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Criticality Safety Analysis for Remote Handled TRU Waste at the Waste Isolation Pilot Plant

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a facility designed to store transuranic (TRU) waste underground in a mined salt bed. All fissile nuclides except U^{235} are considered TRU nuclides. This report presents the results of the nuclear criticality analysis for Remote-Handled (RH) TRU waste stored at the WIPP site. The RH waste material will be contained in steel canisters that are five feet or ten feet long. Each ten foot canister is capable of holding three 55 gallon drums of waste material. The five foot canisters are to be welded together to form one ten foot long canister. In general the fissile waste material is mainly surface contamination on clothing, wipes, wrappings, tools, etc., or mixed in a borosilicate glass matrix or concrete. Other fissile material may be contained in absorbent mixtures. As a result, the fissile material will typically be spread over a large fraction of the volume in most of the waste storage canisters. Typical isotopic content of the fissile/other radioactive material is shown in Table 1-1.

This analysis will analyze the RH waste storage and handling configurations at the WIPP site to show that up to 600 grams of fissile material per ten foot canister can be received and stored at the site without criticality safety concerns.

1.1 DESIGN DESCRIPTION

The RH waste storage canisters are received at the WIPP site hot cell complex in a shipping cask. The hot cell complex provides the required facilities and equipment necessary to transfer the RH waste canister from the shipping cask to the facility cask used for transfer of the RH canister to the underground storage area. The hot cell complex shown in Figure 1-1, includes the shipping cask unloading room, the hot cell, a canister transfer cell and the facility cask loading room. The RH canister is removed from the shipping cask and transferred to the site hot cell for inspection. The hot cell is a concrete shielded room where several RH waste canisters can be handled following removal from the shipping containers.

Following the inspection of the RH waste canister, it is placed in a facility cask for transfer to the underground waste storage area. The waste storage area is composed of a series of rooms connected by corridors with each room measuring approximately 300 ft. long, 33 ft. wide and 13 ft. high. The layout of the storage area is shown in Figure 1-2. The RH storage area utilizes the walls of the waste storage rooms and entries. The canisters will be stored in horizontal sleeved holes on eight foot centers with a five foot concrete end plug (Figure 1-3). The salt bed from which the storage area is mined is comprised of 95% NaCl with approximately 2% water by weight and a density of 2.17 gm/cc.

The RH waste storage canisters received at the site are qualified as DOT Type A. The canisters are designed to be vented through a HEPA filter and have a nominal steel wall thickness of 0.25 inches and a top and bottom end closure thickness of 0.375 inches. Table 1-3 and Figures 1-4 and 1-5 show the basic dimensions of the RH waste canisters and the pictorial representation. The RH storage canister is made of carbon steel with the composition specifications shown in Table 1-2.

Once the RH waste storage canister are emplaced horizontally in the walls of the waste storage area the waste storage rooms will be filled with the contact handled (CH) waste in 55 gallon drums and steel storage boxes. Each 55 gallon waste drum and steel storage box is allowed to hold a fissile loading up to a maximum of 200 and 350 grams Pu^{239} respectively. Reference 6 discusses the criticality analysis performed on the CH waste storage configurations in these rooms.

1.2 CRITICALITY DESIGN CRITERIA

Criticality of the RH waste storage canisters is prevented by the maximum fissile loading requirements per canister and the maximum size of an array of canisters. The maximum size of an array of canisters is fixed by the dimensions of the storage room and administrative handling limits.

The design bases for preventing criticality is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective multiplication factor (K_{eff}) for the most reactive configuration in the storage area and the hot cell complex will be less than 0.95.

Table 1-1. Typical Isotopic Composition In Radioactive Waste

Isotopes	Wt%
Co^{60}	Trace
Sr^{90} /Y^{90}	30
Ru^{106} /Rh^{106}	Trace
Cs^{137} /Ba^{137}	0.2
Eu^{152}	Trace
Eu^{154}	Trace
Pu^{238}	Trace
Pu^{239}	65
Pu^{240}	4.4
Pu^{241}	0.2
Am^{241}	Trace

Table 1-2. Carbon Steel Chemical Composition Limits

Component	Maximum %
Carbon	0.15%
Manganese	0.60%
Phosphorus	0.04%
Sulfur	0.04%

Note: Balance of Steel Composition is Iron

Table 1-3. Remote Handled Waste Canister General Dimensions

Specifications	Long Container	Short Container Single	Short Container Stacked
Length (in.)	121	63	121
Outside diameter (in.)	26	26	26
Normal inside diameter (in.)	25.5	25.5	25.5
Maximun useful volume (cu. ft)	31.7	13.6	27.2
Empty weight (lb)	1,762	1,422	2,844

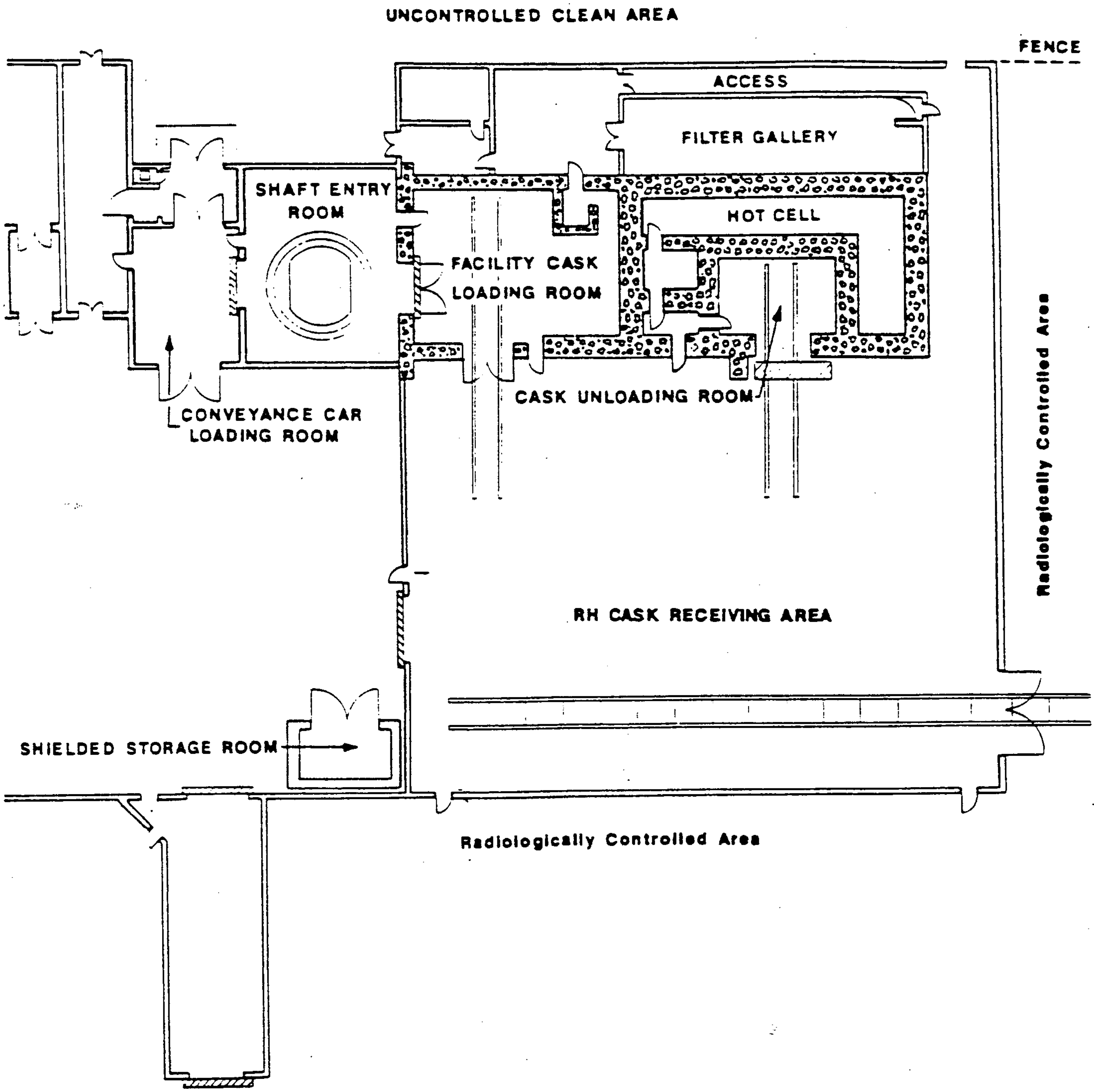


Figure 1-1. WIPP Hot Cell Complex

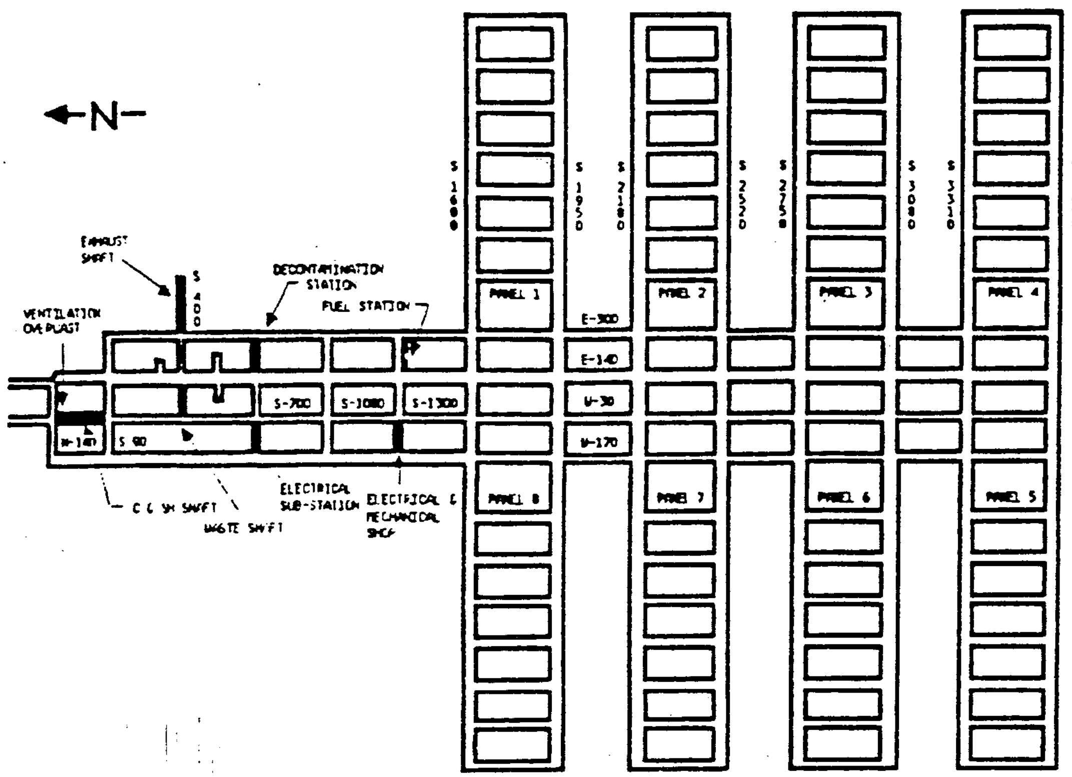


Figure 1-2. WIPP Underground Layout

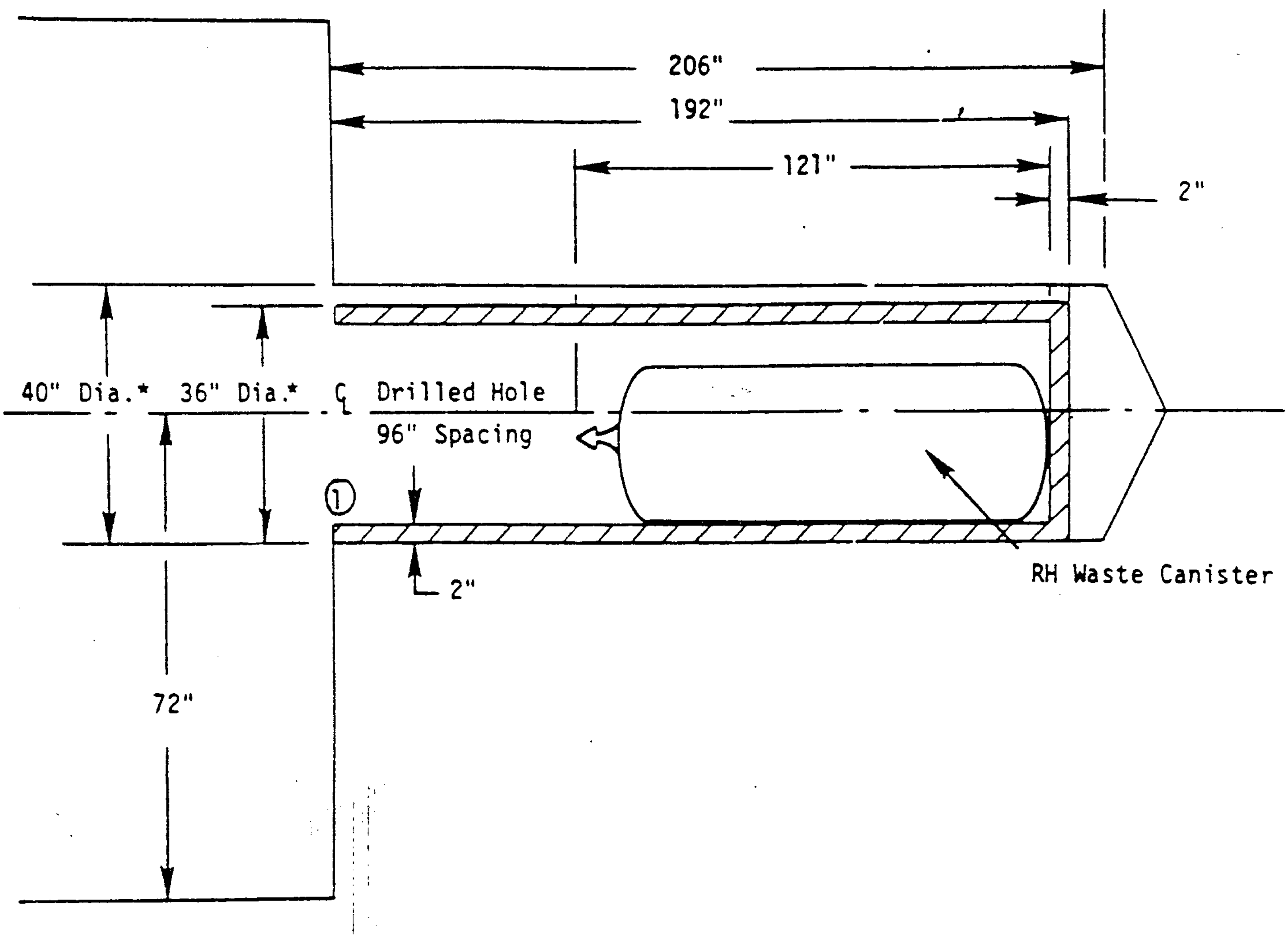


Figure 1-3. Remote Handled Waste Canister Storage Configuration

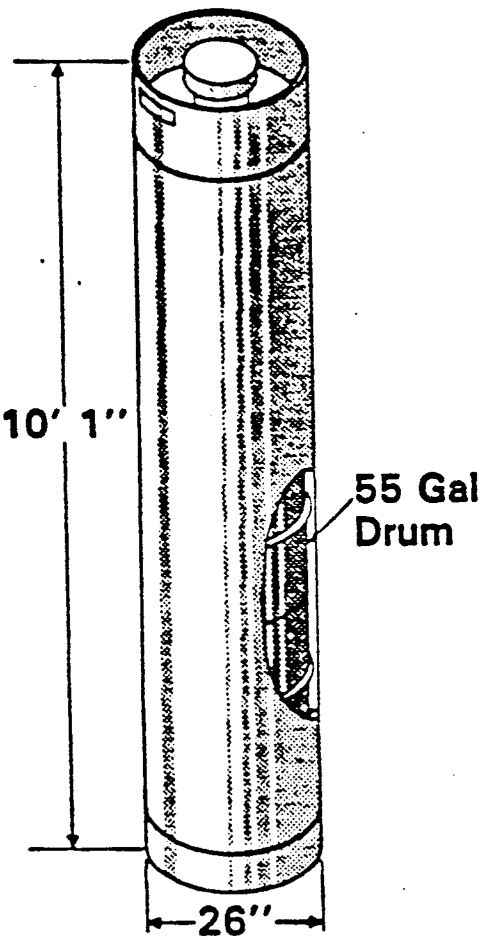


Figure 1-4. Remote Handled Waste Canister Assembly

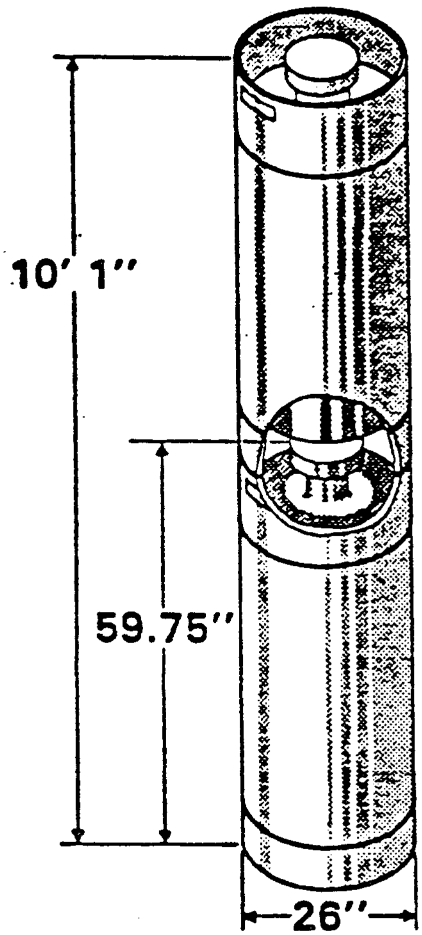


Figure 1-5. Stacked Remote Handled Waste Canister Assembly

2.0 CRITICALITY ANALYTICAL METHOD

The criticality calculation method and cross-section values are verified by comparison with critical experiment data for material and configurations similar to those for which the WIPP site is designed. This benchmarking data is sufficiently diverse to establish that the method bias and uncertainty will apply to conditions which include plutonium solutions at various moderation ratios.

The design method which insures the criticality safety of stored transuranic waste material at the WIPP site uses the AMPX[1, 2] system of codes for cross-section generation and KENO IV[3] for reactivity determination.

The 227 energy group cross-section library that is the common starting point for all cross-sections used for the benchmarks and the storage analysis is generated from ENDF/B-V[1] data. The NITAWL[2] program includes, in this library, the self-shielded resonance cross-sections that are appropriate for each particular geometry. The Nordheim Integral Treatment is used. Energy and spatial weighting of cross-sections is performed by the XSDRNPM[2] program which is a one-dimensional S_n transport theory code. These multigroup cross-section sets are then used as input to KENO IV[3] which is a three dimensional Monte Carlo theory program designed for reactivity calculations.

A set of 14 critical experiments has been analyzed using the above method to demonstrate its applicability to criticality analysis and to establish the method bias and variability. The experiments include nitrate and water moderated plutonium solutions with various plutonium densities, Pu^{240} concentrations and neutron moderation ratios that demonstrate the applicability of the method to the TRU waste handling and storage conditions at the WIPP site.[4] Table 2-1 summarizes these experiments.

The average K_{eff} of the benchmarks is 1.0147. The standard deviation of the bias value is 0.0041 Δk. The 95/95 one sided tolerance limit factor for 14 values is 2.61. Thus, there is a 95 percent probability with a 95 percent confidence level that the uncertainty in reactivity, due to the method, is not greater than 0.0108 Δk.

Table 2-1. Benchmark Critical Experiments

	General Description	H/PU Atom Ratio	Reflector	Geometry	Percent Pu240	Keff
1.	Aqueous Soln Pu-239	3695	None	Infinite	0	1.0027 +/- .0020
2.	Pu(NO3)4 Solution	422	None	Slab	5	1.0158 +/- .0031
3.	Pu(NO3)4 Solution	125	None	Sphere	5	1.0142 +/- .0034
4.	Pu(NO3)4 Solution	758	SS	Sphere	1	1.0203 +/- .0030
5.	Pu(NO3)4 Solution	980	H20	Sphere	5	1.0205 +/- .0027
6.	Pu(NO3)4 Solution	1067	H20	Sphere	5	1.0155 +/- .0028
7.	Pu(NO3)4 Solution	1031	SS + H20	Sphere	5	1.0129 +/- .0025
8.	Pu(NO3)4 Solution	910	None	Cylinder	14	0.9945 +/- .0026
9.	Pu(NO3)4 Solution	210	H20	Cylinder	8	0.9839 +/- .0030
10.	Pu(NO3)4 Solution	623	H20	Cylinder	43	1.0026 +/- .0022
11.	PuO2/Polystyrene Compact	50	None	Parallelepiped	18	1.0179 +/- .0028
12.	PuO2/Polystyrene Compact	50	Plexiglas	Parallelepiped	18	1.0336 +/- .0032
13.	PuO2/Polystyrene Compact	5	None	Parallelipiped	11	1.0369 +/- .0026
14.	PuO2/Polystyrene Compact	5	Plexiglas	Parallelipiped	11	1.0354 +/- .0027

3.0 CRITICALITY ANALYSIS OF REMOTE HANDLED CANISTERS

As discussed in Section 1.1, the RH waste canisters are removed one at a time from the shipping cask and moved to the hot cell. Up to seven canisters may be held in the shuttle transfer car. The canisters will then be moved one at a time to the facility cask and then down to the underground storage area. Calculations are performed to determine the maximum reactivity of the RH waste canisters in the hot cell and in the waste storage array. The maximum K_{eff} for the most credible worst case condition is determined from consideration of the Pu/H_2O configuration inside the canisters. Previous studies[5] have shown that the maximum K_{eff} is obtained if the Pu/H_2O mixture is contained in the minimum container volume and the shape of the mixture approaches that of sphere.

3.1 HOT CELL REACTIVITY CALCULATIONS

The RH waste canister in the hot cell will be placed in the canister shuttle car (Figure 3-1) which can hold up to seven canisters. Calculations are performed to determine the reactivity of the RH waste canisters in the most credible worst case geometry. The following assumptions were used to develop the worst case KENO model for the RH waster canisters in the hot cell:

1. All canisters have the maximum loading of 600 grams of fissile material in an optimum water solution.
2. The fissile material is 100% Pu^{239} No credit is taken for any other waste material in the canister.
3. The optimum plutonium/water solution is homogenized in a cylindrical shape with a height to diameter (H/D) ratio of 1.5. Maximum density is assumed for plutonium oxide and water in calculating the cylinder dimensions.
4. No credit is taken for any polyethylene liners, bags or the 55 gallon drums inside of the waste canister model.
5. No credit is taken for any steel materials outside of the canister shell.

6. The waste canisters are modelled in a 3x3 square pitch array with the canister walls touching.

7. The hot cell concrete room walls are modelled touching the canisters to increase neutron reflection back into the canisters.

8. The lead shielding material is not included in the waste canister models.

9. The area between the canisters is modelled as a void.

10. Iron is the only material used in the composition of the canisters.

The model layout and dimensions are shown in Figure 3-2. Based on the analysis method described in Section 2.0, the following equation is used to develop the maximum K_{eff} for the handling and inspection of the RH waste canisters in the WIPP site hot cell:

$$K_{eff} = K_{worst} + B_{method} + \sqrt{[\ (ks)^2_{worst} + (ks)^2_{method}\ ]}$$

where:

K_{worst}	=	credible worst case KENO K_{eff} that includes limiting Pu/H_2O configurations and dimensions
B_{method}	=	method bias determined from benchmark critical comparisons
ks_{worst}	=	95/95 uncertainty in the worst case KENO K_{eff}
ks_{method}	=	95/95 uncertainty in the method bias

Substituting calculated values in the order listed above, the result is:

$$K_{eff} = 0.9181 - 0.0147 + \sqrt{[(0.0093)^2 + (0.0108)^2\ ]} = 0.9177$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the RH waste canisters in the hot cell loaded with up to 600 grams of fissile material per canister.

Calculations were also performed to determine the reactivity of the normal RH waste canister holding array in the hot cell. The same assumptions were used in the normal case model as in the credible worst case model except only seven canisters were modelled with each canister positioned as in a holding tube of the canister shuttle car. The steel of the shuttle car was not modelled. The KENO calculation for the normal case resulted in a K_{eff} of 0.8729 with a 95 percent probability/95 percent confidence level of ±0.0095.

3.2 CANISTER STORAGE REACTIVITY CALCULATIONS

To show that the maximum calculated reactivity from the credible worst case hot cell model bounds the credible worst case canister storage configuration, calculations were performed to determine the maximum reactivity of the combined RH and CH waste storage array. As discussed in Section 1.1 the RH waste canisters will be placed in the walls of the storage rooms which can then be filled with CH waste drums or boxes. The following assumptions were used to develop the most credible worst case KENO model of RH and CH waste containers in combined underground storage.

1. The fissile material is 100% Pu^{239} No credit is taken for any other waste material in the containers.

2. The optimum H/Pu water solution is homogenized in a cylindrical shape with a height to diameter (H/D) ratio of 1.5. Maximum density is assumed for plutonium oxide and water in calculating the cylinder dimensions.

3. The CH plutonium solution cylinders are modelled at the bottom of the top drum, at the top of the bottom drum and at the center of the center drum (Figure 3-3). The RH plutonium solution cylinders are modelled in the center of the canister.

4. The area between the CH drums is modelled as a void.

5. All CH drums have the maximum loading of 200 grams of fissile material in an optimum water solution. The RH canisters have the maximum loading of 600 grams of fissile material in an optimum water solution.

6. No credit is taken for any polyethylene liners or bags in the containers which will reduce the reactivity.

7. The CH drum array is modelled as infinitely long, 16 drums wide and 3 tiers high.

8. An infinite number of RH canisters are modelled on 5.63 foot centers on both sides of the CH drum array.

9. The storage room walls are modelled touching the CH drums to increase neutron reflection back into the drums.

10. The polyethylene CH drum slip sheets and steel inserts are included in the model but the plywood reinforcements are not. The dimensions of the drum slip sheets are shown in Figure 3-4.

11. A triangular CH drum pitch arrangement was modelled using an equivalent square pitch arrangement. This was accomplished by reducing the CH drum radius such that the effective areal fissile density was maintained between the triangular and square pitch arrays for a given number of CH drums. The material in the CH drum walls was held constant by increasing the density.

12. The CH drum to drum radial separation is determined by assuming the drums are touching at the ridges. This separation distance is less than the distance that will be obtained when the drums are place on the polyethylene slip sheets.

13. Iron is the only material used in the composition of all container walls.

14. The DOT-17C drum is used in the model since nearly all CH drums at the site will be of this type.

15. No credit is taken for the steel sleeves outside of the RH canisters.

16. No plugging material is included in the horizontal holes with the RH canisters. The holes are modelled open to the CH waste storage room.

17. The lead shielding material is not included in the waste canister models.

The model layout and dimensions are shown in Figure 3-5. Reference 6 discusses in detail the worst case CH waste drum model used in this analysis. The KENO calculation for the combined RH and CH waste storage array resulted in a K_{eff} of 0.8620 with a 95 percent probability/95 percent confidence level of ±0.0068. These results are basically identical to those obtained from the worst case CH 55 gallon waste storage drum model[6]. This shows that storage of the RH canisters in the storage room walls has an insignificant effect on the storage room reactivity. Alteration of the actual RH canister storage cavity shown in Figure 1-3 will have no effect on these results since the steel liner and cavity plug are not modelled and a minimum cavity diameter was used in the calculations.

Calculations were also performed to determine the maximum reactivity of the RH waste storage array. A bounding storage array geometry that was infinite in all directions was modelled with the RH waste canisters on eight foot centers in the salt medium and the plutonium/water cylinder centered in each canister. All assumptions in Section 3.1 were applied to the model except assumptions 6,7 and 9. The KENO calculation resulted in a K_{eff} of 0.8774 with a 95 percent probability/95 percent confidence level of ±0.0088.

These results show that the credible worst case RH canister configurations in the underground storage cases are less reactive than the worst case hot cell results. Therefore, the maximum reactivity for the handling and storage of the RH waste canisters is determined by the credible worst case hot cell geometry analyzed in Section 3.1.

3.3 SENSITIVITY ANALYSIS

To show the dependence of the hot cell K_{eff} on the waste and canister parameters, the variation of the K_{eff} with respect to the following parameters was develop using the KENO computer code:

1. H/Pu ratio.

2. Canister iron content.

3. Pu^{240} content.

4. Plutonium loading.

The credible worst case hot cell model analyzed in Section 3.1 is used as the reference model with respect to the above parameters. A constant H/Pu ratio of 1000 is used with parameters 2,3 and 4. The results of the sensitivity analysis for the parameters are shown in Figures 3-6 through 3-9. The error bars shown on all figures are KENO one sigma uncertainties.

The results for parameter three, Pu^{240} content, assume the total plutonium mass remains fixed at 600 grams as Pu^{240} is added.

As the plutonium loading is reduced for sensitivity parameter four, the H/Pu ratio is held constant.

These sensitivity results show that the largest reactivity changes are reactivity decreases associated with the addition of Pu^{240} to the Pu^{239} mixture and reducing the total plutonium loading. The reactivity increase associated with the canister iron content is relatively small for the RH waste storage canisters.

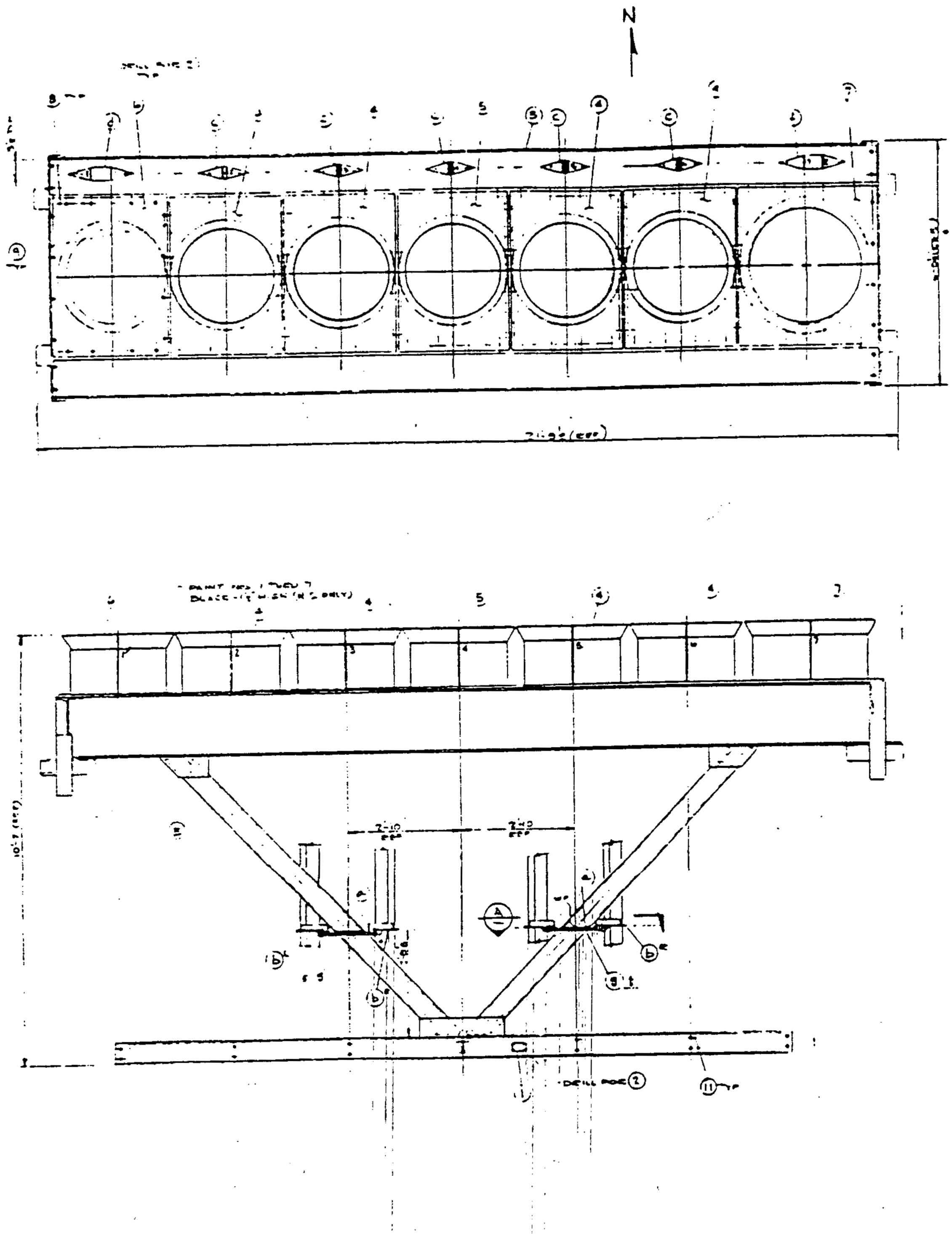
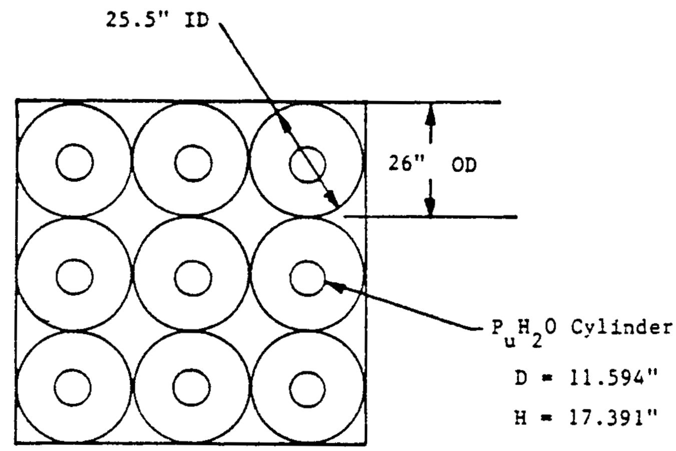


Figure 3-1. Remote Handled Canister Shuttle Car



6' of Concrete Surrounding Array on all sides

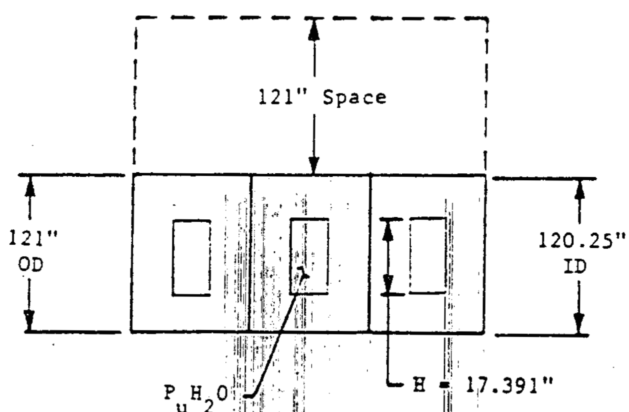


Figure 3-2. Remote Handled Canister Hot Cell Model

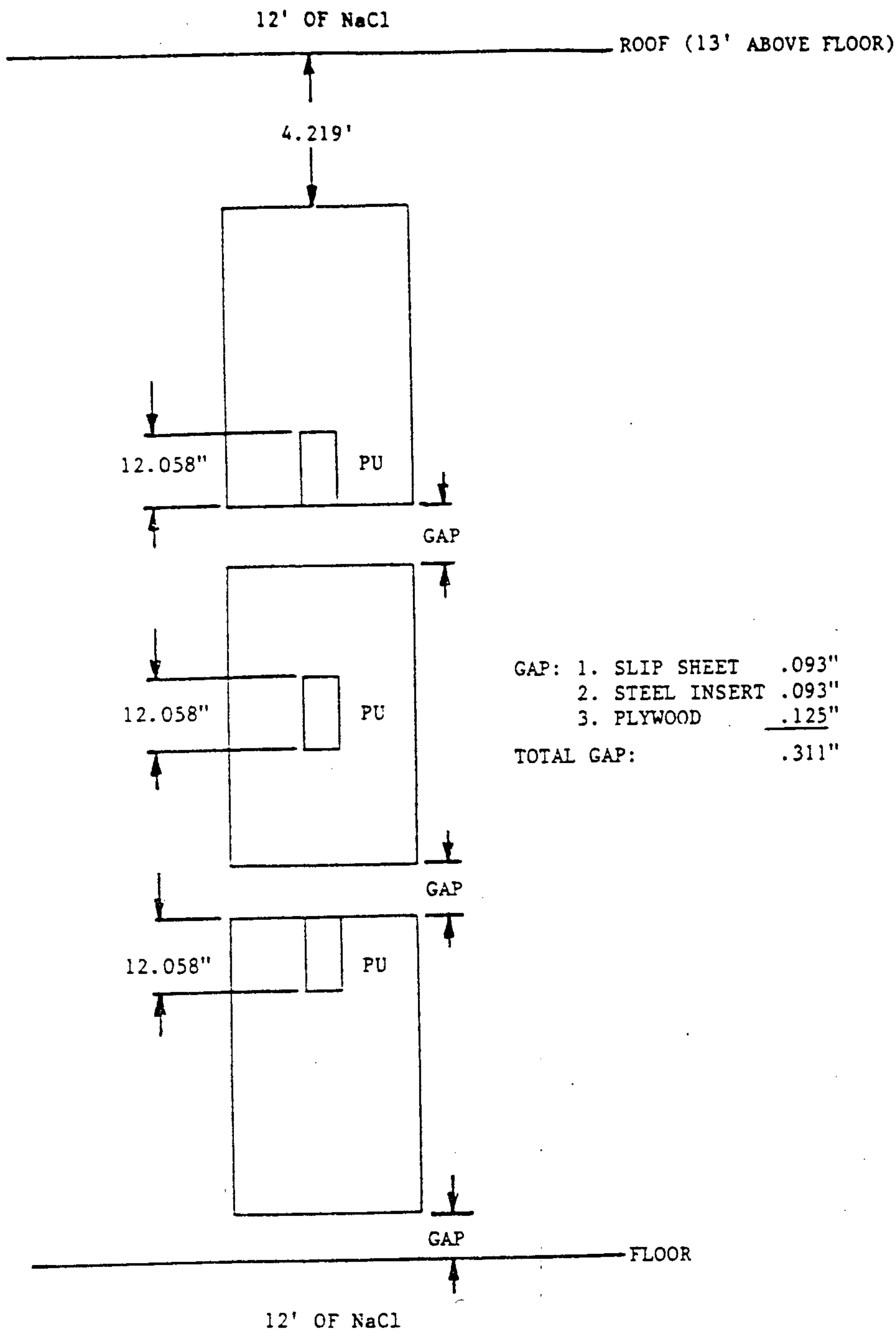


Figure 3-3. Axial Detail of Contact Handled Waste Drum Model

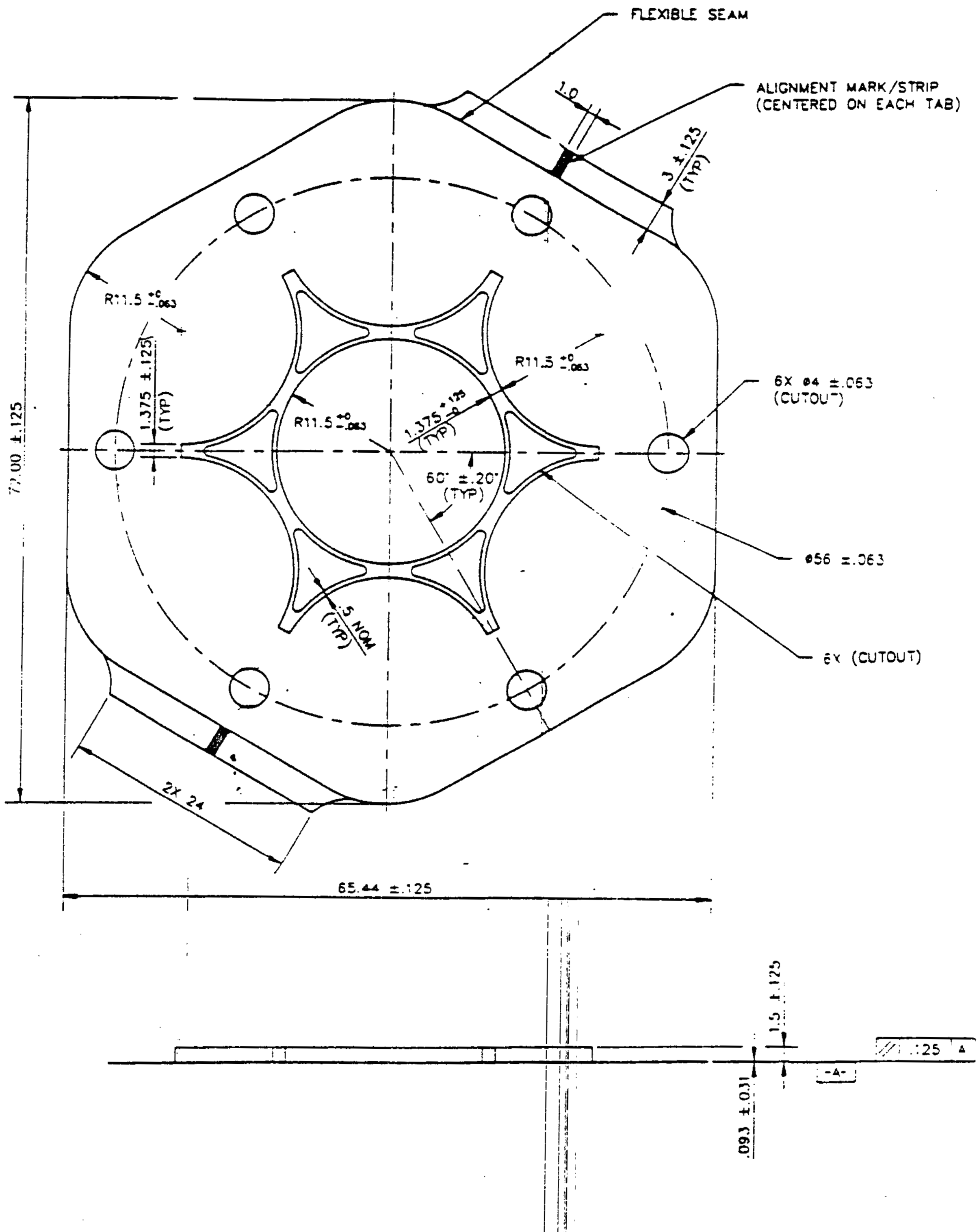


Figure 3–4. Slip Sheet Design for Contact Handled Waste Drums

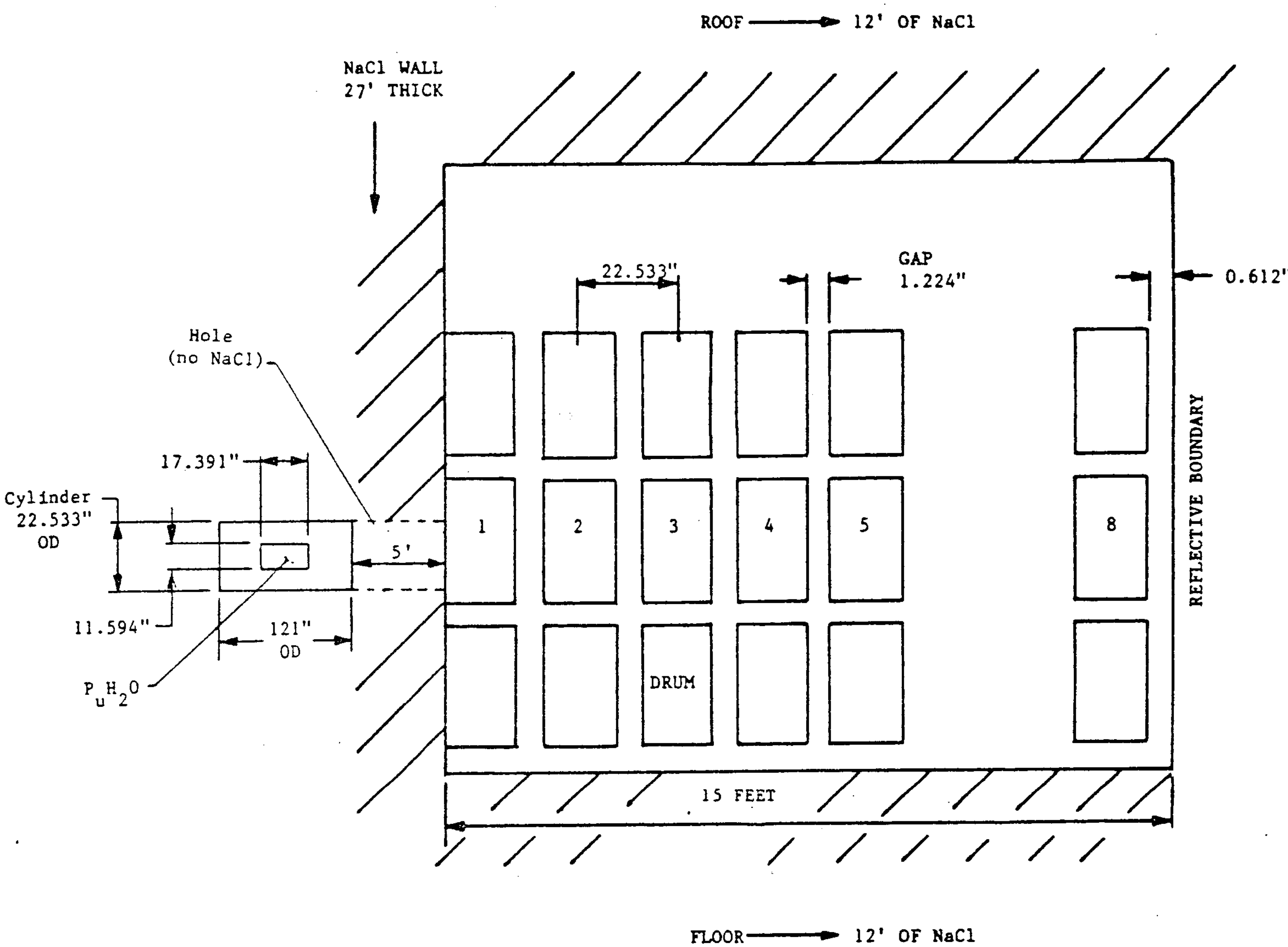


Figure 3-5. Contact and Remote Handled Waste Storage Model

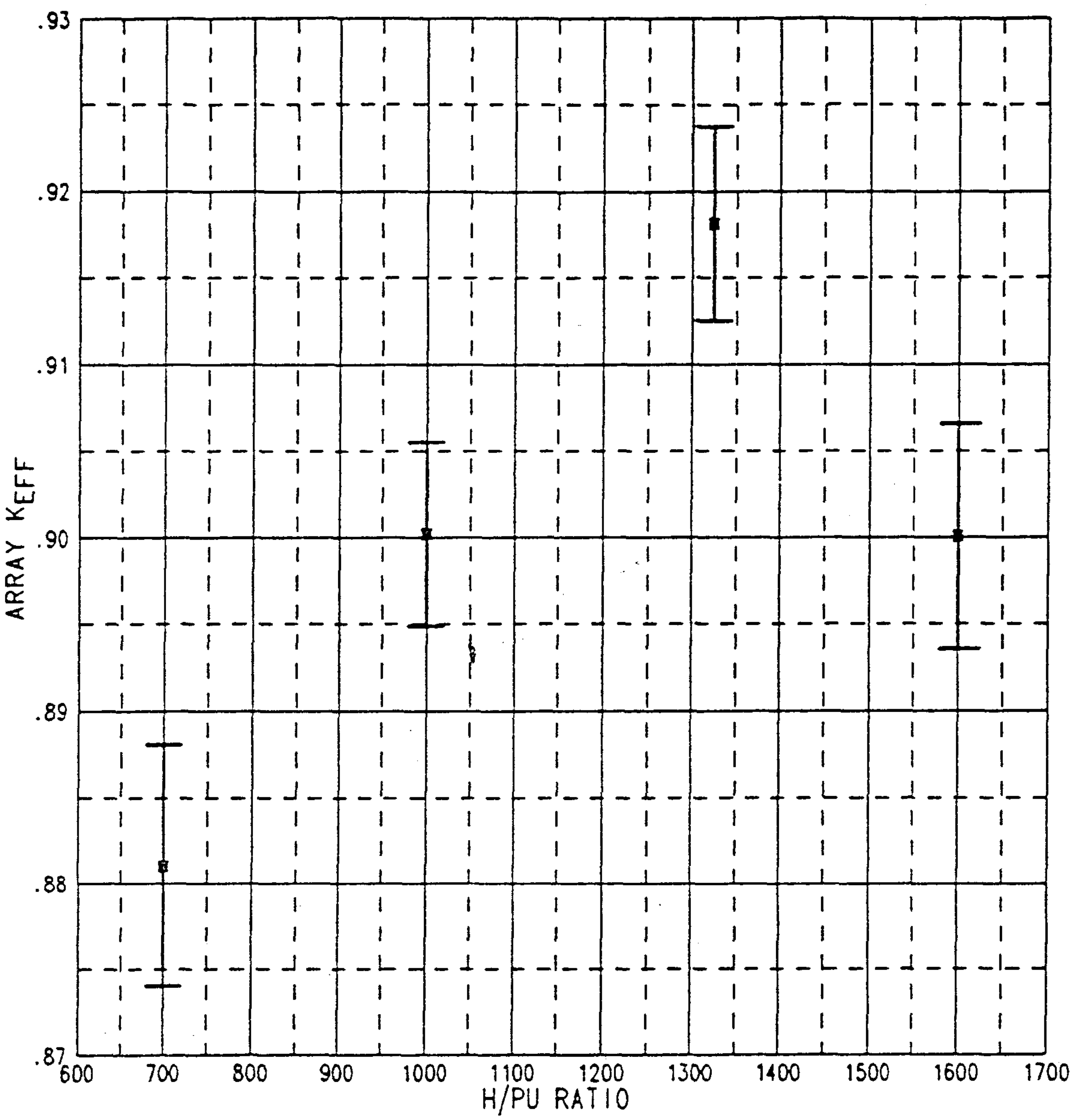


Figure 3–6. Worst Case Hot Cell K_{eff} vs RH Canister H/PU Ratio

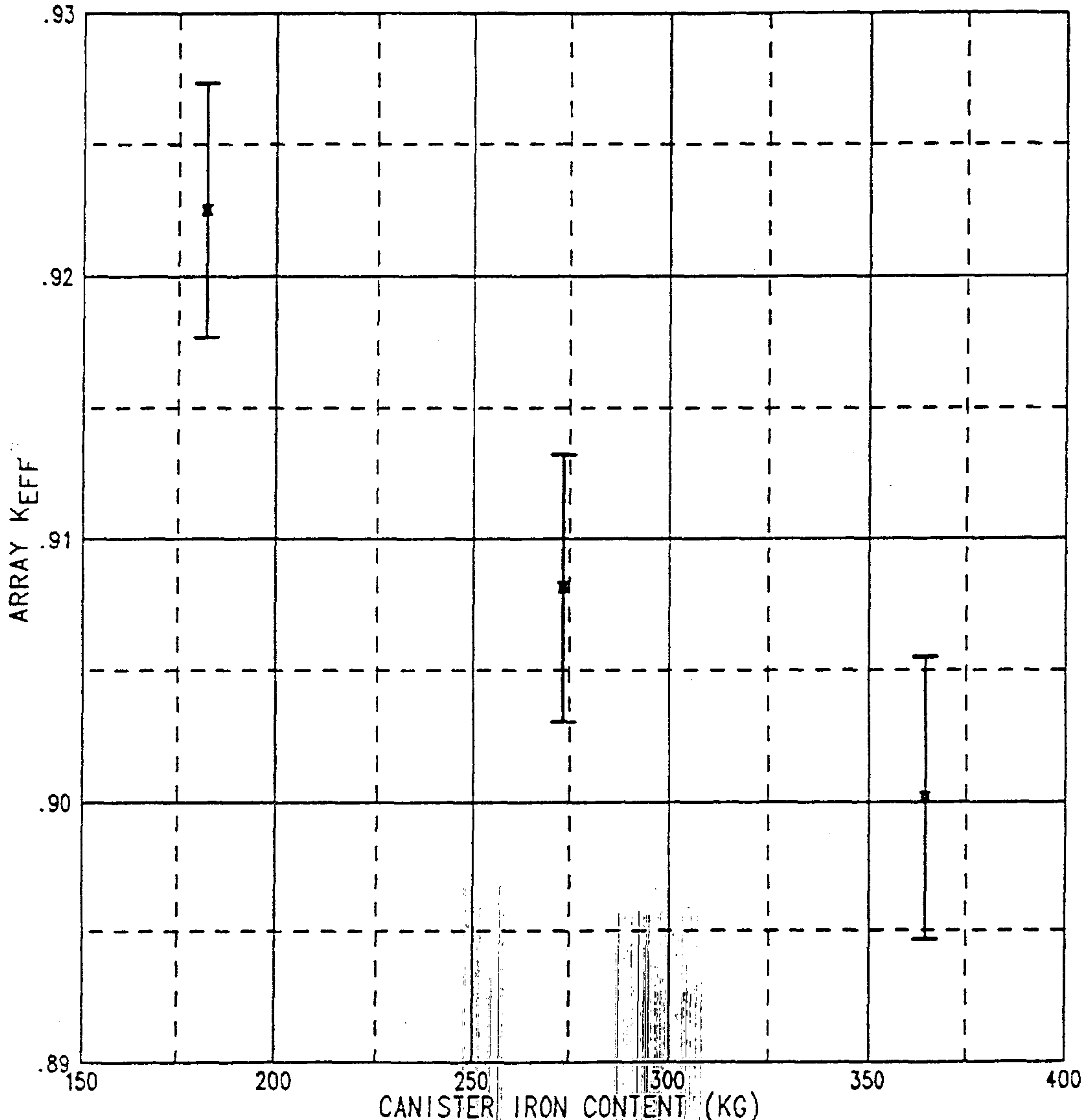


Figure 3-7. Worst Case Hot Cell K_{eff} vs RH Canister Iron Content

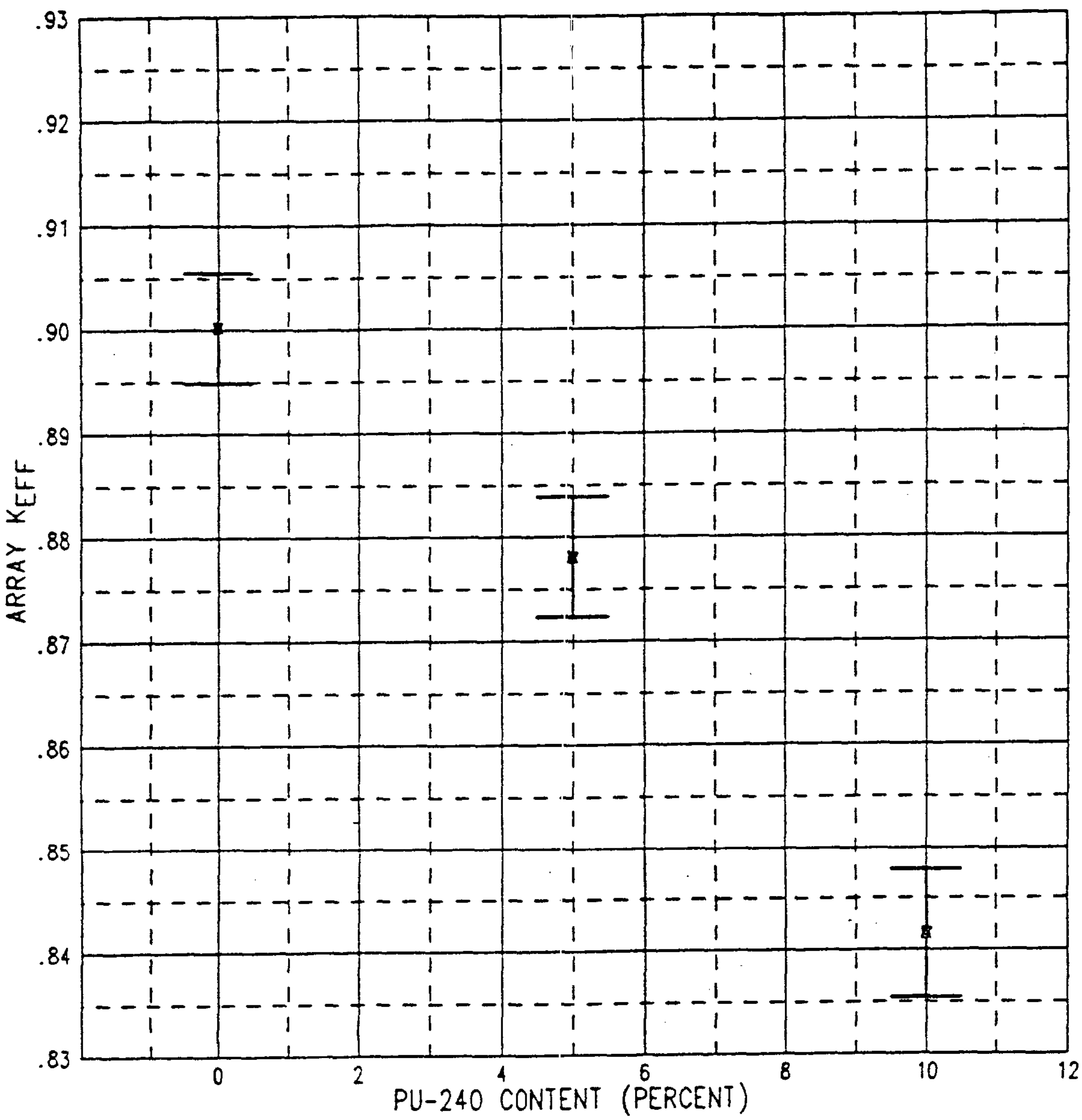


Figure 3-8. Worst Case Hot Cell K_{eff} vs RH Canister Pu^{240} Content

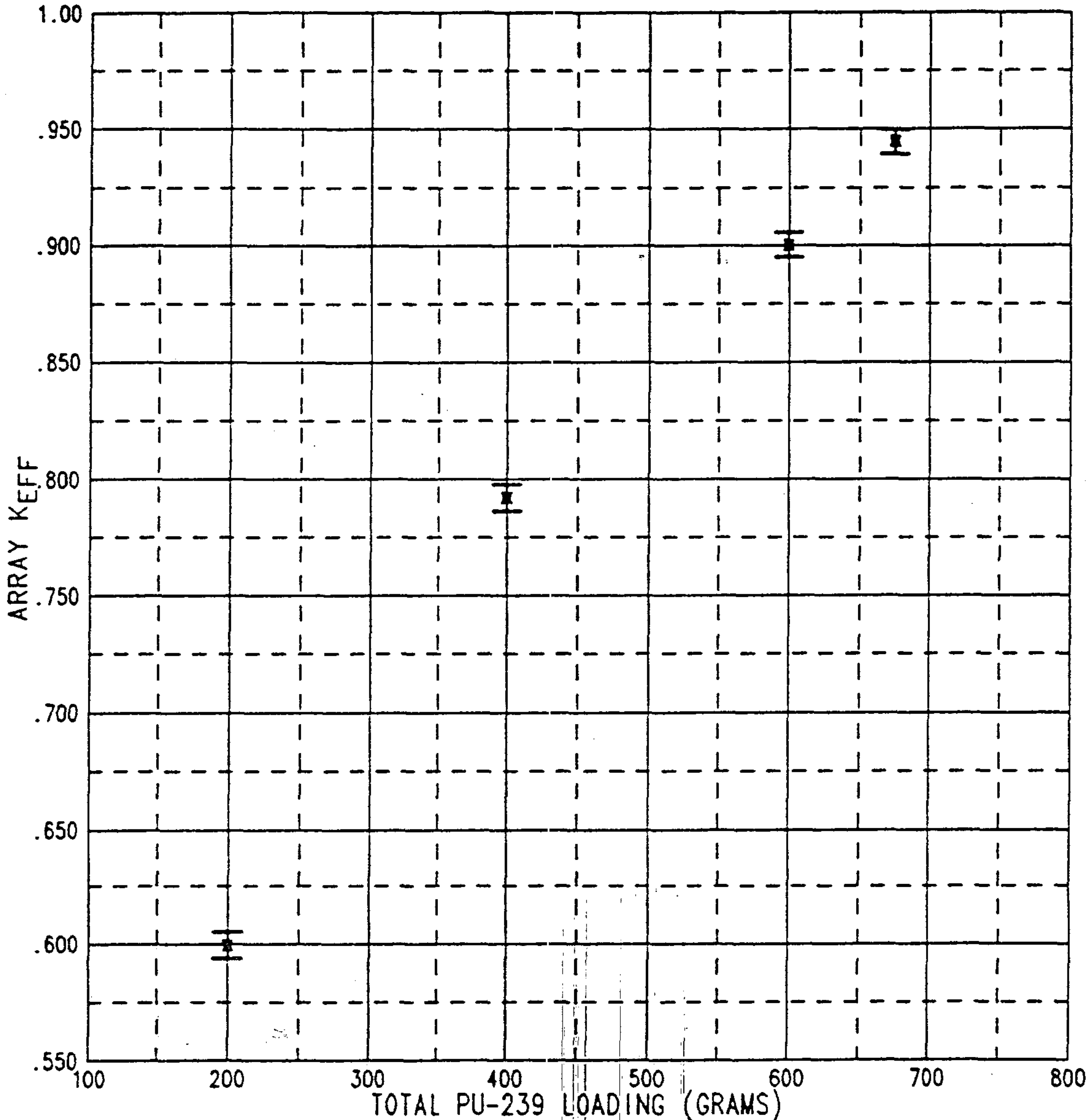


Figure 3-9. Worst Case Hot Cell K_{eff} vs RH Canister Total Pu^{239} Loading

4.0 CONCLUSIONS AND CRITICALITY LIMITS

The acceptance criterion for criticality is that the multiplication factor in the RH waste canister handling and storage areas shall be less than or equal to 0.95, including uncertainties. The analytical methods employed herein conform with ANSI 8.1-1983, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors". The results show that it is acceptable to store RH waste canisters at the WIPP site with the following operating limits:

1. Maximum fissile loading will be 600 grams per ten foot RH waste canister.
2. No more than nine RH waste canisters can be handled in the hot cell at one time.
3. The RH waste canisters are to be stored in a horizontal position in the walls of the underground storage area with a minimum center-to-center spacing of 5.63 feet.

No other operating limits are required to meet the criticality limit for the handling and storage of the RH waste canisters.

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