Enhancing the Criticality Safety Analysis for the Mobile Plutonium Facility

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INTRODUCTION

Savannah River Nuclear Solutions and Savannah River National Laboratory have developed a mobile plutonium facility (MPF) with the capability to receive, assay, stabilize and package plutonium at a remote location. The facility is modular, composed of a number of standard International Standards Organization (ISO) 20-foot cargo containers called modules. Each module has a function which helps the facility carry out this mission. There are a number of process modules which carry out the receipt, assay, identification, handling, stabilization, and packaging of the material. There are also a number of support modules which house the balance of the facility such as empty containers, power supply, administrative control room, personnel rest areas, etc. Each normally occupied module is equipped with its own HVAC system.

By nature the facility must be flexible and adaptive. Since it is designed to handle plutonium, the facility must also have a robust criticality safety program. For the criticality safety program to be robust, flexible, and adaptive, it must then by nature be simple. The objective of this work was to analyze the facility for criticality safety concerns and develop a set of controls, enhanced for facility flexibility. The result was a suite of administrative controls coupled with simple mass and handling limits.

A hazards analysis team identified a set of potential criticality event scenarios. Evaluation of the facility identified bounding normal conditions for single containers of fissile material, a storage array of the containers, and a piece of enclosed instrumentation which bounds other instruments. Those events determined to be credible were analyzed through credible abnormal upsets in the single containers, the storage array, and a bounding piece of instrumentation. Enhancements were made to the initial metal-only analysis to allow for the normal use of radiation shielding if required, non-metal forms, and limited quantities of solution. Two representative containers composed of generic stainless steel and aluminum were analyzed to avoid controls on container types and thicknesses which are difficult to implement in the field.

Computational modeling was performed using KENO-VI in the SCALE 6.1 code package (Ref. 1).

DESCRIPTION OF THE WORK

Process Description

The general process flow for the facility is as follows. A container(s) to be received represents some inherent but acceptable risk. The container(s), handled one at a time, will receive initial imaging and non-destructive assay (NDA). If the container conforms to the facility safety limits it is placed in storage until it is ready to be processed. Otherwise it is isolated; isolated containers are dealt with on a case-by-case basis. Upon leaving storage, the container is processed: its contents are removed, stabilized for safe transport, repackaged, subjected to a final NDA characterization, and packaged for safe transport.

Identification of Hazards

A hazards review team determined upset conditions which could potentially lead to inadvertent criticality scenarios. The scenarios involved upsets in the handling of the fissile material in both receipt and final packaging, interaction of multiple containers of fissile material during handling or storage, and inadvertent reflection or moderation. Through considerations on nature of process and required compliance with shipping standards, events involving beryllium reflection, inadvertent moderation by melted water-extruded polyester shielding, inadvertent moderation in the gloveboxes, and errors in final packaging were determined to be not credible.

Natural phenomenon hazards (NPH) were determined by the hazards team and facility personnel and planners to be a necessary and acceptably low risk for operating the facility based on two aspects of the nature of the facility. First, the location of the facility is not known a priori and therefore the type, frequency, and severity of NPH associated with that location cannot be explicitly evaluated a priori. Two, the facility has by nature an inherently short mission time on the order of months or weeks, compared to decades for a fixed facility. The probability of an NPH which could adversely affect the facility occurring during this short time is by nature very low. Furthermore, NPH that could cause moving or toppling of the facility would likely disperse the containers, just as a vehicular accident would, and the hazards review concluded two cans together bounds the only credible result of such a hazard. NPH that cause water intrusion were also determined to be sufficiently bounded by fully flooding the containers. The modules are not watertight so catastrophic floodwaters would leak out just as they leaked in and by nature of the facility design would not be likely to come into contact with fissile material.

From examination of the remaining upsets postulated in the hazards team review, it was concluded that the facility's criticality safety concerns could be evaluated by bounding considerations of mass, moderation, reflection, and interaction of containers of fissile material in three general conditions. These included the inadvertent occurrence of two containers side by side, the storage array for the containers, and a bounding piece of instrumentation which introduces reflection and moderation to any container placed inside it. Full flooding of the containers in bounding conditions was also evaluated. Water intrusion into the gloveboxes is limited by design features, and any liquids normally or abnormally expected to be in the glovebox are bounded by the flooded container condition.

Modeling and Assumptions

Containers were modeled as representative thin walled slip lid containers (SLCs) and thick-walled Hanford convenience cans (HCCs) in both generic stainless steel and generic aluminum. The SLC and HCC are idealized as cylinders (Fig. 1). The SLC is modeled as 0.13 cm thick, 4.45 cm in radius and 15.24 cm in height. The HCC is modeled as 5.58 cm in radius, 20.56 cm in height, with a bottom thickness of 0.69 cm and a top thickness of 1.57 cm. The fissile material was assumed to be a single 6.5 kg mass of 100 wt.% Pu-239, alpha phase metal of density of 19.84 g/cm^3 in a cylinder shape of height/diameter = 1. This assumption bounds less mass, is near to the reactivity of a sphere in single unit conditions and slightly more conservative in array storage conditions. The facility does not anticipate receiving any single package of more than 6.5 kg FGE Pu-239 of fissile material. Also, fissile gram equivalent Pu-239 is used for the analysis. Fissile material mass received by the facility would be converted to FGE upon initial NDA. No neutron poisons were modeled in any container, process or location. Non-metal forms and multiple pieces of metal are evaluated separate and shown to be safe and bounded by a single metal piece.

The storage array (Fig. 2) is modeled with the as-built number of aluminum storage locations, either tubes or pots, with bounding separation distances between the locations (minimum 63.5 cm) which are more conservative than the as-built configuration. The array has two adjacent, mirror image racks of storage locations. All locations are made of aluminum and are either a horizontal tube with credited retention devices or upright pots with lids. The tubes have an internal diameter of 15.24 cm and the pots a internal diameter of 29.21 cm. The storage array module walls were assumed to be 6” thick steel, but are in reality closer to 0.25” thick steel. The assumption was made in lieu of trying to model deeply corrugated walls while keeping the spacing true to as-built configuration. This is recognized to be unphysical but conservatively adds thick steel reflection.

As part of the receiving process, the containers undergo NDA using various instruments. All of the NDA instruments are bound by a single limiting piece of instrumentation which is evaluated as a simplified model of a polyethylene annulus with inner and outer cadmium liners and graphite and aluminum plugs (Fig. 3).

A number of assumptions about the facility had to be made. The foremost among these is that the package will not arrive critical. While this seems obvious, any scenarios which involve a condition which would violate this are immediately rejected as incredible. Other assumptions included correct and regular calibration of the instrumentation, water not being used to fight fires, any small samples counting toward container or mass control zone mass limits, generally no aqueous solutions allowed to be received, and final processed packages being subject to compliance with shipping requirements.

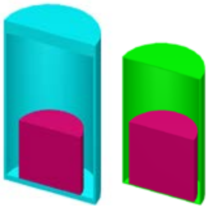

Fig. 1. Normal stainless steel HCC (left) and aluminum SLC (right) with bounding fissile mass.

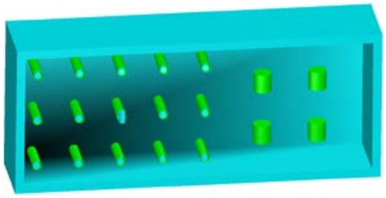

Fig. 2. Left half of the storage array, loaded with stainless steel containers in all locations plus one in transit as close as possible to the container in the array center.

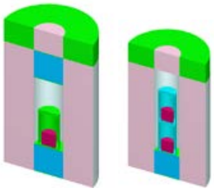

Fig. 3. Bounding piece of instrumentation containing a single aluminum HCC (left) and the upset of two stacked stainless steel HCCs (right).

Normal Conditions

The bounding normal conditions are the containers sitting individually on a reflective surface such as soil or pavement (thick concrete bounds any of the thin steel tables in the modules), a full storage array of containers with one additional container present being moved (which bounds any partial loading of storage), and an individual container in the bounding piece of instrumentation.

Single SLC or HCC containers of either aluminum or stainless steel containing the bounding fissile mass could be placed in air sitting on either the ground (24” of soil) or pavement (6” of concrete on top of 18” of soil). The storage array could have one container of up to 6.5 kg FGE Pu-239 in each tube and pot location with one in transit either as close as possible to the container in the center of the array (maximizing interaction) or to the container in the corner of the array, on the floor of the module (maximizing reflection). The bounding piece of instrumentation normally has one HCC or SLC inside with the device closed and has graphite plugs installed above and below the container. The polyethylene annulus was modeled as 0.96 g/cm^3. A thick aluminum cap is modeled for the instrumentation wiring block. The device can be split to allow for larger containers, but this also provides paths for neutron leakage so the closed device is more conservative to model.

Credible Abnormal Conditions

In general, the credible abnormal conditions for individual containers were full flooding of the container, two cans inadvertently next to each other, and an overmass of a single container to 7 kg FGE Pu-239. Flooding bounds all credible means and amounts of water intrusion identified by the hazards evaluation team. There are limited liquid volumes in the process modules, water is programmatically not used for firefighting, and catastrophic flooding due to NPH is outside the scope of the evaluation. Additionally, the flooding bounds carrying individual containers by hand though containers will typically be carried in pails but there is no specific requirement to do so.

Two cans together bounds credible operator error and credible upsets which could bring loose containers together such as movement of modules, vehicular accident, etc. even though these events are much more likely to disperse containers than bring them together per the hazards review. The two containers modeled side by side also moved the fissile masses within them to the closest credible proximity. The flooding and two-can upsets are shown in Fig. 4. These cases were run on a reflective surfaces (pavement and pavement-soil). The overmass of 7 kg FGE Pu-239 would be an upset found upon initial imaging NDA and the package would thereafter be isolated until it could be dealt with on a specific basis.

The main credible abnormal condition for the storage array was the two halves of the array fallen face to face together so the material is as close as the credited design features would allow. This bounds toppling or shifting of the arrays in random manners (e.g. by vehicular accident) by artificially assuming the storage locations and their associated containers are as close as possible. The single credible abnormal condition for the bounding piece of instrumentation was to have two containers inadvertently stacked inside it (Fig. 3) even though this would preclude the instrument from properly assembling and be a self-evident upset.

Additional beyond credible abnormal branch cases were run which included flooding the can-bag-can configuration, storing a flooded container at various locations in the storage array, and inadvertently placing a flooded container in the bounding piece of instrumentation. Each of these represent multiple concurrent upsets or unexpected conditions.

Operational Flexibility

A number of branch cases were also run. These were intuitively expected to be subcritical but were explicitly analyzed to ensure operational flexibility for the mission.

The ideal can then polyethylene bag then can configuration was examined. A proposed glovebox radiation shield was also examined, and modeled as both thick polyethylene and thick water-extruded polyester (Fig. 5) to provide this requested operational flexibility.

The array was also given the ability to deal with the anticipated abnormal high radiation container. A radiation shield may be needed on one or more tubes or pots so the most limiting unshielded case was rerun modeled with every tube and pot having a 1” thick lead or 1” thick polyethylene shield blanket.

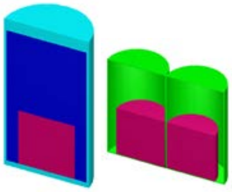

Fig. 4. Upsets of flooding (left) and two cans (right).

Fig. 5. Can-bag-can (left) and glovebox radiation shield (right) branch case models.

The single cylinder of 6.5 kg FGE Pu-239 is bounding but it is possible (normal) that the fissile mass would be in pieces. The most reactive case of the cylinder (stainless steel HCC sitting on pavement) is re-analyzed with the fissile mass subdivided into 2, 3, 4, 6, and 13 equal pieces. These cases are run both flooded and dry.

As a general rule, aqueous solutions are not allowed or processed. It was desired however to possibly bring in a sample of aqueous solution if necessary. Aqueous solutions are expected to be a few grams of plutonium per liter and are kept substantially less than a single mass limit of 450 FGE Pu-239.

To ensure that 6.5 kg FGE Pu-239 of metal was bounding, Ref. 2 was consulted. Bounding conditions of expected non-metal solid forms of plutonium oxide, plutonium oxalate, and plutonium fluoride were cast into concentration versus critical mass data and compared to the minimum condition for Pu-239.

Determination of k_{SAFE}

Savannah River Nuclear Solutions produced an in-house validation for the SCALE 6.1 KENO-VI code for Pu metal systems (Ref. 1). Using a conservative bias for this type of system and an additional subcritical margin, the k_{SAFE} assumed for this work was 0.9697.

RESULTS

The scatter plot in Fig. 6 shows that for all normal condition cases, k_{SAFE} was met in all variations of HCC and SLC with aluminum or stainless steel containers. This includes the combinations of container type (HCC or SLC) and material (aluminum or stainless steel). These are placed onto either soil and pavement or pavement (“Singles” cases), in the storage array with every position loaded and one additional container at one of two bounding locations (“Array” cases) and within the bounding instrumentation with two bounding densities of the polyethylene (“Instrument” cases). The credible abnormal cases are shown in Fig. 7. All data sets included the four combinations of container material and type applied to the upsets discussed above. The “Singles” cases represent the flooded, two-can, and overmass container upsets. The “Array” cases represent the fallen array upsets. The “Instrument” cases are the two-container upset for the bounding piece of instrumentation.

Two thin walled SLCs placed side by side exceeded k_{SAFE}. As such it was necessary to show that placing the SLCs inside another container (i.e. a thick walled HCC) brought the result back below k_{SAFE} (also on Fig. 7). This resulted in an administrative control to require thin walled SLC-like containers to be placed inside another container upon receipt and/or before movement around the complex. All other credible abnormal conditions in the storage array and bounding piece of instrumentation were shown to be safely subcritical.

Results of the beyond credible abnormal cases are shown in Fig. 8. The data presented is only for the most bounding material and container type combinations. All storage array cases but one nominally met k_{SAFE}. The case which did not meet the k_{SAFE} was the one with a flooded container sitting on the floor of the storage array model next to another container in a tube location. The flooded containers inside the bounding piece of equipment did not meet k_{SAFE}.

The bounding concentration versus critical mass conditions for the non-metal solid plutonium forms is compared to the critical data from Ref. 2 on Fig. 9. Only cases exceeding both the 6.5 kg FGE Pu-239 and the 7 kg overmass conditions, due to density and can fill height assumptions, were shown to exceed the critical line, marked “LA-10860”.

The remaining operational flexibility cases are shown in Fig. 10. The results for both the glovebox radiation shields and the storage array radiation shields are marked “Shield”. The can-bag-can configurations including the flooded cases are marked “Bagged”. The cases, both dry and flooded, with the metal unit subdivided into chunks is marked “Pieces-Dry” and “Pieces-Flood”, respectively. In “pieces” cases, the effect of increased surface area for neutron leakage outweighed the effect of interstitial moderation for the same fissile mass as the single cylinder. All cases met k_{SAFE}.

DESIGN FEATUERS AND CONTROL SUITE

There are credible criticality scenarios in the facility. A nuclear incident monitoring system is installed to mitigate the risk to personnel in the event of an inadvertent criticality. The system is a fixed alarm system located in a module in proximity to the credible criticality location. It is audible throughout the facility. Programs are required to be in place to protect assumptions include instrumentation calibration, operator training, facility configuration control, and allowable fire protection methods.

Only design features limiting the spacing of the storage array locations and limiting the positioning of containers inside each tube storage location were credited.

The control suite is based on the limiting 6.5 kg FGE Pu-239 mass, for both metal and non-metal solids, and is comprised of handling and mass controls coupled with administrative requirements. The facility is subdivided into a number of mass control zones. Most of the mass control zones are limited to one container present at a time. The others are limited to the 6.5 kg FGE Pu-239 with two exceptions – storage and processing module. The storage array is limited to 6.5 kg FGE Pu-239 per storage location plus up to 6.5 kg FGE Pu-239 outside of a location. Any tube in the storage array must have retaining features (a fixed spacer and removable retaining pin) installed while a container is present. The processing module is limited to one container plus glovebox holdup of 450 FGE Pu-239. This is loose material which is assumed will primarily be in the filters or dispersed throughout the glovebox. It is bounded by the 7 kg overmass upset. The 450 FGE Pu-239 is continuously estimated via a real time accountability system and also regularly surveyed. Residual material is limited to contamination levels only. Only one container at a time is moved between mas control zones within the complex.

The containers are limited to 6.5 kg FGE Pu-239 with the exception of initial receipt and identification of the container and its contents. Initial receipt and identification is an accepted risk of the facility and containers are assumed to be subcritical upon receipt. Final packaging must comply with the shipping container’s safety requirements which are engineered features not covered in this analysis. Thin walled SLC-like containers are administratively required to be placed in another container.

A container that contains free liquids is usually considered a non-conforming container and would be treated as discussed below. Exception is made for known aqueous plutonium solutions. Allowance is made to permit aqueous solutions up to 3.0 L (approximately 2 HCCs) or up to 450 g FGE Pu-239, whichever is more limiting, provided the solution container is handled individually, is not placed in lead storage, any other mass zones it is placed in are free of other fissile material, and a case-specific disposition path (e.g. drying or calcining) is executed before operations with solids resume in that mass control zone.

As a final control, a non-conforming container which is over the 6.5 kg FGE Pu-239 limit, will not fit in any storage array location, or is in some other way determined to be non-conforming to the analysis may still be received. The non-conforming container must be isolated from any other fissile material by 100 cm of spacing and then dealt with on a case-by-case basis. The spacing is maintained administratively.

ACKNOWLEDGEMENTS

Mr. Vincent Shih, Mr. David Dolin, Mr. John Lint, and Mr. Douglas Lowry provided invaluable feedback throughout the analysis on operational practices of the facility and control development.

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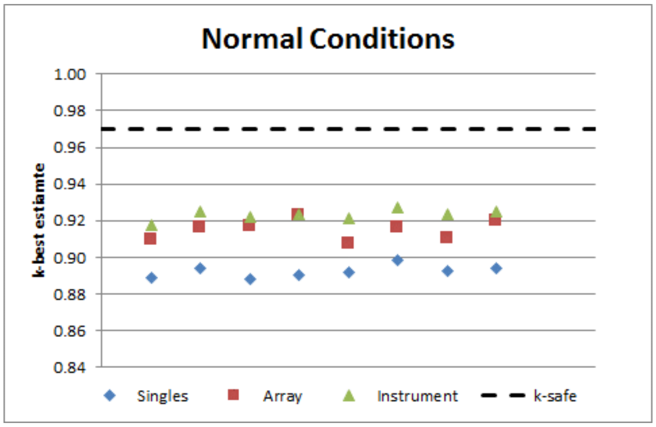

Fig. 6. Normal condition results.

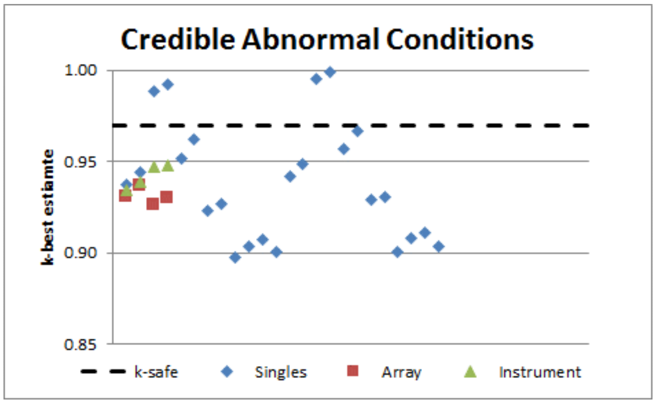

Fig. 7. Credible abnormal condition results.

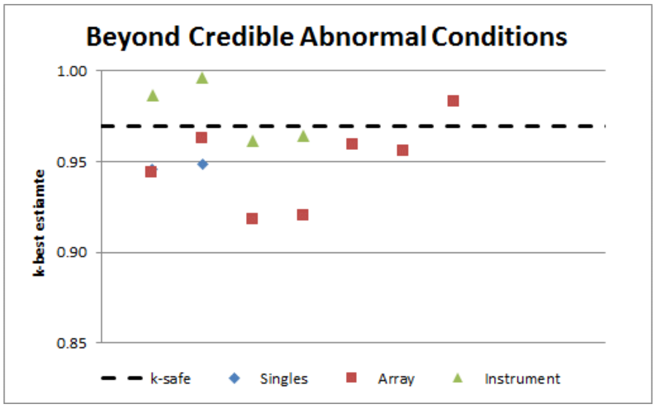

Fig. 8. Beyond credible abnormal condition results.

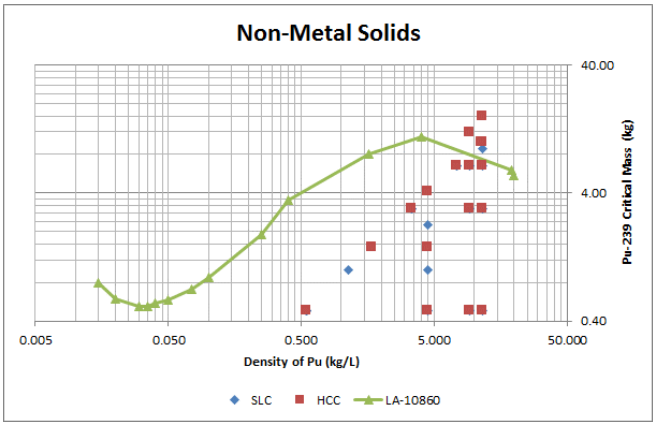

Fig. 9. Non-metal forms analysis.

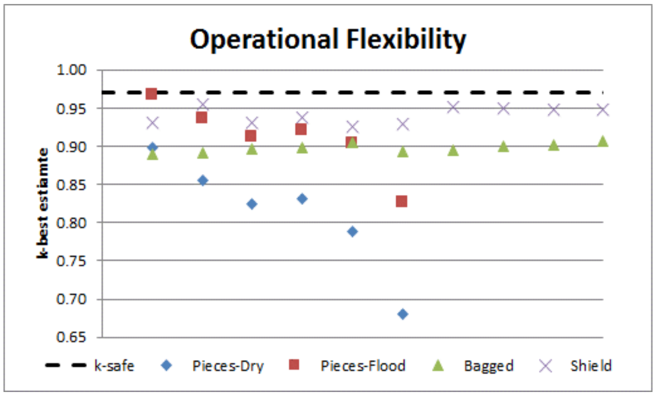

Fig. 10. Operational flexibility cases.