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Evaluation of Containment Failure and Cleanup Time for Pu Shots on the Z Machine

John L. Darby

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Evaluation of Containment Failure and Cleanup for Pu Shots On the Z Machine

John L. Darby
Systems Analysis I
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0415

ABSTRACT

Between November 30 and December 11, 2009 an evaluation was performed of the probability of containment failure and the time for cleanup of contamination of the Z machine given failure, for plutonium (Pu) experiments on the Z machine at Sandia National Laboratories (SNL). Due to the unique nature of the problem, there is little quantitative information available for the likelihood of failure of containment components or for the time to cleanup. Information for the evaluation was obtained from Subject Matter Experts (SMEs) at the Z machine facility. The SMEs provided the State of Knowledge (SOK) for the evaluation. There is significant epistemic- or state of knowledge- uncertainty associated with the events that comprise both failure of containment and cleanup. To capture epistemic uncertainty and to allow the SMEs to reason at the fidelity of the SOK, we used the belief/plausibility measure of uncertainty for this evaluation. We quantified two variables: the probability that the Pu containment system fails given a shot on the Z machine, and the time to cleanup Pu contamination in the Z machine given failure of containment. We identified dominant contributors for both the time to cleanup and the probability of containment failure. These results will be used by SNL management to decide the course of action for conducting the Pu experiments on the Z machine.

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EXECUTIVE SUMMARY

Between November 30 and December 11, 2009 an evaluation was performed of the probability of containment failure and the time for cleanup of contamination of the Z machine given failure, for plutonium (Pu) experiments on the Z machine at Sandia National Laboratories (SNL). Due to the unique nature of the problem, there is little quantitative information available for the likelihood of failure of containment components or for the time to cleanup. Information for the evaluation was obtained from Subject Matter Experts (SMEs) at the Z machine. The SMEs provided the State of Knowledge (SOK) for the evaluation.

There is significant epistemic- or state of knowledge- uncertainty associated with the events that comprise both failure of containment and cleanup. Criticisms of traditional safety and risk evaluations, such as the black swan analogy, are really directed at the difficulty these traditional evaluations have addressing epistemic uncertainty. To capture epistemic uncertainty and to allow the SMEs to reason at the fidelity of the SOK, we used the belief/plausibility measure of uncertainty for this evaluation. The belief/plausibility measure of uncertainty is an extension of the probability measure of uncertainty; with no epistemic uncertainty both belief and plausibility are the single measure, probability. Belief and plausibility can be viewed as lower and upper bounds, respectively, on probability.

We evaluated two issues:

- The probability that the Pu containment system fails given a shot on the Z machine: P_{fail} , and
- The time to cleanup Pu contamination in the Z machine given failure of containment: T_{mitigate} .

A fault tree was developed to delineate the ways that containment can fail; the tree was solved for the combination of events that lead to containment failure, the solution being a union of cut sets each of which causes failure of containment. Each cut set is an intersection of one or more events all of which must occur.

Some of the existing components cannot be cleaned, and new replacement components designed to be cleanable are being built; the new component of most concern for timely delivery is the new C MITL (Magnetically Insulated Transmission Line).

We created a model for the combinations of events that contribute to both P_{fail} and T_{mitigate} . To be specific, P_{fail} is the logical union (OR) of a number of cut sets of a fault tree, each cut set being a logical intersection (AND) of one or more events. T_{mitigate} is formed by the algebraic sum of all the contributing times.

Each event that comprises P_{fail} and T_{mitigate} has uncertainty; that uncertainty was captured by expert elicitation of SMEs. The SMEs were trained in the assignment of evidence in the context of the belief/plausibility measure of uncertainty. Then the SMEs assigned evidence to each event in the model.

The uncertainty for T_{mitigate} and P_{fail} was evaluated using the BeliefConvolution software developed at SNL. This software combines evidence for an algebraic combination of numeric variables to provide the belief/plausibility uncertainty distributions for the resultant variable. We evaluated unreliability, P_{fail} , and time to cleanup, T_{mitigate} , for the first Pu shot scheduled for June, 2010.

P_{fail} is in the interval $[0.0037, 0.033]$. The uncertainty in P_{fail} is dominated by epistemic uncertainty in the SOK of the SMEs.

Ten single event cut sets are the most important contributors to P_{fail} . Of these 10, the two single event cut sets that contribute the most are:

- UCC-FIBER-OPTIC-FAIL, a failure in a fiber optic feed-through due to pressure or shock, and
- UCV-CATHODE-EXT-HE, human error in installing the correct cathode extension resulting in movement of the cathode extension during the shot such that the closure valve fails to seal properly.

The SMEs believe that the probability for UCC-FIBER-OPTIC FAIL is somewhere in the interval $[10^{-3}, 10^{-2}]$. Ways to reduce this probability are being evaluated, including adding a secondary containment.

The SMEs believe that the probability for UCC-CATHODE-EXT-HE is somewhere in the interval $[10^{-3}, 10^{-2}]$. Better quality assurance is being considered to reduce this probability.

There is no chance of mitigation before 5/15/2010 as that is earliest date the new C MITL can be onsite. Due to the constraint imposed by requiring the new C MITL, two cases were evaluated for T_{mitigate} :

- performing the shot before the new C MITL can be onsite (before 5/15/2010), and
- performing the shot after the new C MITL is onsite.

For each case, we evaluated the time with and without considering delay for regulatory review.

The uncertainty in T_{mitigate} is dominated by epistemic uncertainty in the SOK of the SMEs for the times contributing to each case.

The two major contributors to T_{mitigate} are:

- Time for regulatory review, and
- Time for the new C MITL to be built.

The time for regulatory review is highly uncertain, currently estimated as sometime between 63 and 252 work days. If the shot is performed before 5/15/2010, without considering time for regulatory review T_{mitigate} will be between about 78 and 240 work days after 5/15/2010.

Considering the extra time for regulatory review, T_{mitigate} will be between about 142 and 494 work days after 5/15/2010.

The new C MITL cannot be built before 5/15/2010, and it may not be built until 9/30/2010; thus, it will not be available until sometime within about 94 work days after 5/15/2010.

If the shot is delayed until after the arrival of the new C MITL, T_{mitigate} will be reduced as there is no time required to wait for the new C MITL to be built.

With the shot delayed until the new C MITL is built, without considering time for regulatory review, T_{mitigate} will be between about 78 and 147 work days. Considering the extra time for regulatory review, T_{mitigate} will be between about 142 and 399 work days.

As the design of the cleanup system progresses, it may be possible to reduce the uncertainty in the factors that contribute to T_{mitigate} . It is recommended that discussions with regulatory authorities be held to reduce the uncertainty in the time for regulatory review.

These results will be used by SNL management to decide the course of action for conducting the Pu experiments on the Z machine.

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1 INTRODUCTION

This report documents an evaluation of containment and cleanup, if containment fails, for Pu shots on the Z machine. The evaluation was performed in December, 2009. Information for the evaluation was obtained from Subject Matter Experts (SMEs) at the Z machine facility. The SMEs provided the State of Knowledge (SOK) for the evaluation.

Due the unique nature of the Z machine, the Pu containment system, and the cleanup system, there is significant epistemic- or state of knowledge- uncertainty associated with the events that comprise both failure of containment and cleanup. Therefore, traditional probabilistic and classical statistical inference techniques may not be the best approach for the evaluation as they focus on aleatory- stochastic or random- uncertainty and have difficulty dealing with epistemic uncertainty where little quantitative information is available.¹ Also, Bayesian techniques are not particularly useful here; although the Bayesian approach allows probability to be viewed as a state of knowledge, it uses the probability measure of uncertainty and we have little quantitative information for evaluating probabilities. Also, to implement a mechanistic Bayesian update, we require a prior probability distribution and information for the update and we have neither for the events of concern here.

To capture epistemic uncertainty and to allow the SMEs to reason at the fidelity of the SOK, we used the belief/plausibility measure of uncertainty for this evaluation. [Shafer] [Helton] The belief/plausibility measure of uncertainty is an extension of the probability measure of uncertainty; with no epistemic uncertainty both belief and plausibility are the single measure, probability.

There are other techniques that address epistemic uncertainty besides belief/plausibility; we chose to use belief/plausibility for the following reasons:

- It reduces to probability as a special case,
- With a few hours training, SMEs readily grasp the concept of assignment of evidence,
- The SMEs can assign evidence based on their SOK where there is a great deal of epistemic uncertainty, and
- We have software tools readily available to propagate uncertainty using belief/plausibility.

Criticisms of traditional safety and risk evaluations, such as the black swan analogy, are really directed at the difficulty these traditional evaluations have addressing epistemic uncertainty. The belief/plausibility measure of uncertainty provides an axiomatic approach to address epistemic uncertainty.

¹ Confidence intervals from classical statistics could be used, but we have little sample data to infer confidence for parameters of a probability distribution.

We evaluated two issues:

- The probability that the Pu containment system fails given a shot on the Z machine,² and
- The time to cleanup Pu contamination in the Z machine given failure of containment.

Our evaluation was based on our SOK as of December, 2009. For containment, we did not address secondary containment; although there are preliminary concepts for secondary containment they were not definitive enough to evaluate. For example, how the secondary containment would be attached to the machine and details concerning containment penetrations- for measurements and for firing the closure valve detonators- are not clearly defined. The design of the cleanup system is evolving, and our SOK reflects uncertainty in the state of the design of this system.

We considered two random variables:

1. The shot unreliability of the containment system, defined as the probability that containment fails given a shot.
2. The time to mitigate the consequences of containment failure; that is, the time to cleanup Z machine if containment fails.³

The probability that containment fails given a shot, the unreliability, is designated P_{fail} . The time to mitigate the consequences of containment failure is designated $T_{mitigate}$. The shot unavailability of Z machine due to a Pu shot is defined as the fraction of time Z machine would not be available considering a series of shots with Pu planned for completion within a certain time, T_{total} .

$$Unavailability = \frac{n P_{fail} T_{mitigate}}{T_{total}} \quad (\text{Eqn. 1})$$

In equation 1 'n' is the total number of Pu shots to be completed within the required time T_{total} .⁴ We assume complete independence among the shots; the derivation of equation 1 is provided in Appendix A.

We did not address overall facility reliability/availability impacted by events other than Pu experiments that could cause downtime for the Z machine, such as failure of a MARX generator; we focused on issues with Pu experiments that could cause loss of containment and downtime of the machine.

² Here we mean probability in the objective or frequency sense: the fraction of trials for which containment fails. Since we have insufficient quantitative test data to know this, we have an uncertainty in the objective probability. This uncertainty could be modeled with the (subjective) probability measure. But for the reasons discussed, we model the uncertainty with belief/plausibility.

³ We refer to cleanup as mitigation since most safety analyses consider mitigation as efforts to reduce consequences; efforts to reduce the likelihood of events that cause consequences of concern are considered prevention, not mitigation.

⁴ It is assumed that $n P_{fail} T_{mitigate}$ is less than T_{total} in equation 1; otherwise, unavailability greater than one (negative availability) will occur. In this situation, the required time available for the series of shots, T_{total} , cannot be met.

Due to the evolving nature of the design of the cleanup system, we evaluated unreliability, P_{fail} , and time to cleanup, T_{mitigate} , for the first Pu shot scheduled for June, 2010. We did not evaluate unavailability. The design of the cleanup system will mature and be different by the time the first shot is completed; that is, T_{mitigate} will change. In the future, unavailability could be evaluated.

Due to logistical issues, we first evaluated T_{mitigate} then P_{fail} , and that is the order in which the results are subsequently presented.

We evaluated T_{mitigate} using expert elicitation of the SMEs. The following factors affecting the time to cleanup were considered:

- Time for pre-shot prep activities,
- Time for regulatory review if containment has failed,
- Time for initial cleaning,
- Time for cleaning all components that can be cleaned, and
- Time to have new components onsite.

Some of the existing components cannot be cleaned, and new replacement components designed to be cleanable are being built; the new component of most concern for timely delivery is the new C MITL (Magnetically Insulated Transmission Line).

We evaluated P_{fail} using expert elicitation of SMEs. A fault tree was developed to delineate the ways that containment can fail; the top event in the tree is P_{fail} . The tree was input into the SAPHIRE software, and SAPHIRE solved the tree for qualitative minimal cut sets.⁵ [SAPHIRE] As a result of the expert elicitation, we produced a model for the combinations of events that contribute to both T_{mitigate} and P_{fail} . To be specific, T_{mitigate} is formed by the algebraic sum of all the contributing times previously discussed. P_{fail} is the logical union (OR) of a number of minimal cut sets of a fault tree, each cut set being a logical intersection (AND) of one or more events.

Each event that comprises T_{mitigate} and P_{fail} has uncertainty; that uncertainty was captured by expert elicitation of SMEs. The SMEs were trained in the assignment of evidence in the context of the belief/plausibility measure of uncertainty.⁶ Then the SMEs assigned evidence to each event in the model.

⁵ A cut set is a set of events all required to cause the top event; the union of all cut sets is the top event. If a given cut set has another cut set as a subset, that cut set is removed; only minimal cut sets are retained. For example if the cut sets are AB, AG, and ABC, the minimal cut sets are AB and AG, if A and B occur that is sufficient without the occurrence of C.

⁶ The SMEs attended a four hour training session that used the training material from the SNL in-house course "NST 460: Advanced Safety Analysis". [NST 460]

The uncertainty for T_{mitigate} and P_{fail} was evaluated using the BeliefConvolution software. This software combines evidence for an algebraic combination of numeric variables to provide the belief/plausibility distributions for the resultant variable.⁷ [Darby] [LinguisticBelief]

⁷ BeliefConvolution is one of three SNL-developed Java codes to evaluate combinations of variables using the belief/plausibility measure of uncertainty. BeliefConvolution addresses numeric variables. The other two codes, PoolEvidence[®] and LinguisticBelief[®], address purely linguistic variables using fuzzy sets and approximate reasoning in conjunction with belief/plausibility.

2 THE BELIEF/PLAUSIBILITY MEASURE OF UNCERTAINTY

Over the last 50 years, mathematicians and logicians have developed measures of uncertainty that are more general than probability, and that specifically address epistemic uncertainty. This section of the report provides an overview of the belief/plausibility measure of uncertainty by way of an example. Details are provided in the references. [Helton] [Darby]

The belief/plausibility measure of uncertainty from the Dempster/Shافر Theory of Evidence is an extension of the probability measure of uncertainty that can capture epistemic uncertainty. Belief/plausibility is a superset of probability and under certain conditions belief and plausibility both become probability. Under other conditions belief/plausibility become necessity/possibility, respectively.⁸ Belief/plausibility addresses a type of uncertainty called ambiguity. The uncertainty associated with predicting an event in the future is ambiguity.

A simple example illustrates the difference between aleatory and epistemic uncertainty, and the use of a belief/plausibility measure. Consider a fair coin, heads on one side tails on the other with each side equally likely. The uncertainty as to the outcome of a toss- heads or tails- is aleatory. The probability of heads is $\frac{1}{2}$ and the probability of tails is $\frac{1}{2}$. The uncertainty is due to the randomness of the toss. Suppose however that I do not know the coin is fair; the coin could be biased to come up heads, or the coin could even be two-tailed. Now I have epistemic uncertainty; my state of knowledge is insufficient to assign a probability to heads or tails, all I can say is the likelihood of heads (or tails) is somewhere between 0 and 1. To consider epistemic uncertainty as well as aleatory uncertainty, belief/plausibility can be used as the measure of uncertainty. With total ignorance about the coin, the belief that the toss will be heads is 0 and the plausibility that the toss will be heads is 1; similarly, the belief that the toss will be tails is 0 and the plausibility that the toss will be tails is 1. Belief/plausibility form an interval that can be interpreted as giving the lower and upper bound of probability. If I have enough information, both belief and plausibility reduce to a single value, probability. Figure 2-1 illustrates this concept. Epistemic uncertainty can be reduced with more information. If I toss the coin a few times and a heads and a tails occur, I know the coin is two sided; with more tosses I can evaluate the fairness of the coin. Aleatory uncertainty cannot be reduced with more information.

Figure 2-1 Belief/Plausibility as Bounds on Probability

⁸ To be precise, if the focal elements are singletons, belief/plausibility both become probability. If the focal elements are nested, belief/plausibility become necessity/possibility, respectively.

As an example, consider one of the variables that comprise T_{mitigate} ; specifically, the time for cleaning all components that can be cleaned, call that time T_{clean} . In the following, all times are work days.

There will always be uncertainty in T_{clean} - even after the system is developed, tested, and used- as each cleanup is a complex operation and time for cleanup will vary. If the system were “identical” to a system used elsewhere, it might be possible to model the uncertainty in T_{clean} using a probability distribution based on the data available for T_{clean} for all the systems. Suppose that based on the data, a good fit for the uncertainty in T_{clean} is a triangular probability density distribution with minimum 68.5, most likely 100, and maximum 137 as shown in Figure 2-2.⁹ The expected value (mean) of this distribution is 102.

Probability Density

Figure 2-2 Hypothetical Probability Distribution for T_{clean} assuming other Data Available

Figure 2-3 shows the complementary cumulative probability distribution; the probability that T_{clean} is greater than a particular value.

⁹ Mathematica was used to generate Figures 2-2 and 2-3. [Mathematica]

Figure 2-3 Hypothetical Complementary Cumulative Probability Distribution for T_{clean}

For example, using Figure 2-3, the probability that T_{clean} is greater than 120 is 0.11. The cleanup system for Z machine is unique. With the fidelity of the information available for the Z machine, there is insufficient SOK to assign a probability distribution for T_{clean} . Based on their current SOK, the SMEs assigned the evidence shown in Figure 2-4.¹⁰

Figure 2-4 Evidence for T_{clean}

The SMEs believe that T_{clean} will be somewhere within [68.5, 100] work days 2/3 of the time but may be somewhere in [68.5, 137] work days 1/3 of the time. They have insufficient information to provide a more precise evaluation of T_{clean} , and cannot assign a probability distribution to T_{clean} .

For a given event, the belief is the sum of all the evidence that supports the event and the plausibility is the sum of all the evidence that does not contradict the event. For example,

¹⁰ Appendix B contains the part of the training given the SMEs that illustrates the assignment of evidence with a simple example. [NST 460]

consider the event “ T_{clean} exceeds 120”. Figure 2-5 indicates the evidence in relation to the event of interest.

Figure 2-5 Evidence for T_{clean} in relation to event “ T_{clean} exceeds 120”

The belief that “ T_{clean} exceeds 120” is the sum of all the evidence for events totally contained within the circle for “ T_{clean} exceeds 120”; as no circles of evidence are totally contained the belief is zero. The plausibility that “ T_{clean} exceeds 120” is the sum of all the evidence for events totally contained within or overlapping to any extent the circle for “ T_{clean} exceeds 120”; one of the two circles of evidence overlaps- specifically, the circle for [68.5, 137] with evidence 1/3- so the plausibility is 1/3. Based on the evidence available, the belief to plausibility interval for “ T_{clean} exceeds 120” is 0 to 1/3. The probability is somewhere in this interval. Given sufficient information to eliminate the epistemic uncertainty, both belief and plausibility are the same, the probability. For example, if we eventually have enough information to assign the probability distribution of Figure 2-2, the probability that “ T_{clean} exceeds 120” is 0.11. Note that the belief to plausibility interval [0, 1/3] contains the probability 0.11. Just as probability ‘expands’ to a belief to plausibility interval, the point estimate expected value for a probability distribution ‘expands’ to an interval for belief/plausibility. The expected value interval for T_{clean} based on the evidence in Figure 2-4 is [68.5, 112.2] which contains the mean of the probability distribution 102.

In terms of degrees of evidence, belief (Bel) and plausibility (Pl) are defined as follows for any subsets or intervals A and B.

$$\begin{aligned}
 Bel(A) &= \sum_{B|B \subseteq A} m(B) \\
 Pl(A) &= \sum_{B|A \cap B \neq \emptyset} m(B) \quad (\text{Eqn. 2})
 \end{aligned}$$

$m(A)$ represents the evidence for A.

With a belief/plausibility distribution, a random variable X has an expected value interval $[E_*(X), E^*(X)]$ given by:

$$\begin{aligned} E_*(X) &= \sum_{all A_i \subseteq X} \inf(A_i) * m(A_i) \\ E^*(X) &= \sum_{all A_i \subseteq X} \sup(A_i) * m(A_i) \end{aligned} \quad (\text{Eqn. 3})$$

where A_i is a subset/interval with evidence $m(A_i)$.

The BeliefConvolution code automates the calculation of belief and plausibility based on evidence. Using the evidence of Figure 2-4, the complementary cumulative belief/plausibility distribution for T_{clean} is shown in Figure 2-6.

Figure 2-6 Complementary Cumulative Belief and Plausibility Distributions for T_{clean}

For example, the likelihood that T_{clean} exceeds 120 work days is the belief to plausibility interval $[0, 0.33]$. Note that the complementary cumulative probability distribution of Figure 2-3 (a curve) is bounded by the complementary cumulative belief (lower bound) and plausibility (upper bound) curves of Figure 2-6.

Just as the probability distribution for combinations of random variables represented with a probability distribution can be calculated by convolution of the variables, belief and plausibility distributions can be calculated for combinations of random variables that are assigned evidence. The details are discussed in the references, and the convolution is implemented in BeliefConvolution. For example, as discussed in Section 1, we added numerous time variables including T_{clean} to calculate T_{mitigate} , and the addition of the evidence was performed using BeliefConvolution.

3 EVALUATION OF T_{MITIGATE}

T_{mitigate} is the time to mitigate the consequences of a failure of containment for a shot with a Pu target on the Z machine. Mitigation consists of cleanup of the Pu from the Z machine.

We consider the first shot only; it is desired to perform the first shot by 6/30/2010.

We assume 21 work days per month.

All times are work days.

3.1 Assignment of Evidence

Appendix D identifies the SMEs that participated in the identification of factors that comprise T_{mitigate} , and the assignment of evidence for these factors. The SMEs identified the following factors and assigned the indicated evidence by consensus.

Time for pre-shot prep activities:

- [25, 40] days with evidence 1.0

Time for regulatory review if containment fails

- [63, 252] days with evidence 1.0

Time to build new C MITL¹¹

- Earliest possible: 5/15/2010
- Actual onsite somewhere between 5/15/2010 and 9/30/2010
- After 5/15/2010 estimate [0, 94.5] days with evidence 1.0

Initial cleaning

- [10, 10] days with evidence 1.0 (no uncertainty, 10 days)

Clean all components (except C MITL)

- [68.5, 100] days with evidence 0.67
- [68.5, 137] days with evidence 0.33

3.2 Evaluation of Two Cases

Due the constraint imposed by requiring the new C MITL, two cases were evaluated.

¹¹ The current C MITL cannot be cleaned if contaminated with Pu. Given contamination, it must be replaced with the new C MITL that is designed to be easier to cleanup.

3.2.1 Case A. First Shot Before New C MITL Can Be Onsite (before May 15, 2010)

There is no chance of mitigation before 5/15/2010 as that is earliest date the new C MITL can be onsite.

Therefore, the following times are days *after* after 5/15/2010.

We assume pre-shot prep activities are completed before 5/15/2010.

Without considering time for regulatory review

T_{mitigate} = Time after 5/15/2010 for C MITL onsite + Initial Cleaning + Clean All Components (except C MITL). Sum is convolution with the assigned evidence.

Considering time for regulatory review

T_{mitigate} = Time for Regulatory Review if Containment fails + Time after 5/15/2010 for C MITL onsite + Initial Cleaning + Clean All Components (except C MITL). Sum is convolution with the assigned evidence.

3.2.2 Case B. First Shot After New C MITL Is Onsite

Consider the case where the first shot is not performed until after the new C MITL is built. In this situation, the time (and uncertainty in the time) for the new C MITL to be built is not a contributor to T_{mitigate} .

We assume pre-shot prep activities are completed before 5/15/2010.

Without considering time for regulatory review

T_{mitigate} = Initial Cleaning + Clean All Components (except C MITL). Sum is convolution with the assigned evidence.

Considering time for regulatory review

T_{mitigate} = Time for Regulatory Review if Containment fails + Initial Cleaning + Clean All Components (except C MITL). Sum is convolution with the assigned evidence.

3.3 Results of Evaluation for T_{mitigate}

Results for the cases of interest follow.

3.3.1 Results for Case A. First Shot Before May 15, 2010

Without considering time for regulatory review the result is:

Figure 3-1 Likelihood of Exceedance for T_{mitigate} Shot Before 5/15/2010 No Regulatory Review

The likelihood of exceedance for T_{mitigate} is a belief to plausibility interval; the probability is somewhere between the belief and the plausibility. Without considering the time for regulatory review, we believe the minimum time for T_{mitigate} is 78.5 days after 5/15/2010. There is considerable plausibility that T_{mitigate} will exceed 204.5 days after 5/15/2010; it is not very plausible that T_{mitigate} will exceed 241.5 days after 5/15/2010. To decrease the uncertainty for T_{mitigate} (e.g., narrow the belief to plausibility interval) an improvement in the state of knowledge is required.

Considering time for regulatory review the result is:

Figure 3-2 Likelihood of Exceedance for $T_{mitigate}$ Shot Before 5/15/2010 With Regulatory Review

The likelihood of exceedance for $T_{mitigate}$ is a belief to plausibility interval; the probability is somewhere between the belief and the plausibility. Considering the time for regulatory review, we believe the minimum time for $T_{mitigate}$ is 141.5 days after 5/15/2010. There is considerable plausibility that $T_{mitigate}$ will exceed 456.5 days after 5/15/2010; it is not very plausible that $T_{mitigate}$ will exceed 493.5 days after 5/15/2010. To decrease the uncertainty for $T_{mitigate}$ (e.g., narrow the belief to plausibility interval) an improvement in the state of knowledge is required.

3.3.2 Case B. First Shot After New C MITL Onsite

Without considering time for regulatory review the result is:

Figure 3-3 Likelihood of Exceedance for $T_{mitigate}$ Shot After New C MITL Onsite No Regulatory Review

The likelihood of exceedance for $T_{mitigate}$ is a belief to plausibility interval; the probability is somewhere between the belief and the plausibility. Without considering the time for regulatory review, we believe the minimum time for $T_{mitigate}$ is 78.5 days. There is considerable plausibility that $T_{mitigate}$ will exceed 110 days; it is not very plausible that $T_{mitigate}$ will exceed 147 days. To decrease the uncertainty for $T_{mitigate}$ (e.g., narrow the belief to plausibility interval) an improvement in the state of knowledge is required.

Considering time for regulatory review the result is:

Figure 3-4 Likelihood of Exceedance for $T_{mitigate}$ Shot After New C MITL Onsite With Regulatory Review

The likelihood of exceedance for $T_{mitigate}$ is a belief to plausibility interval; the probability is somewhere between the belief and the plausibility. Considering the time for regulatory review, we believe the minimum time for $T_{mitigate}$ is 141.5 days. There is considerable plausibility that $T_{mitigate}$ will exceed 362 days; it is not very plausible that $T_{mitigate}$ will exceed 399 days. To decrease the uncertainty for $T_{mitigate}$ (e.g., narrow the belief to plausibility interval) an improvement in the state of knowledge is required.

3.4 Conclusions for $T_{mitigate}$

Using the state of knowledge as of December, 2009, the values for $T_{mitigate}$ for the cases of interest can be summarized in Figure 3-5.. The lower limit for $T_{mitigate}$ is taken as the minimum value for $T_{mitigate}$ for which the belief of non-exceedance is zero; the upper limit for $T_{mitigate}$ is taken as the minimum value for $T_{mitigate}$ for which the plausibility of non-exceedance is zero.

Figure 3-5 Results for $T_{mitigate}$

The two major contributors to $T_{mitigate}$ are:

- Time for regulatory review, and
- Time for the new C MITL to be built.

The time for regulatory review is highly uncertain, currently estimated as sometime between 63 and 252 work days. If the shot is performed before 5/15/2010, without considering time for regulatory review $T_{mitigate}$ will be between about 78 and 240 days after 5/10/2010. Considering the extra time for regulatory review, $T_{mitigate}$ will be between about 142 and 494 days after 5/10/2010.

The new C MITL cannot be built before 5/15/2010, and it may not be built until 9/30/2010; it will not be available until sometime within 94.5 work days after 5/15/2010.

If the shot is delayed until after the arrival of the new C MITL, $T_{mitigate}$ will be reduced as there is no time required to wait for the new C MITL to be built.

With the shot delayed until the new C MITL is built, without considering time for regulatory review, $T_{mitigate}$ will be between about 78 and 147 days. Considering the extra time for regulatory review, $T_{mitigate}$ will be between about 142 and 399 days.

Based on these results, it is recommended that more information be gathered to reduce the uncertainty in the time for regulatory review, and consider waiting until the new C MITL is built before performing the first shot.

With no time for regulatory review and with the C MITL available, T_{mitigate} is determined mainly by the time for cleanup. As of December, 2009, there is considerable uncertainty in the time to cleanup as indicated by the assignment of evidence. It is recommended that as the design of the mitigation (cleanup) system matures and uncertainty hopefully decreases, the estimate of time to cleanup be revised.

4 EVALUATION OF P_{FAIL}

P_{fail} is a probability, a value in $[0, 1]$.¹² Working with the SMEs, a fault tree for P_{fail} was developed. The qualitative minimal cut sets of the fault tree were generated using the SAPHIRE code. P_{fail} and the cut sets were quantified using the BeliefConvolution code.

4.1 Fault Tree Model

The fault tree and the minimal cut sets for P_{fail} are provided in Appendix C. Figure 4-1 is the top portion of the fault tree.¹³

Figure 4-1 Top Portion of Fault Tree for Failure of Containment

¹² P_{fail} is an objective probability. Due to epistemic uncertainty, we express our uncertainty in P_{fail} with the belief/plausibility measure of uncertainty.

¹³ The logical equation that represents the top event of a fault tree can be expressed as a union of minimal cut sets. A cut set is a set of events all required to cause the top event; the union of all cut sets is the top event. If a given cut set has another cut set as a subset, that cut set is removed; only minimal cut sets are retained. For example if the cut sets are AB, AG, and ABC, the minimal cut sets are AB and AG; if A and B occur that is sufficient without the occurrence of C. Fault tree evaluation codes such as SAPHIRE solve the fault logical tree equation for the minimal cut sets.

Table 4-1 lists the basic events in the fault tree, and the evidence assigned to each event by the SMEs. From the evidence, belief and plausibility for each event and for combinations of events that comprise minimal cut sets can be calculated.

Table 4-1 List of Basic Events in Fault Tree for P_{fail}

Name	Description and Evidence ¹⁴
BAD-DAS-CABLE	Bad DAS Cable [1e-6, 1e-5] 1
CABLE-DISCONNECT	Cable Disconnected [0, 1e-5] 0.5, [0, 1e-6] 0.5
CHARGE-SYS-FAIL	Charging System Failure [0, 0] 1
COAX-FAIL	Undetected Coaxial Switch Failure [1e-6, 1e-5] 1
CONTROL-FAIL	Control System Failure (Marx Voltage too High) [0, 0] 1
DAS-CABLE-HE	DAS Cable Not Connected Human Error [0, 1e-5] 1
DAS-PREFIRE-FAIL	DAS Prefire Circuit Fails [1e-5, 1e-4] 0.5, [1e-4, 1e-3] 0.5
DEBRIS-EARLY	Debris arrives too early [0, 0] 1
DET-RING-FAIL	Det O-Ring Seal Fail [0, 1e-3] 0.5, [0, 5e-4] 0.5
DG-PREFIRE	DG Prefires (triggers SNM prefire circuit) [0, 1e-7] 1
FIRESET-NOT-ARMED	Fireset Not Armed Human Error or Timing [1e-5, 1e-4] 1
SIGNAL-FROM-FIRESET	Signal from Fireset Occurs [1e-6, 1e-5] 1
SNM-DELAY-GEN-FAIL	SNM Prefire Delay Generator Fails [1e-5, 1e-4] 1
UCC-BODY-FAIL	UCC Body Fails due to Pressure [1e-6, 1e-5] 0.33, [1e-5, 1e-4] 0.67
UCC-CONFLAT-NOT-TESTED	UCC Conflat Not Tested Connections Fail, Pressure [0, 2e-3] 1
UCC-CONFLAT-TESTED	UCC Conflat Pretested Connections Fail due to Pressure [0, 1e-4] 0.5, [0, 1e-3] 0.5
UCC-DEBRIS-DIRECT	UCC Direct Failure Debris (load hardware) [0, 1e-6] 0.25, [1e-5, 1e-4] 0.25, [0, 1e-5] 0.25, [1e-6, 1e-5] 0.25
UCC-DEBRIS-INDIRECT	UCC Indirect Failure Debris (baffle) [0, 1e-5] 0.75, [1e-5, 1e-4] 0.25
UCC-FAIL-MAG-PRESS	UCC Fails due to Magnetic Pressure [0, 1e-5] 0.5, [1e-5, 1e-4] 0.5
UCC-FAIL-ZINGER	UCC Fail from Zinger vacuum (arc) [1e-5, 1e-4] 0.67, [1e-4, 1e-3] 0.33
UCC-FIBER-OPTIC-FAIL	UCC Fiber Optic Feed Fails due to Pressure/Shock [1e-3, 1e-2] 1
UCC-HE-FASTEN	Human Error installing UCC Fasteners [0, 0] 1
UCC-HE-SEALS	Human Error installing UCC Seals [1e-4, 1e-3] 1
UCC-RING-SEALS	UCC O Ring Seals Fail due to Pressure (not tested) [1e-5, 1e-4] 1
UCC-SMA-FAIL	UCC SMA Fails due to Pressure [1e-3, 5e-3] 1
UCC-TUBE-FAIL	UCC Tubing Fails due to Overpressure [1e-5, 1e-4] 1
UCC-VENT-VLVS-FAIL	UCC Swagelok Vent Valves Fail (3) [1e-5, 1e-4] 1
UCC-WELDS-FAIL	UCC Welds Fail due to Pressure [1e-6, 1e-5] 0.33, [1e-5, 1e-4] 0.67
UCV-BAD-DETS	UCV Bad Dets [1e-4, 2e-3] 1
UCV-CATHODE-EXT-HE	UCV Cathode Extension Human Error [1e-3, 1e-2] 1
UCV-CLOSE-TUBE-FAIL	UCV Fail to Seal Closure Tube Failure [1e-4, 1e-3] 1
UCV-DETS-CABLE	UCV Dets Cables Bad [1e-5, 1e-4] 1
UCV-DETS-FIRESET-FAIL	UCV Dets Fireset Fails [1e-3, 1e-3] 1
UCV-DETS-HE	Human Error Connecting UCV Dets Cables [1e-5, 1e-4] 1
UCV-HIGH-EXPL-BAD	UCV High Explosive Bad [0, 0] 1
UCV-NO-EXPL-HE	UCV High Explosive Missing Human Error [1e-4, 1e-4] 1
UPPER-TUBE-CLOSE-FAIL	Closure Tube Fails Above Closure Point [3e-3, 7e-3] 0.25, [1e-4, 1e-3] 0.75
VENT-SYS-FAIL	Vent Tank System Fails [0, 1e-3] 1

¹⁴ For example [1e-3, 1e-4] 0.25, [1e-3, 1e-2] 0.75 indicates evidence of 0.25 for the interval [1e-3, 1e-4], and evidence of 0.75 for the interval [1e-3, 1e-2].

Name	Description and Evidence ¹⁴
WRONG-DELAY-HE	Human Error Wrong Delay [1e-5, 1e-4] 1
WRONG-PULSE-HE	Incorrect Pulse Shape due to Human Error [1e-4, 1e-3] 1
Z-PREFIRE	Z PREFIRES [3.3e-3, 2e-2] 0.5, [1e-2, 2e-2] 0.5
Z-PREFIRE-DES	Z PREFIRES Design issue Valve closes late [0, 0] 1

As discussed previously, a cut set is a set of events all of which must occur for the top event in the fault tree- here, failure of containment - to occur. Each cut set is a way in which failure of containment can occur.

The minimal cut sets are summarized in Table 4-2. There are 39 total minimal cut sets for the fault tree: 10 multiple event cut sets and 29 single event cut sets.

Table 4-2 Summary of Minimal Cut Sets

Cut No.	Cut Sets
1	COAX-FAIL, UCV-DETS-FIRESET-FAIL
2	CABLE-DISCONNECT, UCV-DETS-FIRESET-FAIL
3	SIGNAL-FROM-FIRESET, UCV-DETS-FIRESET-FAIL
4	UPPER-TUBE-CLOSE-FAIL, VENT-SYS-FAIL
5	DET-RING-FAIL, UPPER-TUBE-CLOSE-FAIL
6	FIRESET-NOT-ARMED, Z-PREFIRE
7	SNM-DELAY-GEN-FAIL, Z-PREFIRE
8	DAS-PREFIRE-FAIL, Z-PREFIRE
9	DAS-CABLE-HE, Z-PREFIRE
10	BAD-DAS-CABLE, Z-PREFIRE
11	DEBRIS-EARLY
12	Z-PREFIRE-DES
13	UCC-FAIL-MAG-PRESS
14	UCC-WELDS-FAIL
15	UCC-VENT-VLVS-FAIL
16	UCC-RING-SEALS
17	UCC-CONFLAT-TESTED
18	UCC-CONFLAT-NOT-TESTED
19	UCC-BODY-FAIL
20	UCC-FIBER-OPTIC-FAIL
21	UCC-SMA-FAIL
22	UCC-TUBE-FAIL
23	UCC-DEBRIS-DIRECT
24	UCC-DEBRIS-INDIRECT
25	UCC-HE-SEALS
26	UCC-HE-FASTEN
27	UCC-FAIL-ZINGER
28	UCV-DETS-HE
29	UCV-DETS-CABLE
30	UCV-HIGH-EXPL-BAD
31	UCV-NO-EXPL-HE
32	UCV-BAD-DETS
33	UCV-CLOSE-TUBE-FAIL
34	UCV-CATHODE-EXT-HE

Cut No.	Cut Sets
35	WRONG-PULSE-HE
36	CONTROL-FAIL
37	CHARGE-SYS-FAIL
38	DG-PREFIRE
39	WRONG-DELAY-HE

Each multiple event cut set consists of more than one event, and all the events in the cut set must occur for containment to fail. For each single event cut set only one event is necessary to cause failure of containment.

4.2 Quantification of P_{fail}

P_{fail} was quantified using the BeliefConvolution code. Appendix E contains the input listing in BeliefConvolution for evaluating P_{fail} . Appendix D summarizes the expertise of each SME that participated in assigning evidence to the basic events of the fault tree, and the evidence assigned by each expert for all events.

The likelihood of exceedance result for P_{fail} is provided in Figure 4-2. For example, the belief that P_{fail} exceeds 0.015 is 0.0052 and the plausibility that P_{fail} exceeds 0.015 is one; the probability that P_{fail} exceeds 0.015 is somewhere in the belief/plausibility interval 0.0052/1.

Figure 4-2 Complementary Cumulative Belief and Plausibility Distributions for P_{fail}^{15}

Ten single event cut sets are the most important contributors to the probability of containment failure. Of these 10, the two single event cut sets that contribute the most are:

- UCC-FIBER-OPTIC-FAIL, a failure in a fiber optic feed-through due to pressure or shock, and
- UCV-CATHODE-EXT-HE, human error in installing the correct cathode extension resulting in movement of the cathode extension during the shot such that that the closure valve fails to seal properly.

The likelihood of exceedance distributions for the probability of these events are shown in Figure 4-3 and Figure 4-4.

¹⁵ Discrete steps for belief and plausibility are present but are not apparent in Figure 4-2 due to the scale of the abscissa.

Figure 4-3 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-FIBER-OPTIC-FAIL

Figure 4-4 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCV-CATHODE-EXT-HE

The likelihood of exceedance distributions for the eight other important single event cut sets are shown in Figure 4-5 through Figure 4-12.

Figure 4-5 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-CONFLAT-NOT-TESTED

Figure 4-6 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-CONFLAT-TESTED

Figure 4-7 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-SMA-FAIL

Figure 4-8 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-HE-SEALS

Figure 4-9 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCC-FAIL-ZINGER

Figure 4-10 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCV-BAD-DETS

Figure 4-11 Complementary Cumulative Belief and Plausibility Distributions for Probability of UCV-CLOSE-TUBE-FAIL

Figure 4-12 Complementary Cumulative Belief and Plausibility Distributions for Probability of WRONG-PULSE-HE

4.3 Conclusions for P_{fail}

Numerous single events can result in failure of containment. There is significant epistemic uncertainty in the probability of these events.

As indicated in Figure 4-2, there is a sharp reduction in the belief of exceedance at P_{fail} of about 0.0037, and there is a sharp reduction in the plausibility of exceedance at P_{fail} of about 0.033.

We will take these as appropriate lower and upper limits for P_{fail} . Therefore, P_{fail} is somewhere in the interval $[0.0037, 0.033]$ as shown in Figure 4-13.

Figure 4-13 Summary of Results for Probability of Containment Failure

A secondary containment could possibly reduce P_{fail} . The secondary containment could lower the likelihood of failures associated with “upper” primary containment, above where the secondary containment would attach to the primary containment. However, a secondary containment would not lower the likelihood of failures associate with “lower” primary containment, such as failures associated with the closure valve. The secondary containment must be designed in order to evaluate its potential benefit.

The SMEs believe that the probability for UCC-FIBER-OPTIC FAIL is somewhere in the interval $[10^{-3}, 10^{-2}]$. Ways to reduce this probability are being evaluated, including adding a secondary containment.

The SMEs believe that the probability for UCC-CATHODE-EXT-HE is somewhere in the interval $[10^{-3}, 10^{-2}]$. Better quality assurance is being considered to reduce this probability.

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APPENDIX A DERIVATION OF EQUATION FOR UNAVAILABILITY

This appendix derives equation 1 for unavailability.

Given a series shots on the machine, let X be a random variable for the number of containment failures; x is a specific value of X . P_{fail} is the probability of failure of containment given a shot. The total number of shots is n .

We assume X can be modeled with the binomial distribution. $\text{BinomialDistribution}[n, P_{fail}]$ denotes the distribution for X . $\text{PDF}[\text{BinomialDistribution}[n, P_{fail}], x]$ is the probability that exactly x of the n shots result in a failure, where PDF is the probability density function.

$T_{mitigate}$ is the time required to mitigate a failure. Given x failures, the total mitigation time is $x * T_{mitigate}$. Considering the probability of failure over all n shots, the total mitigation time is $\text{Sum}[\text{PDF}[\text{BinomialDistribution}[n, P_{fail}], x] * x * T_{mitigate}]$ summed for x from 0 to n .

The total mitigation time can be calculated with Mathematica. The input is:

```
MyDist = BinomialDistribution[n, P_fail]
Simplify[Sum[PDF[MyDist,x] * x T_mitigate, {x,0,n}]]
```

The result is:

$$n P_{fail} T_{mitigate}.$$

The total mitigation time is the total time the machine is unavailable.

APPENDIX B EXAMPLE OF ASSIGNMENT OF EVIDENCE

Evidence is information assigned weights by subject matter experts. Evidence is not likelihood; likelihood is belief/plausibility. Belief/plausibility is calculated from the evidence.

The concept of evidence is surprisingly simple to use in practice.

This appendix provides a tutorial for the subject matter experts on the assignment of evidence.

On Dec. 31, 2005, Grandma and Grandpa are trying to figure out the age of a distant relative, Jack.

Grandpa says “I think Jack was not born before 1980.”

Grandma says “I think Jack is a teenager.”

Jack has definite age, but there is uncertainty as to his age. The Sample Space is the set of all unique ages: $S = [0, 150]$ years.¹⁶

We have two pieces of *Evidence*: what Grandpa says and what Grandma says.

Evidence #1: What Grandpa says. This is evidence for Jack’s age being somewhere *exactly* in $(0, 26)$.

Evidence #2: What Grandma says. This is evidence for Jack’s age being somewhere *exactly* in $[13, 20)$.

We know that Grandma has a better memory than Grandpa about relatives, so we decide to weight Grandma’s evidence twice as much as Grandpa’s evidence: $2/3$ for Grandma and $1/3$ for Grandpa.

¹⁶ $[a, b]$ contains all values between a and b including a and b . $[a, b)$ contains all values between a and b , including a but not including b .

Our focal elements are as follows. m is a degree of evidence, a value between zero and one. All the evidence must sum to one.

Note that even though $(0, 26)$ contains $[13, 20)$ the evidence 0.33 for $(0, 26)$ is less than the evidence 0.67 for $[13, 20)$, because the evidence for an interval is the evidence of being *exactly* in that interval and *not* localized within any subinterval.

Since $(0, 26)$ contains $[13, 20)$, the belief for $(0, 26)$ will be greater than or equal to than the belief for $[13, 20)$. The belief for an interval is the total evidence of being *in that interval or any other interval within that interval*.

Since $(0, 26)$ contains $[13, 20)$, the plausibility for $(0, 26)$ will be greater than or equal to than the plausibility for $[13, 20)$. The plausibility for an interval is the total evidence of being *in any interval that overlaps that interval (any interval not disjoint with that interval)*. The plausibility is always greater than or equal to the belief, since it include all the evidence for belief plus the additional evidence from the overlapping intervals.

For Jack, the belief for $[13, 20)$ is 0.67 and the plausibility for $[13, 20)$ is 1.0. The belief for $(0, 26)$ is 1.0 and the plausibility for $(0, 26)$ is 1.0. Based on the evidence, we conclude that Jack is not 26 years old or older, and the probability that Jack is a teenager is somewhere in the belief/plausibility interval 0.67 to 1.0.

A given expert can provide more than one piece of evidence. That is, Grandma could have provided **both** pieces of evidence. For example, Grandma could say my best recollection is that Jack is a teenager, but I think I remember Aunt Maude telling me that he is not yet 26. So I will assign evidence of $2/3$ to teenager and $1/3$ to not being yet 26.

APPENDIX C FAULT TREE AND MINIMAL CUT SETS FOR P_{FAIL}

This appendix contains the fault tree developed for the probability of failure of the primary containment, P_{fail} . Also, the minimal cut sets for the tree are provided.

There is no fault tree page #4 in the latest model.

Includes incorrect accelerator configuration.
Too many Marx Generators,
Laser Timing Problem,
Charge Voltage Too High

The 39 minimal cut sets for the fault tree are provided in table C-1. Of the 39, the first 10 are multiple event cut sets and the remaining 29 are single event cut sets.

Table C-1. Minimal Cut Sets for P_{fail}

Cut No.	Basic Event	Description
1	COAX-FAIL	Undetected Coaxial Switch Failure
	UCV-DETS-FIRESET-FAIL	UCV Dets Fireset Fails
2	CABLE-DISCONNECT	Cable Disconnected
	UCV-DETS-FIRESET-FAIL	UCV Dets Fireset Fails
3	SIGNAL-FROM-FIRESET	Signal from Fireset Occurs
	UCV-DETS-FIRESET-FAIL	UCV Dets Fireset Fails
4	UPPER-TUBE-CLOSE-FAIL	Closure Tube Fails Above Closure Point
	VENT-SYS-FAIL	Vent Tank System Fails
5	DET-RING-FAIL	Det O-Ring Seal Fail
	UPPER-TUBE-CLOSE-FAIL	Closure Tube Fails Above Closure Point
6	FIRESET-NOT-ARMED	Fireset Not Armed Human Error or Timing
	Z-PREFIRE	Z PREFIRES
7	SNM-DELAY-GEN-FAIL	SNM Prefire Delay Generator Fails
	Z-PREFIRE	Z PREFIRES
8	DAS-PREFIRE-FAIL	DAS Prefire Circuit Fails
	Z-PREFIRE	Z PREFIRES
9	DAS-CABLE-HE	DAS Cable Not Connected Human Error
	Z-PREFIRE	Z PREFIRES
10	BAD-DAS-CABLE	Bad DAS Cable
	Z-PREFIRE	Z PREFIRES
11	DEBRIS-EARLY	Debris arrives too early
12	Z-PREFIRE-DES	Z PREFIRES Design issue Valve closes late
13	UCC-FAIL-MAG-PRESS	UCC Fails due to Magnetic Pressure
14	UCC-WELDS-FAIL	UCC Welds Fail due to Pressure
15	UCC-VENT-VLVS-FAIL	UCC Swagelok Vent Valves Fail (3)
16	UCC-RING-SEALS	UCC O Ring Seals Fail due to Pressure (not tested)
17	UCC-CONFLAT-TESTED	UCC Conflat Pretested Connections Fail due to Pressure
18	UCC-CONFLAT-NOT-TESTED	UCC Conflat Not Tested Connections Fail, Pressure
19	UCC-BODY-FAIL	UCC Body Fails due to Pressure
20	UCC-FIBER-OPTIC-FAIL	UCC Fiber Optic Feed Fails due to Pressure/Shock
21	UCC-SMA-FAIL	UCC SMA Fails due to Pressure
22	UCC-TUBE-FAIL	UCC Tubing Fails due to Overpressure
23	UCC-DEBRIS-DIRECT	UCC Direct Failure Debris (load hardware)
24	UCC-DEBRIS-INDIRECT	UCC Indirect Failure Debris (baffle)
25	UCC-HE-SEALS	Human Error installing UCC Seals
26	UCC-HE-FASTEN	Human Error installing UCC Fasteners
27	UCC-FAIL-ZINGER	UCC Fail from Zinger vacuum (arc)
28	UCV-DETS-HE	Human Error Connecting UCV Dets Cables
29	UCV-DETS-CABLE	UCV Dets Cables Bad
30	UCV-HIGH-EXPL-BAD	UCV High Explosive Bad
31	UCV-NO-EXPL-HE	UCV High Explosive Missing Human Error
32	UCV-BAD-DETS	UCV Bad Dets
33	UCV-CLOSE-TUBE-FAIL	UCV Fail to Seal Closure Tube Failure
34	UCV-CATHODE-EXT-HE	UCV Cathode Extension Human Error

Cut No.	Basic Event	Description
35	WRONG-PULSE-HE	Incorrect Pulse Shape due to Human Error
36	CONTROL-FAIL	Control System Failure (Marx Voltage too High)
37	CHARGE-SYS-FAIL	Charging System Failure
38	DG-PREFIRE	DG Prefires (triggers SNM prefire circuit)
39	WRONG-DELAY-HE	Human Error Wrong Delay

APPENDIX D SMES AND EVIDENCE

The following SMEs participated in the development of the models and the assignment of evidence.

SMEs for $T_{mitigate}$

For $T_{mitigate}$, the following SMEs participated.

Table D-1. SMEs for $T_{mitigate}$

Name	Organization	Title	Expertise
Randy McKee	SNL	Engineering manager	Mechanical engineering, manufacturing
Matt Christison	Ktech	Mechanical engineer	Mechanical engineering, product development
Drew Kornreich	LANL	R&D engineer	Nuclear engineering, plutonium systems analysis

The assignment of evidence for the factors that comprise $T_{mitigate}$ were a consensus of all the SMEs. The consensus evidence is provided in Section 3.1 of the main report.

SMEs for P_{fail}

For P_{fail} , the following SMEs participated.

Table D-2. SMEs for P_{fail}

Name	Organization	Title	Expertise
Dean Rovang (DR)	SNL	Mechanical engineer	Mechanical engineering, containment systems
Matt Gurule (MG)	NSTech	Mechanical engineer	Mechanical engineering, UCC engineer
Eric Smith (ES)	Ktech	Project engineer	Mechanical engineering, UCV engineer
Devon Dalton (DD)	Ktech	Lead technician	Pu ICE system assembly, installation and operations
Michael Jones (MJ)	SNL	Physicist	Z operations, controls
Barbara Lewis (BL)	Ktech	Electrical Engineer	Z operations, controls

The evidence assigned by each SME to each basic event in the fault tree for P_{fail} follows. Individuals are identified by their initials as provided in Table D-2.

Table D-3. Evidence for Fault Tree Events Assigned by SMEs

Name	Description and Evidence ¹⁷
BAD-DAS-CABLE	Bad DAS Cable [1e-6, 1e-5] 1 (MJ BL)
CABLE-DISCONNECT	Cable Disconnected [0, 1e-5] 0.5 (MJ) , [0, 1e-6] 0.5 (BL)
CHARGE-SYS-FAIL	Charging System Failure [0, 0] 1 (DD BL)
COAX-FAIL	Undetected Coaxial Switch Failure [1e-6, 1e-5] 1 (MJ BL)
CONTROL-FAIL	Control System Failure (Marx Voltage too High) [0, 0] 1 (MJ BL)
DAS-CABLE-HE	DAS Cable Not Connected Human Error [0, 1e-5] 1 (MJ BL)
DAS-PREFIRE-FAIL	DAS Prefire Circuit Fails [1e-5, 1e-4] 0.5 (MJ), [1e-4, 1e-3] 0.5 (BL)
DEBRIS-EARLY	Debris arrives too early [0, 0] 1 (DR ES)
DET-RING-FAIL	Det O-Ring Seal Fail [0, 1e-3] 0.5 (ES), [0, 5e-4] 0.5 (DD)
DG-PREFIRE	DG Prefires (triggers SNM prefire circuit) [0, 1e-7] 1 (MJ BL)
FIRESET-NOT-ARMED	Fireset Not Armed Human Error or Timing [1e-5, 1e-4] 1 (DD DR ES)
SIGNAL-FROM-FIRESET	Signal from Fireset Occurs [1e-6, 1e-5] 1 (DD MJ)
SNM-DELAY-GEN-FAIL	SNM Prefire Delay Generator Fails [1e-5, 1e-4] 1 (MJ BL)
UCC-BODY-FAIL	UCC Body Fails due to Pressure [1e-6, 1e-5] 0.33 (DR), [1e-5, 1e-4] 0.67 (ES DD MG)
UCC-CONFLAT-NOT-TESTED	UCC Conflat Not Tested Connections Fail, Pressure [0, 2e-3] 1 (DD MG)
UCC-CONFLAT-TESTED	UCC Conflat Prestested Connections Fail due to Pressure [0, 1e-4] 0.5 (DD), [0, 1e-3] 0.5 (MG)
UCC-DEBRIS-DIRECT	UCC Direct Failure Debris (load hardware) [0, 1e-6] 0.25 (DD), [1e-5, 1e-4] 0.25 (ES), [0, 1e-5] 0.25 (MG), [1e-6, 1e-5] 0.25 (DR)
UCC-DEBRIS-INDIRECT	UCC Indirect Failure Debris (baffle) [0, 1e-5] 0.75 (DD ES MG), [1e-5, 1e-4] 0.25 (DR)
UCC-FAIL-MAG-PRESS	UCC Fails due to Magnetic Pressure [0, 1e-5] 0.5 (ER), [1e-5, 1e-4] 0.5 (ES)
UCC-FAIL-ZINGER	UCC Fail from Zinger vacuum (arc) [1e-5, 1e-4] 0.67 (DD DR MG), [1e-4, 1e-3] 0.33 (ES)
UCC-FIBER-OPTIC-FAIL	UCC Fiber Optic Feed Fails due to Pressure/Shock [1e-3, 1e-2] 1 (DD MG)
UCC-HE-FASTEN	Human Error installing UCC Fasteners [0, 0] 1 (DD MG)
UCC-HE-SEALS	Human Error installing UCC Seals [1e-4, 1e-3] 1 (DD MG)
UCC-RING-SEALS	UCC O Ring Seals Fail due to Pressure (not tested) [1e-5, 1e-4] 1 (DD MG)
UCC-SMA-FAIL	UCC SMA Fails due to Pressure [1e-3, 5e-3] 1 (DD MG)
UCC-TUBE-FAIL	UCC Tubing Fails due to Overpressure [1e-5, 1e-4] 1 (MG ES)
UCC-VENT-VLVS-FAIL	UCC Swagelok Vent Valves Fail (3) [1e-5, 1e-4] 1 (MG ES)
UCC-WELDS-FAIL	UCC Welds Fail due to Pressure [1e-6, 1e-5] 0.33 (DR), [1e-5, 1e-4] 0.67 (ES DD MG)
UCV-BAD-DETS	UCV Bad Dets [1e-4, 2e-3] 1 (ES DD MG DR)
UCV-CATHODE-EXT-HE	UCV Cathode Extension Human Error [1e-3, 1e-2] 1 (ES DD)
UCV-CLOSE-TUBE-FAIL	UCV Fail to Seal Closure Tube Failure [1e-4, 1e-3] 1 (ES)
UCV-DETS-CABLE	UCV Dets Cables Bad [1e-5, 1e-4] 1 (DD)
UCV-DETS-FIRESET-FAIL	UCV Dets Fireset Fails [1e-3, 1e-3] 1 (based on info from Ray Peabody to all SMEs)
UCV-DETS-HE	Human Error Connecting UCV Dets Cables [1e-5, 1e-4] 1 (DD)
UCV-HIGH-EXPL-BAD	UCV High Explosive Bad [0, 0] 1 (ES)

¹⁷ For example [1e-3, 1e-4] 0.25 (MJ), [1e-3, 1e-2] 0.75 (ES DR MG) indicates evidence of 0.25 for the interval [1e-3, 1e-4] assigned by one SME (MJ), and evidence of 0.75 for the interval [1e-3, 1e-2] assigned by three SMEs (ES DR MG).

Name	Description and Evidence ¹⁷
UCV-NO-EXPL-HE	UCV High Explosive Missing Human Error [1e-4, 1e-4] 1 (ES)
UPPER-TUBE-CLOSE-FAIL	Closure Tube Fails Above Closure Point [3e-3, 7e-3] 0.25, (DR) [1e-4, 1e-3] 0.75 (ES DD MG)
VENT-SYS-FAIL	Vent Tank System Fails [0, 1e-3] 1 (ES MG)
WRONG-DELAY-HE	Human Error Wrong Delay [1e-5, 1e-4] 1 (BL MJ)
WRONG-PULSE-HE	Incorrect Pulse Shape due to Human Error [1e-4, 1e-3] 1 (DD)
Z-PREFIRE	Z PREFIRES [3.3e-3, 2e-2] 0.5, [1e-2, 2e-2] 0.5 (MJ BL)
Z-PREFIRE-DES	Z PREFIRES Design issue Valve closes late [0, 0] 1 (DR and communication from John Weed)

APPENDIX E INPUT FOR EVALUATING P_{FAIL} IN BELIEFCONVOLUTION

// Z machine model in BeliefConvolution

```
// basic variables
Variable T_New_C_MITL = new Variable("Days New C MITL On Site", 0, 100, false);
Variable T_Initial_Clean = new Variable("Days Initial Clean", 0, 20, false);
Variable T_Clean = new Variable("Days to Clean Z", 50, 200, false);
Variable T_Reg_Review = new Variable("Days Reg Review", 50, 400, false);
Variable DEBRIS_EARLY = new Variable("DEBRIS-EARLY", 0, 1, true);
Variable DET_RING_FAIL = new Variable("DET-RING-FAIL", 0, 1, true);
Variable UPPER_TUBE_CLOSE_FAIL = new Variable("UPPER-TUBE-CLOSE-FAIL", 0, 1, true);
Variable UCV_CLOSE_TUBE_FAIL = new Variable("UCV-CLOSE-TUBE-FAIL", 0, 1, true);
Variable VENT_SYS_FAIL = new Variable("VENT-SYS-FAIL", 0, 1, true);
Variable UCC_CONFLAT_NOT_TESTED = new Variable("UCC-CONFLAT-NOT-TESTED", 0, 1, true);
Variable UCC_CONFLAT_TESTED = new Variable("UCC-CONFLAT-TESTED", 0, 1, true);
Variable FIRESET_NOT_ARMED = new Variable("FIRESET-NOT-ARMED", 0, 1, true);
Variable UCC_DEBRIS_DIRECT = new Variable("UCC-DEBRIS-DIRECT", 0, 1, true);
Variable UCC_DEBRIS_INDIRECT = new Variable("UCC-DEBRIS-INDIRECT", 0, 1, true);
Variable UCC_FAIL_MAG_PRESS = new Variable("UCC-FAIL-MAG-PRESS", 0, 1, true);
Variable UCC_FAIL_ZINGER = new Variable("UCC-FAIL-ZINGER", 0, 1, true);
Variable UCC_FIBER_OPTIC_FAIL = new Variable("UCC-FIBER-OPTIC-FAIL", 0, 1, true);
Variable Z_PREFIRE_DES = new Variable("Z-PREFIRE-DES", 0, 1, true);
Variable Z_PREFIRE = new Variable("Z-PREFIRE", 0, 1, true);
Variable BAD_DAS_CABLE = new Variable("BAD-DAS-CABLE", 0, 1, true);
Variable DAS_CABLE_HE = new Variable("DAS-CABLE-HE", 0, 1, true);
Variable CHARGE_SYS_FAIL = new Variable("CHARGE-SYS-FAIL", 0, 1, true);
Variable CONTROL_FAIL = new Variable("CONTROL-FAIL", 0, 1, true);
Variable WRONG_PULSE_HE = new Variable("WRONG-PULSE-HE", 0, 1, true);
Variable CABLE_DISCONNECT = new Variable("CABLE-DISCONNECT", 0, 1, true);
Variable COAX_FAIL = new Variable("COAX-FAIL", 0, 1, true);
Variable DAS_PREFIRE_FAIL = new Variable("DAS-PREFIRE-FAIL", 0, 1, true);
Variable DG_PREFIRE = new Variable("DG-PREFIRE", 0, 1, true);
Variable SIGNAL_FROM_FIRESET = new Variable("SIGNAL-FROM-FIRESET", 0, 1, true);
Variable SNM_DELAY_GEN_FAIL = new Variable("SNM-DELAY-GEN-FAIL", 0, 1, true);
Variable UCV_DETETS_FIRESET_FAIL = new Variable("UCV-DETETS-FIRESET-FAIL", 0, 1, true);
Variable WRONG_DELAY_HE = new Variable("WRONG-DELAY-HE", 0, 1, true);
Variable UCC_HE_FASTEN = new Variable("UCC-HE-FASTEN", 0, 1, true);
Variable UCC_HE_SEALS = new Variable("UCC-HE-SEALS", 0, 1, true);
Variable UCC_RING_SEALS = new Variable("UCC-RING-SEALS", 0, 1, true);
Variable UCC_BODY_FAIL = new Variable("UCC-BODY-FAIL", 0, 1, true);
Variable UCC_WELDS_FAIL = new Variable("UCC-WELDS-FAIL", 0, 1, true);
Variable UCC_TUBE_FAIL = new Variable("UCC-TUBE-FAIL", 0, 1, true);
Variable UCC_VENT_VLVS_FAIL = new Variable("UCC-VENT_VLVS-FAIL", 0, 1, true);
Variable UCC_SMA_FAIL = new Variable("UCC-SMA-FAIL", 0, 1, true);
Variable UCV_DETETS_HE = new Variable("UCV-DETETS-HE", 0, 1, true);
Variable UCV_DETETS_CABLE = new Variable("UCV-DETETS-CABLE", 0, 1, true);
Variable UCV_BAD_DETETS = new Variable("UCV-BAD-DETETS", 0, 1, true);
Variable UCV_HIGH_EXPL_BAD = new Variable("UCV-HIGH-EXPL-BAD", 0, 1, true);
Variable UCV_NO_EXPL_HE = new Variable("UCV-NO-EXPL-HE", 0, 1, true);
Variable UCV_CATHODE_EXT_HE = new Variable("UCV-CATHODE-EXT-HE", 0, 1, true);

// evidence
T_New_C_MITL.addEvidenceInterval(new EvidenceInterval(T_New_C_MITL.getName(), 0, 94.5, 1));
T_Initial_Clean.addEvidenceInterval(new EvidenceInterval(T_Initial_Clean.getName(), 10, 10, 1));
T_Clean.addEvidenceInterval(new EvidenceInterval(T_Clean.getName(), 68.5, 100, 0.67));
T_Clean.addEvidenceInterval(new EvidenceInterval(T_Clean.getName(), 68.5, 137, 0.33));
T_Reg_Review.addEvidenceInterval(new EvidenceInterval(T_Reg_Review.getName(), 63, 252, 1));
DEBRIS_EARLY.addEvidenceInterval(new EvidenceInterval(DEBRIS_EARLY.getName(), 0, 0, 1));
DET_RING_FAIL.addEvidenceInterval(new EvidenceInterval(DET_RING_FAIL.getName(), 0, 5E-4, 0.5));
DET_RING_FAIL.addEvidenceInterval(new EvidenceInterval(DET_RING_FAIL.getName(), 0, 1E-3, 0.5));
UPPER_TUBE_CLOSE_FAIL.addEvidenceInterval(new EvidenceInterval(UPPER_TUBE_CLOSE_FAIL.getName(), 1E-4, 1E-3, 0.75));
UPPER_TUBE_CLOSE_FAIL.addEvidenceInterval(new EvidenceInterval(UPPER_TUBE_CLOSE_FAIL.getName(), 3E-3, 7E-3, 0.25));
UCV_CLOSE_TUBE_FAIL.addEvidenceInterval(new EvidenceInterval(UCV_CLOSE_TUBE_FAIL.getName(), 1E-4, 1E-3, 1));
VENT_SYS_FAIL.addEvidenceInterval(new EvidenceInterval(VENT_SYS_FAIL.getName(), 0, 1E-3, 1));
UCC_CONFLAT_NOT_TESTED.addEvidenceInterval(new EvidenceInterval(UCC_CONFLAT_NOT_TESTED.getName(), 0, 2E-3, 1));
UCC_CONFLAT_TESTED.addEvidenceInterval(new EvidenceInterval(UCC_CONFLAT_TESTED.getName(), 0, 1E-4, 0.5));
UCC_CONFLAT_TESTED.addEvidenceInterval(new EvidenceInterval(UCC_CONFLAT_TESTED.getName(), 0, 1E-3, 0.5));
FIRESET_NOT_ARMED.addEvidenceInterval(new EvidenceInterval(FIRESET_NOT_ARMED.getName(), 1E-5, 1E-4, 1));
UCC_DEBRIS_DIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_DIRECT.getName(), 0, 1E-6, 0.25));
UCC_DEBRIS_DIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_DIRECT.getName(), 1E-5, 1E-4, 0.25));
UCC_DEBRIS_DIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_DIRECT.getName(), 0, 1E-5, 0.25));
UCC_DEBRIS_DIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_DIRECT.getName(), 1E-6, 1E-5, 0.25));
UCC_DEBRIS_INDIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_INDIRECT.getName(), 0, 1E-5, 0.75));
UCC_DEBRIS_INDIRECT.addEvidenceInterval(new EvidenceInterval(UCC_DEBRIS_INDIRECT.getName(), 1E-5, 1E-4, 0.25));
UCC_FAIL_MAG_PRESS.addEvidenceInterval(new EvidenceInterval(UCC_FAIL_MAG_PRESS.getName(), 0, 1E-5, 0.5));
UCC_FAIL_MAG_PRESS.addEvidenceInterval(new EvidenceInterval(UCC_FAIL_MAG_PRESS.getName(), 1E-5, 1E-4, 0.5));
UCC_FAIL_ZINGER.addEvidenceInterval(new EvidenceInterval(UCC_FAIL_ZINGER.getName(), 1E-5, 1E-4, 0.67));
UCC_FAIL_ZINGER.addEvidenceInterval(new EvidenceInterval(UCC_FAIL_ZINGER.getName(), 1E-4, 1E-3, 0.33));
UCC_FIBER_OPTIC_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_FIBER_OPTIC_FAIL.getName(), 1E-3, 1E-2, 1));
//Z_PREFIRE_DES.addEvidenceInterval(new EvidenceInterval(Z_PREFIRE_DES.getName(), 0.0033, 0.02, 0.5)); // OLD
//Z_PREFIRE_DES.addEvidenceInterval(new EvidenceInterval(Z_PREFIRE_DES.getName(), 0.01, 0.02, 0.5)); // OLD
Z_PREFIRE_DES.addEvidenceInterval(new EvidenceInterval(Z_PREFIRE_DES.getName(), 0, 0, 1)); // changed 12-9 2009
Z_PREFIRE.addEvidenceInterval(new EvidenceInterval(Z_PREFIRE.getName(), 0.0033, 0.02, 0.5));
Z_PREFIRE.addEvidenceInterval(new EvidenceInterval(Z_PREFIRE.getName(), 0.01, 0.02, 0.5));
BAD_DAS_CABLE.addEvidenceInterval(new EvidenceInterval(BAD_DAS_CABLE.getName(), 1E-6, 1E-5, 1));
DAS_CABLE_HE.addEvidenceInterval(new EvidenceInterval(DAS_CABLE_HE.getName(), 0, 1E-5, 1));
CHARGE_SYS_FAIL.addEvidenceInterval(new EvidenceInterval(CHARGE_SYS_FAIL.getName(), 0, 0, 1));
CONTROL_FAIL.addEvidenceInterval(new EvidenceInterval(CONTROL_FAIL.getName(), 0, 0, 1));
```

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WRONG_PULSE_HE.addEvidenceInterval(new EvidenceInterval(WRONG_PULSE_HE.getName(),1e-4, 1e-3, 1));
CABLE_DISCONNECT.addEvidenceInterval(new EvidenceInterval(CABLE_DISCONNECT.getName(), 0, 1e-5, 0.5));
CABLE_DISCONNECT.addEvidenceInterval(new EvidenceInterval(CABLE_DISCONNECT.getName(), 0, 1e-6, 0.5));
COAX_FAIL.addEvidenceInterval(new EvidenceInterval(COAX_FAIL.getName(), 1e-6, 1e-5, 1));
DAS_PREFIRE_FAIL.addEvidenceInterval(new EvidenceInterval(DAS_PREFIRE_FAIL.getName(), 1e-5, 1e-4, 0.5));
DAS_PREFIRE_FAIL.addEvidenceInterval(new EvidenceInterval(DAS_PREFIRE_FAIL.getName(), 1e-4, 1e-3, 0.5));
DG_PREFIRE.addEvidenceInterval(new EvidenceInterval(DG_PREFIRE.getName(), 0, 1e-7, 1));
SIGNAL_FROM_FIRESET.addEvidenceInterval(new EvidenceInterval(SIGNAL_FROM_FIRESET.getName(), 1e-6, 1e-5, 1));
SNM_DELAY_GEN_FAIL.addEvidenceInterval(new EvidenceInterval(SNM_DELAY_GEN_FAIL.getName(), 1e-5, 1e-4, 1));
UCV_DETETS_FIRESET_FAIL.addEvidenceInterval(new EvidenceInterval(UCV_DETETS_FIRESET_FAIL.getName(), 1e-3, 1e-3, 1));
WRONG_DELAY_HE.addEvidenceInterval(new EvidenceInterval(WRONG_DELAY_HE.getName(), 1e-5, 1e-4, 1));
UCC_HE_FASTEN.addEvidenceInterval(new EvidenceInterval(UCC_HE_FASTEN.getName(), 0, 0, 1));
UCC_HE_SEALS.addEvidenceInterval(new EvidenceInterval(UCC_HE_SEALS.getName(), 1e-4, 1e-3, 1));
UCC_RING_SEALS.addEvidenceInterval(new EvidenceInterval(UCC_RING_SEALS.getName(), 1e-5, 1e-4, 1));
UCC_BODY_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_BODY_FAIL.getName(), 1e-6, 1e-5, 0.33));
UCC_BODY_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_BODY_FAIL.getName(), 1e-5, 1e-4, 0.67));
UCC_WELDS_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_WELDS_FAIL.getName(), 1e-6, 1e-5, 0.33));
UCC_WELDS_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_WELDS_FAIL.getName(), 1e-5, 1e-4, 0.67));
UCC_TUBE_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_TUBE_FAIL.getName(), 1e-5, 1e-4, 1));
UCC_VENT_VLVs_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_VENT_VLVs_FAIL.getName(), 1e-5, 1e-4, 1));
UCC_SMA_FAIL.addEvidenceInterval(new EvidenceInterval(UCC_SMA_FAIL.getName(), 1e-3, 5e-3, 1));
UCV_DETETS_HE.addEvidenceInterval(new EvidenceInterval(UCV_DETETS_HE.getName(), 1e-5, 1e-4, 1));
UCV_DETETS_CABLE.addEvidenceInterval(new EvidenceInterval(UCV_DETETS_CABLE.getName(), 1e-5, 1e-4, 1));
UCV_BAD_DETETS.addEvidenceInterval(new EvidenceInterval(UCV_BAD_DETETS.getName(), 1e-4, 2e-3, 1));
UCV_HIGH_EXPL_BAD.addEvidenceInterval(new EvidenceInterval(UCV_HIGH_EXPL_BAD.getName(), 0, 0, 1));
UCV_NO_EXPL_HE.addEvidenceInterval(new EvidenceInterval(UCV_NO_EXPL_HE.getName(), 1e-4, 1e-4, 1));
UCV_CATHODE_EXT_HE.addEvidenceInterval(new EvidenceInterval(UCV_CATHODE_EXT_HE.getName(), 1e-3, 1e-2, 1));

// convoluted variables
Variable T_No_Reg_Rev = T_New_C_MITL.convoluteNew("Days mitigate No Reg Review", T_Initial_Clean, "ADD");
T_No_Reg_Rev.convoluteThis(T_Clean, "ADD");
Variable T_With_Reg_Rev = T_No_Reg_Rev.convoluteNew("Days mitigate With Reg Review", T_Reg_Review, "ADD");
Variable T_After_C_MITL_Onsite_No_Reg_Rev = T_Initial_Clean.convoluteNew("Days mitigate After C MITL Onsite No Reg Review", T_Clean, "ADD");
Variable T_After_C_MITL_Onsite_With_Reg_Rev = T_After_C_MITL_Onsite_No_Reg_Rev.convoluteNew("Days mitigate After C MITL Onsite With Reg Review",
T_Reg_Review, "ADD");
Variable TWO_CUT_SETS_WITH_UPPER_TUBE_CLOSE_FAIL = VENT_SYS_FAIL.convoluteNew("TWO-CUT-SETS-WITH-UPPER-TUBE-CLOSE-FAIL",
DET_RING_FAIL, "PROBADD");
// FOR CHECK TWO_CUT_SETS_WITH_UPPER_TUBE_CLOSE_FAIL.printOverallResults();
TWO_CUT_SETS_WITH_UPPER_TUBE_CLOSE_FAIL.convoluteThis(UPPER_TUBE_CLOSE_FAIL, "MULTIPLY");
Variable THREE_CUT_SETS_WITH_UCV_DETETS_FIRESET_FAIL = COAX_FAIL.convoluteNew("THREE-CUT-SETS-WITH-UCV-DETETS-FIRESET-FAIL",
CABLE_DISCONNECT, "PROBADD");
THREE_CUT_SETS_WITH_UCV_DETETS_FIRESET_FAIL.convoluteThis(SIGNAL_FROM_FIRESET, "PROBADD");
THREE_CUT_SETS_WITH_UCV_DETETS_FIRESET_FAIL.convoluteThis(UCV_DETETS_FIRESET_FAIL, "MULTIPLY");
Variable FIVE_CUT_SETS_WITH_Z_PREFIRE = FIRESET_NOT_ARMED.convoluteNew("FIVE-CUT-SETS-WITH-Z-PREFIRE", SNM_DELAY_GEN_FAIL,
"PROBADD");
FIVE_CUT_SETS_WITH_Z_PREFIRE.convoluteThis(DAS_PREFIRE_FAIL, "PROBADD");
FIVE_CUT_SETS_WITH_Z_PREFIRE.convoluteThis(DAS_CABLE_HE, "PROBADD");
FIVE_CUT_SETS_WITH_Z_PREFIRE.convoluteThis(BAD_DAS_CABLE, "PROBADD");
FIVE_CUT_SETS_WITH_Z_PREFIRE.convoluteThis(Z_PREFIRE, "MULTIPLY");
Variable P_FAIL_ALL_CUT_SETS = TWO_CUT_SETS_WITH_UPPER_TUBE_CLOSE_FAIL.convoluteNew("P-fail: All Cut
Sets",THREE_CUT_SETS_WITH_UCV_DETETS_FIRESET_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(FIVE_CUT_SETS_WITH_Z_PREFIRE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(DEBRIS_EARLY, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(Z_PREFIRE_DES, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_FAIL_MAG_PRESS, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_WELDS_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_VENT_VLVs_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_RING_SEALS, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_CONFLAT_TESTED, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_CONFLAT_NOT_TESTED, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_BODY_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_FIBER_OPTIC_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_SMA_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_TUBE_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_DEBRIS_DIRECT, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_DEBRIS_INDIRECT, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_HE_SEALS, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_HE_FASTEN, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCC_FAIL_ZINGER, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_DETETS_HE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_DETETS_CABLE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_HIGH_EXPL_BAD, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_NO_EXPL_HE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_BAD_DETETS, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_CLOSE_TUBE_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(UCV_CATHODE_EXT_HE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(WRONG_PULSE_HE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(CONTROL_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(CHARGE_SYS_FAIL, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(DG_PREFIRE, "PROBADD");
P_FAIL_ALL_CUT_SETS.convoluteThis(WRONG_DELAY_HE, "PROBADD");

// results of interest for Time to mitigate
T_No_Reg_Rev.printOverallResults();
T_With_Reg_Rev.printOverallResults();
T_After_C_MITL_Onsite_No_Reg_Rev.printOverallResults();
T_After_C_MITL_Onsite_With_Reg_Rev.printOverallResults();

// results of interest for Pfail
//UCC_DEBRIS_DIRECT.printOverallResults();
// multiple event cut sets
TWO_CUT_SETS_WITH_UPPER_TUBE_CLOSE_FAIL.printOverallResults();
THREE_CUT_SETS_WITH_UCV_DETETS_FIRESET_FAIL.printOverallResults();

```

```

FIVE_CUT_SETS_WITH_Z_PREFIRE.printOverallResults();
// one event cut sets
DEBRIS_EARLY.printOverallResults();
Z_PREFIRE_DES.printOverallResults();
UCC_FAIL_MAG_PRESS.printOverallResults();
UCC_WELDS_FAIL.printOverallResults();
UCC_VENT_VLVS_FAIL.printOverallResults();
UCC_RING_SEALS.printOverallResults();
UCC_CONFLAT_TESTED.printOverallResults();
UCC_CONFLAT_NOT_TESTED.printOverallResults();
UCC_BODY_FAIL.printOverallResults();
UCC_FIBER_OPTIC_FAIL.printOverallResults();
UCC_SMA_FAIL.printOverallResults();
UCC_TUBE_FAIL.printOverallResults();
UCC_DEBRIS_DIRECT.printOverallResults();
UCC_DEBRIS_INDIRECT.printOverallResults();
UCC_HE_SEALS.printOverallResults();
UCC_HE_FASTEN.printOverallResults();
UCC_FAIL_ZINGER.printOverallResults();
UCV_DETS_HE.printOverallResults();
UCV_DETS_CABLE.printOverallResults();
UCV_HIGH_EXPL_BAD.printOverallResults();
UCV_NO_EXPL_HE.printOverallResults();UCV_BAD_DETS.printOverallResults();
UCV_BAD_DETS.printOverallResults();
UCV_CLOSE_TUBE_FAIL.printOverallResults();
UCV_CATHODE_EXT_HE.printOverallResults();
WRONG_PULSE_HE.printOverallResults();
CONTROL_FAIL.printOverallResults();
CHARGE_SYS_FAIL.printOverallResults();
DG_PREFIRE.printOverallResults();
WRONG_DELAY_HE.printOverallResults();
// overall Pfail
P_FAIL_ALL_CUT_SETS.printOverallResults()

```

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