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CSER 96-023: CSER for PFP Glovebox HC-21A with 4.4 Kilogram Plutonium Cans

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Abstract: This criticality safety evaluation report addresses the criticality impact of increasing plutonium oxide content from 2.5 kg oxide storage cans to 5.0 kg oxide Pu storage cans. Glovebox HC-21A is used to move plutonium metal buttons from cans into furnace boats prior to transferring them to the muffle furnace gloveboxes. Glovebox HC-21A supports muffle furnace operations where plutonium buttons are burned to form PuO_2 (H/Pu < 2). The PuO_2 is returned to glovebox HC-21A and sieved and packed into the 4.4 kg Pu cans.

The plutonium mass limit is set at 7.5 kg plutonium when plutonium metal is present. The plutonium mass limit is set at 15. kg plutonium when no plutonium metal is present. Additionally, there are other requirements to assure criticality safety during this operation.

CSER FOR PFP GLOVEBOX HC-21A WITH 4.4 KILOGRAM PLUTONIUM CANS

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CSER-96-023

Title: CSER 96-023: PFP Glovebox HC-21A with 4.4 kilogram Plutonium Cans

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CRITICALITY SAFETY EVALUATION REPORT 96-023: PFP GLOVEBOX HC-21A WITH 4.4 KILOGRAM PLUTONIUM CANS

1.0 INTRODUCTION AND SUMMARY

This nuclear criticality safety analysis has been performed to increase the approved plutonium mass limit for individual containers in the HC-21A glovebox. This glovebox was approved to hold up to 5 kg of plutonium and only one (1) plutonium metal button of up to 2.5 kg of plutonium metal. The purpose of this CSER is to increase the limit to support operations in burning plutonium metal buttons, preparing plutonium oxide mixed with other materials including moderators for drying and storage of 4.4 kg of plutonium in 5 kg of dried PuO_2 into each individual can.

The HC-21A glovebox supports muffle furnace operations. The muffle furnace burns plutonium metal buttons producing dry PuO_2 (H/Pu < 2). Metal buttons and other plutonium material enter the HC-21A glovebox in containers and cans and are placed in Hastelloy-X boats in preparation for transfer to a muffle furnace glovebox. After being heated in a muffle furnace, the plutonium product, largely PuO_2, is transferred back to glovebox HC-21A in a boat. The dry PuO_2 product is sieved and 4.4 kg Pu (5.0 kg PuO_2) is placed in a can. The PuO_2 from the muffle furnace is checked for H/Pu content, and if acceptable, the can is sealed. This can, a convenience can, is then placed inside an inner can, which is also sealed. The doubly canned PuO_2 is then bagged out of glovebox HC-21A for further operation and storage. Eventually, the PuO_2 is quadruple canned, with each can being sealed. Each of the cans may or may not be normal food pack cans, and all have lids on them.

The normal and off-normal conditions for the glovebox HC-21A considered two different and parallel operations: (1) plutonium metal buttons or plutonium material from cleanout activities (usually limited in quantity, but with an undetermined moisture content) is placed into furnace boats to transfer to a muffle furnace glovebox, and (2) PuO_2 sieving and packing the product transferred from a muffle furnace into the 5.0 kilogram PuO_2 (4.4 kilogram plutonium) food pack cans. The upset condition of plutonium metal buttons together with plutonium compounds was analyzed by performing parametric calculations of the reactivity of plutonium metal covered by plutonium compounds. The upset condition for dry PuO_2 in cans was modeled explicitly by placing a number of cans together. Normal conditions were conservatively modeled by assuming the most reactive normal material composition (maximum normal moderation and density), and arranging cans in the glovebox in close proximity. Water ingress and mixing with uncanned PuO_2 was reviewed for limits on mass and volume limits for aggregates of containers for each glovebox operation.

Criticality safety is controlled by limiting the total mass in the glovebox and by limiting the total mass of plutonium metal in a container or by limiting the volume of a container carrying plutonium compound. The mass limits for the entire HC-21A glovebox are: (1) 7.5 kg of plutonium if plutonium metal is present; OR (2) 15 kg of plutonium if plutonium metal is not present. The accumulation in one container is limited to 2.5 kg of metal. Each operation has a limitation on plutonium mass and volume limit for a container or group of containers holding plutonium in a compound such as PuO_2. Plutonium operations using several containers have a 10 inch spacing requirement from other plutonium operations. No button, boat or container is to be stacked on top of any other fissile item. Other restrictions are a maximum of two filled 4.4 kg Pu containers in the glovebox, and a maximum of 6.0 kg Pu (6.8 kg PuO_2) in a single container such as a sieve pan.

2.0 SUMMARY AND CONCLUSIONS

This criticality safety evaluation report (CSER) shows that the operations described in the process flow description and under the controls listed in the administratively controlled limits section is safe from a criticality stand point. No single identified contingency exceeded the criticality safety limit of k_{eff} = 0.9350 or requires the mass or volume to more than double before a critical configuration is possible. Therefore this CSER meets the requirements for a criticality analysis of the Hanford Site Nuclear Criticality Safety Manual, WHC-CM-4-29.

3.0 DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS

Administratively controlled limits applicable to this evaluation are:

Plutonium metal present in glovebox:

1) When plutonium metal is present, glovebox maximum 7.5 kg plutonium.

2) A maximum of 2.5 kg plutonium metal shall be placed in a furnace boat or other container.

Plutonium oxide operations, no plutonium metal present in glovebox:

3) When plutonium metal is not present, glovebox maximum 15.0 kg plutonium.

4) The following operations have limits of plutonium mass and volume of containers in each group spaced less that 25 cm (10 in.) apart.

4a) Pouring furnace boat (≈ 2.2 Liters) volume into sieve shaker system consisting of sieve pan and one sieve screen (≈ 3.3 Liters). No other plutonium container is allowed within 10 inches edge-to-edge from this container cluster. This operation is allowed a maximum unit volume of 6.0 Liters and 7.5 kg Pu.

4b) Sieving operation composed of sieve shaker system consisting of sieve pan and one sieve screen (≈ 3.3 Liters), and one mortar and pestle (≤ 1 Liter), or one jaw crusher grinding system (≤1 Liter). No other plutonium container is allowed within 10 inches edge-to-edge from this cluster of containers/equipment. This operation is allowed a maximum unit volume of 6.0 Liters and 7.5 kg Pu.

4c) Can filling operation consisting of sieve shaker pan without screen (≈ 1.65 Liters) and one 4.4 kg Pu can (≈ 1.24 Liters). No other plutonium container is allowed within 10 inches edge-to-edge from this cluster of containers. This operation is allowed a maximum unit volume of 2.9 Liters and 7.5 kg Pu.

4d) Storing after a 4.4 kg Pu convenience can (≈ 1.24 Liters) without lid is filled or sealing a lid on the convenience can. No other plutonium container is allowed within 10 inches edge-to-edge from this container. These operations are allowed a maximum unit volume of 1.5 Liters and 4.5 kg Pu.

4e) Storing lidded 4.4 kg Pu convenience cans (≈ 1.24 Liters each) or inner cans (≈ 1.42 Liters each) and canning a lidded 4.4 kg Pu convenience can in an inner can. One sealed 4.4 kg Pu convenience can and one empty inner can may be adjacent for canning an inner can around the convenience can. Two sealed 4.4 kg Pu cans may be adjacent for storage or transferring out of the glovebox. No other plutonium container is allowed within 10 inches edge-to-edge from this cluster of two containers. This operation is allowed a maximum unit volume of 2.9 Liters and 9.0 kg Pu.

5) A maximum of 6.0 kg plutonium in a plutonium compound (this equals 6.8 kg of PuO_2) shall be placed in a sieve shaker pan.

6) A maximum of 4.5 kg plutonium in a plutonium compound (this equals 5.1 kg of PuO_2) shall be placed in a 4.4 kg Pu can.

7) A maximum of 2 filled 4.4 kg Pu size cans are allowed in the glovebox. If a 4.4 kg Pu can is filled to over half full, it is counted as filled.

8) A maximum 2.5 Liter container volume is allowed in glovebox HC-21A. Exception: Sieve system composed of one sieve catch pan with one sieve screen (≈ 3.3 Liters).

9) Only one sieve screen is allowed in the glovebox.

10) Do not stack plutonium bearing containers.

11) The pot sump in glovebox HC-21A is sealed to exclude accumulation of fissile material in the pot sump.

12) During operation, a maximum of 1/8 inch accumulation of solids is allowed on the glovebox floor. Spills are to be cleaned up prior to the next operation.

13) DRY glovebox, meaning no flowing process liquids or liquids for fighting fire within this glovebox (HC-21A). Fire fighting category C. This allows mists and fogs, but no directed solid streams of water.

These limits define an envelope of allowed masses, volumes, and spacings that have been analyzed as meeting criticality safety requirements. The criticality prevention specifications (CPS) for glovebox HC-21A implementing these requirements can be more restrictive than the limits specified in this CSER.

The CPS does not have to repeat these requirements verbatim. Any requirement that is more restrictive, i.e. lower mass, smaller volume, fewer containers, or smaller aggregate volume of grouped containers, will have a larger margin of criticality safety and will meet the goal of ensuring a critically safe operation.

4.0 DESCRIPTION OF SYSTEM AND FACILITY

The 234-5Z Building more commonly referred to as PFP is located in the 200 West area. This facility was historically used to process plutonium into oxide or metal forms. The facility is now undergoing a cleanup phase to stabilize the plutonium still stored there.

4.1 PROCESS FLOW DESCRIPTION

Figure 1 illustrates the layout of the area encompassing the Pu stabilization activities on the first floor of the PFP. Preparation of furnace boat charges is currently done in glovebox HC-21A in Room 230B, as is also the handling of the product after firing in the furnaces. Loaded boats are transferred to the furnace gloveboxes (HC-21C in Room 230A and HA-21I in Room 235B) via the conveyor gloveboxes HC-2, HC-3, HC-4 and HA-28. Thus, the furnace gloveboxes only receive prepared boats, and boats of fired material are output for transfer to other gloveboxes for further processing.

The gloveboxes involved in the processes for preparation, firing and product packaging for the furnace operations are designated as DRY gloveboxes, so that free water is not allowed (except for damp cleanup rags per Criticality Prevention Specifications [CPS] restrictions). There are no water or liquid lines for processes or fire fighting within the DRY gloveboxes.

4.1.1 Preparation of Plutonium for Furnace Burning

Material that will be received in glovebox HC-21A in the near term will be either a plutonium metal button (< 2,500 g Pu) or material from facility clean out activities. The amount of material from clean out activities will be small (typically < 1,000 g Pu per container). The primary feed source through early 1997 will be the plutonium metal buttons. The charges are made up in Hastelloy-X furnace boats (approximately 2.2 Liters). One button will be placed in each boat. Up to five plutonium metal buttons will arrive in a transport wagon and be parked adjacent to the glovebox.

One by one the plutonium metal buttons will be inserted into the glovebox through the sphincter port. Up to three furnace boat charges will be made up at a time. Three charges are sent to the three furnaces in glovebox HA-21I and two charges are sent to the two furnaces in glovebox HC-21C. The boats are sent via conveyor HC-2 to the muffle furnaces in HC-21C, or via conveyor gloveboxes HC-2, HC-3, HC-4 and HA-28 to glovebox HA-21I.

4.1.2 Transfer of Plutonium Oxide into 4.4 Kilogram Cans

After the plutonium buttons are heated in the furnace for about 14 hours to about 1000 °C, the cooled furnace boats containing PuO_2 and contaminants are sent back to HC-21A via the conveyor system. At this time there won't be any plutonium in the form of metal in the glovebox, only PuO_2. The boats now contain a very dry PuO_2 powder. One at a time the boats are emptied into a pan sieve and sieved prior to placing in the 4.4 kilogram plutonium container. It is expected that between 1 and 2 buttons will fit into one 4.4 kilogram plutonium container. There will be an effort to mix big buttons with smaller buttons where possible to get 2 whole buttons in a can. Once a can is filled, it is weighed, sampled for loss of weight on ignition (LOI) and transported to glovebox HC-18BS for temporary storage until the LOI results are returned.

Once all of the plutonium oxide cans are moved to HC-18BS, more metal buttons in cans or other containers will be inserted into glovebox HC-21A through a sphincter port to make up more furnace boat charges for the muffle furnaces. Only a total of three buttons are to be brought into the HC-21A glovebox at one time, although five buttons are normally brought to the glovebox by a five position transport wagon. The glovebox HC-18BS will be used for lag storage until the LOI results are available.

4.1.3 Sealing of Plutonium Oxide in 4.4 Kilogram Cans

Once the metal buttons are put in boats and moved out of HA-21A and the LOI results are complete (4-8 hours) for the open PuO_2 cans in HC-18BS, the 4.4 kilogram Pu cans will be moved back to HC-21A where the open can will be sealed with a can sealer, placed into a second can and sealed again prior to being sealed in a plastic bag and taken out of glovebox HC-21A.

Once outside the glovebox HC-21A, in another operation, each item will be sealed in two more cans prior to transport via a transport wagon to vaults.

4.2 GLOVEBOX HC-21A DESCRIPTION

HC-21A is a conventional glovebox, 42 inches deep, 36 inches high, and 127 inches long supported 54 inches above the room floor by a table frame (WHC 1994a). Figure 2 is from the HC-21A layout drawing (WHC 1995a), and gives the floor plan arrangement for this glovebox. Note that this glovebox has gloveports on two sides. As shown in Figure 1, the north end of HC-21A connects to conveyor glovebox HC-2. The connection to the HC-2 conveyor acts as a criticality drain and eliminates the concern for glovebox holding water and flooding. The table frame supporting the HC-21A glovebox has horizontal members (WHC 1994a) that preclude a transport wagon rolling underneath the glovebox from the front, the back or either end.

Figure 1. Room Configurations for Stabilization Program at PFP

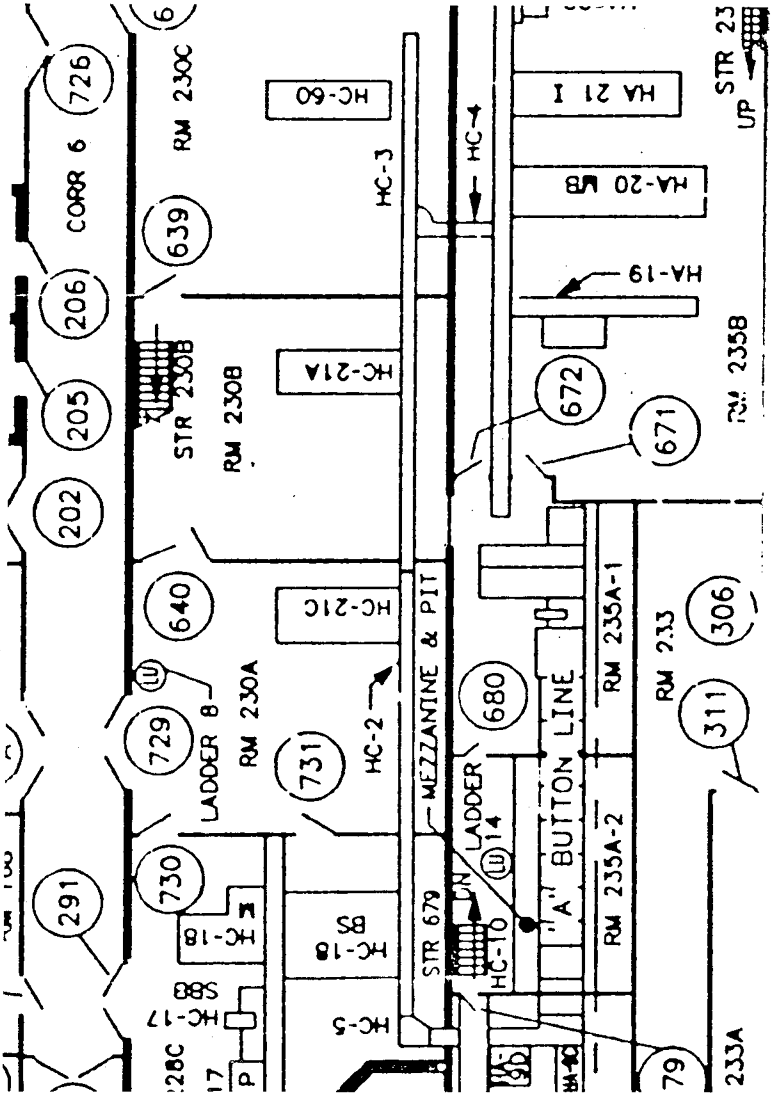
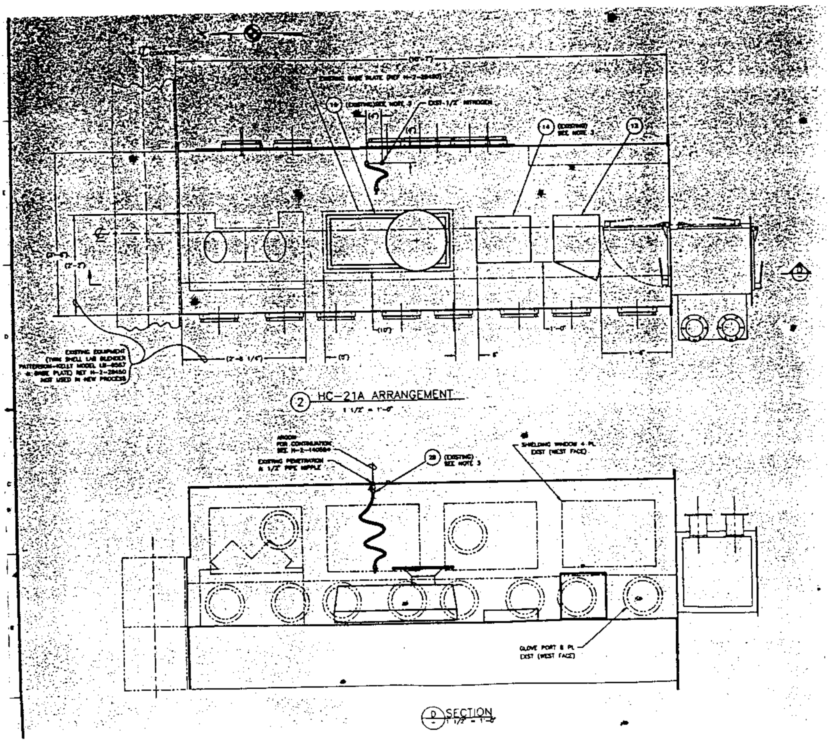


Figure 2. Glovebox HC-21A Layout for Muffle Furnace Operation Support



The north end of glovebox HC-21A connects to the conveyor glovebox HC-2 as shown in Figure 1. The 8-inch deep by 10 inch diameter pot-sump, under the box floor and near the south end of the box in Figure 2, will be sealed to exclude possible drainage of spilled materials into it.

4.3 GLOVEBOX EQUIPMENT AND ALLOWED CONTAINERS

The equipment available in glovebox HC-21A are:

- Canners (2),
- Electric can opener,
- Furnace boats (approximately 2.2 Liter volume),
- Grinder (approximately 1 Liter volume),
- Mortar and pestle (approximately 1 Liter volume),
- Scale,
- Sieve Shaker with one sieve pan and one sieve screen (3.3 Liters),
- Cans less than 2.5 Liter volume, and
- Other containers with less than 2.5 Liter volume.

The sieve shaker has the largest volume. The sieve shaker diameter is 8 in., and catch pan height and each sieve screen height is 5.08 cm (2 in.). The volume is:

$$\pi/4 * (8 \text{ in.})^2 * (2 \text{ in.} + 1*2 \text{ in.}) = 201 \text{ in.}^3 \Rightarrow 3.3 \text{ Liters.}$$

The furnace boat is made from 0.3175 cm (.125 in.) thick Hastelloy-X sheet stock shaped into a "cake pan", with an outside width of 13.34 cm (5.25 in.) and an outside length of 28.58 cm (11.25 in.). Inside, the bottom of the pan has an area of 354.84 cm^2 (5.0 in. x 11.0 in. = 55.0 in^2 = 0.382 ft^2). A measured brim-fill volume of 2.2 liters equates to a inside brim height of 6.20 cm (2.44 in.).

The dimensions and volumes of the four cans to be nested to store the 4.4 kilograms of plutonium (5.0 kilograms of PuO_2) are shown in Table 4.1. The inner can is slightly larger for double canning the innermost convenience can. The cans may or may not be standard food pack cans. They have a wall thickness of approximately 0.02286 cm (0.009 inches). Only the two innermost cans, the convenience can and the inner can, will be used in glovebox HC-21A. The dimensions of the four cans are listed in Table 4.1.

Table 4.1 Can Dimensions.
Calculated Volume Assumed
0.02286 cm (0.009 in.) Wall Thickness

Can	OD cm (inch)	H cm (inch)	Volume (L)
Convenience	8.731 (3.4375)	20.955 (8.250)	1.2389
Inner	9.208 (3.6250)	21.590 (8.500)	1.4203
Middle	10.319 (4.0625)	22.860 (9.000)	1.8910
Outer	10.795 (4.2500)	23.495 (9.250)	2.1280

5.0 REVIEW OF STABILIZATION OPERATIONS AND CONTROLS

The operations of the muffle furnaces in glovebox HC-21C and recently added muffle furnaces in glovebox HA-21I and their support glovebox HC-21A as well as the storage glovebox HC-18BS are closely related and need to be described together. These gloveboxes are used for parts of a one continuing process and need to have consistent limits to avoid mistakes in handling the plutonium.

5.1 PREVIOUS EQUIPMENT AND LIMITS FOR GLOVEBOX HC-21A

CSER 94-007 (Altschuler, 1994a) for the furnace glovebox HC-21C set a 5 kilogram plutonium mass limit (approximately 2 plutonium metal buttons) for slightly moderated (H/Pu < 20), a 2.0 Liter maximum limit on container size and a spacing limit of 10 inches between containers.

CSER 94-008 (Altschuler, 1994b) for the support glovebox HC-21A set a 5 kilogram plutonium mass limit (approximately 2 plutonium metal buttons) for slightly moderated (H/Pu < 20), a 2.0 Liter maximum limit on container size and a spacing limit of 10 inches between containers.

Addendum 1 to CSER 94-007 and CSER 94-008 (Hess 1996a), allowed a container volume of 2.3 Liters, because the new Hastelloy-X furnace boats had a volume greater than 2.0 liters. The previous furnace boats had a volume of only 1.5 Liters. The 5 kilogram plutonium mass limits and spacing limits remained for both HC-21C and HC-21A.

Addendum 2 to CSER 94-007 and CSER 94-008 (Chaio 1996), permits burning of whole plutonium metal buttons (< 2,500 grams plutonium). The new description of the limit included: only one metal button is to be processed per furnace at a single time.

CSER 96-003 (Hess 1996b), for glovebox HC-21A did not change mass limits of 5 kilograms of plutonium, but did eliminate the 10 inch spacing requirements that were untenable for inserting cans back to back through the sphincter port or for pouring powders from one container to another. Additionally, the sieve shaker that was previously assumed to be the sieve catch pan and 3 (three) screen pans for a volume of:

$$\pi/4 * (8 \text{ in.})^2 * (2 \text{ in.} + 3*2 \text{ in.}) = 402 \text{ in.}^3 \Rightarrow 6.6 \text{ Liters},$$

became limited to 2 (two) screen pans for a volume of:

$$\pi/4 * (8 \text{ in.})^2 * (2 \text{ in.} + 2*2 \text{ in.}) = 302 \text{ in.}^3 \Rightarrow 5.0 \text{ Liters}.$$

CSER 96-008 (Hess 1996c), for muffle furnace gloveboxes (HC-21C and HA-21I) set a mass limit of 15 kilograms of plutonium compound (six furnace boats at no more than 2.5 kilograms of plutonium per furnace boat) OR when plutonium metal is present, the mass limit becomes 7.5 kilograms of plutonium. Additional limits are water content limited to 0.60 g H_2O/cm^3 and maximum density for plutonium compounds of 5 g Pu/cm^3 before burning. The 10 inch spacing requirement was eliminated for the muffle furnace gloveboxes.

This represented a change in philosophy from limitations on available plutonium and restriction on available container volumes to a scheme for maintaining a geometrically favorable (for precluding criticality) configuration for any fissile accumulation. The elimination of any lateral spacing requirement precluded the possibility of spacing infractions.

5.2 INCENTIVES FOR REVISED LIMITS

The present furnace glovebox limit of 2.5 kilograms plutonium per container is not acceptable when cans are to be loaded to approximately 5 kg PuO_2 (4.41 kg Pu). This increased amount of plutonium per container is the incentive for revised glovebox limits. This criticality evaluation includes reconsideration of the previous limit of 5 kg Pu.

CSER 96-008 (Hess 1996c) had the following to say about the change from a spacing limit to a boat mass limit:

> The 5 kg total Pu limit for the whole glovebox, although restrictive, has not been a particular impediment to the process throughput rate when most of the scraps and sludges to be stabilized were not of high Pu content.
>
> A higher permitted Pu content for the whole glovebox is needed in order to expedite the throughput when firing more concentrated Pu bearing materials. In order to do this, the essence of criticality prevention has to be changed from rules for limiting total available Pu and for restricting the volume of Pu- bearing containers to a scheme for maintaining a geometrically favorable (for precluding criticality) configuration for any fissile accumulation. The adoption of the "cake pan" style boats of only 2.4 inches height will restrict the fissile material to a geometrically favorable slab configuration if boat stacking is prohibited and the Pu mass per boat is limited. The elimination of any lateral spacing requirement between six allowed boats then considerably eases the boat transfer operations and thus reduces the prospect for spacing infractions.
>
> The operational mode, where there could be boats awaiting firing, being heated inside furnaces, or cooling on the stands outside of the furnace doors, determines a need for about two boats per furnace station to provide an optimized throughput for the processing. Thus, a limitation to six boats maximum for HA-21I is appropriate. Most containers in the PFP storage have a 2500 g upper limit on dry Pu bearing materials, and such a limit per furnace boat will not be inconvenient and can be readily supported as the basis for the slab geometry safety control, where boats can be arrayed side-by-side. These provisions will allow a total of 15 kg Pu, maximum, in HA-21I for stabilization of plutonium oxide compounds. If buttons are to be burned, the limit is reduced to 7.5 kg of Pu in the metal form.

HC-21C has only two muffle furnaces, but also houses a balance scale and room for one or two desiccators. Since the essential control is the prohibiting boat stacking, and the lateral distance of boats inside or outside of furnaces or desiccators is not restricted, the limit of six loaded boats in HC-21C with also no more than 15 kg total Pu as compound powders or 7.5 kg if large metal pieces is also satisfactory.

5.3 NEW CRITICALITY LIMITS LOGIC, RATIONALE, AND JUSTIFICATION

This section provides the logic, rationale and directions to the appropriate document location for the justification for design features and administratively controlled limits.

1. Plutonium metal glovebox limit. This is consistent with Hess (1996c) set glovebox limits for muffle furnace gloveboxes, HC-21C and HA-21I, but permits Pu in PuO_2 as part of the limit for Pu metal. This was also justified because of seismic concerns because HC-21A is not a seismically qualified glovebox and a catastrophic rearrangement of the entire glovebox mass can be argued to remain subcritical.

2. Plutonium metal in furnace boat limit. This is consistent with Hess (1996c) set glovebox limits for muffle furnace gloveboxes, HC-21C and HA-21I.

3. Plutonium oxide glovebox limit. This is consistent with Hess (1996c) set glovebox limits for muffle furnace gloveboxes, HC-21C and HA-21I. This was also justified because of seismic concerns because HC-21A is not a seismically qualified glovebox and a catastrophic rearrangement of the entire glovebox mass can be argued to remain subcritical.

4. Mass and volume limits for separate operations. These are derived from the basic critical parameters for Pu form and content section, mostly these limits are consistent with the Table 6.1, Criticality Parameters for Spherical Configurations, $^{239}PuO_2$-Water Mixes, values. The 10 inch separation assures that these individual limits are applied to the operations separately.

5. PuO_2 mass in a sieve shaker pan. This limit is from the MONK6B results tabulated in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results and the requirements of the double contingency criterion. In this case, the single contingency of adding another furnace boat of 2.5 kg Pu into the sieve shaker pan and raising the mass from 6.0 kg Pu to 8.5 kg Pu still calculates a k_{eff} below 0.935.

6. PuO_2 mass in a 4.4 kg Pu can. This is needed because of assumptions made in other CSER's such as Erickson (1996) for other facilities.

7. Maximum number of filled 4.4 kg Pu cans in a glovebox. This limit is from the MONK6B results tabulated in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results and the requirements of the double contingency criterion. In this case, a cluster of one more than the maximum number of allowed filled 4.4 kg Pu cans should have a k_{eff} below 0.935.

8. Maximum container volume. These criticality limits are as small as possible given the containers required to perform the operation. The maximum container volume is specified to preclude the volume necessary for criticality if water were to be mixed with exposed PuO_2.

9. Maximum number of sieve screens used in the sieve screen system. This is from MONK6B results tabulated in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results, and the requirements of the double contingency criterion. This limit prevents a single volume of more than 3.3 Liters and a combined container volume of 6.0 Liters so a usable limit of 6.0 kg and 7.5 kg on plutonium mass, respectively, is allowable. This limit by itself is not sufficient to assure k_{eff} below 0.935 and there needs to be a container mass limit that will assure k_{eff} below 0.935 in conformance with the double contingency criterion.

10. Stacking of plutonium bearing containers. Stacking could make a group of containers more like a sphere which is more reactive. This criticality limit is consistent with criticality limits for the muffle furnace gloveboxes (Hess 1996c). MONK6B calculations, shown in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results, were performed with stacked boats containing plutonium metal, the most reactive configuration, and shown to have k_{eff} below 0.935 in conformance with the double contingency criterion.

11. Pot sump sealing. Areas where volumes of plutonium bearing compounds may accumulate are to be minimized, reduced or eliminated as part of criticality control.

12. Maximum glovebox floor accumulation. This is routine, and is confirmed by MONK6B calculations tabulated in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results, and the requirements of the double contingency criterion. In this case, the maximum glovebox accumulation is included in limiting single contingency cases and it is required that k_{eff} remain below 0.935.

13. DRY glovebox. The confirmation of this designation requires criticality evaluation of the possibility of water introduction. Criticality evaluations consider container volume and contained plutonium mass and take into account flooding without plutonium position changes, which corresponds to fire fighting category C.

6.0 BASIC CRITICAL PARAMETERS FOR PU FORM AND CONTENT

6.1 SPHERICAL GEOMETRY CORRELATIONS

Table 6.1 presents critical parameter correlations, derived from standard handbook data for spherical geometry, expressed in a manner to illustrate the likelihood of such conditions existing within the muffle furnace and muffle furnace support (HC-21A) gloveboxes. The footnotes to the table explain the typing formats used to indicate various normal and off-normal conditions.

6.1.1 Dry Plutonium Oxide

The upper section of the table concerns only absolutely dry material boat charges, as would be the case for material after firing in the furnaces. Data line one shows a 12 kg minimum critical mass for ^{239}Pu as plutonium oxide, based on experiments with 9.96 g Pu/cm^3 material (Paxton and Provost 1986). The next line, at 10.1 g Pu/cm^3 (close to the theoretical highest density point of 11.46 g PuO_2/cm^3 x 239.0522 / (239.0522 + 2x15.9994) = 10.107 g Pu/cm^3) is from the ARH-600 (Carter et.al. 1968) chart of calculated values for PuO_2, which indicates a slightly lower critical mass (10.8 kg with full reflection), indicating that the chart-derived data is likely to be somewhat conservative. Also conservative is the assumption of 100% ^{239}Pu.

This second line also shows that with nominal reflection, the 15 kg of Pu allowed as a glovebox limit could nearly be made critical; but having PuO_2 at theoretical density is not credible, nor is a factor of 6 overbatch in one boat volume. With full water reflection (deemed implausible because HC-21A is open on the north end to the conveyor glovebox, HC-2), 15 kg of dry Pu as PuO_2 could become critical at a lower density, 8.0 g Pu/cm^3, above the anticipated density for PuO_2, and is not a credible concentration for material in this stabilization process or from past PFP/PRF operations.

The furnace firing usually condenses the charged material, but it is not likely for the Pu to be concentrated to more than 6 g Pu/cm^3. At 6 g Pu/cm^3 of Pu as dry oxide, criticality requires at least 24 kg Pu crammed into a 4 liter accumulation (about two boats) with full reflection. This means multiple violations of the 15 kg total glovebox Pu limit and also a flooded scenario (for full reflection). At lower Pu densities, a dry criticality needs even higher masses and volumes. For a more probable upper Pu density at 4.7 g Pu/cm^3, at least 33 kg of Pu is needed with full reflection, and over 60 kg with nominal reflection. Thus, without even considering the geometry restriction imposed by the plutonium container spacing limits, criticality for dry material with any plausible Pu concentration would be impossible unless all the plutonium containers were nearly triple-batched (or nearly double batched if flooding were possible). This argument also applies to plutonium oxide in the other containers in glovebox HC-21A.

6.1.2 Wet Plutonium Oxide

The lower section of Table 6.1 contains parameters for plutonium oxide at various densities fully soaked with water (i.e., with water filling the available void space between PuO_2 granules). It is assumed that each 1 g Pu/cm^3 as oxide occupies 10 volume percent (v/o). This assumption is consistent with previously stated PuO_2 densities of 9.96 g Pu/cm^3 and 10.1 g Pu/cm^3. Scrap or sludge materials, as initial charges to the boats, are more likely to contain water, but water contents exceeding 60 v/o are highly unlikely. Pu densities over 5 g Pu/cm^3 are not plausible for pre-fired materials except for plutonium metal buttons, and for much lower densities there is likely to be significant volume fractions of lighter element oxides and other materials.

Table 6.1. Criticality Parameters for Spherical Configurations, $^{239}PuO_2$-Water Mixes						
FISSILE MEDIUM		NOMINAL REFLECTION		FULL REFLECTION		
Pu Density, g Pu/cm^3	Volume Fraction Water	Critical Volume, liters	Mass Pu, kg	Critical Volume, liters	Mass Pu, kg	REF*
9.96	dry	-	-	1.2	12	A
10.1	dry	1.53	[15.5]	1.07	10.8	B
9.5	dry	1.85	17.5	1.24	11.8	B
8.0	dry	*3.0*	**24**	1.87	[15]	B
[6.0]	dry	*6.6*	40	*4.0*	**24**	B
4.7	dry	*[13.2]*	63	*6.9*	33	B
8.0	≈ 21%	2.2	17.5	1.5	12.0	B
[5.0]	≈ 50%	*3.9*	**19.5**	2.55	12.8	B
4.0	[60%]	*4.8*	**19.0**	*3.1*	12.4	B
3.0	**≈ 70%**	*5.8*	17.5	*3.9*	11.7	B
2.2	**≈ 78%**	*6.8*	[15]	*4.6*	10.1	B
1.15	> 86%	*8.7*	10.0	*5.8*	6.7	B
0.78	> 91%	*9.5*	7.4	*6.5*	5.0	B

NOTE: As pertains to operations under glovebox CPS Limits allowing six, 2.2 Liter boats maximum with not more than 2.5 kg Pu per boat, stacking prohibited, but no lateral spacing rules;

[Bracketed] items are glovebox mass or volume limit, or maximum likely density
Underlined mass value is 1-boat (2.5 kg) overload of glovebox total Pu limit.
Italicized volumes imply stacking or dumping to get spherical approximation
Bold items are unlikely material conditions or multiple mass overloading
Shaded items are implausible conditions.

* Data Sources:
A) LA-10860-MS, pg 70, Table 16, from experiments _ [Paxton and Provost 1986]
B) ARH-600 Chart III.A.9(100)-5 _ _ _ _ _ _ _ _ _ _ _ _ _ _ [Carter, et.al. 1968]

The correlations for nominally-reflected, wet material in Table 6.1 give two critical points for 17.5 kg Pu, which would be the allowed contents of 7 boats, as an infraction of the limit on number of loaded boats, fully loaded. But the material would have to be either in one boat volume at an impossible density of 8 g Pu/cm^3, or at 3 g Pu/cm^3 soaked to an improbable water content of 70 v/o in almost three boats. Since other volumes in glovebox HC-21A are less than that of a boat, except for the sieve pan with one screen, and mass limits are less than 1/2 the 17.5 kg for containers, this argument again applies to glovebox HC-21A. The sieve pan and screen with a volume of 3.3 Liters is still less than that needed for criticality except for the improbable density of 8 g Pu/cm^3.

With all of the 15 kg Pu allowed in the glovebox clustered into one contiguous volume, the nominally-reflected critical density is 2.2 g Pu/cm^3, which is more typical of materials encountered at PFP; however, soaking to 78% by volume water would be needed as well as double batching of 3 boats, plus stacking. Similar multiple infractions of limits are needed in HC-21A to assemble 15 kg of plutonium and 7 Liters of containers.

With full reflection and plausible maximum water contents (no more than 60 v/o in the assumed pure oxide/water mixture) criticality would require at least 12 kg Pu. This mass is under the glovebox limit, but it would need to occupy less than two boats of volume so the scenario would violate the mass limit per boat or other container. For improbable water fractions of between 60 and 78%, again with full reflection, there would still have to be 10 kg Pu or more as essentially two double-batched boat loads. 10 kg Pu at 1.15 g Pu/cm^3 as four allowed boat loads could be made critical, but such would mean two stacking errors plus an implausible 86 v/o water content. For HC-21A, the spacing requirements would have to be violated for reasonable PuO_2 densities less than 6 g PuO_2/cm^3.

The last line in Table 6.1 indicates that 5 kg Pu (or twice that allowed per boat) configured as a sphere could only be made critical as essentially a solution or thin slurry. Besides this violation of the allowed material consistency, to get the accumulation configured anywhere approaching a spherical shape would entail multiple spacing errors or use of a single container of twice the volume allowed for containers. Although 5 kg PuO_2 is allowed in a convenience can, the 1.24 Liter volume or inner can 1.42 Liter volume is insufficient for criticality. The other containers in HC-21A are limited to about half the volume necessary for criticality.

The Table 6.1 correlations thus show that under the proposed limits on container groupings, their loading and spacing requirements, criticality would require multiple error conditions, so that the double contingency criteria for assured subcriticality is satisfied. Further, because the glovebox has an open end, water could not accumulate to give significant water reflection. Since the plutonium is either metal or oxide, it is not soluble, so it would have to be agitated to a homogeneous PuO_2/H_2O mixture of at least the spherical volume needed for a potential criticality. There is no postulated mechanism for suspension of PuO_2 in H_2O in the container. Criticality in the amounts available and the containers is considered incredible.

6.2 SLAB GEOMETRY CORRELATIONS

There is a concern about the plutonium in boats and a sieve stack if in error they were put side by side or a spill put Pu next to the sieves or the boats. A clustering of two boats and sieve pan begins to approximate a slab configuration. Table 6.2 lists data from Criticality Handbooks (Paxton and Provost 1986, Carter et.al. 1968) pertaining to infinite-slab criticality parameters for pure Pu-water mixes (all Pu is ^{239}Pu), at full soaking without void spaces or other constituents. Except for last line, the first four data columns relate to Pu-water mixes, but the water content listed in the 5th column is for plutonium-oxide plus water; this listing is conservative, because the oxide mixes gives lower H/Pu ratios than the critical ratios inherent to the Pu/water parameters, and with less than 95 v/o water the fissile medium is undermoderated.

The defining data for the Table 6.2 listing of parameters is the critical areal Pu density, which is derived as the boat loading divided by the outside footprint 381 cm^2 (0.410 ft^2) per boat. Then, the critical depth (slab thickness) is read off the cited ARH-600 chart for the given areal density. Finally, a volumetric density (g Pu/cm^3) is established by dividing the Pu mass per boat by the loading volume, which is determined as the depth times the boat inside footprint 355 cm^2 (0.382 ft^2). A slab thickness of more than 6.20 cm (2.44 in.) represents overfilling of boats. For the water content in the last column, it is assumed the Pu is PuO_2 so that each 1 g Pu/cm^3 represents ≈ 10 v/o PuO_2.

This data for boats with normal charges and multiple overcharges is applicable for a 0.3175 cm (0.125 in.) thick layer in the bottom of the glovebox, the boats, and for the sieve pan, which is 5.08 cm (2 in.) tall. The sieve pan, with one screen is addressed in Section 6.1. The sieve pan has a footprint of only:

$$\pi / 4 * (8 \text{ in.} / 12 \text{ in./ft})^2 = 0.349 \text{ ft}^2 = 324.3 \text{ cm}^2,$$

which is less than a boat, and gives the next higher areal density. Since the pan is only 5.08 cm (2 in.) high, the results are still conservative. Also, the round pan with rectangular boats leaves a lot of open space. A square of the pan diameter has a bigger footprint than a boat.

6.2.1 Nominally Reflected Slab

With only nominal reflection above and below the slab (a 1-tier array of boats), the first section of Table 6.2 shows that criticality is not possible without at least two abnormal/implausible conditions. With no more than the allowed boat Pu loadings (2.5 kg each), criticality would require over 90 v/o water overfilling the boats, for which consistency the material would flow.

A criticality for just brim-high filling of the boats (depth = 6.20 cm = 2.44 in.), would require a fully soaked 4.0 g Pu/cm^3 material, which is just at the 60 v/o water limit. However, now there would be 8.8 kg of Pu in every boat, greater than triple batching for all boats, This is a not believable error situation (also see section 9.2.11 on water ingress due to fire).

Table 6.2. Criticality Parameters for Slab Geometry Configurations of ^{239}Pu-Water Mixes

REFLECTION CONDITIONS	KG PU IN EVERY BOAT	AREAL PU DENSITY kg/ft^2	CRITICAL DEPTH, inches	CHARGE DENSITY g Pu/cm^3	VOLUME FRACTION WATER*	DATA SOURCE **
NOMINAL	[2.5]	6.1	**3.6**	0.77	> 92%	A
Represented by 1" water above and below boat array	3.0	7.3	**3.5**	0.95	> 90%	A
	5.0	12.2	**3.15**	1.76	≈ 82%	A
	6.0	14.6	**2.97**	2.24	≈ 78%	A
	8.8	21.5	[2.44]	4.0	[≈ 60%]	A
	10.0	24.5	2.22	[5.0]	≈ 50%	A
Full H_2O above, Nominal below	[2.50]	6.1	**2.78**	1.0	≈ 90%	B
Nominal above, 10" concrete below	2.14	5.2	2.39	1.0	≈ 90%	B
Full Water Reflection Above and Below the Planar Array of Boats	0.35	0.86	[2.44]	0.16	> 99%	A
	1.77	4.32	1.95	1.01	≈ 90%	A
	[2.5]	6.1	1.80	1.54	≈ 85%	A
	4.65	11.7	1.30	4.00	[≈ 60%]	A
	5.00	12.2	1.20	4.62	≈ 54%	A
	5.17	12.6	1.14	[5.0]	≈ 50	A
	6.0	14.6	0.91	7.3	< 27%	A
	6.1	14.8	0.68	9.96	*DRY PuO_2*	C

* Assumes PuO_2-water mix, although critical parameters are for Pu-water.

NOTE: As pertains to CPS limit of 2.5 kg per boat, with stacking prohibited;

[bracketed] items are at-limit mass or density values, or boat brim height
Bold slab depths exceed boat height, which is implausible for finite 1 tier of boats when mix is fluid (greater than 70 v/o water)
Underlined masses are near double batches (in all boats of infinite array)
Bold mass, Pu density or water contents are highly unlikely conditions
Shaded items are implausible conditions.

** Data Sources:
- A) ARH-600 Chart III.A.8(100)-3 [Carter et.al. 1968]
- B) ARH-600 Chart III.A.5(100)-5 [Carter et.al. 1968]
- C) LA-10860-MS, page 70, Table 16 [Paxton and Provost 1986]

6.2.2 Slab with Full Reflection Above or Below

In the second set of data in Table 6.2, it is assumed that there is nominal reflection on one face of the slab, but full reflection on the other. If flooding of the glovebox were possible, an infinite array of boats on the elevated glovebox floor loaded to the allowed 2.5 kg per boat could be critical if the PuO_2-water mixture was 7.06 cm (2.78 in.) deep and the Pu was diluted to 1 g Pu/cm^3. Thus, even if a 25 cm (10 in.) deep flooding event was plausible, some action would be needed to bring the full boat charges up to 0.86 cm (0.3 in.) above the brim, and since a real array would not cover the whole floor the excess height of this dilute mix would drain off.

The second line of the second data set represents the boat array sitting of a concrete floor, somehow being soaked to a highly liquid 90% H_2O content. This scenario is completely out of scope as it would involve severe misconduct of operations. The data points in this second set are at the upper end of Pu concentration on the graph curves of reference B shown in Table 6.2. Critical Pu concentrations less than 1 g Pu/cm^3 would require even higher slab depths.

6.2.3 Fully Reflected Slab

In the bottom portion of Table 6.2, full water reflection is assumed both above and below the slab array of boats. This configuration not plausible unless a.) considerable amount of reflective materials are stored just beneath the glovebox, and b.) a lot of water is introduced inside. Given these two extreme contingencies, criticality would be possible with allowed boat loadings if the flooding could also agitate all boat charges with water and mix such to a dilute slurry, with over 85 v/o water and the Pu at 1.5 g Pu/cm^3 or less density. The first three lines of the last data set represent such an unlikely scenario. A third contingency, under which criticality would be possible even with more realistic PuO_2/water mixture densities, is if all the boats were overloaded.

The last line of Table 6.2 data is based on an experimental determination of the critical thickness for an infinite slab of solid PuO_2 fully reflected on both sides. Reference C of Table 6.2 cites a thickness of 1.6 cm (0.63 inches) with the Pu at 9.96 g/cm^3. This combination equates to a critical areal density of 15.9 g Pu/cm^2 (14.8 kg Pu/ft^2). To achieve the same average areal density for an array of boats loaded with this dry material, the PuO_2 in the boats would have to be 1.7 cm (0.68 in.) deep (0.63 x ratio of outside/inside footprints). The critical boat loadings would be 15.9 g Pu/cm^2 * 381 cm^2 = (14.8 kg/ft^2 x 0.41 ft^2) = 6.1 kg Pu each. Although it was measured for near full density oxide (at ≈ 10 g Pu/cm^3), the 15.9 g Pu/cm^2 (14.8 kg Pu/ft^2) critical point would logically apply for any density of dry plutonium oxide as an infinite, full-water-reflected slab. This condition requires multiple errors of total PuO_2, spacing, spill depth, and boat or sieve overloading.

Thus, for the stated fissile medium (pure ^{239}Pu as oxide fully soaked with water), criticality is not plausible for an infinite 1-tier boat array, 0.3175 cm (0.125 in.) thick floor layer of PuO_2, or sieve pan for even one contingency beyond the conditions allowed in HC-21A. The open ended glovebox and lack of agitation to suspend the PuO_2 makes a critical slab incredible.

7.0 MONK6B MONTE-CARLO GLOVEBOX MODELING

7.1 METHODS VALIDATION

Appendix B provides a standardized summary for the documentation of the validation (Macklin and Miller 1992, Miller 1994) carried out for the MONK6B Monte-Carlo code, and its predecessor versions, as applicable to plutonium materials encountered at PFP. With the cross-section library supplied, the MONK6A/6B validation calculations indicate an allowed maximum k_{eff} value of 0.935 for new system calculations to assure subcriticality with an acceptable margin, including the uncertainties in the analytical methods and benchmark experimental data.

The MONK6B code was used for this analysis. This code is commercially licensed from the British ANSWERS organization. The MONK6B code uses cross sections from a point energy library based on the UKNDL and JEF evaluations. It is currently verified and validated on two Sun workstations in the SECC.

7.2 MODELING ASSUMPTIONS WITH PLUTONIUM METAL BUTTONS

For this analysis the plutonium metal buttons were modeled with dimensions of 7.1 cm (2.8 in.) O.D. and 3.244 cm (1.277 in.) height. The plutonium was modeled as 100 wt% ^{239}Pu with a number density of 0.049034. The metal density calculates to:

$$0.049034 * 10^{24} * 239.0522 / 6.022045E23 = 19.464 \text{ g Pu/cm}^3.$$

This density calculates the mass for a single plutonium metal button to:

$$19.464 \text{ g Pu/cm}^3 * \pi * (3.55 \text{ cm})^2 * 3.244 \text{ cm} = 2{,}500.0 \text{ g Pu}.$$

This plutonium enrichment is limiting and conservative and the plutonium mass per plutonium metal button is also limiting and conservative.

7.2.1 Plutonium Metal in HC-21A Normal and Off-Normal Conditions

The plutonium metal buttons are modeled inside furnace boats, usually centered, because this is their typical HC-21A location. The furnace boats may be adjacent in a side by side geometry. The glovebox is modeled with interior dimensions of 266.7 cm (105 in.) long, 106.68 cm (42 in.) deep, and 91.44 cm (36 in.) high. There is 2.54 cm (1 inch) water reflection on all sides, radial and top of the plutonium metal buttons, and outside all containers. The glovebox sides, top, and bottom are 0.635 cm (0.25 inch) thick stainless steel plate that is 137.16 cm (54 in.) above a concrete floor. There is a full 30 cm of water reflection outside the glovebox on all sides. This model is used for the normal and off-normal calculations in Table 9.1 HC-21A Normal and Off-Normal MONK6B Results.

7.2.2 Plutonium Metal in Parametric Study Calculations

The plutonium metal buttons along with the dry plutonium compounds are modeled together in a very conservative geometry. The conservative geometry is that the plutonium metal buttons are stacked, which is a violation of criticality limits, and the PuO_2 surrounds the buttons in a cylinder, which is another violation of criticality limits. The cylinder was calculated with the diameter equal to height (H/D = 1) to give a maximum in reactivity. There is 5.08 cm (2 in.) water reflection on all sides, radial and top. The assembly bottom is on a 0.635 cm (0.25 inch) thick stainless steel plate that is 121.92 cm (4 feet) above a concrete floor. The glovebox is conservatively modeled as a 91.44 cm (36 inch) diameter cylinder. There is a full 30 cm of water reflection outside the glovebox on the sides. This model is used for the parametric study calculations in Table 9.2, Plutonium Metal and Plutonium Oxide MONK6B Results.

7.3 MODELING ASSUMPTIONS WITH 4.4 KILOGRAM PLUTONIUM CANS

For the purposes of this analysis, only the innermost can was modeled. The can is filled with 5.0 kg of plutonium in PuO_2 with H_2O added for an H/Pu = 2. The maximum assumed Pu density is 5.5 g Pu/cm^3. The plutonium is assumed to be 100 wt% ^{239}Pu. This plutonium enrichment is limiting and is conservative.

The dry PuO_2 returned from the muffle furnaces is modeled in the convenience cans clustered together. The plutonium is assumed to be 100 wt% ^{239}Pu. This plutonium enrichment is limiting and is conservative.

The density considered in these calculations is 5.5 g Pu/cm^3 in the PuO_2. This means that the PuO_2 density considered is:

$$5.5 \text{ g Pu/cm}^3 * ((239.0522 + 2*15.9994) / 239.0522) = 6.236 \text{ g PuO}_2\text{/cm}^3.$$

The density of single crystals of PuO_2 is 11.46. To achieve a practical density of 6.236 g PuO_2/cm^3 from a collection of single grains, the porosity (interstitial void spaces) would have to be:

$$100\% * (1. - (6.236/11.46)) = 45.585\% \text{ or less.}$$

Weakly cemented rocks that are formed of grains dropped as sediment from a suspension, such as sand, sandstone and some limestones, have a porosity range of 25% to 45%. For a tapped collection of PuO_2 grains without application of pressure, this 45% porosity is not considered to be practical to achieve.

The highest tap density for PuO_2 reported (ARH-600 Table II.C.2-2) was only 5.8 g PuO_2/cm^3, inferring a porosity of:

$$100\% * (1. - (5.8/11.46)) = 49.4\% \text{ minimum.}$$

Because the calculated PuO_2 density is much greater that historical experience of PuO_2 density, the calculations performed at this density are considered to be conservative.

8.0 DISCUSSION OF CONTINGENCIES

Contingencies were considered as Nuclear Criticality Safety Parameters. The following parameters were addressed: 1. Mass, 2. Enrichment, 3. Volume, 4. Geometry, 5. Concentration/Density, 6. Moderation, 7. Interaction, 8. Reflection, 9. Neutron Absorption, and 10. Other.

(1) Mass: There is a glovebox mass limit, so one contingency is: glovebox mass limit exceeded. There is a container mass limit of 2.5 kg Pu metal for any container, so a second contingency is: 2.5 kg plutonium metal mass container limit exceeded. Another limit on mass is of 6.0 kg plutonium in a plutonium compound for any container, so a third contingency is 6.0 kg Pu in PuO_2 mass container limit exceeded. Another limit on mass is on the number of filled 4.4 kg cans, so a fourth contingency is filled 4.4 kg Pu can number limit exceeded.

(2) Enrichment: There is no enrichment limit and all cases were calculated at, conservatively, 100 wt% ^{239}Pu, so there is no enrichment based contingency.

(3) Volume: There are volume limits on containers, so a fifth contingency is container volume limit exceeded.

(4) Geometry: Geometry is limited by not stacking containers with plutonium, so a sixth contingency is stacking of plutonium bearing containers. Geometry is also limited by not moving a plutonium bearing materials such as a transport wagon underneath the HC-21A glovebox, so a seventh contingency is transport wagon underneath glovebox.

(5) Concentration/Density: The density for plutonium oxide used in this CSER is a conservative density of 5.5 g Pu/cm^3 based on the most dense limit allowed, the vertical calciner product (Geiger 1995). This PuO_2 density is higher than all criticality handbook (Carter et. al. 1968) entries for PuO_2 densities. A reasonable, 19.464 g Pu/cm^3, density was used for plutonium metal density.

MONK6B calculations were performed at these densities. Reactivity goes up as the PuO_2 density goes up, so the assumptions used in the computer calculations need to be conservative. This 5.5 g Pu/cm^3 density is very conservative. 5.5 g Pu/cm^3 equals 6.23 g PuO_2/cm^3.

There is no density based contingency because the values used in these calculations are considered sufficiently conservative.

(6) Moderation: Moderation is controlled because plutonium compounds are limited to H/Pu $\leq$ 2, so an eighth contingency is: H/Pu > 2 material inside glovebox.

(7) Interaction: Interaction is explicitly limited by horizontal spacing requirements and by container stacking limits (covered as a geometry contingency), the container cluster interaction contingency is covered as a ninth contingency.

(8) Reflection: Reflection is controlled because HC-21A is classified as a DRY glovebox without flowing liquids and only limited size containers of moisture bearing materials, so a tenth contingency is introduction of water into glovebox.

(9) Neutron Absorption: Neutron absorbing materials are not specified as part of any safety system, so there is no contingency associated with neutron poisons.

(10) Other: Other, at Hanford, has come to mean fire and seismic concerns, so an eleventh contingency is water ingress due to fire, and an twelfth contingency is seismic concerns.

The contingencies to be considered by MONK6B calculations are:

1) Glovebox Mass Limit Exceeded,
2) 2.5 kg Plutonium Metal Mass Container Limit Exceeded,
3) 6.0 kg Pu in PuO_2 Mass Container Limit Exceeded,
4) Filled 4.4 kg Pu Can Number Limit Exceeded,
5) Container Volume Limit Exceeded,
6) Stacking of Plutonium Bearing Containers,
7) Transport Wagon Underneath Glovebox,
8) H/Pu > 2 Material Inside Glovebox,
9) Container Cluster Interaction,
10) Introduction of Water into Glovebox,
11) Water Ingress due to Fire, and
12) Seismic Concerns.

8.1 GLOVEBOX MASS LIMIT EXCEEDED

This mass limit applies to the entire glovebox. The mass limit is 7.5 kg Pu when plutonium metal is present. The mass limit is 15. kg Pu when no plutonium metal is present. The mass limit requirement limits the plutonium metal in the form of buttons or plutonium in the form of a compound such as PuO_2. This contingency, by itself, does not compromise criticality safety, but it could increase the likelihood of exceeding the 2.5 kg plutonium metal in a single container mass limit or the plutonium compound volume limit. Both of these items are considered separately in the calculations, so no specific calculations were deemed necessary for glovebox mass limit exceeded.

8.2 2.5 KG PLUTONIUM METAL MASS CONTAINER LIMIT EXCEEDED

This 2.5 kg mass limit applies to plutonium metal in individual containers. The mass limit requirements limits the plutonium metal in the form of buttons per container. This contingency, too much plutonium metal in one container, is considered in the calculations.

8.3 6.0 KG PU IN PUO_2 MASS CONTAINER LIMIT EXCEEDED

This 6.0 kg Pu in PuO_2 mass limit applies to plutonium in plutonium compounds in individual containers. The mass limit applies to plutonium in any compound, but is expected to be applied to PuO_2. This contingency, too much plutonium in a plutonium compound in one container, is considered in the calculations.

8.4 FILLED 4.4 KG PU CAN NUMBER LIMIT EXCEEDED

The number of filled 4.4 kg Pu cans in the glovebox is limited to a certain number. This contingency, too many filled 4.4 kg Pu cans in the HC-21A glovebox, is considered in the calculations.

8.5 CONTAINER VOLUME LIMIT EXCEEDED

Container volume is limited and this limit could be exceeded. There are several container volumes to be considered: the Hastelloy-X furnace boats at approximately 2.2 Liters, the innermost can at 1.24 Liters, the next to innermost can at 1.42 Liters, the mortar has a volume of ≈ 1 Liter, the sieve shaker with a catch pan and one screen sieve has a calculated volume of 3.3 Liters. The sieve shaker is a special case because several interlocking tubes fit together and only the catch pan is closed on the bottom. The catch pan with diameter of 20.32 cm (8 in.) and a height of 5.08 cm (2 in.) calculates out to a volume of 1.65 Liters (100 in^3). The sieve shaker with a catch pan and two screen sieves has a calculated volume of 5.0 Liters. The sieve shaker with a catch pan and three screen pans has a calculated volume of 6.65 Liters. The allowed volume container is 2.5 Liters for PuO_2. This contingency will be considered by calculating the reactivity of accumulations of PuO_2 with H/Pu = 2, to represent plutonium compounds, with volumes greater than the allowed container volume of 2.5 Liters for plutonium compounds.

The accumulation of plutonium metal is limited by a 2.5 kg Pu mass limit per container instead of a container volume limit.

8.6 STACKING OF PLUTONIUM BEARING CONTAINERS

Loss of geometry means putting too much plutonium metal in one container or too much plutonium compound in one container or stacking of containers with plutonium. This contingency will be considered by the same technique as the container volume limit exceeded contingency, namely by calculating the reactivity of accumulations of plutonium metal and PuO_2 with volumes greater than these container volumes. This contingency is not calculated separately because the issues are considered in previously mentioned contingencies.

8.7 TRANSPORT WAGON UNDERNEATH GLOVEBOX

This contingency is that a fully loaded transport wagon is driven underneath the HC-21A glovebox while the glovebox is at its mass limit. The transport wagon is 17 inches wide, 35 inches long and 19.25 inches high. The five cans are in two staggered rows, with the two rows across the 17 inch width, and the staggered rows are along the 35 inch length. The plutonium bearing cans are vertically positioned such that the bottom of the cans is 10 inches above the floor and the top of the can is 17 inches above the floor. The HC-21A glovebox rests on a table frame with the glovebox floor 54 inches above the concrete floor. The top of the can is therefore (54 in. - 17 in. = 37 in.) 37 inches away from the bottom the glovebox. According to documentation (WHC 1977, WHC 1994a) the table frame support has horizontal cross members positioned at 6 inches to 10 inches above the floor, and again about 20 inches above that. There are horizontal cross members on the sides and on the ends. This structure has been designed for structural stability. This contingency is addressed.

8.8 H/PU>2 MATERIAL INSIDE GLOVEBOX

One way that the contingency of loss of moderation control was considered is by calculating the PuO_2 with a H/Pu > 2. Higher concentrations of water than H/Pu = 2 will be noticeable and not appear dry. The 14 hour furnace burn as well as the LOI test makes the H/Pu > 2 concentration very unlikely. The situations of concern are: (1) that moderated material can be introduced from clean out activities and placed in the furnace boats, and (2) that flooding could occur due to some catastrophic failure.

The flooding and mixing with water portion of this contingency has already been considered in Section 6.0 that covered plutonium at all moderations and water reflections with different mass and volume constraints. This contingency was addressed by considering all of these of situations, loss of moderation control, introduction of water, and the water ingress due to fire (flooding) cases together.

8.9 CONTAINER CLUSTER INTERACTION

There are spacing controls of 25 cm (10 in.) between groups of containers for separate operations. These separate operations are:

- Pouring Furnace Boat PuO_2 into Sieve Shaker Screen and Pan,
- PuO_2 Grinding and Sieving Operation,
- Can Filling Operation,
- Storing Unsealed Can and Sealing Can with Lid, and
- Sealing Can Inside a Second Can and Sphincter Port Exit.

The main feature of these separate operations is keeping the 4.4 kg Pu can separate from the other plutonium containers. This contingency will be considered as getting the 4.4 kg Pu can close to the furnace boat and more than one can adjacent to the sieve shaker pan.

8.10 INTRODUCTION OF WATER INTO GLOVEBOX

Glovebox HC-21A is designated as a DRY glovebox and there are no liquid lines running through this glovebox. There are three ways to introduce moderation: 1) catastrophic: breakage of plastic glovebox panels concurrently with room and water sprinklers introducing water, 2) contingency: introduction of containers with moderating liquid, and 3) routine: introduction of objects that can cause a moderating effect, such as human hand and arms inside rubber gloves. Calculations considered, as part of the normal situation with nominal reflection, one inch of water reflection around individual containers to conservatively model human hands moving containers around.

The situation of introduction of water into the glovebox has already been covered in Section 6.0 that covered plutonium at all moderations and water reflections with different mass and volume constraints. This contingency was addressed by considering all of these of situations, loss of moderation control, introduction of water, and the water ingress due to fire (flooding) cases together.

8.11 WATER INGRESS DUE TO FIRE

This situation involves roof sprinklers spraying on this glovebox which had the roof plastic break such that water can enter the glovebox and collect in containers. Because the glovebox is open to a conveyor, there is not the concern for the glovebox flooding.

The situation of water ingress due to fire has already been covered in Section 6.0 that covered plutonium at all moderations and water reflections with different mass and volume constraints. This contingency was addressed by considering all of these of situations, loss of moderation control, introduction of water, and the water ingress due to fire (flooding) cases together.

8.12 SEISMIC CONCERNS

This situation involves tipping a non-seismically qualified glovebox such that all fissile material is collected together. This contingency is considered separately in Section 9.2.12.

9.0 EVALUATION AND RESULTS

The computer calculation evaluation took two separate approaches, one is modeling of the HC-21A glovebox in normal and off-normal situations, and the other was a parametric study of material expected inside the glovebox. The normal and off-normal MONK6B results are listed in Table 9.1 and were used to set the HC-21A glovebox mass limits subject to administrative controls. The parametric study, listed in Table 9.2, was used to determine the mass limits possible with no administrative controls.

9.1 NORMAL CONDITIONS

Because of the multiple uses for glovebox HC-21A in support of the muffle furnace operation, it was useful to consider three situations individually: (1) plutonium metal buttons in furnace boats before heating in the furnace, (2) sieving and pouring into open cans, and (3) open cans being closed after the confirmation of dryness tests (LOI) are performed.

The glovebox dimensions and conditions outside the glovebox are identical for these three situations and for all normal and off-normal conditions listed in Table 9.1. The containers inside the glovebox have some close fitting water reflector, 2.54 cm (1 in.) or larger depending on the geometry being surrounded. The glovebox inside is modelled as air filled. The container collection is placed adjacent to one corner of the glovebox for maximum reflection off the glovebox walls. The glovebox is modeled as 0.635 cm (0.25 in.) of 304 stainless steel. The standard outside glovebox configuration uses air space below the glovebox for the 137.16 cm (54 in.) distance down to the top of the concrete floor. Immediately outside the glovebox is 30.00 cm (12 in.) of water reflector on all sides of the glovebox up to the glovebox roof. Immediately outside this water reflector is 30.00 cm (12 in.) of air space on all sides of the water reflector up to the glovebox roof. Finally is 20 cm (8 in.) of concrete below this glovebox model.

The different cases depended on the plutonium loading within the glovebox and the different containers.

9.1.1 Preparation of Plutonium for Furnace Burning

Three plutonium metal buttons, each assumed to be 2.5 kg, are placed into separate Hastelloy-X furnace boats. These boats are modeled as being side by side with the plutonium metal buttons centered in each Hastelloy-X boat. 2.54 cm (1 in.) of water reflection is assumed to be present on radial sides and on the top of each of the plutonium buttons simulating rubber gloved hands.

The nominal situation of three furnace boats with a 2.5 kg of plutonium metal button in each, HC21AA1 had a k_{eff} = 0.7633 ± 0.0029. The series of MONK6B calculations modeling the plutonium metal buttons in furnace boats is the HC21AA_ series listed in Table 9.1. Case HC21AA6, with k_{eff} = 0.9268 ± 0.0033, had 5 kg plutonium in each furnace boat, a single contingency situation for each of 3 boats. That is 3 contingencies of double batching. All HC21AA_ series cases, many of which represent multiple contingencies of double batching (two 2.5 kg buttons), spacing (more than 3 boats together), stacking (3 boats on top of 3 boats), and overbatching (more than 7.5 kg metal in the glovebox), had k_{eff} less than 0.935.

Table 9.1 HC-21A Normal and Off-Normal MONK6B Results.
PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2
2.5 Kilogram Metal Buttons
Nominal Reflection is 1 Inch Water on Sides and Top

Case #	Pu Metal in Boats	Sieve Stack	PuO_2 in Cans	PuO_2 on GB floor		RESULTS $k_{eff} \pm \sigma$
HC21AA1	3@2.5 kg					0.7633±0.0029
HC21AA2	6@2.5 kg					0.7646±0.0029
HC21AA3	3@2.5 kg			0.125"		0.7736±0.0037
HC21AA4	6@2.5 kg			0.125"		0.7875±0.0034
HC21AA5	4@2.5 kg					0.7718±0.0028
HC21AA6	3@5.0 kg					0.9268±0.0033
HC21AA7	3@2.5 kg, 5 kg PuO_2					0.8022±0.0036
HC21AA8	3@2.5 kg	1.65 L				0.7808±0.0033
HC21AA9	3@2.5 kg		4 @ 5 kg			0.9255±0.0033
HC21AAA	6@2.5 kg					0.8844±0.0030
HC21AAB	3@2.5 kg, 5 kg PuO_2					0.8799±0.0039
HC21AB1		1.65 L				0.6899±0.0030
HC21AB2		3.29 L				0.9584±0.0033
HC21AB3		4.94 L				1.1084±0.0036
HC21AB4		6.59 L				1.1783±0.0037
HC21AB5		1.65 L	3@ 5 kg			0.9170±0.0033
HC21AB6		1.65 L	3@ 5 kg	0.125"		0.9378±0.0036
HC21AC1			3@ 5 kg			0.9081±0.0033
HC21AC2			4@ 5 kg			1.0140±0.0036
HC21AC3			5@ 5 kg			1.0512±0.0035
HC21AC4			6@ 5 kg			1.0887±0.0035
HC21AC5			7@ 5 kg			1.1319±0.0035
HC21AC6			3@ 5 kg	0.125"		0.9226±0.0038
HC21AC7			4@ 5 kg	0.125"		1.0300±0.0038
HC21AC8			5@ 5 kg	0.125"		1.0712±0.0038
HC21AC9			6@ 5 kg	0.125"		1.1006±0.0038
HC21ACA			7@ 5 kg	0.125"		1.1443±0.0039

The contingencies included 5 kg PuO_2 powder in each of three boats with the 2.5 kg button which was case HC21AA7. Addition of water inside the furnace boat up to the brim is the additional contingency in HC21AAB that distinguishes it from HC21AA7. Additional contingencies considered 3 loaded boats with an 0.3175 cm (0.125 in.) layer of PuO_2 on the glovebox floor, or with four 4.4 kg Pu cans with 5 kg Pu in each, or with a full sieve pan, and 6 loaded boats in a single layer with an 0.3175 cm (0.125 in.) layer of PuO_2 on the glovebox floor, and 6 loaded boats of 3 in a double layer. In all the mentioned cases, the k_{eff} remained less than 0.935.

9.1.2 Transfer of Plutonium Oxide into 4.4 Kilogram Cans

PuO_2 is present in Hastelloy-X furnace boats, in the screen pan and catch pan sieve shaker, and in the innermost of the 4.4 kg Pu cans. No plutonium metal is allowed to be present. 2.54 cm (1 in.) of water reflection is assumed to be present on the top and around the outermost surface of the cluster of plutonium bearing containers simulating rubber gloved hands. Calculations focussed on the effect of loading the sieve shaker assembly with PuO_2.

The volume of the sieve shaker pan alone is not larger than the 2.5 Liter volume permitted according to the administratively controlled features. When sieve screens are added, then the volume can exceed the 2.5 Liter volume, so it is relevant to calculate the plutonium mass in the sieve shaker model calculated in the HC21AB_ series listed in Table 9.1. The conversions from volume to mass assumes 5.5 g Pu/cm^3.

$\pi/4$ * (8 in.)^2 * (2 in. + 0*2 in.) = 101 in.^{3} => 1.65 Liters => 9.06 kg Pu,

$\pi/4$ * (8 in.)^2 * (2 in. + 1*2 in.) = 201 in.^{3} => 3.29 Liters => 18.1 kg Pu,

$\pi/4$ * (8 in.)^2*(2 in. + 2*2 in.) = 302 in.^{3} => 4.94 Liters => 27.2 kg Pu, and

$\pi/4$ * (8 in.)^2 * (2 in. + 3*2 in.) = 402 in^3 => 6.59 Liters => 36.2 kg Pu.

The above mass quantities explain the unrealistically high k_{eff}'s for cases HC21AB2, HC21AB3 and HC21AB4. This also provides the basis for a 6.0 kg Pu in PuO_2 mass limit for single containers. The closest to a nominal situation, one full sieve shaker pan with 3 filled cans, although with extra plutonium and partial water reflection, case HC21AB5 had a k_{eff} = 0.9170 ± 0.0033.

Case HC21AB6 with a sieve pan, three 4.4 kg cans and a 0.3175 cm (0.125 in.) PuO_2 layer on the glovebox floor exceeds the allowed k_{eff} of 0.935 with a value of 0.938. Thus spills of PuO_2 must be cleaned up between each incident of a loaded sieve pan being brought to fill a 4.4 kg Pu can.

9.1.3 Sealing of Plutonium Oxide in 4.4 Kilogram Cans

PuO_2 is present in the innermost of the 4.4 kg Pu cans (convenience can), and the next innermost can (inner can) is also present for double canning the PuO_2 before it is bagged out of the HC-21A glovebox. No plutonium metal is allowed to be present. 2.54 cm (1 in.) of water reflection is assumed to be present on the top and around the outermost surface of the cluster of plutonium bearing containers simulating rubber gloved hands.

Different numbers of filled cans clustered together and water reflector with at least 2.54 cm (1 in.) thickness were considered. The HC21AC_ series reported in Table 9.1 records the calculations for clustered cans. The maximum number of 4.4 kg Pu cans that can be clustered with $k_{eff} < 0.935$ is three. This also provides a basis for a glovebox total plutonium of 15 kg plutonium. The single contingency situation, three full plutonium storage cans, although with extra plutonium (5 kg Pu modeled rather than the nominal 4.4 kg Pu loading) and partial water reflection, case HC21AC1 had a k_{eff} = 0.9081 ± 0.0033. Note that four cans k_{eff} exceeds 1.0. A second contingency of four cans with 20 kg is calculated to go critical. Fortunately, only two hands could not give sufficient neutron reflection for so many cans, so there is conservatism in this calculation. Still these contingency calculations point out the care that must be exercised with this much Pu in PuO_2 in a can.

9.2 OFF-NORMAL CONDITIONS

For off-normal conditions the following contingencies were considered for MONK6B calculations:

1) Glovebox Mass Limit Exceeded,
2) 2.5 kg Plutonium Metal Mass Container Limit Exceeded,
3) 6.0 kg Pu in PuO_2 Mass Container Limit Exceeded,
4) Filled 4.4 kg Pu Can Number Limit Exceeded,
5) Container Volume Limit Exceeded,
6) Stacking of Plutonium Bearing Containers,
7) Transport Wagon Underneath Glovebox,
8) H/Pu>2 Material Inside Glovebox,
9) Container Cluster Interaction,
10) Introduction of Water into Glovebox,
11) Water Ingress due to Fire, and
12) Seismic Concerns.

9.2.1 Glovebox Mass Limit Exceeded

This contingency, by itself, does not compromise criticality safety, but it could increase the likelihood of exceeding the 2.5 kg plutonium metal in a single container mass limit or the plutonium mass limit for a single container. Both of these items are considered in the calculations, so no specific calculations were performed for exceeding the glovebox mass limit.

9.2.2 2.5 kg Plutonium Metal Mass Container Limit Exceeded

This contingency, too much plutonium metal in one container, is considered in case HC21AA6 with 5.0 kg pu metal in each of three furnace boats which had a k_{eff} = 0.9268 ± 0.0033. This calculation is conservative because the two plutonium buttons were modeled as a cylinder 3.632 cm (1.430 in.) radius and 6.20 cm (2.441 in.) high for a total mass of:

$$\pi(3.632\ \text{cm})^2 * (6.20\ \text{cm}) * 19.464\ \text{g Pu/cm}^3 = 5{,}001.1\ \text{g Pu}.$$

This plutonium mass is twice 2,500 grams, which is larger than any single plutonium metal button. The water reflection was modeled as another cylinder 6.172 cm (2.43 in.) radius for a water thickness of 2.54 cm (1 in.) on the sides and on the top of this cylinder.

The plutonium mass limit could also be exceeded by spilling a container of 5 kg Pu in PuO_2 into a furnace boat. Case HC21AA7, with 2.5 kg plutonium metal and 5 kg in PuO_2 in each of three furnace boats, had a $k_{eff} = 0.8022 \pm 0.0036$. This illustrates that double batching metal systems is more reactive that double batching metal and PuO_2 systems. Both of these cases did not exceed the criticality safety limit of 0.935.

9.2.3 6.0 kg Pu in PuO_2 Mass Container Limit Exceeded

The mass accumulation in a container is considered in the sieve shaker system because this system is the only container that exceeds the volume limit of 2.5 Liters for any container in glovebox HC-21A. The volume of the sieve shaker pan alone is not larger than the 2.5 Liter volume permitted according to the administratively controlled features. When sieve screens are added, then the volume can exceed the 2.5 Liter volume, so it is relevant to calculate the plutonium mass in the sieve shaker model calculated in the HC21AB_ series listed in Table 9.1. The conversions from volume to mass assumes 5.5 g Pu/cm^3.

$$\pi/4 * (8 \text{ in.})^2 * (2 \text{ in.} + 0*2 \text{ in.}) = 101 \text{ in.}^3 \Rightarrow 1.65 \text{ Liters} \Rightarrow 9.06 \text{ kg Pu},$$

$$\pi/4 * (8 \text{ in.})^2 * (2 \text{ in.} + 1*2 \text{ in.}) = 201 \text{ in.}^3 \Rightarrow 3.29 \text{ Liters} \Rightarrow 18.1 \text{ kg Pu},$$

$$\pi/4 * (8 \text{ in.})^2*(2 \text{ in.} + 2*2 \text{ in.}) = 302 \text{ in.}^3 \Rightarrow 4.94 \text{ Liters} \Rightarrow 27.2 \text{ kg Pu, and}$$

$$\pi/4 * (8 \text{ in.})^2 * (2\text{in.} + 3*2 \text{ in.}) = 402 \text{ in.}^3 \Rightarrow 6.59 \text{ Liters} \Rightarrow 36.2 \text{ kg Pu}.$$

The above mass quantities explain the k_{eff}'s for cases HC21AB1 (1.65 L, 9.06 kg Pu, $k_{eff} = 0.6899 \pm 0.0030$), HC21AB2 (3.29 L, 18.1 kg Pu, $k_{eff} = 0.9584 \pm 0.0033$), HC21AB3 (4.94 L, 27.2 kg Pu, $k_{eff} = 1.1084 \pm 0.0036$) and HC21AB4 (6.59 L, 36.2 kg Pu, $k_{eff} = 1.1783 \pm 0.0037$). This provides the basis for a container mass limit of 6.0 kg Pu in plutonium compounds. This 6.0 kg Pu mass limit for single containers is lower than the case HC21AB1, which represents a single contingency with 9.06 kg Pu, with $k_{eff} = 0.6899 \pm 0.0030$ and shows that this single contingency does not exceed the criticality safety limit of 0.935. The normal boat loading is 2.5 kg Pu. Adding an extra boat load to the 6.0 kg Pu limit for a container would be one contingency resulting in 8.5 kg Pu which is less than the calculated 9.06 kg Pu. Interpolating between k_{eff}'s for HC21AB1 and HC21AB2, even a second contingency of 2.5 kg more Pu in PuO_2 would not exceed the safety limit of 0.935. However, the rapid change in reactivity with plutonium addition should be noted to prevent exceeding the 6.0 kg plutonium mass limits in a single container.

9.2.4 Filled 4.4 kg Pu Can Number Limit Exceeded

This situation was modeled with series HC21AC_ and considered different numbers of 4.4 kg Pu cans clustered tightly together and reflected by a minimum of 2.54 cm (1 in.) of H_2O. Each 4.4 kg Pu can was modeled with 5.0 kg of Pu in PuO_2 with H/Pu = 2 and a density of 5.5 g Pu/cm^3. Case HC21AC6, with only three (3) 4.4 kg Pu cans, had k_{eff} = 0.9226 ± 0.0038 does not exceed the criticality safety limit of 0.935. This defines three (3) filled 4.4 kg Pu cans as being a single contingency case where the can number limit was exceeded. This result sets the limit on the number of 4.4 kg Pu cans in HC-21A to be two (2).

Case HC21AC2 with four filled 4.4 kg Pu cans adjacent and with at least 2.54 cm (1 in.) of water reflection on all radial sides and on top, calculates a k_{eff} of 1.0140 ± 0.0036 (Prompt Critical!). Enough emphasis cannot be placed on the requirement for strict procedural checks on the number of adjacent 4.4 kg Pu cans.

9.2.5 Container Volume Limit Exceeded

Container volume is limited 2.5 Liters and this limit could be exceeded. The sieve shaker with a catch pan and one, two, or three screen sieves was considered in HC21AB1, HC21AB2, HC21AB3, HC21AB4. The conclusion is that all but the sieve pan alone are unsafe volumes, but that the glovebox mass limit of 15 kg Pu does not permit accumulation of plutonium to the volumes calculated in this series of calculations.

A filled to the brim screen pan, with a volume of 1.65 Liters (100 in^3) and PuO_2 at a density of 5.5 g Pu/cm^3 is a mass of 9.06 kg Pu. This mass is considered to be a contingency because the limit of 6.0 kg Pu in PuO_2 per container is exceeded. This calculation mimics exceeding the 2.5 Liter volume limit for PuO_2 containers. This case, HC21AB1, has k_{eff} = 0.6899 ± 0.0030 which is below the allowable 0.935. The multiple contingency case with 3 cans filled with PuO_2 (5 kg Pu each totalling 15 kg) next to a filled sieve pan, HC21AB5, has a k_{eff} = 0.9170 ± 0.0033 and shows that this multiple contingency does not exceed the criticality safety limit of 0.935.

9.2.6 Stacking of Plutonium Bearing Containers

Stacking of containers with plutonium was considered for the case of plutonium metal buttons in furnace boats. This had been calculated previously by Hess (1996c). Because water reflection inside the glovebox was not considered by Hess (Hess 1996c), this contingency was calculated again with 2.54 cm (1 in.) of H_2O. Case HC21AA4 with 6 furnace boats, 2.5 kg Pu each, in a two rows of 3 furnace boats had a k_{eff} = 0.7875 ± 0.0034. Case HC21AAA with 6 furnace boats, 2.5 kg Pu each, double stacked as one row of 3 contiguous furnace boats had a k_{eff} = 0.8844 ± 0.0030 shows that this double stacking is more reactive. This multiple contingency (15.0 kg Pu metal, spacing errors) with a k_{eff} = 0.8844 ± 0.0030 does not exceed the criticality safety limit of 0.935.

9.2.7 Transport Wagon Underneath Glovebox

This contingency is that a fully loaded transport wagon is driven underneath the HC-21A glovebox while the glovebox is at its mass limit. The transport wagon carrying five cans of 4.4 kg Pu is the form of PuO_2 could not be rolled under the glovebox from any side. The distance from the top of the 4.4 kg Pu cans is (54 in. - 17 in. = 37 in.) 37 inches vertical distance from the bottom the glovebox. This distance will cause the position of the transport wagon adjacent to the glovebox to have a very small effect in comparison to conditions inside the glovebox.

This contingency was calculated by Erickson (1996) for a much more reactive situation, the wagon in Vault #2 where the wagon is on the same level as the 4.4 kg Pu storage cans. The calculated normal case (V-N-02-A) k_{eff} was raised from 0.830 ± 0.003 to the adjacent wagon contingency case (V-C-31-A) k_{eff} of 0.837 ± 0.003. This calculated model had the wagon cans touching three of the storage rack cans while adjacent to the concrete floor. Each 4.4 kg Pu can was modeled with 4.5 kg Pu in PuO_2 with H/Pu = 2. The wagon under the glovebox contingency, with an edge-to-edge spacing of 37 inches would have a much reduced effect on k_{eff} than this bounding MONK6B calculation which showed a 7 mk increase in reactivity. Therefore, it can be stated, this single contingency of a transport wagon, carrying five 4.4 kg Pu cans, underneath the HC-21A glovebox does not exceed the criticality safety limit of 0.935.

9.2.8 H/Pu>2 Material Inside Glovebox

The criticality safety of the full range of H/Pu material was considered in Section 6.0 The basic argument is that at low H/Pu rations, criticality is unlikely due to the high required mass, while at higher H/Pu ratios, criticality is unlikely due to high required container volume. At low water dilution, a large mass, approaching or exceeding the entire allowed glovebox inventory of 15 kg Pu is required for criticality. The argument continued that at higher water dilution, the mass required for criticality diminishes, but the necessary volume for criticality is greater than the allowed total of clustered container volumes.

9.2.9 Container Cluster Interaction

There is a 25 cm (10 in.) spacing requirement between different, operation based, clusters of containers. These clusters of containers are set in the administrative limits to be:

- Pouring Furnace Boat PuO_2 into Sieve Shaker Screen and Pan,
- PuO_2 Grinding and Sieving Operation,
- Can Filling Operation,
- Storing Unsealed Can and Sealing Can with Lid, and
- Sealing Can Inside a Second Can and Sphincter Port Exit.

The main feature of these separate operations is keeping the 4.4 kg Pu can separate from the other plutonium containers. This contingency will be considered as getting the 4.4 kg Pu can close to the furnace boat and more than one can adjacent to the sieve shaker pan.

The situation of 4.4 kg cans close to furnace boats is bounded by the calculation of case HC21AA9. Case HC21AA9 had 3 furnace boats with centered 2.5 kg Pu buttons side by side and adjacent to a line of four 4.4 kg Pu cans, which represented multiple contingencies, and had a calculated k_{eff} of 0.9255 ± 0.0033, which is still below the criticality safety limit for a single contingency of 0.9350.

The situation of 4.4 kg cans close to the sieve pan is bounded by the calculation of case HC21AB5. Case HC21AB5 had the sieve pan with 9.06 kg of Pu in PuO_2, in itself a multiple contingency, tangent to three 4.4 kg Pu cans, which also represents a multiple contingency, and had a calculated k_{eff} of 0.9170 ± 0.0033, which is still below the criticality safety limit for a single contingency of 0.9350.

These two cases bound the effect of interaction and demonstrate that criticality safety is not compromised with the occurrence of this single contingency, but that another, additional and concurrent, contingency would have to occur before criticality safety would become compromised.

9.2.10 Introduction of Water into Glovebox

Glovebox HC-21A is designated as a DRY glovebox and there are no liquid lines running through this glovebox. The contingency of introduction of small amount of water into glovebox HC-21A was already calculated in the normal cases because a standard 2.54 cm (1 in.) of water reflection was assumed around the plutonium. Section 6.0 covered plutonium at all moderations and water reflections with different mass and volume constraints. This contingency was addressed by considering all three situations, loss of moderation control, introduction of water, and the water ingress due to fire (flooding) cases together.

9.2.11 Water Ingress Due to Fire

The furnace support glovebox, HC-21A, is also designated as a "DRY" glovebox, so no water or chemical solution pipelines are within the box and there may be only very limited volumes of water in containers. This design feature and this CSER restriction on maximum material moisture content substantially limit the degree of moderation and reflection of the fissile medium to be expected as normal. It is possible for water to be introduced in the event of a fire inside or near the glovebox, due to overhead room sprinklers or firefighter-directed streams. Based on years of operational history, however, the probability for this scenario is exceedingly low. Conformance with the "double contingency" principle, therefore, requires only that with any plausible normal, no-error arrangement of fissile-bearing containers in the glovebox a criticality could not result due to water ingress.

Glovebox HC-21A opens on one end into a conveyor glovebox, so that for the water ingress incident supposed above the depth of flooding on this glovebox floor would be minimal, certainly not enough to render a full reflection condition above plutonium containers arrayed on the floor.

With the containers being as flat open top boats, however, there is the potential for water dilution of the fissile-bearing material to H/Pu > 2. If the water ingress occurs as a spray or overhead "rain", the fissile material is not expected to be disturbed, and will occupy its original volume fraction, or it could slump to a greater concentration by the wetting action. For the sake of the safety assurance argument, however, we will assume the maximum reactivity dilution is achieved, by filling the container with a uniform PuO_2-water mixture with the allowed mass and volume for the container. But to get 2500 g Pu per boat in a large array critical with only nominal reflection requires water dilution to a depth of 9.1 cm (3.6 inches) (Hess 1996c), which by overflowing would render this an unrealistic situation.

Hess (1996c) did consider criticality to be possible with between 350 g Pu and 2500 g Pu per boat in an boat array without overfilling, but to achieve the full reflection condition below the glovebox floor, as well as the flooding depth above the boats was not considered to be credible. Movement of the loaded boats due to any plausible water stream impact is very unlikely due to the gross weights of these containers.

9.2.12 Seismic Concerns

Similar to the fire-water ingress event, conformance with the "double contingency" principle requires that with any plausible normal, no-error arrangement of fissile-bearing containers in the glovebox a criticality could not result from the agitation and damage from an earthquake. The most likely scenario would have the Pu-bearing boat materials being spilled out and scattered over a larger area so as to be less reactive. Furnace support glovebox HC-21A is not seismically qualified, so there is the prospect for tilting of the floor due to fracture or bending of the box support table legs.

In a tilted situation material would tend to sift down to a lower end or corner of the glovebox. Ignoring the structural impediments for full drifting throughout the glovebox length, all the allowed Pu inventory of 15 kg formed as a triangular wedge at the end of the box would not be critical (Hess 1996c). This is also possible to glean from Table 9.4, 15.0 Kilogram Plutonium Oxide Cylinder MONK6B Results, for the case of 15 kg PuO_2 in a cylinder with height/diameter = 1, and water reflected, and with H/Pu = 2. The disruptive nature of a seismic event would not assemble an ideal critical configuration, but rather disperse the Pu metal or PuO_2 in a confused configuration.

Water ingress would be considered as another contingency, because even though water pipe failures or sprinkler activation could result from the seismic forces, the probability of such failures and their occurrence over the glovebox would be less than unity and thus have to be compounded with the earthquake probability. Here too the potential for criticality, with a pool slurry forming in the bottom box edge, is low because of the non-optimum geometry attained.

9.3 PARAMETRIC STUDY OF PLUTONIUM METAL WITH PLUTONIUM OXIDE

Parametric studies are unrealistic and do not apply to physical situations, but are meant to represent the very extremes possible with certain quantities of plutonium materials.

The five results of this parametric study are:

- 2.5 kg plutonium metal per container is a necessary limit,
- PuO_2 mass limits can be much higher than Pu metal mass limits,
- Defined a plutonium metal/PuO_2 mass range where no other administrative controls are necessary,
- Demonstrated the necessity of including tight fitting H_2O reflection for a conservative computer model, and
- Demonstrated the conservatism inherent in using H/Pu = 2 composition.

The following cases have plutonium metal buttons surrounded by PuO_2 with plutonium density at 5.5 g/cm^3 and H/Pu = 2, 100 wt% ^{239}Pu, in a cylindrical geometry of height to diameter equal to one. The blocked area in Table 9.1, on the side of low Pu metal and low PuO_2, shows where no administrative controls, other than mass limits, are necessary for criticality safety. Outside the blocked area, there will be reliance on administrative controls to support criticality safety.

In Table 9.2, the columns across from the left to the right are for zero, one, two, three, and four 2.5 kg plutonium metal buttons stacked up. The rows down are for increments of 2.5 kg PuO_2 at a density of 5.5 g Pu/cm^3.

Table 9.2 Plutonium Metal and Plutonium Oxide MONK6B Results.
Plutonium Metal Density 19.465 g/cm^3
PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2
2.5 Kilogram Metal Buttons Stacked
Surrounding PuO_2 Cylinder Height = Diameter
Reflection is 2 Inch Water on Sides and Top
EXTREMELY CONSERVATIVE CALCULATIONS

	0.0 kg Pu	2.5 kg Pu	5.0 kg Pu	7.5 kg Pu	10.0 kg Pu
0.0 kg PuO_2	0.0000±0.0000	0.7067±0.0028	0.9215±0.0031	1.0320±0.0033	1.0970±0.0035
2.5 kg PuO_2	0.5441±0.0024	0.8057±0.0034	0.9944±0.0035	1.1103±0.0036	1.1537±0.0036
5.0 kg PuO_2	0.6916±0.0029	0.8624±0.0034	1.0303±0.0037	1.1392±0.0039	1.2018±0.0038
7.5 kg PuO_2	0.7790±0.0029	0.9134±0.0033	1.0577±0.0037	1.1728±0.0040	1.2297±0.0039
10.0 kg PuO_2	0.8461±0.0030	0.9510±0.0034	1.0816±0.0040	1.2052±0.0039	
12.5 kg PuO_2	0.9050±0.0032	0.9855±0.0036	1.1041±0.0037		
15.0 kg PuO_2	0.9566±0.0033	1.0179±0.0036			
17.5 kg PuO_2	0.9925±0.0034	1.0521±0.0035			
20.0 kg PuO_2	1.0290±0.0035				

The first column shows that the single contingency of double batching of PuO_2 for 10 kg Pu in a single cylinder does not compromise criticality safety. The double contingency of triple batching of PuO_2 together for 15 kg plutonium in a single cylinder does exceed the criticality safety limit. The volume required is 15,000 g Pu/5.5 g Pu/cm^3 = 2,727.27 cm^3 = 2.73 Liters, which is larger than any single container except the sieve shaker pan and one sieve screen in a stack.

The second column shows that the single contingency of double batching of one 2.5 kg plutonium metal button with 5 kg of PuO_2 in a single cylinder does not compromise criticality safety. The double contingency of triple batching of one 2.5 kg plutonium metal button with 10 kg of PuO_2 together in a single cylinder also does not compromise criticality safety. The volume required is one plutonium metal button and 10 kg PuO_2 is:

2.5 kg Pu/19.465 g Pu/cm^3 + 10. kg Pu/5.5 g Pu/cm^3 = 1,946.62 cm^3 = 1.95 Liters,

which approaches the size of single containers and the sieve shaker catch pan.

The third column shows that a single contingency of double batching two 2.5 kg plutonium metal buttons does not compromise criticality safety. An additional contingency of combining 2.5 kg of PuO_2 with double batched 5.0 kg of plutonium metal does exceed the k_{eff} = 0.9350 criticality safety limit.

The fourth and fifth columns show that multiple contingencies of stacking multiple 2.5 kg plutonium metal buttons does exceed the k_{eff} = 0.9350 criticality safety limit.

There is conservatism in Table 9.2, Plutonium Meal and Plutonium Oxide MONK6B Results, due to the H/Pu = 2 composition, and the thickness of the water reflector being 2 inches instead of the 1 inch used in Table 9.1, HC-21A Normal and Off-Normal MONK6B Results.

The conservatism in Table 9.2 calculations is demonstrated by two additional series of calculations. Table 9.3, Three Button Plutonium Metal Stack MONK5B Results, shows the effect of changing the water reflection and the ^{240}Pu wt%. Table 9.4, 15.0 Kilogram Plutonium Oxide Cylinder MONK6B Results, shows the effect of changing the H/Pu = 2 and the water reflection.

Table 9.3 shows that the 30 cm (12 in.) of H_2O reflection outside the glovebox has only a small effect of the k_{eff}, while the 5.08 cm (2 in.) of close fitting H_2O reflection is sufficient to raise the k_{eff} from 0.9078 ± 0.0033 (acceptable according to the k_{eff} < 0.935 limit) to k_{eff} of 1.0320 ± 0.0033 (prompt critical!). The ^{240}Pu wt% did not change the k_{eff} more than the uncertainty of these Monte Carlo calculations. The point here is that glovebox models must include at least 2.54 cm (1 in.) of water reflection inside the glovebox as part of the model in order to bound the effect of human hands inside plastic gloves picking up parts and containers.

Table 9.3 Three Button Plutonium Metal Stack MONK6B Results. Plutonium Metal Density 19.465 g Pu/cm^3 2.5 Kilogram Metal Buttons Stacked Variation on Top Line (from Table 9.2)	
3 Stacked Buttons, 12" H_2O outside HC-21A, 2" H_2O around stack, 100% ^{239}Pu, 0% ^{240}Pu	1.0320±0.0033
Top Situation, only without 12" H_2O outside HC-21A	1.0259±0.0034
Top Situation, only without 2" H_2O around stack	0.9078±0.0033
Top Situation, only with 97% ^{239}Pu, 3% ^{240}Pu	1.0223±0.0032
Top Situation, only with 95% ^{239}Pu, 5% ^{240}Pu	1.0304±0.0034

Table 9.4, 15.0 Kilogram Plutonium Oxide Cylinder MONK6B Results, investigated the effect of H_2O reflection and the H/Pu = 2 composition effect on k_{eff}. Reducing the 5.08 cm (2 in.) of close fitting H_2O reflection down to 2.54 cm (1 in.) lowered the k_{eff} from 0.9566 ± 0.0033 (not acceptable according to the k_{eff} < 0.935 limit) down to k_{eff} of 0.8832 ± 0.0033 (within the acceptable range!). The composition change from H/Pu = 2 to composition of H/Pu = 0 k_{eff} also dropped the k_{eff} down to 0.7716 ± 0.0029 (well within the acceptable range). The dominant conservatism is the H/Pu = 2 composition assumption. The H/Pu = 2 is a conservatism for PuO_2 that had been heated in the muffle furnaces, but with water entered into the glovebox, it would not be a conservative assumption. The 5.08 cm (2 in.) of water reflection is more than two gloved hands could cause in neutron reflection around a 7.572 cm (2.98 in.) radius, 15.143 cm (5.96 in.) high cylinder. Either conservative assumption relaxed from the Table 9.2 results would show that 15 kg Pu in PuO_2 has a k_{eff} < 0.935, even in one cylinder with H/D = 1.

Table 9.4 15.0 Kilogram Plutonium Oxide Cylinder MONK6B Results. Plutonium Density 5.50 g Pu/cm^3 H/D = 1 and Water Reflection Outside Variation on Top Line (from Table 9.2)	
PuO_2 + H_2O for H/Pu = 2, H_2O reflection 2 inches	0.9566±0.0033
PuO_2 for H/Pu = 0, H_2O reflection 2 inches	0.7716±0.0029
PuO_2 + H_2O for H/Pu = 2, H_2O reflection 1 inch	0.8832±0.0033
PuO_2 for H/Pu = 0, H_2O reflection 1 inch	0.7014±0.0026

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APPENDIX A

INDEPENDENT REVIEW COMMENTS AND CHECKLIST

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TECHNICAL PEER REVIEW

E. M. Miller of the Criticality & Shielding Group carried out an independent, technical review of this CSER 96-023, for which the following comments were provided.

The first concern of this reviewer is that the high reactivity of the buttons and cans be impressed on fissile material handlers assigned to this glovebox. Two plutonium metal buttons placed flat ends together and cupped in two gloved hands is close to a sphere of 5 kg of plutonium metal reflected by one inch of water. This assembly needs only a few more inches of reflection to go critical. A fully reflected sphere of 5.45 kg of plutonium metal is a critical assembly. Fortunately, plutonium buttons are normally less than 2.5 kg each and the glovebox has an end open to the conveyor to let water flow out before a depth representative of full water reflection could accumulate. Table 9.1 shows that 3 loaded 4.4 kg Pu cans are safely subcritical even with one inch of water reflection from hands in plastic gloves. However, four of the cans similarly reflected are a critical assembly. The potential for a problem arises because each container has so much fissile material. It is fortunate that one person's hands can not give one inch reflection to four cans. But the change that one can can make needs to be communicated to operators as well as the amount of reflection that a plastic ALARA shield represents. Note well the sensitivity k_{eff} has to reflector thickness shown in Table 9.4.

The technical arguments for qualifying the criticality safety of the HC-21A glovebox were found to be sound, the computer runs fairly represented, and the quoted criticality parameters in the text and tables were confirmed by review of the referenced data and computer runs. The limits presented in the analysis are not optimum for operations, but are safely subcritical even for water entry into the glovebox. A revision 1 to the CSER may improve the operability of the criticality limits.

The assessment of criticality safety for water entry is based on handbook values to set mass and volume limits for groupings of containers. These values were checked. The limits for dry product were assessed by computer run. These runs were reviewed for atom densities of plutonium and other materials, for the geometry by the input and by the pictorial representation in scan runs, for the volumes of containers computed by the program as a check on the input dimensions, that the energy spectrum of the neutrons was a hard spectrum, that all plutonium masses had fissions, and that each calculation converged. Not all computer runs were checked, but all runs in Table 9.1 were and the runs along the highlighted boundary in Table 9.2 were.

A number of conservative representations were found in the input that were not given in the text. Table 9.1 was originally labelled as having a one inch water reflection while the model run had two inches, a conservative representation. A plutonium metal button height of 3.5615 cm was used rather than the usual 3.244 cm. This translates to a button mass of 2.74 kg rather than the normal 2.5 kg upper limit. Again this is a conservative representation. For Table 9.1, the glovebox height is 54 inches above the concrete floor. For Table 9.2 runs, the height is 48 inches. This is a conservative representation of the actual 54 inch height. Cases HC21AA7 and HC21AAB both are listed in Table 9.1 as modelling 3 side-by-side boats containing a 2.5 kg button and 5 kg of plutonium oxide. The k_{eff}s are 0.80 and 0.89. The difference is the higher k_{eff} is due to two inches of water on top and filling the space in the boat water while the other case has only one inch of water reflector. The analyses used an albedo to model thick concrete on the outside surface of a 20 cm thick concrete slab. This is correct for a thermalized neutron spectrum, but the dry plutonium has a hard spectrum. At least 40 cm of concrete needs to be modeled before the albedo is used. However, this arrangement returns more neutrons than would the thicker concrete slab model. The only nonconservative modelling found was the use of 19.464 g/cc for plutonium metal rather than the theoretical value of 19.81 g/cc or 19.6 g/cc for measured solid plutonium. This is a small difference from the most conservative values and is more dense than would be expected for actual buttons.

The contingencies used to ensure that it took two contingencies before an operation had a k_{eff} greater than 1.0 were found to cover all reasonable challenges to the operational limits. An added container or an added mass unit to each operation was considered. Adding water to open containers and the glovebox, fire, and earthquake were considered. The groupings of container volume and contained plutonium mass were limited to maintain an adequate margin from criticality allowables. The highest plutonium density, 5.5 g/cc, in oxide of any allowed operation at PFP, the vertical calciner output density limit, is used in the analysis. This is another conservatism in the analysis.

This CSER adequately analyzes the criticality hazards of processing plutonium in glovebox HC-21A. Contingencies have been adequately analyzed. Based on the limits specified in this CSER, the processing of plutonium metal buttons and of plutonium oxide can be carried out within criticality allowables.

CHECKLIST FOR INDEPENDENT REVIEW

Document Reviewed: CSER 96-023:
PFP Glovebox HC-21A With 4.4 Kilogram Plutonium Cans
Author: Warren D. Wittekind

Yes	No	N/A	
[X]	[ ]	[ ]	Problem completely defined.
[X]	[ ]	[ ]	Necessary assumptions explicitly stated and supported.
[X]	[ ]	[ ]	Computer codes and data files documented.
[X]	[ ]	[ ]	Data checked for consistency with original source information as applicable.
[X]	[ ]	[ ]	Mathematical derivations checked including dimensional consistency of results.
[X]	[ ]	[ ]	Models appropriate and used within range of validity or use outside range of established validity justified.
[X]	[ ]	[ ]	Hand calculations checked for errors.
[X]	[ ]	[ ]	Code run streams correct and consistent with analysis documentation.
[X]	[ ]	[ ]	Code output consistent with input and with results reported in analysis documentation.
[X]	[ ]	[ ]	Acceptability limits on analytical results applicable and supported. Limits checked against sources.
[X]	[ ]	[ ]	Safety margins consistent with good engineering practices.
[X]	[ ]	[ ]	Conclusions consistent with analytical results and applicable limits.
[X]	[ ]	[ ]	Results and conclusions address all points required in the problem statement.
[X]	[ ]	[ ]	Have all reasonable accidents been considered?
[ ]	[ ]	[X]	Has low density water (steam) been evaluated as a moderator?
[X]	[ ]	[ ]	Is the fuel and other hardware composition correct?
[X]	[ ]	[ ]	Are the cases considered conservative?
[X]	[ ]	[ ]	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?
[X]	[ ]	[ ]	Has the analysis been reviewed by Safety? This may not be required in a preliminary design.
[X]	[ ]	[ ]	Has the reviewer completed the Criticality Safety Course for Managers and Engineers? Date completed 06/15/95

Reviewed by: Edward M. Miller (original signed) Date 12/3/96

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.

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APPENDIX B

MONK COMPUTER CODE VALIDATION

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B.1 VALIDATION PROCEDURE

The validation of the methods used in the analysis consists of testing the ability of the code and neutron cross-sections in calculations of known critical configurations, which are various benchmark experiments with the fissile material in question. Such analyses determine a calculational bias (the deviations of calculated k_{eff} values from unity for the benchmark cases) and the uncertainties culminating from the experimental and calculational errors.

The safety criteria for future calculations on undetermined systems requires that the bias-adjusted k_{eff} does not exceed 0.95 at the 95% confidence level. This is expressed by the following formula;

$$k_{eff} = k_{calc} - bias + (U_b^2 + U_c^2)^{1/2} \leq 0.95$$

where k_{calc} = k value given by calculation for system in question,
bias = mean difference (k_{calc} - 1.0) for benchmark criticals
U_b = 95% confidence level uncertainty in the bias determination,
and U_c = 95% confidence level uncertainty in new calculation.

Thus, the bias-adjusted k_{eff} includes the statistical uncertainties.

B.2 GENERIC VALIDATION FOR PLUTONIUM SYSTEMS

A report by L. L. Macklin and E. M. Miller, *MONK6A Pu Validation* (Macklin and Miller 1992), presents the results of calculations to determine a generic bias for plutonium configurations, as encountered in the Plutonium Finishing Plant. Seventy benchmark experiments were calculated, ranging from simple metal spheres to highly dilute (9 g plutonium per liter) plutonium nitrate solution spheres, and also compacts of PuO_2 blended with polystyrene. A mean k_{eff} value of 1.0047 was determined over the full experimental range, with an overall standard deviation of 0.0097.

The direct calculational bias is thus +0.0047 (average k_{eff} greater than unity). Accounting for the uncertainties using a tolerance limit analysis, the report then concludes that

> At least 95% of all critical experiments of this type computed by the MONK6A code will produce calculated k_{eff} values greater than 0.9857 with 95 % confidence.

For a standard deviation (σ) of 0.01 or less for the convergence of a future calculation (U_c), the 0.9857 value is lowered to 0.9855. Rounded conservatively, a value of +0.015 can be used for [-bias + $(U_b^2 + U_c^2)^{1/2}$]. On this basis, it is determined that the true k_{eff} of an analyzed configuration with plutonium will not exceed 0.95 with a 95% confidence level if the calculated value (k_{calc}, $\sigma \leq 0.01$) is limited to a maximum value of **0.935**.

The 95% confidence level on 99.9% of the data is 0.9699. So a subcritical margin of 5% is 3.5% larger than the uncertainties between the 95.0% and 99.9% coverage of the benchmark data.

B.3 VALIDATION OF MONK6B

The validation of the MONK6B code on the SUN microcomputers was documented in Miller, 1994. The essence of the validation was cross-correlation of calculational results obtained with this code version and computer with results for identical input models done on the CRAY machine with MONK6A, as reported in the previous subsection. Also, the equivalence of MONK6B to MONK6A was well documented by the code vendors, the United Kingdom Atomic Energy Authority, in the verification package supplied with the software.

The abstract from CCVR 94-001 summarizes the validation study as follows;

> The MONK6B validation for bare plutonium and plutonium water systems on the SUN computer and operating system is established in this report. Because the calculational method and nuclear cross-sections have not changed from the MONK6A code to the MONK6B code, the bias determination done for MONK6A is valid for MONK6B.

APPENDIX C

REPRESENTATIVE MONK6B INPUT FILES

CASE	Description
HC21AA9.INP,	Glovebox, 3 Furnace Boats, 4 - 4.4 kg Pu cans, nominal reflection
HC21AB6.INP,	Glovebox, Sieve Pan, 3 - 4.4 kg Pu cans, 1/8" PuO_2, nominal refl.
HC21AC6.INP,	Glovebox, 3 - 4.4 kg Pu cans, 1/8" PuO_2 layer, nominal reflection
B3P000N.INP,	7.5 kg Pu metal, 0.0 kg Pu in PuO_2, nominal reflection

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*************** HC21AA9.INP ***************

* HC21AA9        MONK6B model for HC-21A
* HC-21A Glovebox with: Furnace Boats, Sieve Pan stack,
4.4 kg Pu cans
* Outside Glovebox is side water reflector, Concrete
floor, open to roof
* (2.5 kg Pu ea) buttons, R=3.55 cm, H=3.244 cm, 19.466
g/cm3
* PuO2 mixed with H2O for H/Pu=2
*
FISSION
* Number of Materials          Number of Nuclides
       6                            11
NUCNAMES
* Keyword          Nuclide       Number density
At/(barn-cm)
* Material #1: Button at Pu metal density
CONC               PU239         0.049034
* Material #2: PuO2 at 5 g Pu/cm3 with H2O mixed in
CONC               PU239         0.012596
                   O             0.044034
                   HINH2O        0.037686
* Material #3: Water
CONC               HINH2O        0.066855
                   O             0.033427
* Material #4: Hastelloy X
CONC               C             0.000413
                   SI            0.001765
                   CR            0.020969
                   MN            0.000902
                   FE            0.015975
                   NI            0.041284
                   MO            0.004691
* Material #5: Hanford 304 Stainless Steel cans (Tom
Nirider)
CONC               CR            0.01743
                   MN            0.00174
                   FE            0.05936
                   NI            0.00772
* Material #6: Hanford ordinary concrete density= 2.26
g/cc
* (Lee Carter, 1983; short list)
CONC               HINH2O        0.00418
                   O             0.03855
                   SI            0.01567
                   CA            0.04678
                   FE            0.00195
*
CM
*
* The following input describes the geometry
* PART-1:   FURNACE BOAT  2.5 KG PU METAL BUTTON
  NEST 4
 1   ZROD ORIGIN   6.67   22.15    0.3175   1     3.550
3.5615
 2   ZROD ORIGIN   6.67   22.15    0.3175   3     6.090
6.1015
 3   BOX  ORIGIN   0.3175  0.3175  0.3175   0    12.70
27.94    6.20
 4   BOX  ORIGIN   0.000   0.000   0.000    4    13.335
28.575   6.518
* PART-2   SIEVE SHAKER (PAN=5.08 CM, 1S=>10.16 CM,
2S=>15.24 CM, 3S=>20.32 CM
* NEST  4
* 1  ZROD                                   2    10.16
5.08
* 2  ZROD                                   0    10.16
10.16
* 3  ZROD                                   0    10.16
15.24
* 4  ZROD                                   0    10.16
20.32
* PART-2   4.4 kg PuO2 CANS, DRY PuO2 (H/Pu=2)
(HEIGHT=>5 kg Pu)
  NEST 2
  1 ZROD    2   4.3656  15.1834
  2 ZROD    0   4.3656  20.9550
* PART-3   GLOVEBOX ARRANGEMENT: THREE FURNACE BOATS IN
A ROW, WATER AROUND
  CLUSTER  8
  1   BOX  ORIGIN   2.540    2.540    0.000    P1    13.335
28.575   6.518
  2   BOX  ORIGIN  15.875    2.540    0.000    P1    13.335
28.575   6.518
  3   BOX  ORIGIN  29.210    2.540    0.000    P1    13.335
28.575   6.518
  4   ZROD ORIGIN   6.906   35.481    0.000    P2
4.3656 20.9550
  5   ZROD ORIGIN  15.638   35.481    0.000    P2
4.3656 20.9550
  6   ZROD ORIGIN  24.370   35.481    0.000    P2
4.3656 20.9550
  7   ZROD ORIGIN  33.102   35.481    0.000    P2
4.3656 20.9550
  8   BOX                                          3    45.085
42.387  23.495
* PART-4   HC-21A GLOVEBOX, 30 CM H2O REFLECTION ON ALL
FOUR SIDES
  NEST 7
   1  BOX                                            P3
45.085  42.387  23.495
   2  BOX                                             0
266.700 106.680  91.440
   3  BOX  ORIGIN   -0.635    -0.635    -0.635    5
267.970 107.950  96.520
   4  BOX  ORIGIN   -0.635    -0.635 -137.795    0
267.970 107.950 233.680
   5  BOX  ORIGIN  -30.635   -30.635 -137.795    3
327.970 167.950 233.680
   6  BOX  ORIGIN  -60.635   -60.635 -137.795    0
387.970 227.950 263.680
   7  BOX  ORIGIN  -60.635   -60.635 -157.795    6
387.970 227.950 283.680
*
ALBEDO  0   0   0   0   0  -0.74
* End of geometry input
*
* Superhistory option using 10 generation per
superhistory
* and nu multiplication factor = 1.0
SUPERHIST  10  1.0
* First stage  Last stage  Neutrons per stage  time
limit  Source
     -3           10            1000              160
   -1
*
* Starting source
MULTIFISS
STD
REGION 1 IN PART 1 /
END
CODE 6
POWHSC
* Horizontal Slice:  Glovebox and Contents
  -0.63 107.31 1.939       267.33 107.31 1.939      -0.63
-0.63  1.939
* Horizontal Slice:  Glovebox in Room
 -60.63 167.31 1.939       327.33 167.31 1.939     -60.63
-60.63  1.939
* Vertical Slice:  Glovebox in Room
 -60.63  24.69 125.88      327.97 24.69 125.88     -60.63
24.69 -157.79
END

*************** HC21AB6.INP ***************

* HC21AB6        MONK6B model for HC-21A
* HC-21A Glovebox with: Furnace Boats, Sieve Pan stack,
4.4 kg Pu cans
* Outside Glovebox is side water reflector, Concrete
floor, open to roof
* (2.5 kg Pu ea) buttons, R=3.55 cm, H=3.244 cm, 19.466
g/cm3
```

```
* PuO2 mixed with H2O for H/Pu=2
*
FISSION
* Number of Materials          Number of Nuclides
      6                             11
NUCNAMES
* Keyword         Nuclide      Number density
At/(barn-cm)
* Material #1: Button at Pu metal density
CONC              PU239        0.049034
* Material #2: PuO2 at 5 g Pu/cm3 with H2O mixed in
CONC              PU239        0.012596
                  O            0.044034
                  HINH2O       0.037686
* Material #3: Water
CONC              HINH2O       0.066855
                  O            0.033427
* Material #4: Hastelloy X
CONC              C            0.000413
                  SI           0.001765
                  CR           0.020969
                  MN           0.000902
                  FE           0.015975
                  NI           0.041284
                  MO           0.004691
* Material #5: Hanford 304 Stainless Steel cans (Tom
Nirider)
CONC              CR           0.01743
                  MN           0.00174
                  FE           0.05936
                  NI           0.00772
* Material #6: Hanford ordinary concrete density= 2.26
g/cc
* (Lee Carter, 1983; short list)
CONC              HINH2O       0.00418
                  O            0.03855
                  SI           0.01567
                  CA           0.04678
                  FE           0.00195
*
CM
*
* The following input describes the geometry
* PART-1:   FURNACE BOAT  2.5 KG PU METAL BUTTON
* NEST 4
* 1   ZROD ORIGIN   6.67   14.29    0.3175   1    3.550
 3.5615
* 2   ZROD ORIGIN   6.67   14.29    0.3175   3    6.090
 6.1015
* 3   BOX  ORIGIN   0.3175  0.3175  0.3175   0    12.70
27.94    6.20
* 4   BOX  ORIGIN   0.000   0.000   0.000    4    13.335
28.575   6.518
* PART-1   SIEVE SHAKER (PAN=5.08 CM, 1S=>10.16 CM,
2S=>15.24 CM, 3S=>20.32 CM
  NEST  2
  1  ZROD                                    2    10.16
5.08
  2  ZROD                                    0    10.16
10.16
* PART-2   4.4 kg PuO2 CANS, DRY PuO2 (H/Pu=2)
(HEIGHT=>5 kg Pu)
  NEST 2
  1 ZROD    2   4.3656  15.1834
  2 ZROD    0   4.3656  20.9550
* PART-3   GLOVEBOX ARRANGEMENT: FULL SIEVE SHAKER PAN
AND 0 SIEVES, H2O AROUND
  CLUSTER  5
  1   ZROD                                   P1   10.16
10.16
  2   ZROD ORIGIN  13.321  -5.794   0.000    P2
4.3656 20.955
  3   ZROD ORIGIN  14.329   2.902   0.000    P2
4.3656 20.955
  4   ZROD ORIGIN  10.081  10.589   0.000    P2
4.3656 20.955
  5   ZROD                                    3   21.526
23.495
* PART-3   HC-21A GLOVEBOX, 30 CM H2O REFLECTION ON ALL
FOUR SIDES, 1/8" PuO2
  NEST 8
  1  ZROD ORIGIN   21.53    21.53     0.318  P3
21.526  23.495
  2  BOX  ORIGIN    0.000    0.000    0.318   0
266.700 106.680  91.122
  3  BOX                                      2
266.700 106.680  91.440
  4  BOX  ORIGIN   -0.635   -0.635   -0.635   5
267.970 107.950  96.520
  5  BOX  ORIGIN   -0.635   -0.635 -137.795   0
267.970 107.950 233.680
  6  BOX  ORIGIN  -30.635  -30.635 -137.795   3
327.970 167.950 233.680
  7  BOX  ORIGIN  -60.635  -60.635 -137.795   0
387.970 227.950 263.680
  8  BOX  ORIGIN  -60.635  -60.635 -157.795   6
387.970 227.950 283.680
*
ALBEDO   0   0   0   0   0  -0.74
* End of geometry input
*
* Superhistory option using 10 generation per
superhistory
* and nu multiplication factor = 1.0
SUPERHIST  10  1.0
* First stage  Last stage  Neutrons per stage  time
limit  Source
     -3           10           1000               160
   -1
*
* Starting source
MULTIFISS
STD
REGION 1 IN PART 1 /
END
CODE 6
POWHSC
* Horizontal Slice:  Glovebox and Contents
  -0.63 107.31 1.939      267.33 107.31 1.939     -0.63
-0.63  1.939
* Horizontal Slice:  Glovebox in Room
  -60.63 167.31 1.939      327.33 167.31 1.939    -60.63
-60.63  1.939
* Vertical Slice:  Glovebox in Room
  -60.63  21.53 125.88     327.97 21.53 125.88    -60.63
21.53 -157.79
END

*************** HC21AC6.INP ***************

* HC21AC6        MONK6B model for HC-21A
* HC-21A Glovebox with: Furnace Boats, Sieve Pan stack,
4.4 kg Pu cans
* Outside Glovebox is side water reflector, Concrete
floor, open to roof
* (2.5 kg Pu ea) buttons, R=3.55 cm, H=3.244 cm, 19.466
g/cm3
* PuO2 mixed with H2O for H/Pu=2
*
FISSION
* Number of Materials          Number of Nuclides
      6                             11
NUCNAMES
* Keyword         Nuclide      Number density
At/(barn-cm)
* Material #1: Button at Pu metal density
CONC              PU239        0.049034
* Material #2: PuO2 at 5 g Pu/cm3 with H2O mixed in
CONC              PU239        0.012596
                  O            0.044034
                  HINH2O       0.037686
* Material #3: Water
CONC              HINH2O       0.066855
                  O            0.033427
```

```
* Material #4: Hastelloy X
CONC            C          0.000413
                SI         0.001765
                CR         0.020969
                MN         0.000902
                FE         0.015975
                NI         0.041284
                MO         0.004691
* Material #5: Hanford 304 Stainless Steel cans (Tom
Nirider)
CONC            CR         0.01743
                MN         0.00174
                FE         0.05936
                NI         0.00772
* Material #6: Hanford ordinary concrete density= 2.26
g/cc
* (Lee Carter, 1983; short list)
CONC            HINH2O     0.00418
                O          0.03855
                SI         0.01567
                CA         0.04678
                FE         0.00195
*
CM
*
* The following input describes the geometry
* PART-1:   FURNACE BOAT  2.5 KG PU METAL BUTTON
* NEST 4
* 1   ZROD ORIGIN   6.67   14.29   0.3175   1    3.550
 3.5615
* 2   ZROD ORIGIN   6.67   14.29   0.3175   3    6.090
 6.1015
* 3   BOX  ORIGIN   0.3175  0.3175  0.3175   0   12.70
27.94    6.20
* 4   BOX  ORIGIN   0.000   0.000   0.000    4   13.335
28.575   6.518
* PART-1   SIEVE SHAKER (PAN=5.08 CM, 1S=>10.16 CM,
2S=>15.24 CM, 3S=>20.32 CM
* NEST  4
* 1  ZROD                                  2    10.16
5.08
* 2  ZROD                                  3    10.16
10.16
* 3  ZROD                                  0    10.16
15.24
* 4  ZROD                                  0    10.16
20.32
* PART-1   4.4 kg PuO2 CANS, DRY PuO2 (H/Pu=2)
(HEIGHT=>5 kg Pu)
  NEST 2
  1 ZROD    2   4.3656  15.1834
  2 ZROD    0   4.3656  20.9550
* PART-2   GLOVEBOX ARRANGEMENT: 3 FULL 4.4 KG
PLUTONIUM CANS, H2O AROUND
CLUSTER 4
  1  ZROD ORIGIN      0.0        0.0        0.0   P1
4.3656  20.955
  2  ZROD ORIGIN    -4.3660     7.5621      0.0   P1
4.3656  20.955
  3  ZROD ORIGIN     4.3660     7.5621      0.0   P1
4.3656  20.955
  4  ZROD ORIGIN      0.0       3.781       0.0    3
10.687   23.495
* PART-3   HC-21A GLOVEBOX, 30 CM H2O REFLECTION ON ALL
FOUR SIDES + 1/8" PUO2
  NEST 8
  1  ZROD ORIGIN   10.690   10.690    0.318  P2
10.687  23.495
  2  BOX  ORIGIN    0.0      0.0      0.318   0
266.700 106.680  91.122
  3  BOX                                      2
266.700 106.680  91.440
  4  BOX  ORIGIN   -0.635   -0.635   -0.635   5
267.970 107.950  96.520
  5  BOX  ORIGIN   -0.635   -0.635 -137.795   0
267.970 107.950 233.680
  6  BOX  ORIGIN  -30.635  -30.635 -137.795   3
327.970 167.950 233.680
  7  BOX  ORIGIN  -60.635  -60.635 -137.795   0
387.970 227.950 263.680
  8  BOX  ORIGIN  -60.635  -60.635 -157.795   6
387.970 227.950 283.680
*
ALBEDO   0   0   0   0   0  -0.74
* End of geometry input
*
* Superhistory option using 10 generation per
superhistory
* and nu multiplication factor = 1.0
SUPERHIST  10  1.0
* First stage  Last stage  Neutrons per stage  time
limit  Source
     -3           10          1000               160
   -1
*
* Starting source
MULTIFISS
STD
REGION 1 IN PART 1 /
END
CODE 6
POWHSC
* Horizontal Slice:  Glovebox and Contents
  -0.63 107.31 1.939      267.33 107.31 1.939     -0.63
-0.63  1.939
* Horizontal Slice:  Glovebox in Room
  -60.63 167.31 1.939      327.33 167.31 1.939    -60.63
-60.63  1.939
* Vertical Slice:  Glovebox in Room
  -60.63  10.69 125.88      327.97 10.69 125.88    -60.63
10.69 -157.79
END
```

```
*************** B3P000N.INP ***************

* B3P000N          MONK6B model for HC-21A
* 3 (2.5 kg Pu ea) buttons, R=3.55 cm, H=3.244 cm,
19.466 g/cm3
* 00.0 kg PuO2,     PuO2 mixed with H2O, shaped to H/D =
1
* Reflected by 5.08 cm of H2O on radius and top
* Sitting on Carbon steel in air over concrete
*
FISSION
* Number of Materials          Number of Nuclides
        6                            10
NUCNAMES
* Keyword          Nuclide        Number density
At/(barn-cm)
* Mat #1 - Button at Pu metal density
CONC              PU239          0.049034
* Mat #2 - PuO2 + H2O, 5.5 g Pu/cm3 (H/Pu = 2)
CONC              PU239          0.013855
                  O              0.041565
                  HINH2O         0.027710
* Mat #3 - Water
CONC              HINH2O         0.066855
                  O              0.033427
* Mat #4 - Carbon Steel (1% Carbon),  7.86 g/cm3
CONC              FE             0.083491
                  C              0.003921
* Mat #5 - Concrete per Bob Richard
CONC              O              0.041519
                  HINH2O         0.014868
                  CA             0.011588
                  SI             0.006037
                  C              0.003814
                  AL27           0.000735
                  MG             0.000587
                  NA23           0.000304
                  FE             0.0001968
* Mat #6 - Concrete per ARH-600, page II.F.1-2
CONC              O              0.04608
                  SI             0.01663
```

```
                HINH2O       0.01375
                AL27         0.00175
                NA23         0.00175
                CA           0.00152
                FE           0.00035
*
CM
*
* The following input describes the geometry
NEST 9
* This nest: three Pu buttons, then PuO2+H2O, then H2O
* Pu metal buttons
1 ZROD ORIGIN 37.0  0  0.635    1   3.55     9.732
* PuO2+H2O mixture (H/D = 1)
2 ZROD ORIGIN 37.0  0  0.635    0   3.56     9.733
* H2O reflector inside Glovebox
3 ZROD ORIGIN 37.0  0  0.635    3   8.64    14.813
* Air region inside Glovebox
4 ZROD ORIGIN  0    0  0.635    0  45.72    45.72
* Carbon Steel of Glovebox
5 ZROD ORIGIN  0    0  0        4  46.355   46.99
* Air Space under Glovebox
6 ZROD ORIGIN  0  0 -121.92     0  46.355  168.91
* H2O reflector outside Glovebox
7 ZROD ORIGIN  0  0 -121.92     3  76.355  168.91
* Air region outside Glovebox
8 ZROD ORIGIN  0  0 -121.92     0 106.355  198.91
* Concrete reflector floor
9 ZROD ORIGIN  0  0 -141.92     5 106.355  238.91
*
ALBEDO    0   0   -0.74
* End of geometry input
*
* Superhistory option using 10 generation per
superhistory
* and nu multiplication factor = 1.0
SUPERHIST  10  1.0
* First stage  Last stage  Neutrons per stage  time
limit  Source
     -3          10            1000               160
   -1
*
* Starting source
MULTIFISS
STD
REGION 1 IN PART 1 /
END
CODE 6
POWSCC
 0.0  0.0  30.0   90.0  0.0  30.0  0.0  0.0  -5.0
* Vertical Slice: 3 Buttons, PuO2+H2O 0 kg, H2O in
Glovebox
 -100.0  0.0 238.9   100.0  0.0  238.9    -100.0  0.0
0.0
* Vertical Slice:  Big Glovebox picture
END
```

APPENDIX D

PARAMETRIC STUDY SPREADSHEET FILES

Table D.1	0 Plutonium Buttons	PuO_2 Radius and PuO_2 Height Calculation
Table D.2	1 Plutonium Buttons	PuO_2 Radius and PuO_2 Height Calculation
Table D.3	2 Plutonium Buttons	PuO_2 Radius and PuO_2 Height Calculation
Table D.4	3 Plutonium Buttons	PuO_2 Radius and PuO_2 Height Calculation
Table D.5	4 Plutonium Buttons	PuO_2 Radius and PuO_2 Height Calculation

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The parametric study of plutonium metal buttons stacked, surrounded by PuO_2 with an H/D = 1 geometry, and 5.08 cm (2 in.) H_2O on the radius and height had dimensions calculated by spreadsheets. The Pu button is assumed to have 3.255 cm radius and 3.244 cm height, and a 2,500.0 g Pu mass. The results of the spreadsheet calculations are tabulated in the following tables. The columns in the followig tables need some description:

- Column 1 PuO_2 mass in kg
- Column 2 PuO_2 volume in cm^3
- Column 3 Pu volume + PuO_2 volume in cm^3
- Column 4 Calculated D from $\pi/4*D^2*H$ = (PuO_2 + Pu) Volume (for D = H)
- Column 5 Calculated Volume from $\pi/4*D^2*H$ (for D = H)
- Column 6 Radius = D in Column 4 / 2.0
- Column 7 Height = D in Column 4
- Column 8 Radius of Pu + PuO_2 when height < Pu button stack height
- Column 9 Height of Pu + PuO_2 when height < Pu button stack height

These were the Pu and PuO_2 dimensions used in the MONK6B calculations.

Table D.1 0 Plutonium Button Calculation for Radius, Height

Dimension calculations for PuO2 in an H/D = 1 geometry					0	Buttons
Pu metal	0.00	Pu(PuO2)=	5.50	g/cm3		
PuO_2 kg	PuO_2 cm^3	Pu cm^3	D = H	Cal'd cm^3	radius	height
0.0	0.00	0.00	ERR	ERR	ERR	ERR
2.5	454.55	454.55	8.334	454.55	4.167	8.334
5.0	909.09	909.09	10.500	909.09	5.250	10.500
7.5	1363.64	1363.64	12.019	1363.64	6.010	12.019
10.0	1818.18	1818.18	13.229	1818.18	6.614	13.229
12.5	2272.73	2272.73	14.250	2272.73	7.125	14.250
15.0	2727.27	2727.27	15.143	2727.27	7.572	15.143
17.5	3181.82	3181.82	15.941	3181.82	7.971	15.941
20.0	3636.36	3636.36	16.667	3636.36	8.334	16.667

Table D.2 1 Plutonium Button Calculation for Radius, Height								
Dimension calculations for PuO2 in an H/D = 1 geometry					1	Button		
Pu metal	128.44	Pu(PuO2)=	5.50	g/cm³				
PuO_2 kg	PuO_2 cm^3	Pu cm^3	D = H	Cal'd cm^3	radius	height	radius	height
0.0	0.00	128.44	5.468	128.44	2.734	5.468	3.2550	3.2440
2.5	454.55	582.98	9.054	582.98	4.527	9.054	0.0000	0.0000
5.0	909.09	1037.53	10.972	1037.53	5.486	10.972	0.0000	0.0000
7.5	1363.64	1492.07	12.385	1492.07	6.193	12.385	0.0000	0.0000
10.0	1818.18	1946.62	13.533	1946.62	6.767	13.533		
12.5	2272.73	2401.16	14.514	2401.16	7.257	14.514		
15.0	2727.27	2855.71	15.377	2855.71	7.689	15.377		
17.5	3181.82	3310.25	16.153	3310.25	8.077	16.153		

Table D.3 2 Plutonium Button Calculation for Radius, Height								
Dimension calculations for PuO2 in an H/D = 1 geometry					2	Button		
Pu metal	256.87	Pu(PuO2)=	5.50	g/cm³				
PuO_2 kg	PuO_2 cm^3	Pu cm^3	D = H	Cal'd cm^3	radius	height	radius	height
0.0	0.00	256.87	6.890	256.87	3.445	6.890	3.2550	6.4880
2.5	454.55	711.42	9.676	711.42	4.838	9.676	0.0000	0.0000
5.0	909.09	1165.96	11.408	1165.96	5.704	11.408	0.0000	0.0000
7.5	1363.64	1620.51	12.731	1620.51	6.365	12.731	0.0000	0.0000
10.0	1818.18	2075.05	13.824	2075.05	6.912	13.824		
12.5	2272.73	2529.60	14.768	2529.60	7.384	14.768		

Table D.4 3 Plutonium Button Calculation for Radius, Height

Dimension calculations for PuO2 in an H/D = 1 geometry					3	Button		
Pu metal	385.31	Pu(PuO2)=	5.50	g/cm^3				
PuO_2 kg	PuO_2 cm^3	Pu cm^3	D = H	Cal'd cm^3	radius	height	radius	height
0.0	0.00	385.31	7.887	385.31	3.943	7.887	3.2550	9.7320
2.5	454.55	839.85	10.226	839.85	5.113	10.226	0.0000	0.0000
5.0	909.09	1294.40	11.812	1294.40	5.906	11.812	0.0000	0.0000
7.5	1363.64	1748.94	13.059	1748.94	6.529	13.059	0.0000	0.0000
10.0	1818.18	2203.49	14.104	2203.49	7.052	14.104		

Table D.5 4 Plutonium Button Calculation for Radius, Height

Dimension calculations for PuO2 in an H/D = 1 geometry					4	Button		
Pu metal	513.74	Pu(PuO2)=	5.50	g/cm3				
PuO_2 kg	PuO_2 cm^3	Pu cm^3	D = H	Cal'd cm^3	radius	height	radius	height
0.0	0.00	513.74	8.681	513.74	4.340	8.681	3.2550	12.976
2.5	454.55	968.29	10.723	968.29	5.361	10.723	4.8737	12.976
5.0	909.09	1422.84	12.191	1422.84	6.095	12.191	5.9079	12.976
7.5	1363.64	1877.38	13.371	1877.38	6.685	13.371	0.0000	0.000

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APPENDIX E

MONK6B CASE DESIGNATION AND SUMMARY

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Case designations for the MONK6B calculations can be ascertained from the following tables

Table E.1 HC-21A Furnace Boat MONK6B Results. PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2 2.5 Kilogram Metal Buttons Nominal Reflection is 1 Inch Water on Sides and Top						
Case #	Pu Metal in Boats	Sieve Stack	PuO_2 in Cans	PuO_2 on GB floor		RESULTS $k_{eff} \pm \sigma$
HC21AA1	3@2.5 kg					0.7633±0.0029
HC21AA2	6@2.5 kg					0.7646±0.0029
HC21AA3	3@2.5 kg			0.125"		0.7736±0.0037
HC21AA4	6@2.5 kg			0.125"		0.7875±0.0034
HC21AA5	4@2.5 kg					0.7718±0.0028
HC21AA6	3@5.0 kg					0.9268±0.0033
HC21AA7	3@2.5 kg, 5 kg PuO_2					0.8022±0.0036
HC21AA8	3@2.5 kg	1.65 L				0.7808±0.0033
HC21AA9	3@2.5 kg		4 @ 5 kg			0.9255±0.0033
HC21AAA	6@2.5 kg					0.8844±0.0030
HC21AAB	3@2.5 kg, 5 kg PuO_2					0.8799±0.0039

Table E.2 HC-21A Sieve Screen Pan MONK6B Results. PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2 2.5 Kilogram Metal Buttons Nominal Reflection is 1 Inch Water on Sides and Top						
Case #	Pu Metal in Boats	Sieve Stack	PuO_2 in Cans	PuO_2 on GB floor		RESULTS $k_{eff} \pm \sigma$
HC21AB1		1.65 L				0.6899±0.0030
HC21AB2		3.29 L				0.9584±0.0033
HC21AB3		4.94 L				1.1084±0.0036
HC21AB4		6.59 L				1.1783±0.0037
HC21AB5		1.65 L	3@ 5 kg			0.9170±0.0033
HC21AB6		1.65 L	3@ 5 kg	0.125"		0.9378±0.0036

Table E.3 HC-21A 4.4 kg Pu Cans MONK6B Results.
PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2
2.5 Kilogram Metal Buttons
Nominal Reflection is 1 Inch Water on Sides and Top

Case #	Pu Metal in Boats	Sieve Stack	PuO_2 in Cans	PuO_2 on GB floor		RESULTS $k_{eff} \pm \sigma$
HC21AC1			3@ 5 kg			0.9081±0.0033
HC21AC2			4@ 5 kg			1.0140±0.0036
HC21AC3			5@ 5 kg			1.0512±0.0035
HC21AC4			6@ 5 kg			1.0887±0.0035
HC21AC5			7@ 5 kg			1.1319±0.0035
HC21AC6			3@ 5 kg	0.125"		0.9226±0.0038
HC21AC7			4@ 5 kg	0.125"		1.0300±0.0038
HC21AC8			5@ 5 kg	0.125"		1.0712±0.0038
HC21AC9			6@ 5 kg	0.125"		1.1006±0.0038
HC21ACA			7@ 5 kg	0.125"		1.1443±0.0039

Table E.4 Parametric Study of Pu and PuO_2 MONK6B Results.
Plutonium Metal Density 19.465 g/cm^3
PuO_2 with Pu 5.5 g/cm^3 and Hydrogen/^{239}Pu = 2
2.5 Kilogram Metal Buttons Stacked
Surrounding PuO_2 Cylinder Height = Diameter
Reflection is 2 Inch Water on Sides and Top
EXTREMELY CONSERVATIVE CALCULATIONS

	0.0 kg Pu	2.5 kg Pu	5.0 kg Pu	7.5 kg Pu	10.0 kg Pu
0.0 kg PuO_2	0.0000±0.0000	0.7067±0.0028 b1p000n	0.9215±0.0031 b2p000n	1.0320±0.0033 b3p000n	1.0970±0.0035 b4p000n
2.5 kg PuO_2	0.5441±0.0024 b0p025n	0.8057±0.0034 b1p025n	0.9944±0.0035 b2p025n	1.1103±0.0036 b3p025n	1.1537±0.0036 b4p025n
5.0 kg PuO_2	0.6916±0.0029 b0p050n	0.8624±0.0034 b1p050n	1.0303±0.0037 b2p050n	1.1392±0.0039 b3p050n	1.2018±0.0038 b4p050n
7.5 kg PuO_2	0.7790±0.0029 b0p075n	0.9134±0.0033 b1p075n	1.0577±0.0037 b2p075n	1.1728±0.0040 b3p075n	1.2297±0.0039 b4p075n
10.0 kg PuO_2	0.8461±0.0030 b0p100n	0.9510±0.0034 b1p100n	1.0816±0.0040 b2p100n	1.2052±0.0039 b3p100n	
12.5 kg PuO_2	0.9050±0.0032 b0p125n	0.9855±0.0036 b1p125n	1.1041±0.0037 b2p125n		
15.0 kg PuO_2	0.9566±0.0033 b0p150n	1.0179±0.0036 b1p150n			
17.5 kg PuO_2	0.9925±0.0034 b0p175n	1.0521±0.0035 b1p175n			
20.0 kg PuO_2	1.0290±0.0035 b0p200n				

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution	Criticality and Shielding	Date 11/19/96
Project Title/Work Order		EDT No. 619222
CSER 96-023 : CSER for PFP Glovebox HC-21A with 4.4 Kilogram Plutonium Cans		ECN No. N/A

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
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E.P. Bonadie	T5-55	X			
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D.G. Erickson	H0-35	X			
S.R. Gedeon	H0-35	X			
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L.L. Pedersen (3)	H0-35	X			
R.F. Richards	H0-35	X			
S.P. Roblyer	H0-35	X			
L.H. Rodgers	T5-54	X			
R.H. Ruben	H0-35	X			
K.N. Schwinkendorf	H0-35	X			
S.S. Tsai	H5-30	X			
W.D. Wittekind (2)	H0-35	X			
W.T. Watson	H0-35	X			
Central Files	A3-88	X			