3	3.175	1	*FUEL

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ARRAY 70 1 1 34.290 216 *SIXTH RING: #16 PIN
RODSUB 70 1 1.324 3 *INNER WATER
RODSUB 70 2 1.352 2 *CLAD
RODSUB 70 3 3.175 1 *FUEL
ARRAY 71 1 1 34.290 228 *SIXTH RING: #17 PIN
RODSUB 71 1 1.324 3 *INNER WATER
RODSUB 71 2 1.352 2 *CLAD
RODSUB 71 3 3.175 1 *FUEL
ARRAY 72 1 1 34.290 239 *SIXTH RING: #18 PIN
RODSUB 72 1 1.324 3 *INNER WATER
RODSUB 72 2 1.352 2 *CLAD
RODSUB 72 3 3.175 1 *FUEL
ARRAY 73 1 1 34.290 251 *SIXTH RING: #19 PIN
RODSUB 73 1 1.324 3 *INNER WATER
RODSUB 73 2 1.352 2 *CLAD
RODSUB 73 3 3.175 1 *FUEL
ARRAY 74 1 1 34.290 263 *SIXTH RING: #20 PIN
RODSUB 74 1 1.324 3 *INNER WATER
RODSUB 74 2 1.352 2 *CLAD
RODSUB 74 3 3.175 1 *FUEL
ARRAY 75 1 1 34.290 274 *SIXTH RING: #21 PIN
RODSUB 75 1 1.324 3 *INNER WATER
RODSUB 75 2 1.352 2 *CLAD
RODSUB 75 3 3.175 1 *FUEL
ARRAY 76 1 1 34.290 286 *SIXTH RING: #22 PIN
RODSUB 76 1 1.324 3 *INNER WATER
RODSUB 76 2 1.352 2 *CLAD
RODSUB 76 3 3.175 1 *FUEL
ARRAY 77 1 1 34.290 297 *SIXTH RING: #23 PIN
RODSUB 77 1 1.324 3 *INNER WATER
RODSUB 77 2 1.352 2 *CLAD
RODSUB 77 3 3.175 1 *FUEL
ARRAY 78 1 1 34.290 308 *SIXTH RING: #24 PIN
RODSUB 78 1 1.324 3 *INNER WATER
RODSUB 78 2 1.352 2 *CLAD
RODSUB 78 3 3.175 1 *FUEL
ARRAY 79 1 1 34.290 320 *SIXTH RING: #25 PIN
RODSUB 79 1 1.324 3 *INNER WATER
RODSUB 79 2 1.352 2 *CLAD
RODSUB 79 3 3.175 1 *FUEL
ARRAY 80 1 1 34.290 331 *SIXTH RING: #26 PIN
RODSUB 80 1 1.324 3 *INNER WATER
RODSUB 80 2 1.352 2 *CLAD
RODSUB 80 3 3.175 1 *FUEL
ARRAY 81 1 1 34.290 342 *SIXTH RING: #27 PIN
RODSUB 81 1 1.324 3 *INNER WATER
RODSUB 81 2 1.352 2 *CLAD
RODSUB 81 3 3.175 1 *FUEL
ARRAY 82 1 1 34.290 354 *SIXTH RING: #28 PIN
RODSUB 82 1 1.324 3 *INNER WATER
RODSUB 82 2 1.352 2 *CLAD
RODSUB 82 3 3.175 1 *FUEL
*
LINES 4 2 6 2 21 21 22 21 21 21 3 60
BVECTOR 0 0.00
BEGIN
WPIP 4
*
* PERFORM K-EFF CALCULATION -- AXIAL BUCKLING CORRECTION
*
BUCKLING 1.389E-03 1
BEGIN
FINISH
STOP

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APPENDIX D
INDEPENDENT REVIEW

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CHECKLIST FOR INDEPENDENT REVIEW

Document Reviewed: Criticality Safety Evaluation Report for K Basin Filter CartridgesAuthor: K. N. Schwinkendorf

Yes No N/A

☒	☐	☐	Problem completely defined.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☒	☐	☐	Computer codes and data files documented.
☐	☐	☒	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivations checked including dimensional consistency of results.
☒	☐	☐	Models appropriate and used within range of validity or use outside range of established validity justified.
☐	☐	☒	Hand calculations checked for errors.
☒	☐	☐	Code run streams correct and consistent with analysis documentation.
☒	☐	☐	Code output consistent with input and with results reported in analysis documentation.
☒	☐	☐	Acceptability limits on analytical results applicable and supported. Limits checked against sources.
☒	☐	☐	Safety margins consistent with good engineering practices.
☒	☐	☐	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.
☒	☐	☐	Have all reasonable accidents been considered?
☒	☐	☐	Has low density water (steam) been evaluated as a moderator?
☒	☐	☐	Is the fuel and other hardware composition correct?
☒	☐	☐	Are the cases considered conservative? Too conservative?
☒	☐	☐	Do the computer models adequately reflect the actual geometry? Have cross sectional cuts of the geometry been made and do they show the desired geometry?
☒	☐	☐	Has the analysis been reviewed by Safety? This may not be required in a preliminary design.
☒	☐	☐	Has the reviewer completed the Criticality Safety Course for Managers and Engineers?

Date completed 17 February 1994

Reviewed by:

Warren D. Wittahind

Date

23 November 1994

NOTE: Any hand calculations, notes, or summaries generated as part of this review should be signed, dated, and attached to this checklist. Materials should be labeled and recorded so that it is intelligible to a technically-qualified third party.

REVIEW COMMENTS BY S. J. Altschuler

K Basin Filter Cartridge AssembliesReviewer's Comments:

The purpose of this CSER was to allow operation without a Criticality Alarm System by demonstrating that a criticality was not possible. While this analysis does so, it is based upon rates of fissile material buildup under the present quiescent conditions. The planned reencapsulation of N Reactor fuel in new containers may cause an increase in the rate of fissile material buildup which would be sufficient to require more frequent filter cartridge changes. It would be prudent to delay removal of the CAS until after the reencapsulation operation is complete or take other measures to provide coverage in case of a criticality.

Some estimates of the minimum amount of plutonium required to cause criticality:

The volume of the 30" diameter, 30" high assembly is 347.5 liters. From ARH-600, III.A.9(100)-4: For a fully water reflected sphere, the required concentration is 0.01 g/cm^3 which requires about 3.5 kg Pu.

For 88 filter cartridges, each 30" long with 2.5" OD and 1.06" ID, a void fraction of 0.7283, and a maximum oxide density of 4.0 g/cm^3 allows the accumulation of 507 kg of heavy metal oxide. For a U/Pu ratio of 400, this is 1.12 kg Pu. For a U/Pu ratio of 10, 40.7 kg Pu. According to ARH-600, III.A.9(100)-5, the former is safely subcritical. The latter is about three times the amount required for criticality although it will take a long time to accumulate.

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Project Title/Work Order Criticality Safety Evaluation Report for K Basin Filter Cartridges		EDT No. 130166			
		ECN No. 186721			
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G. M. Davis	X3-80	X			
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