AVLIS Criticality Risk Assessment

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This paper was prepared for and presented at the
EFCOG 1998 Safety Analysis Workshop
Park City, Utah
June 15-19, 1998

April 29, 1998

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AVLIS Criticality Risk Assessment

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Introduction

Evaluation of criticality safety has become an important task in preparing for the Atomic Vapor Laser Isotope Separation (AVLIS) uranium enrichment runs that will take place during the Integrated Process Demonstration (IPD) at Lawrence Livermore National Laboratory (LLNL). This integrated operation of AVLIS systems under plant-like conditions will be used to verify the performance of process equipment and to demonstrate the sustained integrated enrichment performance of these systems using operating parameters that are similar to production plant specifications. Because of the potential criticality concerns associated with enriched uranium, substantial effort has been aimed towards understanding the potential system failures of interest from a criticality standpoint, and evaluating them in detail.

The AVLIS process is based on selective photoionization of uranium atoms of atomic weight 235 (U-235) in a vapor stream, followed by electrostatic extraction. The process is illustrated in Figure 1. Two major subsystems are involved: the uranium separator and the laser system. In the separator, metallic uranium is fed into a crucible where it is heated and vaporized by an electron beam. The atomic U-235/U-238 vapor stream moves away from the molten uranium and is illuminated by precisely tuned beams of dye laser light. Upon absorption of the tuned dye laser light, the U-235 atoms become excited and eject electrons (become photoionized), giving them a net positive charge. The ions of U-235 are moved preferentially by an electrostatic field to condense on the product collector, forming the enriched uranium product. The remaining vapor, which is depleted in U-235 (tails), passes unaffected through the photoionization/extractor zone and accumulates on collectors in the top of the separator. Tails and product collector surfaces operate at elevated temperatures so that deposited materials flow as segregated liquid streams. The separated uranium condensates (uranium enriched in U-235 and uranium depleted in U-235) are cooled and accumulated in solid metallic form in canisters. The collected product and tails material is weighed and transferred into certified, critically safe, shipping containers (DOT specification 6M with 2R containment vessel). These will be temporarily stored, and then shipped offsite either for use by a fuel fabricator, or for disposal. Tails material will be packaged for disposal.

A criticality risk assessment was performed for AVLIS IPD runs. In this analysis, the likelihood of occurrence of a criticality was examined. For the AVLIS process, there are a number of areas that have been specifically examined to assess whether or not the frequency of occurrence of a criticality is credible (frequency of occurrence > 10^-9/yr). In this paper, we discuss only two of the areas: the separator and canister operations.
Methodology

A criticality safety appraisal methodology utilizing both Probabilistic Risk Assessment (PRA, scenario development using Event Trees / Fault Trees) and nuclear criticality Monte Carlo analysis has been utilized to assess the criticality risk of AVLIS systems. This work focused on scenario development, and the assessment of the likelihood that sufficient mass, moderator, and favorable geometry will coexist. A companion report (Evarts et al., 1998) presents the Monte Carlo analyses and provides the determination of k-eff for a number of scenarios. Those conservative deterministic calculations established boundaries for safe operation. The boundaries, defined in terms of both enrichment and mass, were an enrichment limit of 3.5% U-235 and as a mass limit of 1.4 kg U-235. The AVLIS run plan requires that operations stay within these criticality limits. Furthermore, any scenarios involving mass and enrichments below the limits are also critically safe, requiring no further analysis (Evarts et al., 1998). Those accident scenarios that could exceed the limits were evaluated with PRA techniques to estimate their frequency of occurrence. However, just exceeding the limits does not imply a criticality. The necessary geometry and moderation were also considered in those scenarios, in order to estimate the risk of a criticality. This section summarizes the methodologies used to assess the probability of occurrence of a criticality accident.

Probabilistic Risk Assessment (PRA) is the process of identifying those events that could endanger workers or the public health and safety, estimating the frequency at which they would be expected to occur, and estimating the consequences. An FMEA prepared for the yet-to-be-built AVLIS plant was utilized here for identification of potential failure modes associated with the separator. This was supplemented by detailed review of the IPD systems. As part of this work, FMEAs were generated for the additional areas of concern beyond the separator (e.g., withdrawal and canister change-out). The results were then used to identify and group together similar initiating events identified as important to criticality. Event trees and fault trees models were constructed using SAPHIRE/IRRAS (1997).

Using PRA, a complete set of scenarios, where mass, moderator, and favorable geometry could potentially co-exist, was established. Literally, hundreds of scenarios were identified. Because of the very large number of scenarios generated, it was necessary to reduce the set of scenarios to be quantified to a manageable number. This was accomplished in three ways:

1. Sequences where all three required components would not be present were eliminated.
The sequences were ranked in terms of their likelihood (using judgment, and in consultation with AVLIS technical personnel), and the most likely ones were retained for further study. Many of the highest likelihood scenarios were analyzed using Monte Carlo calculations to determine k-eff. This type of study is very time intensive, however, and it is not possible to analyze every potential accident condition. Scenarios shown to be sub-critical were eliminated. Conversely, scenarios that could result in a criticality were retained for further study.

Once the scenarios or failure combinations were identified, they could be quantified. This requires a component-data base, which is developed by compiling data, selecting appropriate reliability models, establishing the parameters for those models, and then estimating the probabilities of component failures and the frequencies of initiating events. Failure probabilities for each mode of hardware failure and for test and maintenance failures are developed from both generic and specific data. This data base of initiating event and basic event parameter estimates, along with the data on dependent failures and human error, forms the basis for the subsequent quantification of the accident sequence frequencies. Since AVLIS is a state-of-the-art facility, only sparse data specific to the facility and its operations are available for use in our analyses. We used this wherever possible. For the remaining data, we have relied on generic data bases for component failure rates.

During the course of the criticality safety analysis, an attempt was made to understand general and specific human-system interactions. AVLIS Operations failure modes that had human error source terms were identified and incorporated into the probabilistic analyses. Given the unique nature of AVLIS operations and management, there are few data that are directly applicable in determining Human Error Probabilities (HEP). However, we did examine error probabilities associated with other operations and found estimates for errors similar to those identified in our analysis of AVLIS. In many scenarios developed as part of this work, multiple human errors would have to take place in order for a condition of concern to exist. Although it may be possible to take this into account (and multiply the error probabilities, thereby lowering the overall event probability), this was generally not done. Detailed human reliability or task analyses were not performed as part of this work, due to lack of time.

Results

Separator Analysis

The separator was analyzed to determine the frequency of criticality scenarios for the separator itself, as well as the frequency of potential initiating or contributing events to criticality scenarios in subsequent operations (e.g., canister operations). An initial screening was done on all separator failures that could contribute to a buildup of enriched uranium anywhere in the separator or canisters, or contribute to producing an enrichment level in excess of the limit, or provide any changes in potential neutron moderation in the separator or canisters. Information to perform this screening came from meetings with AVLIS operations personnel, inspections of the facilities and components, and an extensive failure modes and effects analysis done by AVLIS personnel for a full-scale enrichment plant.

The results of the initial screening allowed us to concentrate on those failures that had the potential for a significant contribution to an accidental criticality. Fault trees were then constructed to analyze those significant failure modes in detail. The top events from the fault trees included:

- Flooding the separator with water
- Accumulating mass of U-235 in the separator in excess of the 1.4-kg limit
- Collecting mass in a product or tails canister in excess of the 1.4-kg limit
- Exceeding the enrichment level of 3.5% U-235 in a canister
Exceeding the enrichment level of 3.5% U-235 in the separator holdup. The results of the fault trees are summarized in the rest of this section.

The separator is cooled by a water system comprised of 6-in diameter pipes, a distribution manifold, connections, and tubing running to various components. It is possible for break in the cooling system to flood the separator, providing the moderation necessary for a criticality scenario in the separator. A flooded separator would also flood the canisters. Although the product canister is critically safe when flooded, the tails canister is not, giving rise to another scenario. The dominant cut sets causing a flooded separator, from an operational failure standpoint, consist of either connection or tubing breaks, coupled with failure of a water shutoff valve. It was estimated that the probability of flooding the separator is $8 \times 10^{-5}$ per run.

The fault tree for the accumulation of excess mass in the separator analyzes failure scenarios for both the upper and lower separator sections. The upper separator is where the enrichment occurs, as the uranium is melted, vaporized, separated, and condensed into product and tails liquid streams. The dominant scenario for upper separator accumulation involves a plugging of the product flow stream and its subsequent pooling in the upper separator, along with a failure of the continuously performed automatic holdup calculation to detect the increased holdup. In the lower separator the separated uranium streams solidify into discrete splats on a rotating caster, and are pushed into the appropriate collection canisters. The dominant failures in the lower separator include buildups due to a failed caster and buildups in the collection chute between the caster and canister due to a closed valve in the chute. Both scenarios also require failure of the holdup calculation to detect the situation, as well as failure of other surveillance provisions. It was estimated that the probability of exceeding the separator mass limit is $3 \times 10^{-4}$ per run.

It is possible to overfill a product canister and exceed the 1.4-kg U-235 mass limit. Controls to prevent this include administrative procedures requiring timely canister changeouts, as well as interlocks monitoring mass in the canister, the vapor rate, and the collection time. The dominant cut set for exceeding the product canister mass limit involves a failure of the vapor rate monitor allowing an abnormally high vapor rate to produce excess product within the time limit, and a failure of the mass interlock. Exceeding the mass limit in the product canister was estimated to occur with a probability of $7 \times 10^{-5}$ per run.

It is also possible for a common cause failure to simultaneously block the flow of the tails stream, while redirecting the product flow into the tails canister. This scenario also requires the failure of the operators to diagnose the situation. Exceeding the mass limit in the tails canister was estimated to occur with a probability of $4 \times 10^{-8}$ per run.

Failures in separator components could cause an enrichment excursion, possibly in excess of the limit of 3.5% U-235. The component failures dominating these scenarios are the external magnet, the vapor rate controller, and the feeder. The scenarios also require failure of the operators to diagnose the situation, allowing overly enriched product to be collected for an extended period. Exceeding the enrichment limit in the canister was estimated to occur with a probability of $1 \times 10^{-4}$ per run.

The enrichment of each product canister is assayed immediately after collection. If the separator has been over-enriching, the assay measurement is likely to detect it. However, if the assay fails to detect the over enrichment, it is assumed that the failures continue for a long duration, such that the average separator holdup could exceed the 3.5% U-235 limit. The probability that the separator holdup will exceed the enrichment limit at the end of the run is estimated to be $6 \times 10^{-8}$.

Criticality scenarios for the separator are initiated by exceeding the expected separator hold-up mass or assay limit. Exceeding the mass limit is more likely. In order to have a criticality, the
The separator must also be flooded. The combined frequency of occurrence of this event was determined to be 
2 x 10^-7/yr.

The separator was not constructed with any specific seismic criteria, nor has any seismic analysis been performed on it. Consequently, some damage of separator interior components could be expected under severe seismic conditions (10^-3/yr). In order for a criticality to result from an earthquake, either the assay of the separator hold-up must exceed 3.5%, or the hold-up mass must exceed 1.4 kg U-235 at the time the earthquake strikes (more likely). The earthquake is assumed to fail the coolant system, providing moderator. This gives a frequency of a potential criticality resulting from a severe earthquake of 1x10^-7/yr.

Less severe earthquakes were also considered. However, an automatic water shut-off system was designed and seismically qualified to at least the 150-yr earthquake. Less likely earthquakes could fail this system, but the sequence frequency would then be incredible.

**Analysis of Canister Operations**

Canister operations include filling of canisters during operations, the change-out of full canisters and replacing them with empty ones, movement of canisters between buildings, and the transferring and packaging of product into DOT 6M/2R shipping containers. Excess enriched mass, excess enrichment, introduction of moderator, as well as creation of favorable geometry are criticality concerns that may result from equipment failure or violation of procedures. A simplified failure mode and effect analysis focusing on criticality concerns during the canister operation was performed. Based on the failure mode and effect analysis, eleven scenarios that could potentially result in a criticality were identified. A typical example is described in the following.

During product transfer, the procedures specify that enriched nuggets from product canisters are to be dumped into a trough and then collected in #3 juice cans. The enriched nuggets, however, may be erroneously dumped into a 30 gallon drum used to hold the depleted nuggets from tail canisters. This could occur if there is confusion about the type of material in the different canisters.

In a bounding scenario, it is assumed that the enriched nuggets are erroneously dumped into a 30-gallon drum. The product canister is assumed to hold more than 1.4 kg of U-235 or have an enrichment larger than 3.5%. In addition, the drum is assumed to be flooded by water due to the rupture of water lines or the actuation of sprinkler heads above the drum.

The erroneous dumping accident is depicted by an event tree shown in Figure 2. The event tree results in five sequences. The numerical evaluation of the probabilities of these events are either based on historical data or estimated by conservative engineering judgment as described in Table 1. Sequence 1 is shown to be sub-critical (k-eff < 0.95) by a detailed Monte Carlo calculation (Evarts et al., 1998). Sequences 2 and 4 are also sub-critical since there is no water in the drum to serve as moderator. Sequences 3 and 5 involve the drum being flooded by water with either a mass larger than 1.4 kg U-235 or an enrichment larger than 3.5%. The probability of occurrence of these two sequences, however, is estimated to be below 10^-9/yr. Thus, their occurrence is incredible.

In summary, the above results indicate that for an erroneous dumping accident, the scenarios are either sub-critical or incredible. Therefore, a criticality accident is incredible for the product canister dumping operation. Other canister operational scenarios were also shown to either be sub-critical or incredible.
### Table 1. Frequencies of events for the dumping operation

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequencies (failure rate)</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 hrs IDP run</td>
<td>6 IDP run/yr</td>
<td>Assumption</td>
</tr>
<tr>
<td>Product canister change-out</td>
<td>450 change-out/yr</td>
<td>300/yr every 12 hrs and 150/yr every 24 hrs.</td>
</tr>
<tr>
<td>Water system pipe rupture</td>
<td>$10^{-10}/hr$-ft</td>
<td>Blanton and Eide (1993)</td>
</tr>
<tr>
<td>Sprinkler head inadvertent actuation</td>
<td>$1.6 \times 10^6$/yr</td>
<td>Factory Mutual Research (1977)</td>
</tr>
<tr>
<td>Facility fires</td>
<td>0.019/yr</td>
<td>Historical data</td>
</tr>
<tr>
<td>Erroneous dumping</td>
<td>0.5/yr</td>
<td>This event is the result of a procedure violation. The human error probability (HEP) for procedure violation is considered as $1 \times 10^{-3}$/operation based on the following references:  &lt;br&gt;• Failure of administrative controls, HEP $&lt; 10^{-3}$, (Benhardt, 1994).  &lt;br&gt;• Supervisor verification error, HEP $&lt; 10^{-3}$, (Benhardt, 1994).  &lt;br&gt;• Errors of omission per item of instruction when use of written procedures is specified, HEP $&lt; 10^{-3}$, (Swain, 1983).  &lt;br&gt;• Selection errors for locally operated, clearly labeled valves, HEP $&lt; 10^{-3}$, (Swain (1983) and Gertman (1994)).  &lt;br&gt;There are 450 product canister dumping operations per year. Thus the annual probability of erroneous dumping is: $1 \times 10^{-3}$/op x 450op/yr = 0.5/yr.</td>
</tr>
<tr>
<td>Product canister holds nuggets with enrichment &gt; 3.5% (but &lt; 5%)</td>
<td>$4 \times 10^9$ per 24-hrs canister</td>
<td>(based on separator analysis) $10^{-4}$/run * 24 h/600 h/run = $4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Product canister holds more than 1.4 kg of U-235</td>
<td>$3 \times 10^{-5}$ per 24-hrs canister</td>
<td>(based on separator analysis) $7 \times 10^{-5}$/run * 24 h/600 h/run = $3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Drum is flooded by water</td>
<td>$5 \times 10^{-5}$/dumping</td>
<td>The dumping and collection of product is conservatively assumed to last 24 hr. This is the vulnerable period of time for flooding.  &lt;br&gt;The 30-gal drum may be flooded due to the rupture of water line above the drum, or due to the inadvertent actuation of sprinkler heads above the drum. Assuming conservatively that the water line above the drum is 10 ft and that the drum is within the range of 4 sprinkler heads, the probability of drum flooded due to the above random sources is:  &lt;br&gt;$24$ hr/dumping $x (10$ ft $\times 10^{-9}$/hr-ft $+ 4 \times 1.6 \times 10^{-5}$/yr) $= 4.2 \times 10^{-9}$ dumping.  &lt;br&gt;The 30-gal drum may also be flooded by the actuation of sprinkler heads by a facility fire. The probability of actuation of sprinkler heads by a facility fire is $24$ hr/dumping $\times 0.019$/yr $= 5.2 \times 10^{-5}$/dumping.  &lt;br&gt;Thus, probability of water source $= 5.2 \times 10^{-5}$/dumping.</td>
</tr>
</tbody>
</table>
Figure 2. Event Tree for Erroneously Dumping Enriched Products into a 30-gal Drum

<table>
<thead>
<tr>
<th>Enriched Product</th>
<th>Enrichment is less than or equal to 3.5%</th>
<th>U-235 mass is less than or equal to 1.4 kg</th>
<th>Drum is flooded by water</th>
<th>Criticality Potential</th>
<th>Frequency (1/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erroneously dumped into a 30-gal drum</td>
<td>1 No (small enrich/mass)</td>
<td>2 No (not enough water)</td>
<td>3 Yes (large mass/water)</td>
<td>4 No (not enough water)</td>
<td>5 (large enrich/water)</td>
</tr>
<tr>
<td>0.5/yr</td>
<td>3E-5</td>
<td>5E-5</td>
<td>8E-10</td>
<td>5E-5</td>
<td>1E-10</td>
</tr>
</tbody>
</table>

It is conceivable that an earthquake could cause a spill of canister contents to occur during transfer of the product. Assuming this operation takes one hour per canister, and there are at most 450 such operations during the year, the frequency of a severe earthquake (10^-3/yr) during the operation is 5x10^-9/yr. The earthquake is assumed to fail any water piping in the vicinity of the canister resulting in flooding. In order for a criticality to occur, there would have to be another full canister in the vicinity or the spilled canister would have to have excess U-235 mass or too high assay. The frequency of attaining the conditions for a criticality would be higher for less severe earthquakes that could still fail the water piping, e.g., the 100 yr earthquake (10^-2/yr). In this case, the probability of the earthquake occurring during any operation would be 5x10^-9/yr. With a water accumulation probability of 0.1 (because of the numerous drainage pathways available), the probability of flooding during a transfer operation is 5x10^-5. The frequency of a criticality due to an earthquake induced spill/flood, with a second canister present is 5x10^-9/yr. The scenarios with an earthquake induced spill/flood, involving a canister with either excess U-235 mass or too high assay, both result in a frequency of a criticality of 2x10^-10/yr.

Summary

A review of the AVLIS IPD equipment and operations from a criticality standpoint has been performed. Failure modes of criticality concern were identified and sequences were developed that could lead to potential criticalities. Scenarios of higher risk were identified. These scenarios were studied in detail. They were either shown to be sub-critical or determined to be incredible.

Conservatisms, such as forming a favorable geometry, acquiring sufficient excess mass in a location (if excess mass could accumulate, sufficient mass was assumed to be available without regards to any intervention), caps being knocked off canisters if they were impacted, etc., give further confidence that the true frequency estimates would be even lower than documented in this
report. We took credit for minimal mitigation in the analysis. This lends further confidence that the frequency estimates are conservative (i.e., actual frequency would be lower).

Scenarios of concern were determined to have a frequency of occurrence on the order of $10^7$/yr or less. The highest risk is associated with the separator. Scenarios involving exceeding the separator hold-up limit combined with flooding (either due to random failure of the coolant system, or failure of the coolant system caused by a severe earthquake) are major contributors to the risk. Earthquakes less severe than the design basis earthquake (e.g., 100-yr earthquake) contribute to higher risk scenarios in canister operations.

A complete risk assessment considers the contributions of all scenarios to risk. We were complete in our identification of sequences. However, time would not permit quantification of all of them. We eliminated a number of scenarios based on the absence of all required components for a criticality, or if a scenario was shown to be sub-critical. Remaining scenarios were ranked, using judgment, and the higher risk ones were evaluated quantitatively. The total frequency of all scenarios analyzed is $8 \times 10^7$/yr. Although this does not include the contribution of many lower risk scenarios, it represents a very conservative total of the frequency of the higher risk scenarios. This total is beyond the $10^8$/yr threshold for incredibility.

References


