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Uncertainty Analysis of the Results of Potential Cask Drops in the K West Basin South Loadout Pit

B. S. Lew for

Fluor Daniel Hanford

Richland, WA 99352

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Abstract: If a cask and Multi-Canister Overpack (MCO) were to be dropped, the analysis established possible initial volumetric flow rates. The results of the uncertainty analysis demonstrated that even if a cask and MCO were to be dropped the possible initial volumetric flow rate through the opened floor/wall joint would be small. There is a 95% confidence (probability of 0.95) that the initial volumetric flow rate would be smaller than 411 gpm and a 99% confidence (probability of 0.99) that it would be smaller than 916 gpm.

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**UNCERTAINTY ANALYSIS OF THE RESULTS OF
POTENTIAL CASK DROPS IN THE K-WEST BASIN SOUTH
LOADOUT PIT**

Prepared for

FLUOR DANIEL HANFORD
Contract No. 263, Release 54
Line Item 60
Report No. 9904561-001
Revision 0

November 1999

Prepared by

ARES CORPORATION
636 Jadwin Avenue Suite B
Richland, Washington 99352

UNCERTAINTY ANALYSIS OF THE RESULTS OF POTENTIAL CASK DROPS IN THE K-WEST BASIN SOUTH LOADOUT PIT

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Prepared by: Lewis D. Muhlestein, Ph.D.

Approved by: Lewis D. Muhlestein
Robert L. Fritz *for*

Date: Nov. 12, 1999

EXECUTIVE SUMMARY

The Spent Nuclear Fuel (SNF) Project will transfer SNF from the K-East and K-West Basins through the South Loadout Pit (SLOP) using the transfer bay crane and cask loading system. The initial basis for design, fabrication, installation, and operation of the cask handling and loading system was a worst case cask drop event that would not result in basin leakage. However, of the several cask drop analyses that have been performed, no attempt has been made to quantify the uncertainties or the risk associated with the various drop events.

This analysis: 1) determines the initial volumetric flow rate through the SLOP floor/wall joint gap assuming that a cask and Multi-Canister Overpack (MCO) have been dropped into the K-West Basin SLOP, and 2) determines the uncertainty associated with the initial volumetric flow rate. It is emphasized that the results are, therefore, conditioned on a cask and MCO being dropped into the SLOP. However, the likelihood of dropping a cask and MCO into the SLOP is very small and is preventable by following the K-West Basin SLOP transfer bay crane lifting procedures.

If a cask and MCO were to be dropped, the analysis established possible initial volumetric flow rates by considering: 1) the uncertainty associated with the potential impact energy to the SLOP basin concrete floor, 2) the uncertainty associated with the transmission of the impact energy to yield the concrete floor and produce a resultant residual floor/wall gap, 3) the uncertainty in the resultant residual floor/wall gap separation, and 4) the likely flow rate through the floor/wall gap assuming flow through a porous medium.

The results of the uncertainty analysis demonstrated that even if a cask and MCO were to be dropped the possible initial volumetric flow rate through the opened floor/wall joint would be small. There is a 95 percent confidence (probability of 0.95) that the initial volumetric flow rate

would be smaller than 411 gpm. The results of the uncertainty analysis are summarized in the following table.

Summary Results

	Probability	Initial Volumetric Flow Rate Is Less Than (gpm)
Mean		51
50th Percentile	0.50	50
90th Percentile	0.90	268
95th Percentile	0.95	411
99th Percentile	0.99	916

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ACRONYMS

IPSS	Immersion Pail Support Structure
MCO	Multi-Canister Overpack
SLOP	South Loadout Pit
SNF	Spent Nuclear Fuel

1.0 INTRODUCTION

The Spent Nuclear Fuel (SNF) Project will transfer SNF from the Hanford 105 K-East and 105 K-West Basins to safe interim storage in the Canister Storage Building in the 200 Area. The fuel transfer from the K-East and K-West Basins will be conducted through the South Loadout Pit (SLOP) using a cask loading system. The empty Multi-Canister Overpack (MCO) and cask will be lifted from the transport trailer and placed into an immersion pail that is contained in the Immersion Pail Support Structure (IPSS) in the SLOP. The immersion pail is used to minimize contamination of the MCO and cask during the fuel loading operation. The IPSS is used to suspend and support the immersion pail containing the MCO and cask at the desired elevation in the SLOP.

The initial basis for the design, fabrication, installation, and operation of the cask handling and loading system in the SLOP was a worst case cask drop event that would not result in excessive basin leakage. Several analyses of various cask drop scenarios have been performed over the past several years. One of the latest analyses was that of an immersion pail support structure drop into the SLOP (Moore 1997). An independent review of this analysis (Wagenblast 1999) was completed which concluded that the analysis did not address all potential failure modes. The analysis results of Kanjilal (1999) also indicate that previous cask drop analyses were not conservative in their assumptions and loading conditions. The analysis of Kanjilal (1999) used more detailed boundary conditions in the finite element model and considered the loads at the joint between the concrete slab and the concrete wall in the SLOP. No attempt has been made in any of the analyses to quantify uncertainties associated with the various drop events.

The objectives of this analysis are to: 1) determine the initial volumetric flow rate through the SLOP floor/wall joint gap assuming that a cask and MCO have been dropped into the K-West Basin SLOP, and 2) determine the uncertainty associated with the initial volumetric flow rate. It is emphasized that the results are, therefore, conditioned on a cask and MCO being dropped into the SLOP, and the first line of defense is to prevent a cask and MCO from being dropped into the SLOP. The likelihood of dropping a cask and MCO into the SLOP is very small and is preventable by following the K-West Basin SLOP transfer bay crane lifting procedures.

The initial volumetric flow rate uncertainty analysis is a risk-based uncertainty analysis where best engineering judgement is used to represent each variable in the analysis. The uncertainty associated with each variable is represented by a probability distribution (probability density function). Uncertainty exists because of the normal randomness associated with the distribution of values that a variable may assume, and because of a lack of knowledge concerning a variable. Engineering judgement and technical information are used to develop the variable probability density functions, while the bounds of the probability density function are based on physical limitations. The uncertainty, described by probability distributions, is propagated through the

analysis by Monte Carlo convolution techniques. The corresponding results are developed as a probability distribution and the risk is expressed in terms of the corresponding complementary cumulative distribution function ("risk curve"). The total risk is the area under the "risk curve".

An uncertainty analysis is well suited for evaluating the possible results of a cask drop in the K-West Basin SLOP. Only very conservative information or analyses exist relative to precisely how a dropped cask might impact the concrete floor, damage the concrete, and produce cracks through which the basin water may be released. If such analyses were to be completed they would be lengthy to perform and may provide results that would be difficult to interpret.

On the other hand, an uncertainty analysis can provide very good results in the form of a risk curve with the uncertainty in the variables represented by probability density functions. To be effective, the uncertainty distributions used for each variable must be represented by realistic and physical bounds, and the median value of the distribution must be generated using the best available engineering judgment. In this analysis some of the variable distributions were developed by using the results of more detailed models. By using realistic distributions to represent both the randomness of variables and the lack of information, the exact details become less important.

The following sections provide summaries of: 1) background information relative to the risk analysis process, 2) a description of the K-West Basin SLOP cask loading system, 3) the evaluation process, and 4) the results of the risk analysis process. Technical details and specific analyses required to support the information provided in the main sections of this document are provided in Appendices A, B, C, D, and E. Appendix A develops the distribution for the impact energy that may impact the SLOP concrete floor due to specific and random crane drop scenarios. Appendix B is the finite element analysis of concrete wall-joint deformation for various cask drop accidents. The correlation between the impact energy and the associated residual floor/wall gap distance is developed in Appendix C using the information of Appendix B. Appendix D discusses fluid flow in a porous media and presents the information necessary to determine the volumetric flow rate for flow through a porous medium. Appendix E brings all of the information together and completes a Monte Carlo convolution process to evaluate the distribution for the volumetric flow rate given a cask load drop occurs. Appendix F contains a validation of the analysis models and a record of the review comments received relative to this document and the corresponding changes that were made based on the review comments. It is important to realize that a great deal of information and analyses are developed and presented in the appendices. Only summary information is presented in this main body of the report.

2.0 DESCRIPTION OF K-WEST BASIN SLOP

A plan view of the K-West Basin SLOP is shown in Figure 1; a partial elevation view is shown in Figure 2. Figure 1 shows the eight vertical rails that are permanently attached to the concrete walls of the SLOP that are used to position the IPSS. The IPSS is shown in Figure 1 and partially shown in Figure 2 with its four leg structures. Each leg is supported by a leveling foot.

**Figure 1. Plan View of the K-West Basin South Loadout Pit
Showing the Immersion Pail Support Structure.**

Figure 2 also shows the water stop that was placed in the concrete to help form a water-tight seal between the concrete floor and the concrete wall. Also depicted in Figure 2 is the floor/wall gap between the concrete floor and the concrete wall that could be formed by a sufficient impact

energy on the concrete floor. These specific points are discussed in greater detail in the appropriate appendices.

**Figure 2. Partial Elevation View of the K-West Basin South Loadout Pit
Showing the Immersion Pail Support Structure.**

3.0 UNCERTAINTY ANALYSIS PROCESS

The uncertainty analysis considers a sequence of events which assumes that a cask and MCO have been dropped into the K-West Basin SLOP. The uncertainty analysis then considers the potential impact of the dropped cask and MCO on the concrete basin floor, damage of the floor/wall joint, and potential water flow through the damaged floor/wall joint. Several probability density function which represent specific information relative to the analysis are combined to provide the results that may be expected should a cask and MCO be dropped into the SLOP. Each of the probability density functions are representative of conditional probabilities. That is, probabilities that are conditional on a previous event occurring.

The conditional probabilities are determined based on the uncertainty associated with each of the variables involved in each individual calculation. The conditional probabilities are combined in a final model which is solved using Monte Carlo convolution techniques. In this analysis it was expeditious to partition the solution into various sections in order to examine each portion of the analysis to gain additional insight into the results.

The initiating event of the analysis is the assumption that a load has been dropped into the K-West Basin SLOP using the transfer bay crane. As noted earlier, the likelihood of this event is very small.

Given the assumption of a load drop by the transfer bay crane, the next event is the distribution for the potential impact energy that the basin concrete floor may experience from a variety of load configurations which include several cask/MCO configurations, drop heights, and absorbing energies. This distribution is developed in Appendix A and represents the conditional probability of an impact energy given that a load drop occurs.

The dependence of the residual floor/wall gap on the impact energy was developed in Appendix C using the wall-floor joint deformation predictions from Appendix B. The result was then used to develop a probability distribution for the residual gap in the floor/wall joint given an impact energy on the concrete.

Given a residual gap in the floor/wall joint, the next conditional probability distribution developed was the initial volumetric flow of water through the gap considering flow through a porous medium. The results are given in Appendix D.

The three conditional probabilities were convoluted using Monte Carlo convolution techniques to consider all of the uncertainties associated with the applicable variables. The four steps combined in the model are: 1) the probability of an impact energy given a load drop (Appendix A), 2) the residual floor/wall gap dependence on the impact energy (Appendix B and C), 3) the

probability of the residual floor/wall gap given an impact energy (Appendix C), and 4) the potential volumetric flow rate through the floor/wall gap assuming flow through a porous medium (Appendix D and E).

4.0 UNCERTAINTY ANALYSIS RESULTS

The results of the uncertainty analysis are presented in the order discussed above in the process. The initiating event of the analysis is the assumption that a load has been dropped in the K-West Basin SLOP using the transfer bay crane.

4.1 Impact Energy Distribution for Cask and MCO Drops

The potential impact energy that could be experienced by the concrete at the bottom of the K-West Basin SLOP was determined given that a cask was dropped by the transfer bay crane. Potential cask/MCO drop configurations were identified in five vertical drop scenarios. The drop scenarios (see Appendix A, Figures A-1, A-2 and A-3) are:

- (1) Dropping a cask and empty MCO from the nominal transfer bay crane height and impacting the immersion pail. The cask, empty MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.
- (2) Dropping a cask, empty MCO, and immersion pail from the immersion pail locking position height. The cask, empty MCO and immersion pail impact the concrete.
- (3) Dropping a cask, loaded MCO and immersion pail from a few feet above the bottom of the SLOP. The cask, loaded MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.
- (4) Dropping a cask, loaded MCO and immersion pail from the immersion pail locking position height. The cask, loaded MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.
- (5) Dropping a cask and loaded MCO from the nominal crane lifting height and impacting the immersion pail. The cask, loaded MCO, and immersion pail fall and impact the concrete at the bottom of the SLOP.

Gravitational, buoyant and drag forces were considered for each of the vertical drop scenarios. The equation of motion was solved in closed form (see Appendix A) to determine the velocity of the falling mass. If the object fell first in air the velocity equation was solved twice; once to

evaluate the velocity at the end of the fall in air, and the second to evaluate the velocity at the end of the fall in water. The final velocity of the first solution was used as the initial velocity for the second solution.

The buoyant force of the immersion pail was determined including the foam attached to the lower two-thirds of the outside of the immersion pail (see Appendix A). Also included was the five inches of foam which is being designed to be attached to the bottom of the immersion pail as an impact limiter.

The velocity of the object just before impact was determined from which the kinetic energy at impact was determined. The energy lost due to the impact of the cask and MCO with the bottom of the immersion pail and the subsequent shearing of the pins that secure the immersion pail to the immersion pail support structure was determined. The energy to shear the immersion pail locking pins was subtracted from the kinetic energy before impact to determine the kinetic energy after impact. The kinetic energy after impact was used to determine the initial velocity for the second part of the drop scenario.

The velocity of the object just before hitting the bottom of the immersion pail support structure was evaluated and used to determine the kinetic energy just before impact. The energy absorbed by the impact limiter at the bottom of the immersion pail was determined as well as the energy absorbed by the loaded immersion pail striking the bottom of the immersion pail support structure. The kinetic energy of the system was reduced by the energy absorbed by the impact limiting foam and the energy absorbed by yielding the bottom of the immersion pail support structure. This final kinetic energy was assumed to be the energy that impacted the concrete at the floor of the SLOP basin.

Each of the variables involved in the impact energy calculation were represented by appropriate probability density functions. It was assumed that a drop from any height was equally possible. The weight of the total cask was determined by randomly varying between two states; either a loaded MCO or an empty MCO. If a loaded MCO was chosen, then the mass considered was a cask and loaded MCO for drop heights above the immersion pail. For drop heights below the immersion pail the mass considered was a cask, loaded MCO and immersion pail. If an empty MCO was chosen then the mass considered was a cask and empty MCO for drop heights above the immersion pail and a cask, empty MCO, and immersion pail for drop heights below the immersion pail. Out of the four lifts for each MCO, half of the lifts will be with a loaded MCO and the other half will be with an empty MCO. This result was verified with a nearly equal 50:50 split between the two states.

The results of this analysis was a distribution for the impact energy that could be imparted to the SLOP concrete floor if a cask were to be dropped. The results are presented in Figure 3.

Because of all of the parameters that were varied in the analysis the scatter in the data was more than is usual for an analysis of this type. However, the data were fitted to a probability density function. The probability density function that best fit the data was a Weibull probability density function. A Lognormal probability density function did not have an extensive enough tail in the distribution to adequately represent the larger impact energies that were observed in the data. The fitted probability density function is used to represent the impact energy from a dropped cask in the remainder of the uncertainty analysis.

Figure 3. Probability Distribution for the Impact Energy That Could be Imparted to The SLOP Concrete Floor by a Dropped Cask.

A summary of the results presented in Figure 3 is provided in Table 1 which gives the impact energy that could be imparted to the SLOP concrete floor should a cask be dropped by the SLOP transfer bay crane. The parameters that defined the Weibull probability density function that was the best fit to the data (solid line in Figure 3) are also listed in Table 1.

**Table 1. Summary Results of Impact Energy That Could Be Imparted
to SLOP Concrete Floor by a Dropped Cask**

Percentile	Impact Energy Imparted to SLOP Concrete Floor	
	(nt-m)	(ft-lb)
50 th	394,400	290,700
90 th	1,059,690	781,070
95 th	1,224,050	902,220
95 th	1,448,600	1,067,740
Weibull Parameters for Fitted Distribution		
Location Parameter	Scale Parameter, η	Shape Parameter, β
0	639,756 nt-m	1.61

4.2 Wall-Floor Joint Deformation Predictions

The potential deformation in the SLOP Basin concrete joint between the basin floor and the basin wall was evaluated and included as Appendix B. Based on the analysis in Appendix A, a range in potential concrete impact energies was provided to M&D Professional Services Inc. from which several finite element model analyses were completed. The input for the finite element analysis in Appendix B was an impact energy and the corresponding impact velocity. The intent was to provide a large distribution of impact energies for which a large distribution of floor/wall residual gap dimensions could be developed. The impact energy corresponds to the weights of the objects given in Table 1-1 of Appendix B for the various vertical drops scenarios. The cask drop cases and corresponding drop scenarios evaluated are listed in Table 2.

Two sets of analyses were completed; one using the best available values for the input parameters and one using conservative values for the input parameters. Based on prior experience in evaluating cask drops on the SLOP concrete floor, the primary leak path following a cask drop is the construction joint between the SLOP concrete floor and the concrete walls. Therefore, a finite element model of the lower portion of the SLOP was developed which focused on the wall/floor joint. The finite element model was used to perform a transient dynamic analyses for each of the 12 cask drop cases listed in Appendix B, Table 1-1. From the dynamic analysis results, residual gap predictions for the floor/wall joint were obtained for each

drop case. Immediately following the time of impact, the maximum gap opening occurs, followed by some gap closure due to foundation soil rebound. The remaining "residual gap" is the item of interest for predicting leakage flow.

For the lower impact energy drops, inelastic stretching of the joint rebar was limited to minor yielding in the middle of the walls of the SLOP. For the other impact energy drops, significant yielding of the joint rebar occurred in all but the east wall (the wall furthest away from the immersion pail support structure in Figure 1). The east wall is more heavily reinforced and is furthest from the cask drop location. Thus, the floor/wall residual gap is wedge shaped, with the maximum gap on the west wall and essentially zero at the east wall (pivot line). The residual gap predictions for the twelve drop cases and corresponding drop scenarios are listed in Table 2.

Table 2. Residual Floor/Wall Gap Predictions for the Cask Drop Cases and Drop Scenarios

Drop Case No	Drop Scenario	Impact Energy (ft-lbs)	Analysis Category	Maximum Residual Gap	
				(in)	(mm)
1	3	58,279	Best Estimate	< 0.001	< 0.025
2	4	848,314	Best Estimate	0.25	6.35
3	4	848,314	Conservative	0.88	22.4
4	5	2,006,135	Best Estimate	0.63	16.0
5	5	2,006,135	Conservative	1.74	44.2
6	3	58,279	Conservative	< 0.001	< 0.025
7	1	1,095,554	Best Estimate	0.4	10.2
8	1	1,095,554	Conservative	1.16	29.5
9	4	115,990	Best Estimate	< 0.001	< 0.025
10	4	115,990	Conservative	< 0.01	< 0.025
11	2	527,160	Best Estimate	0.15	3.81
12	2	527,160	Conservative	0.56	14.2

4.3 Impact Energy and Associated Floor/Wall Gap Crack Diameter

The results of the residual gap predictions for the twelve drop cases listed in Table 2 are graphed in Figure 4 with the residual floor/wall gap diameter as a function of the concrete impact energy for both the best engineering and conservative values of the parameters. The results for each set of data are reasonably linear, specifically in light of the uncertainty associated with the analysis.

Therefore, each set of data were fit to a linear expression. The fitted linear curves as well as the 5th and 95th percent confidence levels for the fitted curves are given in Figure 4.

Figure 4. Uncertainty in the Residual Gap as a Function of the Impact Energy.

The uncertainty in the residual floor/wall gap diameter as a function of the impact energy given in Figure 4 was assumed to be lognormally distributed. The curve representing the results of the analysis using best engineering parameters was assumed to be the median value of the Lognormal distribution. The Lognormal standard deviation was varied until the spread in the distribution enveloped the results of the analysis using the conservative parameters. This process was repeated for each set of data in Figure 4. As the median value of the Lognormal distribution decreased, the spread in the distribution also decreased such that a constant Lognormal standard deviation appeared to be representative of all of the data. Assuming a constant Lognormal

standard deviation while varying the median value of the Lognormal distribution simplifies the analysis that follows. The results for the distribution of residual floor/wall gap as a function of the impact energy is also shown in Figure 4 as an over-laid Lognormal distribution.

For each value of the concrete impact energy the median value of the distribution for the floor/wall gap is determined using the linear equation that represents the results in Figure 4 using the best engineering parameters. This median value and the constant standard deviation represents a Lognormal distribution from which a value of the floor/wall gap is determined. This process was repeated for 10,000 iterations, each time selecting a new impact energy from the distribution that represents the impact energy (Figure 3). Based on the selected impact energy value, a median value of the Lognormal distribution was selected and from the associated Lognormal distribution for the floor/wall gap, a value for floor/gap was obtained. The results are presented in Figure 5 as the cumulative distribution function which represents the probability of not exceeding a specific floor/wall gap diameter in millimeters. From Figure 5, the most likely floor/wall gap diameter is 0.177 in (4.5 mm). There is a probability of 0.95 that the floor/wall gap diameter will not exceed 0.472 in (12 mm). Conversely, there is a probability of 0.05 that the floor/wall gap diameter will be larger than 0.472 in (12 mm).

4.4 Flow In A Porous Medium

The pressure gradient through the floor/wall gap is defined for a porous medium in terms of a viscous pressure drop, an inertial pressure drop, and a pressure drop due to the resistance of the exterior soil (see Appendix D). The expression for the pressure gradient is presented in terms of the superficial velocity and the equivalent hydraulic diameter, from which the superficial velocity is determined. The volumetric flow rate is then equal to the flow area times the superficial velocity. As noted earlier the flow area of the floor/wall gap is a triangular wedge from which the flow area is equal to the SLOP base plus width times the floor/wall gap distance.

Figure 5. Cumulative Distribution Function of the Residual Floor/Wall Gap.

The contribution due to the soil resistance was not included in the uncertainty analysis because the analysis evaluates the initial flow rate through the floor/wall gap caused by the impact energy of dropping a cask and MCO. The uncertainty analysis does not consider the continuing flow rate that would result from the changing pressure head of the K Basin water level impeded by soil resistance outside of the basin. See Appendix D for more detailed discussion relative to the contribution to the initial volumetric flow rate from each of the contributions included in the pressure gradient equation. Table 3 provides the volumetric flow rate for flow through a porous medium for various floor/wall gap distances. The parameters used in the analysis are given in Appendix D.

**Table 3. Volumetric Flow Rate for Flow Through a Porous Medium
for Various Floor/Wall Gap Distances**

Floor/Wall Gap Distance		Flow Through Porous Medium Without Soil Resistance		Flow Through Porous Medium with Soil resistance	
d		Q	Q	Q	Q
(mm)	(in)	(m ³ /sec)	(gpm)	(m ³ /sec)	(gpm)
0.1	0.0039	5.1×10^{-5}	0.8	4.8×10^{-5}	0.8
0.2	0.0078	1.9×10^{-4}	3.0	1.6×10^{-4}	2.5
0.5	0.0197	8.3×10^{-4}	13	4.5×10^{-4}	7.1
0.6	0.0236	1.2×10^{-3}	19	5.3×10^{-4}	8.3
1.0	0.0394	2.4×10^{-3}	38	6.1×10^{-4}	9.7
2.0	0.0787	6.8×10^{-3}	108	6.5×10^{-4}	10.3
5.0	0.1969	2.7×10^{-2}	430	6.6×10^{-4}	10.4
10.0	0.394	7.7×10^{-2}	1217	6.6×10^{-4}	10.4

As discussed in more detail in Appendix D, when the soil resistance is included in the pressure drop equation, the volumetric flow rate is substantially reduced for larger floor/wall gap distances. The volumetric flow rate asymptotes to a constant value for floor/wall gap distances larger than 5 mm (0.197 in). However, the exact contribution to the volumetric flow rate is highly uncertain because the values of the soil permeability around the K Basin where the leak may occur is uncertain. As noted above, the uncertainty analysis focuses on the initial volumetric flow rate through the floor/wall gap and does not consider the continuing flow rate that would result from the changing pressure head of the K Basin water level impeded by soil resistance outside of the basin. Therefore, the contribution due to the soil resistance is not included in the following analysis.

4.5 Contribution Due to the Water Stop

Figure 2 and the figures in Appendix D identify a water stop located midway in the concrete wall that was used as a flow limiter in fabrication of the floor-wall joint. The primary function of the water stop is to prevent water from escaping through the concrete construction or contraction joint across which the water stop is installed. Appendix D identifies the material of the water stop and its physical specifications.

The water stops in the K Basin SLOP could be damaged or torn by the motion which would separate the concrete floor from the concrete wall. The most likely damage would be vertical

tears in the water stop as the aged material is stretched and placed in tension. The aged material may not have its initial elongation property (450 percent elongation). Further there could be openings created around the bulbs at each end of the water stop around which water could seep.

The contribution of the water stop was represented in the analysis in conjunction with the flow area through the floor/wall gap in terms of the fraction of the flow area that is not available for water flow due to the presence of a portion of the water stop that is intact [i.e., $A = p d (1-F)$]. If the fraction of flow area that is not available is one ($F=1$) then there would be zero flow area that is available for water flow. If the fraction of flow area not available is zero ($F=0$) then the full flow area would be available for water flow. A uniform probability density function was used to represent the fraction of the flow area that is not available for water flow due to the water stop. The uniform probability density function means that any value of the fraction of area not available for water flow is equally likely.

4.6 Initial Volumetric Flow Rate

Each of the conditional probabilities discussed in this section formed a model which was analyzed using Monte Carlo convolution methods. The conditional probabilities that were combined in the final model were: 1) the probability of an impact energy given a load drop, 2) the residual floor/wall gap dependence on the impact energy, 3) the probability of the residual floor/wall gap given an impact energy, and 4) the volumetric flow rate through the floor/wall gap based on flow through a porous medium. Each of the conditional probability distributions were sampled 10,000 times to provide a floor/wall gap distance. Based on the floor/wall gap distance the initial volumetric flow rate was calculated using the equations appropriate for flow in a porous medium. The results were calculated in m^3/sec but were converted to gallons per minute for presentation of the results.

The probability density function for the distribution for the volumetric flow rate is provided in Figure 6. The corresponding cumulative distribution function is provided in Figure 7. The probability density function that represents the initial volumetric flow rate, for larger flows, is exponentially decreasing. However, the best fit to all of the data is a Lognormal probability density function with log-mean of 3.79 and a log-standard deviation of 1.57, which relates to a mean of 51.2 gpm and a standard deviation of 29.8 gpm. A summary of the results presented in Figures 6 and 7 is given in Table 4.

Figure 6. Probability Density Function for the Initial Volumetric Flow Rate.

Figure 7. Cumulative Distribution Function for the Initial Volumetric Flow Rate.

Table 4. Probability of Not Exceeding a Specified Initial Volumetric Flow Rate

	Probability	Initial Volumetric Flow Rate Is Less Than (gpm)
Mean		51
50th Percentile	0.50	50
90th Percentile	0.90	268
95th Percentile	0.95	411
99th Percentile	0.99	916

From Table 4, for example, there is a probability of 0.95 that the volumetric flow rate will be less than 411 gpm given that a cask and MCO are dropped in the K-West Basin SLOP. The associated percentile figures in Table 4 indicate, for example, that 95 percent of the time the volumetric flow rate was less than 411 gpm. Stated another way, given the conditional probability that a cask and MCO have been dropped in the K-West Basin SLOP, there is a 95 percent confidence that the resulting initial volumetric flow rate will be less than 411 gpm. In the analysis there were a few volumetric flow rates that were as large as 1,000 gpm to 2,000 gpm, but these flow rates occurred less than 1 percent of the time. Hence, as noted from Table 4, 99 percent of the time the volumetric flow rate is less than 916 gpm.

A sensitivity analysis was completed to identify the variables that contribute the most to the uncertainty in the initial volumetric flow rate. The results are as expected. The uncertainty in the initial volumetric flow rate is predominantly due to the height at which a cask and MCO may be dropped into the K-Basin SLOP. The uncertainty in the cask drop height is reflected in the uncertainty in the floor/wall gap thickness. Other variables that provide significant contributions to the uncertainty in the initial volumetric flow rate are the effectiveness of the waterstop and the porosity of the concrete rubble in the floor/wall gap. Therefore, as expected, the most effective way to prevent any water flow from the K-Basins is to prevent a cask and MCO from being dropped.

5.0 SUMMARY AND CONCLUSIONS

The initiating event considered in this uncertainty analysis was the assumption that a load (cask and MCO) had been dropped using the transfer bay crane in the K-West Basin SLOP. If a cask and MCO were to be dropped, the analysis considered the conditional probability of the potential impact energy to the SLOP basin concrete floor. Given the potential impact energy to the basin concrete floor, a distribution was determined for the resultant residual floor/wall gap separation. As a function of the potential floor/wall gap separation, the likelihood of the volumetric flow rate through the floor/wall gap was determined assuming flow through a porous medium.

The results of the uncertainty analysis demonstrated that even if a cask and MCO were to be dropped, the possible initial volumetric flow rate through the opened floor/wall joint would be small. There is a 95 percent confidence (probability of 0.95) that, given a load drop, the initial volumetric flow rate would be smaller than 411 gpm.

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Appendix A
Impact Energy Distribution for Cask and MCO Drops

A.1 Introduction

This appendix calculates the distribution for the impact energy that could be experienced by the concrete at the bottom of the K-West Basin SLOP should a loaded cask be dropped by the transfer bay crane. To evaluate the potential impact sequences, it is necessary to identify the component weights for the cask, MCO, and immersion pail. These component weights are provided in Table A-1 along with several combinations of the weights. These weights were identified in a Type II Calculation (Ard 1999) and as noted were obtained from various SNF project literature, including NAC International Drawings and HNF-SD-SNF-FDR-003 (Brisbin 1997). It is noted that various component weights exist in the available SNF project literature which are slightly different from those provided in Table A-1. However, the differences are usually small and the component weights provided in Table A-1 appear to be from the latest design media.

Table A-1. Cask, MCO, Immersion Pail Component Weights

Component Weights	Weight (lb)	Mass (kg)
Empty MCO w/ Locking Ring	2400	1089
Cask and Cask Lid	38178	17317
Loaded MCO, wet	20457	9279
MCO/Cask Annulus Water	250	113
Immersion Pail, Plug & Lid	6356	2883
Pail Slings & Lift Beam	950	431
Total Full Load	66191	30024
System Weights (Combinations)		
Cask and Empty MCO	40578	18406
Cask, Empty MCO, & Immersion Pail	46934	21289
Cask, Empty MCO, Immersion Pail & Slings	47884	21720
Cask, Loaded MCO & Annulus Water	58885	26710
Cask, Loaded MCO, Annulus Water & Immersion Pail	65241	29593
Cask, Loaded MCO, Annulus Water, Immersion Pail & Slings	66191	30024

It should be specifically noted that the weights provided in Table A-1 are close but not identical to the weights listed in Table 1-1 of Appendix B. The input for the finite element analysis in Appendix B was the impact energy and the corresponding impact velocity. The impact energy corresponds to the weights of the objects given in Table 1-1 of Appendix B for the various

vertical drops scenarios defined later in this appendix. The intent in Appendix B was to provide a large distribution of impact energies for which a large distribution of floor/wall residual gap dimensions could be developed.

A.2 Falling Mass Velocity and Kinetic Energy Calculation

Consider an object of mass m falling a distance z through a fluid. The object will experience a gravitational force, a drag force and a buoyant force, defined by;

$$\vec{F}_T = \vec{F}_g + \vec{F}_D + \vec{F}_B \quad [A-1]$$

The gravitational force is given by;

$$F_g = -mg, \quad [A-2]$$

where m is the mass of the object, and g is the gravitational constant.

The buoyant force is equal to the weight of the fluid displaced and is given by;

$$F_B = \text{weight} = mg = \rho g V_{\text{disp}}, \quad [A-3]$$

where ρ is the density of the fluid and V_{disp} is the volume of the fluid that the object displaces.

The drag force is given by;

$$F_D = \frac{1}{2} C_D \rho_{\text{liquid}} A_{Fr} v^2 = k v^2, \quad [A-4]$$

where C_D is the drag coefficient, A_{Fr} is the frontal surface area of the object, v is the velocity of the object, and k is defined by;

$$k = \frac{1}{2} C_D \rho A_{Fr}. \quad [A-5]$$

The forces act on the center of mass of the object as depicted in the sketch below.

For the falling object, Newton's second law of motion becomes;

$$m \frac{dv}{dt} = -mg + \rho g V_{\text{disp}} + k v^2. \quad [A-6]$$

The acceleration term in Equation A-6 is expanded as follows;

$$\frac{dv}{dt} = \frac{dv}{dz} \frac{dz}{dt} = v \frac{dv}{dz} \quad [A-7]$$

Rearranging the terms in Equation A-6 and the expanded form of the acceleration term, Equation A-6 becomes;

$$\frac{m v dv}{(k v^2 + \rho g V_D - mg)} = dz \quad [A-8]$$

Integrating the above expression gives;

$$\int_h^z dz = \int_{v_0}^{v_z} \left(\frac{m v}{k v^2 + \rho g V_D - mg} \right) dv \quad [A-9]$$

Substituting variables the integral is of the form;

$$\int_a^b \frac{dx}{x} = \ln(a) - \ln(b) = \ln\left(\frac{a}{b}\right) \quad [A-10]$$

Therefore,

$$z - h = \frac{m}{2k} \ln \left(\frac{k v^2 + \rho g V_D - mg}{k v_0^2 + \rho g V_D - mg} \right) \quad [A-11]$$

Taking the exponent of each side of Equation A-11 gives;

$$e^{-\frac{2k}{m}(h-z)} = \left(\frac{kv^2 + \rho g V_D - mg}{kv_o^2 + \rho g V_D - mg} \right) \quad [A-12]$$

Rearranging the terms in Equation A-12 gives the following equation;

$$v^2 = v_o^2 e^{-\frac{2k}{m}(h-z)} - \frac{\rho g V_D}{k} \left(1 - e^{-\frac{2k}{m}(h-z)} \right) + \frac{mg}{k} \left(1 - e^{-\frac{2k}{m}(h-z)} \right) \quad [A-13]$$

The velocity of the falling object in a fluid is, therefore, given by the equation;

$$v = \sqrt{v_o^2 e^{-\frac{2k}{m}(h-z)} - \frac{\rho g V_D}{k} \left(1 - e^{-\frac{2k}{m}(h-z)} \right) + \frac{mg}{k} \left(1 - e^{-\frac{2k}{m}(h-z)} \right)} \quad [A-14]$$

v = the objects velocity at any value of $z < h$,

v_o = the objects initial velocity at $z = h$,

$$k = \frac{1}{2} C_D \rho A_{Fr} ,$$

C_D = the drag coefficient,

ρ = the density of the fluid,

A_{fr} = the frontal area of the object falling through the fluid,

g = the gravitation constant,

h = the initial height of the object,

m = the mass of the object, and

V_D = the volume of the object.

Note that when $z = h$, at the point where the object begins to fall, $v = v_o$.

If the drag force is neglected, Equation A-9 becomes;

$$\int_h^z dz = \left(\frac{m}{\rho g V_D - mg} \right) \int_{v_o}^{v_z} v dv \quad [A-15]$$

or,

$$\frac{2}{m}(\rho g V_D - mg)(z - h) = v^2 - v_o^2 \quad [A-16]$$

$$v = \sqrt{v_o^2 + \frac{2}{m}(mg - \rho g V_D)(h - z)} \quad [A-17]$$

If the buoyance force is neglected, Equation A-14 becomes;

$$v = \sqrt{v_o^2 e^{-\frac{2k}{m}(h - z)} + \frac{mg}{k} \left(1 - e^{-\frac{2k}{m}(h - z)}\right)} \quad [A-18]$$

If the drag force and the buoyancy force are neglected, the velocity is given by;

$$v = \sqrt{v_o^2 + 2g(h - z)} \quad [A-19]$$

The kinetic energy of the object at any time is given by;

$$E_{KE} = \frac{1}{2}mv^2 \quad [A-20]$$

The force at impact is then given by;

$$F_{\text{impact}} = -mg + \rho g V_{\text{disp}} + kv_{\text{impact}}^2 \quad [A-21]$$

A.3 Potential Cask / MCO Drop Configurations

As the K-West Basin transfer bay crane lifts a cask and MCO, there are several situations for which a potential vertical cask drop could occur. These potential vertical cask drop situations are illustrated in Figures A-1, A-2 and A-3. A discussion of each potential vertical cast drop scenario follows the appropriate figures. The applicable dimensions through which the cask and MCO could be dropped are also provided on each figure.

Figure A-1. Vertical Drop Scenarios 1 and 2.

Vertical Drop Scenario 1

A cask with an empty MCO is lifted from the transport trailer and positioned over the immersion pail support structure in the K-West Basin SLOP. The cask is at a nominal transfer bay crane height. The cask and empty MCO are assumed to drop, impacting the immersion pail. The cask, empty MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.

Vertical Drop Scenario 2

The cask and empty MCO are situated in the immersion pail. The entire system is lifted by the transfer bay crane and the pins are removed that hold the immersion pail in place. The entire system is assumed to drop such that the cask, empty MCO and immersion pail impact the concrete at the bottom of the SLOP.

Figure A-2. Vertical Drop Scenarios 3 and 4.

Vertical Drop Scenario 3

The cask, loaded MCO, and immersion pail are lifted from the bottom of the immersion pail support structure. The cask, loaded MCO and immersion pail are assumed to fall a few feet (1 to 2 feet) and impact the concrete at the bottom of the SLOP.

Vertical Drop Scenario 4

The cask, loaded MCO and immersion pail are lifted to the top of the immersion pail support structure. However, before the pins can be placed to secure the immersion pail, the cask, loaded MCO and immersion pail are assumed to be dropped. The cask, loaded MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.

Vertical Drop Scenario 5

Cask with Loaded MCO Drops into Immersion Pail. Cask and Immersion Pail Drop into Pit

Figure A-3. Vertical Drop Scenario 5.

Vertical Drop Scenario 5

The cask and loaded MCO are removed from the immersion pail and lifted by the transfer bay crane. A "two-blocking" event or load hangup event are assumed to occur. Thus, the cask and loaded MCO are assumed to be dropped from the nominal transfer bay crane height, impacting the immersion pail. The cask, loaded MCO and immersion pail fall and impact the concrete at the bottom of the SLOP.

A.4 Immersion Pail Design

A schematic of the immersion pail design is shown in Figure A-4. Foam is attached to the lower two-thirds of the outside of the immersion pail which provides an additional buoyant force. This additional buoyant force reduces the net load of the cask, loaded MCO, and immersion pail such that the load required by the transfer bay crane is less than the design rating of 32 tons (64,000 lb.). Note from Table A-1 that the cask, loaded MCO, annulus water, immersion pail and slings weigh 66,191 pounds. However, the buoyant force of the immersion pail decreases the required load by approximately 8,600 pounds, and the added foam further increases the buoyant force by another

1,800 pounds. An additional design being considered for the immersion pail is to add five to six inches of foam to the bottom of the immersion pail. This additional five to six inches of foam would act as an impact limiter in the event of an immersion pail drop. The five to six inches of foam would also add an additional buoyant force (approximately 400 pounds). The design of the immersion pail shown in Figure A-4 together with the five to six inches of foam at the bottom of the immersion pail were taken into account in the impact energy calculations.

Figure A-4. Schematic of the Immersion Pail and Associated Surface Foam.

A.5 Cask Drop Results Including Drag and Buoyant Forces

Using the component weights (Table A-1) for the cask, MCO, and immersion pail, the velocity at concrete impact was calculated including the buoyant and drag forces using Equations A-14, A-17 and A-18. The analysis was completed for each of the five vertical drop scenarios. When the system first drops in air and then in water, the equations were solved twice, once to evaluate the drop in air and the second to evaluate the continuing drop in water. The final velocity of the first drop was used as the initial velocity for the second drop. An example for Vertical Drop Scenario 5 is presented in Figure A-5 where the velocity is graphed as a function of the height.

Figure A-5. Velocity of a Dropped Cask, Loaded MCO and Immersion Pail from the "Two-Blocking" Height.

A summary of the results in Figure A-5 are presented in Table A-2. The contribution in decreasing the velocity at impact, and, hence, the impact kinetic energy is illustrated in Table A-2. Note that in Figure A-5 and Table A-2 no energy was assumed to be lost due to the cask and loaded MCO impacting the immersion pail and shearing the pins which secure the immersion pail. Further, at this stage, no energy was assumed to be lost due to the foam impact limiter attached to the bottom of the immersion pail, nor the impact with the bottom of the immersion pail support structure. These effects are, however, discussed later and are considered in the uncertainty analysis. Also note that both the SI and English units are provided in Table A-2 for the impact velocity and the impact kinetic energy.

Table A-2. Summary Results for Vertical Drop Scenario 5

Impact Velocity (m/sec / ft/sec)			
Without Buoyant & Drag Forces	Without Buoyant Force	Without Drag Force	With Buoyant & Drag Forces
14.67 / 48.1	13.39 / 43.9	14.14 / 46.4	12.87 / 42.2
Impact Kinetic Energy (nt-m / ft-lb)			
$3.2 \times 10^6 / 2.4 \times 10^6$	$2.7 \times 10^6 / 2.0 \times 10^6$	$3.0 \times 10^6 / 2.2 \times 10^6$	$2.5 \times 10^6 / 1.8 \times 10^6$

A cask drop analysis was completed for each of the vertical drop scenarios identified above. As noted earlier, for those vertical drop scenarios where a cask and loaded MCO, or a cask and empty MCO, were dropped in air (Scenarios 1 and 5), the equations for the velocity were solved twice; first, for the drop in air until the cask bottom contacted the bottom of the immersion pail and, second, for the system dropping in water. The final velocity of the first drop was used as the initial velocity for the second drop (see Equation A-14). However, the energy that may be lost due to the cask and MCO impacting the immersion pail and shearing the pins that secure the immersion pail to the immersion pail support structure was considered in the analysis. This energy to shear the four pins will result in an impact force which can be described by a change in the system momentum.

Starting from the fundamental relations;

$$F = m \frac{dv}{dt} \quad \text{and} \quad P = m v$$

$$F = \frac{dP}{dt} = \frac{dP}{dz} \frac{dz}{dt} = v \frac{dP}{dz}$$
[A-21]

and integrating,

$$\int F dz = m \int v dv$$

$$F \delta = \frac{1}{2} m (v_f^2 - v_i^2) = KE_i - KE_f$$
[A-22]

$$KE_f = KE_i - F \delta = KE_i - U_{\text{lost}}$$

such that the change in kinetic energy (KE) is just equal to the energy lost in the impact of the cask and MCO with the immersion pail bottom.

The energy required to shear the pins can be written as;

$$U_{\text{shear}} = \frac{1}{2} F \delta = \frac{1}{2} \frac{F}{A} A \delta,$$
[A-23]

where F/A is the pressure exerted on the pins and δ is the displacement of the pin during the shear. For the immersion pail there are four lifting lugs through which the locking pins are inserted to secure the immersion pail to the immersion pail support structure. A shear stress for double shear of the locking pins is included in the cask Design Analysis Report (Brisbin 1997). The shear stress (force per unit area) is evaluated to be 49,020 psi with a safety margin to 81,000 psi. The locking pin is a square pin with cross sectional area of 1.5-in by 1.5-in. Assuming the entire displacement of 1.5-in for complete shear of the pins gives an energy to shear the pins of approximately 26,600 ft-lb. (36,000 nt-m) for the maximum 81,000 psi double shear stress. It is understood that this energy to shear the pins is an approximation because shearing of the pins is actually a dynamic situation. Therefore, in the analysis the energy to shear the pins was varied by a triangular probability density function between 0 ft-lb (0 nt-m) to 73,889 ft-lb (100,000 nt-m) with the most likely energy of 26,600 ft-lb (36,000 nt-m).

The energy to shear the pins is subtracted from the kinetic energy at impact to determine the kinetic energy after impact. The kinetic energy after impact is used to evaluate the system velocity after impact which is used as the initial velocity for the second part of the drop.

For those drop scenarios that start with the cask and MCO in the immersion pail, either at the height of the secured immersion pail or lower, only one drop was considered. Equation A-14 was used to evaluate the velocity of the system at the bottom of the drop. The total buoyant force of the immersion pail including the additional volume of the foam around the bottom part of the immersion pail (including the foam at the bottom of the immersion pail) was included in solving Equation A-14.

Credit was taken for the energy absorbed by the impact limiter foam at the bottom of the immersion pail. Credit was also taken for the energy absorbed by the loaded immersion pail striking the bottom of the immersion pail support structure and shearing the threads of the four legs that hold the immersion pail support structure above the concrete floor. The kinetic energy of the system just before hitting the concrete floor of the SLOP was calculated from the velocity of the system just before hitting the concrete floor. This kinetic energy of the system was then reduced by the energy absorbed by the impact limiting foam and the energy absorbed by yielding the bottom of the immersion pail support structure.

The design of the foam impact limiter at the bottom of the immersion pail was predicated on an energy absorption capacity based on a maximum crush force of 450,000 lb (Langevin 1999) and a maximum foam height of five inches (Islam 1999). Based on the foam manufacturer's data, this equates to an average crush strength of 400,580 lb from 10 percent to 70 percent strain. The energy absorbing capacity is taken as the average crush strength times the displacement ($F \delta$). The nominal energy absorbing capacity of the five-inch foam is 140,202 ft-lb (190,000 nt-m). A total displacement of five inches provides a nominal crush strength of 200,000 ft-lb (272,000 nt-m) and a minimum 10 percent energy absorbing capacity at five-inches is 177,300 ft-lb (240,000 nt-m). Therefore, the energy absorbed by the impact limiter foam at the bottom of the immersion pail was expressed as a triangular probability density function ranging from 125,100 ft-lb (170,000 nt-m) to 199,500 ft-lb (270,000 nt-m) with the most likely value of 177,300 ft-lb (240,000 nt-m).

The energy absorbed by the loaded immersion pail striking the bottom of the immersion pail support structure and shearing the threads of the four legs was assumed to be similar to the energy absorbed by shearing the locking pins. However, it was realized that there was much greater uncertainty (unknown) in this energy such that a much wider range in the absorbing energy was used. Therefore, the energy absorbed by the bottom of the immersion pail support structure was expressed as a triangular probability density function ranging from 0 ft-lb (0 nt-m) to 199,500 ft-lb (270,000 nt-m) with the most likely value of 14,800 ft-lb (20,000 nt-m).

The other variables for which the uncertainty was expressed as a probability density function include the drag coefficient and the drop height. Literature values for the drag coefficient of a flat plate with the velocity perpendicular to the plate diameter range from a high of 2 to a low of

0.5 with the best estimate of 1.2. Therefore, the drag coefficient was expressed as a triangular probability density function ranging from 0.1 to 2.0 with the most likely value of 1.2.

The drop height was expressed as a uniform probability density function ranging from zero to 30.24 feet (9.2 meters) which is the nominal crane transfer height. That is, it was assumed that a drop from any height was equally possible. A "two-blocking" event, if it were to occur, could conceivably result in a cask drop from 36 feet (11 meters). However, before the cask could reach this height the limit switch would terminate power to the crane motor and prevent further raising of the cask. The likelihood of a "two-blocking" event is reasonably small. Therefore the maximum drop height of a cask and MCO was considered to be the just above the nominal transfer crane height

The weight of the total cask was randomly varied between two states; either a loaded MCO or an empty MCO. If a loaded MCO was chosen, then the mass considered was a cask and loaded MCO for drop heights above the immersion pail. For drop heights below the immersion pail the mass considered was a cask, loaded MCO and immersion pail. If an empty MCO was chosen, then the mass considered was a cask and empty MCO for drop heights above the immersion pail and a cask, empty MCO, and immersion pail for drop heights below the immersion pail. The random selection of the two states was very nearly equal to 50:50; that is, equally likely to have an empty MCO as a loaded MCO. This is very reasonable because of the four lifts for each MCO half of the lifts will be with a loaded MCO and the other half will be with an empty MCO.

All of the variables were varied between their limits (i.e., described by their probability density function) using a Monte Carlo process. The calculated result was the remaining impact energy that could be imparted to the concrete floor of the SLOP. This process equated to calculating the velocity of the mass before impact taking into account the uncertainty in the drag coefficient, the drop height, and the energy to shear the immersion pail locking pins. The kinetic energy at impact was calculated from the impact velocity. The energy absorbed by the impact limiting foam and the energy absorbed by the loaded immersion pail striking the bottom of the immersion pail support structure was subtracted from the kinetic energy at impact to obtain the available impact energy. The process was repeated 10,000 times. This equates to completing 10,000 what if analyses varying all of the available parameters.

The results of this analysis are given in Figure A-6 which gives the distribution of data for the impact energy in nt-m that could be imparted to the SLOP concrete floor if a cask were to be dropped. Note that because of the many parameters that are being varied in this analysis, the scatter in the data is more than is usual for an analysis of this type. However, the data were fitted to a probability density function. The probability density function that best fit the data was a Weibull probability density function (solid line in Figure A-6). A Lognormal probability density function did not have an extensive enough tail in the distribution to adequately represent the

larger impact energies that were observed in the data. The fitted probability density function is used to represent the impact energy from a dropped cask in the remainder of the uncertainty analysis.

Figure A-6. Probability Distribution for the Impact Energy That Could be Imparted to The SLOP Concrete Floor by a Dropped Cask.

A summary of the results presented in Figure A-6 is provided in Table A-3, which gives the impact energy that could be imparted to the SLOP concrete floor should a cask be dropped by the SLOP transfer bay crane. The parameters that defined the Weibull probability density function that was the best fit to the data (solid line in Figure A-6) are also listed in Table A-3.

**Table A-3. Summary Results of Impact Energy That Could Be Imparted
to SLOP Concrete Floor by a Dropped Cask**

Percentile	Impact Energy Imparted to SLOP Concrete Floor	
	(nt-m)	(ft-lb)
50 th	394,400	290,700
90 th	1,059,690	781,070
95 th	1,224,050	902,220
95 th	1,448,600	1,067,740
Weibull Parameters for Fitted Distribution		
Location Parameter	Scale Parameter, η	Shape Parameter, β
0	639,756 nt-m	1.61

Appendix B
K Basin South Load Out Pit Wall-floor Joint Deformation Predictions

M & D

Professional Services Inc.

**K BASIN SOUTH LOAD OUT PIT
WALL-FLOOR JOINT DEFORMATION PREDICTIONS
FOR VARIOUS CASK DROP ACCIDENTS**

Prepared by:

**M&D Professional Services, Inc.
1305 Mansfield, Suite 5
Richland, WA 99352
Phone: (509) 943-1625 ext 231
Fax: (509) 946-2213**

Prepared for:

ARES Corporation

Prepared By: _____

Bob Winkel, Ph.D., P.E.

11-3-99

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SOUTH LOAD OUT PIT CASK DROP ANALYSES SUPPORTING PROBABILISTIC RISK ASSESSMENT EVALUATION

1.0 PURPOSE AND OBJECTIVES

As input to a probabilistic risk assessment of cask drops into the K Basin South Load Out Pit (SLOP), a series of twelve dynamic analyses of cask drops onto the SLOP floor have been performed. Definitions of the cask drop cases is provided in Table 1-1. Note that drop energies ranging from 58,000 to 2,000,000 ft-lbs with drop weights ranging from 45,300 (empty MCO) to 66,200 lbs. (loaded MCO) were considered. The objective of each drop analysis is to estimate the peak impact force and the wall/floor joint opening magnitudes resulting from the impact.

The impact load path from the cask to the floor is illustrated in Figure 1-1. The properties of the foam impact limiter shown on the bottom of the immersion pail have not been finalized, but, per current estimates, the impact limiter will have a crushing strength of 450,000 lb. and will be 5-in. thick. The 450,000 lb. crushing strength corresponds to the floor "capacity" (zero leakage) reported in Appendix I of Reference 13. Assuming an effective crush magnitude of 50%, the energy absorption capacity of the foam is about $(2.5/12)(450,000) = 93,800$ ft-lb. Thus, for a 66,200 lb. cask, a drop height greater than about $(93,800/66,200) = 1.4$ ft. will exceed the impact limiter capacity, resulting in a "bottoming out" of the impact limiter, and much higher forces imparted to the SLOP floor. Note that only Case Nos. 1 and 6 have drop energies less than the capacity of the impact limiter.

Based upon prior experience with evaluating drops onto the SLOP floor, the primary leak path following a cask drop, is the construction joint between the SLOP floor and the SLOP walls. Therefore, a finite element model of the lower portion of the SLOP was developed which focused on the wall/floor joint. This finite element model was used for performing dynamic analyses for each of the 12 cask drop cases listed in Table 1-1. The analysis methodology is described in Section 4.0. A summary of the results and the conclusions drawn are provided in Section 2.0.

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Table 1-1 - Definitions of Cask Drops into South Load Out Pit

Case No.	Drop Weight (lbs.)	Impact Velocity (fps)	Impact Energy (ft.-lbs.)	Analysis Uncertainty Basis
1	66,200	7.53	58,279	Best Estimate
2	66,200	28.72	848,314	Best Estimate
3	66,200	28.72	848,314	Conservative
4	66,200	44.16	2,006,135	Best Estimate
5	66,200	44.16	2,006,135	Conservative
6	66,200	7.53	58,279	Conservative
7	46,600	38.89	1,095,554	Best Estimate
8	46,600	38.89	1,095,554	Conservative
9	66,200	10.62	115,990	Best Estimate
10	66,200	10.62	115,990	Conservative
11	45,300	27.36	527,160	Best Estimate
12	45,300	27.36	527,160	Conservative

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Figure 1-1 - Cask Drop Configuration in South Load Out Pit

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Figure 1-2 - Impact Limiter Assumed Force/Deflection Properties

2.0 SUMMARY AND CONCLUSIONS

Using a finite element model of the lower portion of the South Load Out Pit (SLOP), a transient dynamic analysis was performed for each of the cask drop cases listed in Table 1-1. From the dynamic analysis results, residual gap predictions for the wall/floor joint were obtained for each drop case. Immediately following the time of impact, the maximum gap opening occurs, followed by some gap closure due to foundation soil rebound. The remaining "residual gap" is the item of interest for predicting leakage flow.

For the lower energy drops (Energy < 120,000 ft-lbs), inelastic stretching of the joint rebar was limited to minor yielding in the middle of the west, south, and north walls of the SLOP. For the remaining drops, significant yielding of the joint rebar occurred in all but the east wall. The east wall is more heavily reinforced and is furthest from the cask drop location. Thus, for the higher energy drops, the wall/floor residual gap is wedge shaped, with the maximum gap on the west wall and essentially zero at the east wall (pivot line). A plot of the maximum residual gap versus drop energy is provided in Figure 2-1.

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Figure 2-1 - Maximum Residual Gap Versus Impact Energy

3.0 DESIGN INPUT/ASSUMPTIONS

3.1 DESIGN INPUT

The structural concrete of the K Basin South Load Out Pit is defined in Drawing No. H-1-21072 (Reference 9). As indicated above, the cask handling weights considered for the drop analyses range from 45,300 to 66,200 lbs. The floor impact velocities provided as input to this calculation are listed in Table 1-1.

3.2 LOADS AND LOAD COMBINATIONS

The potential loads associated with the wall/floor joint are 1) drop loads, 2) wall soil pressure, 3) wall water pressure, 4) dead weight of the concrete structure, 5) water pressure on the floor, and 6) seismic loading. It is conservative to ignore the reinforced concrete structure dead weight loading because the concrete dead weight results in compression of the wall/floor joint, whereas a drop onto the SLOP floor places the joint in

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tension. The soil and water pressure on the basin walls tend to balance each other. Concerning seismic loading, it is unlikely that a seismic event would coincide with a drop accident and highly unlikely that the peak loadings on the wall/floor joint from a drop and seismic event would coincide in time. Therefore, for the current evaluation only the floor water pressure was considered to be coincident with the drop event.

3.3 ASSUMPTIONS

The following assumptions have been applied to the drop evaluation:

1. For analysis simplification, the reinforced concrete structure and supporting soil are modeled as linear components. The effects of concrete cracking on the section stiffness was conservatively ignored (higher concrete stiffness transfers more load to wall/floor joint). The one exception to the concrete structure linear behavior is the use of elastic/plastic rebar elements at the wall/floor joint. Also soil plasticity was considered in estimating the magnitude of floor rebound, as discussed in Section 3.4.
2. It is assumed that the rebar has not experienced significant corrosion. This assumption is primarily based upon the fact that basin inspections have revealed no evidence of rebar corrosion (Reference 3, Table 1). The minimum rebar yield strength of 40 ksi is assumed for the conservative analyses. For the best estimate analyses, average rebar strengths were considered, as well as strain rate effects on the rebar yield strength.
3. A maximum water depth of 21 feet (K West) was used to calculate the maximum pressure loading on the basin floor.
4. The impact is critically damped, i.e. no significant bouncing of the missile occurs following impact. The adequacy of this assumption is addressed in the drop test data benchmark study summarized in Appendix B.

3.4 MATERIAL PROPERTIES

The drop load reaction load path is sensitive to the relative stiffness of the concrete and soil. For example, for a very stiff basin foundation soil, a relatively high portion of the drop load would be reacted directly through the floor to the foundation soil. For a softer foundation soil, more of the drop load is reacted at the wall/floor connection. Therefore, significant attention was given to addressing the uncertainties in the soil stiffness properties, as indicated in the design input parameters discussed below.

The material properties used in the basin drop calculations are listed in Table 3-1 - M. Some explanations are in order to provide the basis for some of the material properties listed. For the maximum concrete elastic modulus value, an upper bound concrete compressive strength of 6000 psi was used ($E = 57,000[f_c']^{0.5}$) per Section 8.5.1 of Reference 1) which is based upon limited non-destructive testing of the basin concrete (Reference 3) plus other experience with older concrete structures at the Hanford site. The lower bound soil subgrade modulus of 100 psi/in is based upon limited load/deflection testing data found in Reference 10, as discussed in Appendix U of Reference 13. The average subgrade modulus value of 300 psi/in is based upon typical values listed for dense sand/gravel materials. See, for example, Table 9-1 of Reference 4.

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Table 3-1 - Material Properties Used in the Basin Drop Load Calculations

Material	Property	Values Used
Concrete	Density	150 lb/ft ³
	Upper Bound Elastic Modulus	4.4x10 ⁶ psi
	Poisson's Ratio	0.2
	Compressive Strength	3000 - 6000 psi
Soil	Lower Bound Subgrade Modulus	100 psi/in
	Average Subgrade Modulus	300 psi/in
Reinforcing Bar	Minimum Yield Strength	40,000 psi
	Average Yield Strength	48,000 psi

One of the limitations of the elastic soil modeling is the quantifying of the rebound of the floor following the impact loading. The use of elastic springs over predicts the amount of floor rebound. A better estimate of the floor rebound can be obtained by reviewing load test results on foundation piles. The typical pile test involves load magnitudes equal to 200% of the pile design loads. From Figure 10-11 of Reference 7, the rebound results summarized in Table 3-2 and

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Rebound Versus Max. Soil Deformation

Figure 3-1. Note that the pile deformations ranged from 0.20 to 2.80 in., and the corresponding rebounds ranged from 95 to 21%.

The Table 3-2/

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Rebound Versus Max. Soil Deformation

Figure 3-1 rebound percentages were used to approximate the rebound magnitudes for the cask drop accidents. Specifically, the SLOP floor rebound was estimated by correlating the maximum floor deformation to the corresponding gross settlement and rebound percentage from the pile test results. This is conservative in the sense that maximum floor deformations were used, which is about twice the average floor deformation. The approach is unconservative in the sense that the predicted gross floor deformations are based upon an elastic soil model. As shown below, the range of pile settlements are similar to the maximum predicted floor deformations. Also note that for small deformations (<0.1 in.), the response is elastic, i.e. the rebound is close to 100%.

The 40 ksi minimum yield strength of the reinforcing bars corresponds to the specified minimum value for the Grade 40 rebar used in the basin construction. The average value is 20% higher than the minimum, which is typical for rebar fabricated from low carbon steel. See, for example, Figure 3-25 of Reference 13. The yield strengths listed in Table 3-1 are quasi-static values. For drop accidents, the strain rate dependency of the rebar increases the yield strength. For Grade 40 steel, Appendix C of Reference 1, a 20% increase in the yield strength is specified for strain rates associated with impact loading. This 20% strain rate increase was applied to both the best estimate and conservative dynamic analyses.

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Table 3-2 – Pile Load Tests, Rebound Results

Test Load (kips)	Gross Settlement (in.)	Rebound (in.)	Rebound (% of Gross Settlement)
100	0.20	0.19	95
200	0.45	0.34	76
300	0.76	0.44	58
400	1.25	0.53	42
500	2.80	0.60	21

Figure 3-1 - Soil Rebound Percentage Versus Maximum Deformation

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4.0 ANALYSIS APPROACH

Transient dynamic analyses were performed for the twelve cask drop cases listed in Table 1-1, using the ANSYS computer code. A description of the ANSYS finite element model of the South Load Out Pit follows below.

4.1 FINITE ELEMENT MODEL

The ANSYS structural model of the K Basin wall/floor joint developed for the dynamic analysis is shown in Figure 4-1. This model was adapted from a model that has been previously used for SLOP drop analyses and has been subjected to checking and independent reviews. Note that to keep the analysis run times to reasonable values, only the lower portion of the SLOP walls was modeled. This model simplification is conservative, but reasonable, based upon prior experience with drop analyses in the SLOP. Vertical support to the floor is provided by soil springs, which are input using the elastic foundation stiffness (EFS) parameter for the ANSYS SHELL63 elements.

The top of the SLOP wall was fixed vertically, which was found to be reasonably conservative in prior experience since the actual walls are constrained by soil friction and attachment to the basin. Since the focus of the wall/floor joint evaluation is yielding in the reinforcing bars, which connect the floor to the wall, the rebar was explicitly modeled using elastic/plastic spar elements (ANSYS LINK8). The basis for the rebar element modeling details is described in the next section.

4.1.1 Wall/floor Rebar Modeling Details

Accurate predictions of rebar stress and strain (and joint deformations) require an accurate representation of rebar bond slip at the wall/floor construction joint. The effective length of the joint rebar increases with load magnitude, and can be quantified by using the simplifying assumption that the rebar stress is balanced by a uniform shear stress at the O.D. of the rebar equal to the bond strength. Reasonable estimates of rebar "effective lengths" are 16 inches (#10 rebar) and 15 inches (#9 rebar), as derived below.

Based upon the testing at the University of Illinois (Reference 5), a reasonable estimate of the bond strength of deformed bars is

$$\sigma_{bond} = 14\sqrt{f'_c},$$

where f'_c is the concrete design strength and σ_{bond} is the ultimate bond strength.

When the rebar reaches the material yield strength, the length of the distributed ultimate bond stress can be estimated by assuming that the rebar stress is balanced by a uniform shear/bond stress at the rebar periphery, equal to the above bond strength. For the uniform bond stress assumption, the rebar stress would be transferred in a linear fashion from the yield stress at the joint down to zero at the end of the balanced rebar bond strength stress. The associated length of rebar achieving the bond ultimate strength is found by equating the bond force to the rebar yield force:

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$$\sigma_y A_{rebar} = \sigma_{bond} (circum_{rebar}) l_{eff}$$

$$\sigma_y \frac{\pi d^2}{4} = 14 \sqrt{f_c'} (\pi d) l_{eff}$$

Solving for l_{eff} :

$$l_{eff} = \frac{\sigma_y d}{4(14 \sqrt{f_c'})} = \frac{40,000(0.625)}{56 \sqrt{3,000}} = 8.15 \text{ in.},$$

where σ_y is the rebar yield strength, d is the rebar diameter (#5 bars), and f_c' is the concrete 28-day design strength. Repeating the same calculation for a d value of 0.875 inches (#7 bars) results in an effective length of 11.4 inches. For modeling simplicity and conservatism, the shorter length of 8.15 in. was used for both bar sizes.

The actual effective rebar length varies with load magnitude, due to a progressive bond slip, which is highest near the construction joint. The higher bond slip near the joint results in a bond stress of near zero, adjacent to the joint, which means that upon yielding, the rebar stress does not drop below the yield stress for some finite distance from the joint. Based upon comparisons with rebar bond test load/deflection data, it is reasonable to assume an effective length of half of l_{eff} on each side of the joint, for a total effective length of l_{eff} . The adequacy of this approximation in selecting an effective rebar modeling length at the construction joint was bench-marked by comparing the rebar model, with a constant effective length of l_{eff} deformation predictions with actual rebar bond test data, as shown in Figure 4-2. The "model" prediction shown was based upon the same geometry and material properties used in the test program (#7 rebar, $f_y = 42$ ksi, $f_c' = 5000$ psi). Note that the bilinear shape of the constant length model response curve differs somewhat from the rebar test data curves, but is close to the average response at a stress level of 100% of the yield strength.. Thus, the effective length, l_{eff} , derived above, was judged to be adequate for the elastic/plastic rebar elements in the finite element model shown in Figure 4-1.

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Figure 4-1 - Finite Element Model of the K Basin Wall/Floor Joint

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Figure 4-2 -- Evaluation of Construction Joint Rebar Model Adequacy

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4.1.2 Loading and Other Analysis Details

Drop Loading

The drop loading was applied by using a mass element (ANSYS MASS21), with a mass magnitude equal to the cask mass value listed in Table 1-1. The lateral position of the mass element corresponded to the centerline of the cask. Contact of the mass element to the floor was made using rigid links to the elements representing the four Immersion Pail Support Structure (IPSS) feet which are appropriately positioned on the floor. Gap and damper elements (ANSYS CONTAC52 and COMBIN14) connect the ends of the rigid links to the floor, as shown in Figure 4-1. The mass was given an initial velocity corresponding to the values listed in Table 1-1.

Missile/Floor Contact Element Properties

A total "contact stiffness" of 1×10^6 lb/in was used for the gap elements representing the IPSS feet, based upon the benchmark evaluation presented in Appendix B. Damper elements (ANSYS COMBIN14) were used in parallel with the impact spring elements. To achieve critical damping (see Assumption 4, Section 3.3), the following damper element constant was used for the 66,200-lb. basket (Reference 14, page 23):

$$c_c = 2\sqrt{km} = 2\sqrt{1 \times 10^6 \cdot 66,200 / 386.4} = 26,000 \text{ lb/in/sec.}$$

The corresponding values for the 46,600-lb. and 45,300-lb. casks are 22,000 and 21,700 lb/in/sec, respectively.

Floor Pressure Loading

Using the SLOP water depth of 22.5 feet (K East basin), the water pressure on the floor was calculated to be

$$p_{\text{water}} = \gamma h = 62.4(22.5) = 1404 \text{ psf} = 9.75 \text{ psi.}$$

Transient Time Step

Transient dynamic analyses were performed (ANSYS ANTYPE,TRANS) using automatic time stepping with an initial time step of 0.5×10^{-4} seconds. Drop analyses were performed for all cask drop cases listed in Table 1-1.

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5.0 ANALYSIS RESULTS

The typical SLOP floor deformation pattern for a cask drop event is shown in Figure 5-1. Note that the maximum deformation occurs on the west side of the floor and is close to zero on the east end. This pattern is due to 1) the eccentricity of the load (closer to the west side), and 2) larger rebar on the east side of the wall/floor joint. Using the outside rebar on the middle of the west wall as the "maximum gap". As described in Section 4.1.2, this maximum gap occurring during the transient is reduced by an approximate rebound value, resulting in the final maximum "residual gap" values. It is also noted that the wedged-shape joint gap described above is not typical for the low energy drops (Case Nos. 1, 6, 9, and 10). For the low energy drops, the rebar at the wall intersections (corners) does not yield resulting in a floor deformation pattern which is somewhat bowl-shaped.

Figure 5-1 - Typical Floor Deformation Pattern

The residual gap predictions for the twelve drop cases are listed in Table 5-1.

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Table 5-1 - Residual Gap Predictions for the Cask Drop Cases

Drop Case No.	Impact Energy (ft-lbs)	Analysis Category	Maximum Residual Gap (in.)
1	58,279	Best Estimate	<0.001
2	848,314	Best Estimate	0.25
3	848,314	Conservative	0.88
4	2,006,135	Best Estimate	0.63
5	2,006,135	Conservative	1.74
6	58,279	Conservative	<0.001
7	1,059,554	Best Estimate	0.40
8	1,059,554	Conservative	1.16
9	115,990	Best Estimate	<0.001
10	115,990	Conservative	<0.010
11	527,160	Best Estimate	0.15
12	527,160	Conservative	0.56

A graphical presentation of the residual gap predictions is provided in Figure 2-1.

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6.0 REFERENCES

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APPENDIX A

TYPICAL ANSYS INPUT FILE

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```

/prep7
/title, Load Out Pit Model
!element types
et,1,63 !concrete
et,2,8 !rebar
et,3,52 !gap elements (outside rebar)
et,4,4 !rigid link
et,5,39,1,,3 !nonlinear spring(foam)
et,6,21,,,2 !impacting mass element
et,7,14,,3 !dashpot
!real constants
r,1,17.75,,,,100 !West Pit Wall
r,2,16,,,,0 !Remaining Pit Walls
r,3,27,,,,100 !Basin Walls
r,4,21,,,,100 !Pit Floor
r,5,24,,,,100 !Basin Floor/Pit E. Wall (bottom)
r,6,18,,,,100 !Sump Bottom Thickness
r,7,0.31 !#5 rebar
r,8,0.60 !#7 rebar
r,9,17 !rigid plate, floor/wall conn.
r,10,1e9 !gap element spring
r,11,1e8,,,0.0,17965 !pit walls friction
r,12,1e8,,,11700 !basin/channel walls friction
r,13,171.3 !impacting mass (64,900 lbs.)
r,14,2.5e5,,3446 !impact gap element
r,15,0,6545 !impact dashpot element constant
r,16,10,1000,1000,10,10,,,1000 !rigid link
r,17,0,0,,085,450000,2.5,450000
rmore,3.5,1.4e6,4,4e6 !nonlinear spring (39)
!material prop.
!concrete
mp,ex,1,4.4e6
mp,nuxy,1,0.2
mp,dens,1,,000225
!rebar, elas./plas.
mp,ex,2,29e8
mp,nuxy,2,0.3
Tb,Bkin,2,1
Tbdata,1,48e3,8e5
!rigid plates, wall-to-floor conn.
mp,ex,3,4.0e6
mp,nuxy,3,0.2
!inelas. floor
mp,ex,4,4.4e6
mp,nuxy,4,0.2
mp,dens,4,,000225
Tb,Bkin,4,1
Tbdata,1,457,8e5 !pseudo yield strength, floor eles.

n,1,0,0,0
n,3,9.32
fill
n,21,118.68
fill,3,21
n,23,128
fill,21,23
ngen,3,23,1,23,,,5.16
ngen,3,23,47,69,,,5.685
ngen,2,23,93,115,,,5.83
ngen,2,23,116,118,,,5.83
n,143,18.94,33.35
fill,141,143
n,157,109.06,33.35
fill,143,157
n,159,118.68,33.35
fill,157,159
n,161,128,33.35
fill,159,161
ngen,17,23,139,161,,,5.831
ngen,2,414,116,138,,,104.96
ngen,2,460,93,115,,,116.62
ngen,4,23,553,575,,,6.083
ngen,3,23,622,644,,,4.72
!modify nodes @ sump boundary
n,126,58,24.75
n,130,82,24.75
fill
n,218,58,48.75
n,222,82,48.75
fill
fill,126,218,3
fill,130,222,3
!n,103,57.93,20.7
!n,107,82.2,20.7
!fill
n,241,57.6,56.2
n,245,83.4,56.2
fill
!generate floor elements
real,4
type,1
mat,1
e,1,2,25,24
egen,22,1,-1
egen,29,23,-23
!delete eles. in sump hole
edele,121,124
edele,143,146
edele,165,168
edele,187,190
!generate sump elements
real,6
ngen,2,700,126,130,,, -16.5
ngen,2,700,218,222,,, -16.5

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ngen,2,700,149,195,23,,,16.5	k,4,128,0,0
ngen,2,700,153,199,23,,,16.5	k,5,0,15.88
fill,849,853	k,6,14,15.88,8.15
fill,872,876	k,7,114,15.88,8.15
fill,895,899	k,8,128,15.88
e,826,827,850,849	k,9,0,147
egen,4,1,-1	k,10,14,147,8.15
egen,4,23,-4	k,11,37.5,147,8.15
e,126,127,827,826	k,12,89.0,147,8.15
egen,4,1,-1	k,13,114,147,8.15
e,149,126,826,849	k,14,128,147,8.15
egen,4,23,-1	k,15,0,166,
e,130,153,853,830	k,16,14,166
egen,4,23,-1	k,17,37.5,166
e,219,218,918,919	k,18,89.0,166
egen,4,1,-1	k,19,114,166
!generate rebar eles.	k,20,128,166
ngen,2,700,49,67,2,,,8.15	k,21,14,15.88,63
ngen,2,700,95,113,2,,,8.15	k,22,114,15.88,63
ngen,2,700,141,509,46,,,8.15	k,23,14,147,63
ngen,2,700,143,511,46,,,8.15	k,24,37.5,147,63
ngen,2,700,157,525,46,,,8.15	k,25,90.5,147,63
ngen,2,700,159,527,46,,,8.15	k,26,114,147,63
ngen,2,700,555,573,2,,,8.15	k,27,14,15.88,324
ngen,2,700,624,642,2,,,8.15	k,28,114,15.88,324
	k,29,14,147,324
real,7	k,30,37.5,147,324
type,2	k,31,90.5,147,324
mat,2	k,32,114,147,324
e,49,749	k,33,37.5,215,63
egen,10,2,-1	k,34,90.5,215,63
e,95,795	k,35,37.5,215,324
egen,10,2,-1	k,36,90.5,215,324
e,141,841	k,37,37.5,0
egen,9,46,-1	k,38,89.0,0 !sump edge loca.
e,143,843	k,39,37.5,15.88,8.15
egen,9,46,-1	k,40,89.0,15.88,8.15
e,157,857	k,41,37.5,15.88,63
egen,9,46,-1	k,42,90.5,15.88,63
e,159,859	k,43,37.5,15.88,324
egen,9,46,-1	k,44,90.5,15.88,324
e,555,1255	k,45,-200,215,63
egen,10,2,-1	k,46,-200,215,324
e,624,1324	k,47,250,215,63
egen,10,2,-1	k,48,250,215,324
type,1	k,49,-200,153.5,63
mat,1	k,50,37.5,153.5,63
	k,51,90.5,153.5,63
!Keypoints	k,52,250,153.5,63
k,1,0,0,0	k,53,37.5,153.5,324
k,2,14,0,0	k,54,90.5,153.5,324
k,3,114,0,0	k,55,-200,335,63

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k,56,37.5,335,63
 k,57,90.5,335,63
 k,58,250,335,63
 k,59,14,15.88,348
 k,60,37.5,15.88,348
 k,61,90.5,15.88,348
 k,62,114,15.88,348
 k,63,14,147,348
 k,64,37.5,147,348
 k,65,90.5,147,348
 k,66,114,147,348

!Areas

a,1,2,6,5
 a,2,37,39,6
 a,37,38,40,39
 a,38,3,7,40
 a,3,4,8,7
 a,5,6,10,9
 a,6,39,11,10
 a,39,40,12,11
 a,40,7,13,12
 a,7,8,14,13
 a,9,10,16,15
 a,10,11,17,16
 a,11,12,18,17
 a,12,13,19,18
 a,13,14,20,19 !Area 15
 aatt,,4
 asel,none
 a,6,39,41,21
 a,39,40,42,41
 a,40,7,22,42
 a,27,43,60,59
 a,43,44,61,60
 a,44,28,62,61 !Area 21
 aatt,,1
 asel,none
 a,10,6,21,23
 a,13,7,22,26
 a,29,27,59,63
 a,32,28,62,66 !Area 25
 aatt,,2
 asel,none
 a,21,41,43,27
 a,41,42,44,43
 a,42,22,28,44
 aatt,,1
 asel,none
 a,23,21,27,29
 a,26,22,28,32
 a,24,23,29,30

a,26,25,31,32
 a,33,50,53,35
 a,50,24,30,53
 a,34,51,54,36
 a,51,25,31,54 !Area 36
 aatt,,2
 asel,none
 a,45,33,35,46
 a,34,47,48,36
 aatt,,3
 asel,none
 a,11,10,23,24
 a,12,11,24,25
 a,13,12,25,26
 a,45,49,50,33
 a,33,50,51,34
 a,50,24,25,51
 a,34,51,52,47
 a,55,45,33,56
 a,56,33,34,57
 a,57,34,47,58 !Area 48
 aatt,,5
 alls
 esize,8.3
 eshape,2
 !amesh,1,7
 !amesh,9,15
 !sel,s,loc,z,8.15
 !lesize,all,6.5
 alls
 esize,13
 amesh,16,48
 !amesh,16,18
 !amesh,22,23
 !amesh,39,41
 aclear,19,21
 aclear,24,38
 aclear,42,48
 !wall/floor connection plates
 real,9
 mat,3
 e,749,751,1345,1344
 e,751,753,1343,1345
 e,753,755,1365,1343
 e,755,757,1364,1365
 e,757,759,1363,1364
 e,759,761,1362,1363
 e,761,763,1361,1362
 e,763,765,1392,1361
 e,765,767,1391,1392
 e,795,749,1344,1344
 e,841,795,1344,1434

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e,887,841,1434,1435
 e,933,887,1435,1436
 e,979,933,1436,1437
 e,1025,979,1437,1438
 e,1071,1025,1438,1439
 e,1117,1071,1439,1440
 e,1163,1117,1440,1441
 e,1209,1163,1441,1442
 e,1255,1209,1442,1443
 e,1255,1443,1433,1324
 e,1326,1324,1433,3328
 e,1328,1326,3328,3327
 e,1330,1328,3327,3341
 e,1332,1330,3341,3340
 e,1334,1332,3340,3339
 e,1336,1334,3339,3338
 e,1338,1336,3338,3337
 e,1340,1338,3337,3366
 e,1342,1340,3366,1499
 e,1273,1342,1499,1509
 e,1273,1509,1508,1227
 e,1227,1508,1507,1181
 e,1181,1507,1506,1135
 e,1135,1506,1505,1089
 e,1089,1505,1504,1043
 e,1043,1504,1503,997
 e,997,1503,1502,951
 e,951,1502,1501,905
 e,905,1501,1500,859
 e,859,1500,1391,813
 e,767,813,1391,1391
 e,1344,1345,797,797
 e,1345,1343,799,797
 e,1343,1365,801,799
 e,1365,1364,803,801
 e,1364,1363,805,803
 e,1363,1362,807,805
 e,1362,1361,809,807
 e,1361,1392,811,809
 e,1392,1391,811,811

e,1344,797,843,1434
 e,1434,843,889,1435
 e,1435,889,935,1436
 e,1436,935,981,1437
 e,1437,981,1027,1438
 e,1438,1027,1073,1439
 e,1439,1073,1119,1440
 e,1440,1119,1165,1441
 e,1441,1165,1211,1442
 e,1442,1211,1257,1443
 e,1443,1257,3328,1433

e,1257,1259,3327,3328
 e,1259,1261,3341,3327
 e,1261,1263,3340,3341
 e,1263,1265,3339,3340
 e,1265,1267,3338,3339
 e,1267,1269,3337,3338
 e,1269,1271,3366,3337
 e,1271,1509,1499,3366
 e,1271,1225,1508,1509
 e,1225,1179,1507,1508
 e,1179,1133,1506,1507
 e,1133,1087,1505,1506
 e,1087,1041,1504,1505
 e,1041,995,1503,1504
 e,995,949,1502,1503
 e,949,903,1501,1502
 e,903,857,1500,1501
 e,857,811,1391,1500

!Gap elements on outside rebar
real,10

type,3
 e,49,749
 egen,10,2,-1
 e,624,1324
 egen,10,2,-1
 e,95,795
 egen,11,46,-1
 e,113,813
 egen,11,46,-1

nummrg,all

n,4192,38.251,45.012,6
 n,4200,89.749,45.012,6
 n,4330,38.251,79.998,6
 n,4338,89.749,79.998,6
 !impacting mass
 n,4400,64,62.5,6
 n,4401,64,62.5,12

type,6
 real,13
 e,4401 !mass

type,3
 real,14
 type,5
 real,17

e,4400,4401 !nonlinear spring (impact limiter)
 e,192,4192 !gap elements
 e,200,4200
 e,330,4330
 e,338,4338

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type,7
 real,15
 e,192,4192 !dashpots
 e,200,4200
 e,330,4330
 e,338,4338
 type,4
 real,16
 e,4192,4400 !rigid links
 e,4200,4400
 e,4330,4400
 e,4338,4400

solve
 fini
 /post26
 nsol,2,4401,u,z,uzmass
 deriv,3,2,1,,vzmass
 plvar,2
 ESOL,4,2791,,SMIS,1,FZ
 PLVAR,4
 NSOL,5,57,U,Z,uz57
 plvar,5

/VIEW, 1, 0.126685636958 , -0.479200338424E-01,
 0.990784749451
 /ANG, 1, -61.5345416226
 eplo

!Water Pressure Loading
 esel,s,real,,4
 nsle
 nsel,s,loc,y,15.8,147.1
 nsel,r,loc,x,13.9,114.1
 nsel,r,loc,z,0
 esln,,1
 sfe,all,,pres,, -9.75 !pit floor water pressure
 alls

nsel,s,loc,z,62.9,63.1
 d,all,uy,,,,ux,uz
 nsel,s,node,,4000,4500
 d,all,ux,,,,uy
 nall
 d,l,ux,,,,uy
 d,23,uy

fini
 /solu

antype,trans
 outres,all,all
 timint,off
 d,4401,uz,-.3446
 d,4401,ux
 d,4401,uy
 time,0.001 !initial veloc.
 nsubst,4
 solve
 ddel,4401,uz
 timint,on
 time,.05
 deltim,.00005,.00001,.001

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APPENDIX B

BENCHMARK TESTING OF ANALYSIS METHODOLOGY

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1.0 INTRODUCTION

The purpose of this appendix is to address the adequacy of the dynamic analysis methodology used in evaluating the structural response to a drop onto the 105 K fuel storage basin floor. The basis for addressing the methodology adequacy is by analytically duplicating impact testing performed at Sandia Laboratories (Reference 15) and comparing the analytical results with the test data. By appropriately modifying the analytical model parameters, the analytical approach can be tuned to the test data and the resulting modeling/methodology is "benchmarked" against actual drop tests which are similar to the fuel storage basin drop accident configurations.

2.0 LOW VELOCITY IMPACT TEST PROGRAM REVIEW

Reference 15 summarizes the results from a series of four low velocity impact testing programs performed at Sandia and Lawrence Livermore Laboratories. All of the tests involved steel billets (weight: 6475 and 6600 lbs.) dropping onto 12-in and 18-in. thick concrete pads. The drop heights ranged from 18 in. to 72 in. Tests #233 and #234 of Test Series No. 3 involve 72-in. end drops of 6600-lb. billets onto a 1-ft. thick concrete slab, which is closest to the 3400-lb. fuel basket drop of 8-ft, 1-in. These two test configurations were selected to benchmark the drop analysis approach used in the K Basin floor drop evaluations.

For the tests of interest (#233 and #234) the steel billets were instrumented with six accelerometers—four on the top and two on the side of each billet. Acceleration time histories are reported for all six instrumented locations.

3.0 BENCHMARK TEST ANALYSIS MODEL

The benchmark test configuration involved a 6-ft. by 6-ft. slab, with a thickness of 1 ft. The slab for test #233 was supported with a 1-ft. thick "engineered fill" on top of an "unknown soil B". The test #234 slab was supported directly on grade ("unknown soil B"). Consistent with the K Basin drop analysis approach, the concrete slab was modeled using shell elements (ANSYS SHELL63). The ANSYS model is shown in Figure B-1. The 6600-lb. billet was modeled with a single mass element (ANSYS MASS21), which was given an impact velocity of 236 in./sec. (72-in. drop). The interface between the mass and the slab included a gap element (ANSYS CONTAC52) and a damper (ANSYS COMBIN14).

The slab was supported on elastic springs using a lower-bound subgrade modulus of 100 psi/in. An upper-bound modulus of 500 psi/in. was also considered, but the predicted mass deceleration was found to be relatively insensitive to the soil stiffness. The peak predicted mass decelerations were found to be relatively sensitive to the mass/slab interface stiffness and damper constants. A range of interface element parameters were considered, as described below. Consistent with the analysis approach described in Section 4.1.2, the damper dashpot constant magnitude corresponded to the critical damping value ($c = 2(km)^{1/2}$).

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Figure B-1 - Finite Element Model of Benchmark Test Configuration

4.0 COMPARISON OF ANALYSIS AND TEST RESULTS

The predicted mass deceleration histories for various values of interface stiffness are shown in Figure B-2. The peak decelerator values for the 12 reported test data sets ranged from 121 to 210 g's. The "Sandia Tests" curve shown represents the upper bound test results for test #233 and #234. Note that a model impact stiffness of 1×10^6 lb./in. predicts a peak acceleration above the bounding test data.

5.0 CONCLUSION

Based upon the analytical/test data comparisons described above, the most important model parameters for duplicating the Sandia drop test data are the interface stiffness and damper constant. By assuming critical damping and a model interface stiffness of 1×10^6 lb./in., a reasonable upper bound to the test data can be obtained.

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Figure B-2 - Comparison of Drop Test Data with Analytical Predictions

Appendix C
Impact Energy and Associated Concrete Crack Diameter

C.1 Introduction

In Appendix B the residual gap diameter between the SLOP basin floor and wall was determined for a range of concrete impact energies. The analysis used both best engineering values as well as conservative values for the parameters used in the analysis over the range of concrete impact energies. In this Appendix the results of Appendix B are combined with uncertainty distributions to determine the distribution of the residual gap diameters between the SLOP basin floor and wall. These residual gap diameters are used in Appendix D to determine the initial flow rate through this gap.

C.2 Uncertainty in the Residual Gap Diameter

The results of Appendix B, Table 5-1, are graphed in Figure C-1 as the residual floor/wall gap diameter as a function of the concrete impact energy for the analyses using both the best engineering and conservative values of the parameters. The results for each set of data are reasonably linear, specifically in light of the uncertainty in the analysis. Therefore, each set of data were fit to a linear expression. The fitted linear curves as well as the 5th and 95th percent confidence levels for the fitted curves are given in Figure C-1.

The uncertainty in the residual floor/wall gap diameter given by the curves for the analyses using best engineering and conservative parameters was assumed to be lognormally distributed. The curve representing the results of the analysis using best engineering parameters was assumed to be the median value of the Lognormal distribution. The Lognormal standard deviation was varied until the spread in the distribution enveloped the results of the analysis using the conservative parameters. This process was repeated for each set of data given in Figure C-1. As the median value of the Lognormal distribution decreased (as represented by the curve that represents the results using best engineering parameters) the spread in the distribution also decreased such that a constant Lognormal standard deviation appeared to represent all of the data. Assuming a constant Lognormal standard deviation while varying the median value of the Lognormal distribution simplifies the analysis to follow. The results for the distribution of residual floor/wall gap as a function of the impact energy is shown in Figure C-2. The over-laid Lognormal distribution in Figure C-2 represents the uncertainty in the floor/wall gap at each concrete impact energy.

The information in Figure C-2 is used as follows. For each value of the concrete impact energy the median value of the distribution for the floor/wall gap is determined using the linear equation that represents the results in Figure C-2 using best engineering parameters. This median value and the constant standard deviation represents a Lognormal distribution from which a value of the floor/wall gap is determined. This process is repeated for 10,000 iterations, each time selecting a new impact energy, a median value of a Lognormal distribution for the floor/wall gap

and a value from the distribution for the floor/wall gap.

Figure C-1. Residual Floor / Wall Gap as a Function of the Impact Energy.

Figure C-2. Uncertainty in the Residual Gap as a Function of the Impact Energy.

The results of the analysis are presented in Figures C-3 and C-4. Figure C-3 is the cumulative distribution function which represents the probability of not exceeding a specific floor/wall gap diameter in millimeters. Figure C-4 is the complementary cumulative distribution function which represents the probability of exceeding a specific floor/wall gap diameter. The most likely floor/wall gap diameter is 4.5 mm (0.177 in). There is a probability of 0.95 that the floor/wall gap diameter will not exceed 12 mm (0.472 in). Conversely, there is a probability of 0.05 that the floor/wall gap diameter will exceed 12 mm (0.472 in). There is a probability of 0.99 that the floor/wall gap diameter will not exceed 18 mm (0.709 in). These results are used in the analysis of Appendix D.

Figure C-3. Cumulative Distribution Function of the Residual Floor/Wall Gap.

Figure C-4. Complementary Cumulative Distribution Function of the Residual Floor/Wall Gap.

Appendix D
Flow In A Porous Media

D.1 Introduction

This appendix evaluates the volumetric flow rate through the floor/wall gap created by an impact energy to the SLOP basin concrete floor from dropping a cask and MCO. The analysis starts with fluid flow which in general is given by the expression $Q = A U$, where A is the cross-sectional area of the floor/wall gap and U is the superficial fluid velocity. The pressure gradient through the floor/wall gap is expressed as $\Delta P = f(U)$. The pressure gradient through the floor/wall gap is defined due to various conditions as a function of the superficial velocity and other physical parameters. The superficial velocity is determined from the pressure gradient, and is used to evaluate the fluid flow. In this appendix the equations are expressed in SI units, but the final results will be expressed in English units.

D.2 Early Analysis

In a series of letter reports Plys (Plys 1999) estimated the initial leak rate from the SLOP due to an assumed drop of the cask. The initial leak rate was through the floor/wall joint that was separated due to the impact energy on the concrete floor. The first estimate considered tubular flow through the floor/wall gap. The volumetric flow rate was given by the expression;

$$\frac{Q}{A} = C_D \sqrt{2 g H} , \quad [D-1]$$

where Q = volumetric flow rate in m^3/sec ,
 C_D = loss coefficient,
 g = gravitational acceleration ($9.81 m^2/sec$), and
 H = water depth.

The loss coefficient is approximated by the expression;

$$C_D = \frac{1}{\sqrt{K + \frac{4fL}{D}}} , \quad [D-2]$$

where K = total loss coefficient for acceleration, contraction, expansion, etc,
 f = friction factor,
 L = length of the flow path, and
 D = equivalent hydraulic diameter which is $2 \times$ gap thickness.

In this analysis, there were discussions about the concrete path roughness, ϵ , and friction factors. Ranges of ϵ were provided (0.3 to 3 mm) from which ranges of ϵ/D could be estimated.

In the second analysis (Plys 1999) consideration was given to estimating the initial leak rate through the floor/wall gap at the SLOP floor wall joint using a porous medium approach. It was presented that a porous medium approach was applicable because the roughness (ϵ) is as large or larger than the floor/wall gap thickness. Plys notes that there is an experimental basis for application of the porous medium approach to correlate flow through cracks in reinforced concrete (Rizkalla, et al. 1979).

The pressure gradient in a porous medium is given by (Macdonald, et al. 1979)

$$\frac{\Delta P}{L} = \frac{180(1 - \epsilon)^2}{D_n^2 \epsilon^3} \mu U + \frac{B(1 - \epsilon)}{D_n \epsilon^3} \rho U^2, \quad [D-3]$$

where ΔP = pressure drop, which is given by $\Delta P = \rho g H$ (Pa),
 L = the length for the flow through the floor/wall gap (m),
 ρ = water density (kg/m^3),
 g = gravitational acceleration (9.81 m/s^2),
 H = K Basin water height (7.4 m),
 D_n = equivalent average flow diameter (m),
 ϵ = porosity
 μ = viscosity ($1 \times 10^{-3} \text{ kg/m-sec}$),
 U = superficial velocity (m/sec),
 A = flow area (m^2), and
 B = roughness parameter.

Plys noted that the roughness parameter ranges from 2 for smooth particles to 4 for rough particles in a porous medium.

In a third analysis Epstein (Plys 1999) included in the equation for the pressure gradient in a porous medium a contribution for the flow resistance imposed by the soil just out side of the floor/wall gap. For this case the pressure gradient from the floor/wall gap inlet region to the soil outside and downstream of the gap outlet is given by;

$$\Delta P = \frac{180(1 - \epsilon)^2}{D_n^2 \epsilon^3} \mu L U + \frac{B(1 - \epsilon)}{D_n \epsilon^3} \rho L U^2 + \frac{2 \mu D_n U}{\kappa_{\text{soil}}} \quad [D-4]$$

where κ = the soil permeability.

The last term in Equation D-4 represents the pressure drop in the exterior soil. The soil permeability is related to the saturated hydraulic conductivity by the expression;

$$\kappa_{\text{soil}} = \frac{\mu k_{\text{soil}}}{\rho g} \quad [D-5]$$

Therefore Equation D-4 becomes;

$$\Delta P = \frac{180(1 - \epsilon)^2}{D_n^2 \epsilon^3} \mu L U + \frac{B(1 - \epsilon)}{D_n \epsilon^3} \rho L U^2 + \frac{2 \rho g D_n U}{k_{\text{soil}}} \quad [D-6]$$

Note that in Equation D-6 the first term is a viscous pressure drop, the second term is an inertial pressure drop, and the third term is a pressure drop due to the resistance of the exterior soil. The viscous pressure drop varies as $1/D_n^2$, the inertial pressure drop varies as $1/D_n$, while the pressure drop due to the exterior soil resistance varies as D_n . Thus, as the equivalent diameter increases the viscous pressure and inertial pressure decrease while the pressure drop due to the exterior soil resistance increases.

D-3 Considerations of the Flow Through a Porous Medium

Equation D-6 is a quadratic equation in the superficial velocity U . Equating the pressure gradient as $\Delta P = \rho g H$, the quadratic equation can be written as;

$$aU^2 + bU + c = 0 \quad \text{with} \quad [D-7]$$

$$U = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

where

$$a = \frac{B(1 - \epsilon)\rho L}{D_n \epsilon^3}$$

$$b = \frac{180(1 - \epsilon)^2 \mu L}{D_n^2 \epsilon^3} + \frac{2 \rho g D_n}{k_{\text{soil}}} \quad [D-8]$$

$$c = -\rho g H$$

The volumetric flow is given by $Q = A U$. Note that D_n is the equivalent hydraulic diameter which is 2 times the floor/wall gap thickness.

The asymmetric impact location of a dropped cask on the K Basin SLOP concrete floor results in the largest separation of the floor/wall joint in the wall nearest to the drop location (west side of the SLOP floor). The separation of the floor/wall joint is close to zero on the east end of the SLOP floor (nearest to the K Basin entrance). Besides the asymmetric impact location this asymmetry is also due to larger rebar on the east side of the floor/wall joint (see Appendix B). Figure D-1 provides a layout of the K Basin SLOP both in plan view and in a section view. The section view in Figure D-1 shows that the floor/wall gap around the perimeter of the SLOP is approximated by two triangles on the north and south walls and a rectangle on the west wall. Therefore the area of the floor/wall gap is approximated by;

$$A = 2 \left(\frac{1}{2} \text{ base} * \text{height} \right) + \text{width} * \text{height} = (b + w) * d \quad [\text{D-9}]$$

In Equation D-9, b is the base of the SLOP, w is the width of the SLOP, and d is the height of the floor/wall gap. Note that the sum of the base and the width is just equal to the perimeter of the SLOP. As noted in Figure D-1 there is a water stop located midway in the concrete wall that was used as a flow limiter in fabrication of the floor wall joint. For this analysis, the equivalent hydraulic flow area is taken to be the area of the floor/wall gap at the location of the water stop. Therefore, the dimensions used to calculate the perimeter of the SLOP are taken from Figure D-1 and are given by;

$$\begin{aligned} \text{base} &= 10'-11 \frac{1}{8}" = 131.125\text{-in} = 3.3 \text{ m,} \\ \text{width} &= 8'-6" = 102\text{-in} = 5.6 \text{ m,} \\ \text{perimeter} &= \text{base} \times \text{height} = 233 \text{ in} = 5.92 \text{ m, and} \\ d &= \text{floor/wall joint gap distance.} \end{aligned}$$

Note in Equation D-4, $D_n = 2 d$.

The volumetric flow rate is given by $Q = A U = p d U = p (D_n/2) U$. The contribution to the volumetric flow rate due to the pressure drop of the exterior soil is approximated by;

$$Q \sim p \frac{D_n}{2} \frac{k_{\text{soil}} \Delta P}{2 \rho g D_n} \sim \frac{D_n}{D_n} \quad [\text{D-10}]$$

Equation D-10 shows that the resistance to the flow due to the presence of the exterior soil against the SLOP basin wall soon asymptotes to a constant value independent of the floor/wall joint gap.

The contribution of the inertial pressure drop to the volumetric flow rate is approximated by;

$$Q \sim p \frac{D_n}{2} \sqrt{\frac{\Delta P \epsilon^3}{B(1 - \epsilon) \rho L}} D_n \sim D_n^{\frac{3}{2}} \quad [\text{D-11}]$$

Figure D-1. Layout of the K-West Basin SLOP.

Similarly the contribution of the viscous pressure drop to the volumetric flow rate is approximated by;

$$Q \sim p \frac{D_n}{2} \frac{\Delta P \epsilon^3}{180(1 - \epsilon)^2 \mu L} D_n^2 \sim D_n^3 . \quad [D-12]$$

For small floor/wall gap distances, the contribution to the volumetric flow rate is dominated by the inertial pressure drop term. The viscous pressure drop term is very small but increases approximately as D_n^3 . However, for large floor/wall gap distances the contribution to the volumetric flow rate is dominated by the pressure drop of the exterior soil which asymptotes to a constant value. Therefore, the volumetric flow rate, when all of the contributions in Equation D-6 are included, asymptotes to a constant value for floor/wall gap distances beyond 5 mm (0.197 in) even for largely varying values of the soil permeability.

Point-values for each of the parameters included in Equation D-6 are given in Table D-1. Based on these point-values, the superficial velocity, U , was calculated solving the quadratic equation, Equation D-6. Using this superficial velocity, the volumetric flow rate was calculated for a range of floor/wall gap distances. The results are presented in Table D-2 for floor/wall gap distance up to 10 mm (0.394 in).

Table D-1. Point-Values for Each of the Parameters Listed in Equation D-6

Parameter	Parameter Point Value	Units
Viscosity, μ	1.0×10^{-3}	kg/m-sec
Water Density, ρ	1.0×10^3	kg/m ³
Roughness Parameter, B	2.5	
Porosity, ϵ	0.7	
Soil Hyd. Conductivity, k_{soil}	5.8×10^{-5}	m/sec
Gravitational Acc., g	9.81	m/sec ²
SLOP Basin Height	7.6	m
SLOP Basin Width	2.6	m
SLOP Basin Length	3.3	m
SLOP Basin Perimeter, p	5.9	m
SLOP Basin Wall Thickness	0.406	m

**Table D-2. Volumetric Flow Rate for Flow Through a Porous Medium
for Various Floor/Wall Gap Distances**

Floor/Wall Gap Distance		Flow Through Porous Medium Without Soil Resistance		Flow Through Porous Medium with Soil resistance	
d	d	Q	Q	Q	Q
(mm)	(in)	(m ³ /sec)	(gpm)	(m ³ /sec)	(gpm)
0.1	0.0039	5.1×10^{-5}	0.8	4.8×10^{-5}	0.8
0.2	0.0079	1.9×10^{-4}	3.0	1.6×10^{-4}	2.5
0.5	0.0197	8.3×10^{-4}	13	4.5×10^{-4}	7.1
0.6	0.024	1.2×10^{-3}	19	5.3×10^{-4}	8.3
1.0	0.039	2.4×10^{-3}	38	6.1×10^{-4}	9.7
2.0	0.079	6.8×10^{-3}	108	6.5×10^{-4}	10.3
5.0	0.197	2.7×10^{-2}	430	6.6×10^{-4}	10.4
10.0	0.394	7.7×10^{-2}	1217	6.6×10^{-4}	10.4

When the soil resistance is included in the pressure drop, the volumetric flow rate is substantially reduced for larger floor/wall gap distances. As noted above, the volumetric flow rate asymptotes to a constant value for floor/wall gap distances larger than 5 mm (0.197 in).

Reported values of the soil permeability around the Hanford site vary significantly as reported by Kee (1997). A value of $k_s = 14.8$ cm/hr (0.00013 ft/sec) was reported as the log-based mean of 16 measured values for the Hanford formation gravels in the 200 Areas (Khaleel and Freeman 1995). However, the soil permeability outside of the immediate wall of the SLOP K Basin is unknown. Even though it is recognized that there will be some resistance to the flow imposed by the soil outside of the wall this contribution is neglected in this uncertainty analysis.

Consequently, the uncertainty analysis evaluates the initial flow rate through the floor/wall gap caused by the impact energy of dropping a cask and MCO. The uncertainty analysis does not consider the continuing flow rate that would result from the changing pressure head of the K Basin water level impeded by soil resistance.

The parameters in Equation D-6 that are represented by uncertainty probability density functions are the porosity (ϵ) and the roughness parameter (B). All other parameters in Equation D-6 are for water or physical parameters for the K Basin SLOP. The soil saturated hydraulic conductivity is not included because the pressure drop due to soil resistance was not included in the analysis.

A value of the porosity of 0.7 would represent a fairly dense medium. Values of the porosity of various materials are given in Table D-3. Note that clay has a porosity of 0.45 while sand and gravel has a porosity of 0.2. For the uncertainty analysis the porosity of the rubbalized concrete in the floor/wall gap was represented by a uniform probability density function ranging from 0.2 to 0.7. The uniform probability density means that any value of the porosity from 0.2 to 0.7 is equally likely.

The roughness parameter could range from 2 for smooth particles to 4 for rough particles in a porous medium. For the uncertainty analysis the roughness parameter was represented by a uniform probability density function ranging from 2 to 4. Again this means than any value from 2 to 4 is equally likely.

Table D-3. Ranges of the Value of the Porosity

System	Porosity
Clay	0.45
Sand	0.35
Gravel	0.25
Sand and Gravel	0.20
Sandstone	0.15
Quartzite / Granite	0.01

D.4 Contribution Due to the Water Stop

As noted in Figure D-1 there is a water stop located midway in the concrete wall that was used as a flow limiter in fabrication of the floor wall joint. The primary function of a water stop is to prevent water from escaping through the concrete construction or contraction joint across which the water stop is installed. The construction documents for the 105-K Building (H-1-21072, HW-4754) indicate that the water stop installed in the K-West Basin SLOP at the joint between the concrete floor slab and the concrete wall is a rubber dumbbell, 2-bulb type. The water stop consists of a basic polymer of either natural rubber or a co-polymer of butadiene and styrene or a blend of both. The water stop was specified to have the following characteristics:

- Tensile strength (minimum) 2500 psi
- Elongation at break (minimum) 450 percent.

The water stop specification stated that "all splices shall be at least equal to the performance and physical characteristics of adjoining unspliced stops (except that the tensile strength may be reduced 50 percent)."

The joint between the concrete floor slab and the wall in the K Basin SLOP was designed as a construction joint and was expected to incur little or no movement. Thus, the water stop would not need to be designed to accommodate any floor/wall movement. The dumbbell 2-bulb type water stop used in this application relies on the bulbs at the ends of the section to provide anchorage in the concrete. When tension is applied to this water stop shape, the web portion of the water stop is reduced in thickness, leaving only the bulbs at the ends in contact with the concrete. Since concrete is not completely impervious, some water may seep past the small area along the web portion of the water stop.

Comparative leak tests have been performed on different shapes of water stops (Kellam 1959). These leak tests indicated that leakage rates with a 1/8-in (3 mm) joint opening were almost non-existent but that "The dumbbell samples, while being watertight with closed joints, almost without exception leaked with a 1/2-in joint opening." However, they also indicated that when the joint was closed and an additional test run, the joints were effectively watertight.

Another concern would be the condition of the existing K-Basin water stops, which are almost 50 years old. Rubber water stops are longest lived when they are completely out of contact with oxygen and protected from sunlight. When exposed to oxygen or sunlight, rubber water stops harden and crack. The conditions existing inside the K-Basins concrete create a favorable environment for the water stop material, there is no sunlight and there is minimal exposure to oxygen.

The water stops in the K Basin SLOP could be damaged or torn by the motion which would separate the concrete floor from the concrete wall. The most likely damage would be vertical tears in the water stop as the aged material is stretched and placed in tension. The aged material may not have a comparable elongation property as the initial material (450% elongation). Further there could be openings created around the bulbs at each end of the water stop around which water could seep.

The contribution of the water stop was represented as follows. The flow area through the floor/wall gap, which includes the exposed area of the water stop, was represented by:

$$A = p d (1 - F) , \quad [D-13]$$

where as before p is the basin perimeter, d is the floor/wall gap distance. F is the fraction of the flow area that is not available for water flow due to the presence of a portion of the water stop that is intact. If $F = 1$, then $1-F=0$ which means that there is zero flow area that is available for

water flow. The fraction of flow area not available with the presence of the water stop was represented by a uniform probability density function with values from 0 to 1. A fraction of flow area not available of 1 ($1-1 = 0$) means that the water stop was completely effective and there is essentially no flow area. A fraction of flow area not available of 0 ($1-0 = 1$) means that the water stop is not effective and the full flow area is available for water flow. The uniform probability density function means that any value of the fraction of area not available for water flow is equally likely.

Appendix E
Uncertainty Analysis Results

E.1 Introduction

In this appendix the information discussed in each of the other appendices is brought together to form a model which is evaluated using a Monte Carlo convolution process. Several probability density functions which represent specific information relative to the analysis are combined to provide the results that may be expected should a cask and MCO be dropped into the K Basin SLOP. Each of the probability density functions are representative of conditional probabilities. That is, probabilities that are conditional on a previous event occurring.

The conditional probabilities that are combined in the final model are: (1) the probability of an impact energy given a load drop (Appendix A), (2) the residual floor/wall gap dependence on the impact energy (Appendix B and C), (3) the probability of the residual floor/wall gap given an impact energy (Appendix C), and (4) the volumetric flow rate through the floor/wall gap given a residual floor/wall gap (based on Appendix D). The convolution model combines each of these probability density functions which in turn are based on the uncertainty associated with each of the variables involved in each calculation. In this analysis it was expeditious to partition the solution into the various sections that were discussed in each appendix. In reality, a composite model could have been developed which would have combined all of the analysis together into one model. However, for this analysis it was more instructive to examine each portion of the analysis to gain additional insight into the results.

E.2 Results for the Initial Volumetric Flow Rate

Each of the conditional probabilities identified above were sampled 10,000 times to provide a floor/wall gap distance. Based on the floor/wall gap distance, the initial flow rate was calculated using the equations and appropriate variable uncertainties presented in Appendix D. The superficial velocity was determined and used to calculate an initial volumetric flow rate through a porous medium. The volumetric flow rate was calculated for each of the 10,000 iterations in m^3/sec , but was converted to gallons per minute for presentation of the results. The probability density function for the distribution for the volumetric flow rate is provided in Figure E-1. The corresponding cumulative distribution function is provided in Figure E-2. The probability density function that represents the initial volumetric flow rate, for larger flows, is exponentially decreasing. However, the best fit to all of the data is a Lognormal probability density function with log-mean of 3.79 and a log-standard deviation of 1.57, which relates to a mean of 51.2 gpm and a standard deviation of 29.8 gpm. A summary of the results presented in Figures E-1 and E-2 is given in Table E-1.

Figure E-1. Probability Density Function for the Initial Volumetric Flow Rate.

Figure E-2. Cumulative Distribution Function for the Initial Volumetric Flow Rate.

Table E-1. Probability of Not Exceeding a Specified Initial Volumetric Flow Rate

	Probability	Initial Volumetric Flow Rate Is Less Than (gpm)
Mean		51
50th Percentile	0.50	50
90th Percentile	0.90	268
95th Percentile	0.95	411
99th Percentile	0.99	916

From Table E-1, for example, there is a probability of 0.95 that the volumetric flow rate will be less than 411 gpm. The associated percentile figures in Table E-1 indicate, for example, that 95 percent of the time the volumetric flow rate was less than 411 gpm. Stated another way, given the conditional probability that a cask and MCO have been dropped in the K-West Basin SLOP, there is a 95% confidence that the resulting initial volumetric flow rate will be less than 411 gpm. In the analysis there were a few volumetric flow rates that were as large as 1,000 gpm to 2,000 gpm, but these flow rates occurred less than 1% of the time. Hence, as noted from Table E-1, 99% of the time the volumetric flow rate is less than 916 gpm, or there is a 99% confidence that the initial volumetric flow rate will be less than 916 gpm.

A sensitivity analysis was completed to identify the variables that contribute the most to the uncertainty in the initial volumetric flow rate. The results are as expected. The uncertainty in the initial volumetric flow rate is predominantly due to the height at which a cask and MCO may be dropped into the K-Basin SLOP. The uncertainty in the cask drop height is reflected in the uncertainty in the floor/wall gap thickness. Other variables that provide significant contributions to the uncertainty in the initial volumetric flow rate are the effectiveness of the waterstop and the porosity of the concrete rubble in the floor/wall gap. Therefore, as expected, the most effective way to prevent any water flow from the K-Basins is to prevent a cask and MCO from being dropped.

Appendix F
Validation of Analysis Models

F.1 Introduction

This appendix provides the documentation for the functional reviews and specific hand calculations to demonstrate that the model analysis is correct.

F.2 Functional Reviews

During the functional reviews, the client decided that an appendix that was provided with the original draft report should be removed from the document. This appendix, original Appendix A, SLOP Transfer Bay Crane Fault Tree Analysis, determined the distribution for the probability of dropping a cask and MCO into the K-West Basin South Loadout Pit (SLOP) while using the K-West Basin transfer bay crane. Therefore, the focus of the present report was changed to consider the conditional probability that a cask and MCO had been dropped and then determine the subsequent results in terms of the initial volumetric flow rate from the K Basin.

Comments resulting from the functional reviews are documented on Review Comment Records (RCRs). The report was modified as appropriate to incorporate these comments. Attachment F-1 provides the approved and signed RCRs.

F.3 Validation of Models

The calculations used in Appendix A, C, D, and E were checked for appropriateness and accuracy. In most cases point value solutions were checked by appropriate hand calculations and/or spreadsheet calculations. Attachment F-2 provides the checked calculations and/or calculation notes.

Attachment F-1
Review Comment Record

REVIEW COMMENT RECORD (RCR)

REVIEW COMMENT RECORD (RCR)									
1. Date 10/13/99			2. Review No. 1						
3. Project No. CTFM A.5/A.6			4. Page 1 of 3						
5. Document Number(s)/Title(s)	6. Program/Project/Building Number	7. Reviewer	8. Organization/Group	9. Location/Phone					
9904561-001, Uncertainty Analysis of the Results of Potential Cask Drops in the K West Basin South Layout Pit	Spent Nuclear Fuel Project	K. E. Ard	SNF Engineering	MO293/C108/100K 376-8712					
17. Comment Submittal Approval:		10. Agreement with indicated comment disposition(s)			11. CLOSED				
Organization Manager (Optional)		Reviewer/Point of Contract Date 11-4-99			Reviewer/Point of Contract Date 11-4-99		Author/Originator		
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)			16. Status			
1.	Figures 3 and 4 little too small to read.		Accept. As stated in the document, these figures were intended to convey a process and were not intended to be read. Because of the confusion they are being deleted.			REA			
2.	Page 9, second paragraph. Reference J. L. Weamer memo that justifies the 5 inches of foam based on programmatic and ALARA considerations. J. L. Weamer to J. A. Swenson, dated September 29, 1999, Subject: Justifications of Maximum Thickness Crushable Pad.		Accept. The reference will be added.			REA			
3.	Page 9, second paragraph. Also included was the minimum five inches of foam....		Accept. The appropriate changes will be made to the document.			REA			
4.	General Comment: It would be helpful to use English units throughout the document rather than SI units, or at least reference both English and metric units. The SNF Project is exempt from having to use SI units you choose not to use SI units.		Accept. Where possible, English units will be added to the text. Some figures will not be changed due to the time available.			REA			
5.	Page 20, second paragraph. There are four lifts per MCO. 1. Trailer to immersion pail, 2. Immersion pail stand height to floor of basin, 3. Floor of basin to stand height, 4. Immersion pail to trailer. Does 400 lifts really become 800 lifts? Lifts 1 and 2 are empty cask-MCO. Lifts 3 and 4 are fully loaded.		Accept. The lifts considered were for a cask and empty MCO and for a cask and loaded MCO. There are 800 lifts over two years or 400 lifts per year. No change required to the document.			REA			
6.	6.0 References - Add J. L. Weamer memo discussed in comment 2, and other references discussed below.		Accept. The reference will be added to the document.			REA			
7.	Page A-2, Second paragraph. Change Transfer Crane to transfer bay crane.		Accept. The change will be made.			REA			
8.	Page A-10, rewrite 4 th sentence. There are two settings programmed for the load cells that would respond.		Accept. The paragraph will be changed to reflect the two programmed settings.			REA			

REVIEW COMMENT RECORD (RCR)					1. Date 10/13/99	2. Review No. 1
					3. Project No. CTFM A.5/A.6	4. Page 2 of 3
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status		
9.	Page A-10, second para. I don't think the double hooks and cables would help much. If you lost one side, the full load would be applied to one trunion at an angle that would likely yield the end cap on the trunion and the hook would slip off. Also, there are not double drums on the crane.		Accept. The reference to double drums will be changed and the logic of the fault trees will be changed. We agree with the comment relative to the failure of the second set of hooks. In fact the analysis did not consider the redundancies in the calculations.	Rea		
10.	Page B-2. The MCO weight is the largest uncertainty because it depends on the payload. The weight of a fully loaded cask can vary depending on the baskets of SNF inside. I used the number from the MCO specification because it was referencable at the time and seems to be an upper mid-range weight. I think that the content and weight of various payloads are available from the MCO topical. I don't have a reference for it, but Lou Goldmann (373-6371) might since he's the design authority. There is some percentage of the lifts that won't be at full weight, but I don't know if it changes much as far as the impact loads go.		Agree, but this would not change the results of this analysis. Section B.1 states "that various component weights exist in the available SNF project literature which are slightly different than those provided in Table B-1. However, the differences are usually small and the component weights provided in Table B-1 appear to be from the latest design media." Since some of the lifts won't be at full weight, the report is taking a conservative approach. Further the full range of potential weights were considered in the uncertainty analysis.	Rea		
11.	Page B-8. Can a 1 to 2 foot drop assumption in "Vertical Drop Scenario 3" really be substantiated? How do these drop definitions tie back to the cases that Bob Winkle ran in Appendix C?		Accept. Potential drop scenarios were identified for finite element analyses that would provide a full range of potential impacts to the basin concrete floor. These drop scenarios are the results that were evaluated by Bob Winkle. Therefore, the drop scenarios coincide with the other calculations that were completed in this analysis but there are some differences in the drop weights. Table 2 will be changed to provide a mapping between the 12-drop cases and the 5-drop scenarios.	Rea		
12.	Page B-10. The impact limiter will be a minimum of 5 inches thick. 1 inch of structure was assumed to be needed around the foam, adding to a total height of 6 inches. This will depend on design details from Mo Islam's calculations.		Accept. At the time of the analysis it was understood that the impact limiter would be six inches thick. When it is confirmed that the calculation/ECN has been finalized then we will have to evaluate if any changes are required in the calculations. Because of the uncertainty used in the impact force absorbed by the impact limiter it is doubtful that the calculations will need to be changed.	Rea		
13.	Page B-14, third para. The first sentence describes the 450,000 lb. crush force, but no reference is provided in the document regarding why 450,000 lb. was chosen. The calculation produced during the immersion pail support structure conceptual design provides backup for the 450 kips. Bob Winkle produced that calculation and it is in Appendix I of HNF-4576, Rev. 0. Here is the full reference: HNF-4576, Rev. 0, <i>Conceptual Design Report - Cask Loadout System/Cask Drop Redesign for the Immersion Pail Support Structure and Operator Interface Platform, 105 K West Basin, Project A1.5/A.6</i> , July 12, 1999, Fluor Daniel Hanford, Richland, Washington, 99352.		Accept. The document will add reference to HNF-4576 report.	Rea		

REVIEW COMMENT RECORD (RCR)

				1. Date 10/13/99	2. Review No. 1
				3. Project No. CTFM A.5/A.6	4. Page 3 of 3
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status	
13.	You should also get Bob Winkle's later analysis document that ran that number up to 750 kips, therefore indicating that the 450 kips can be considered conservative. Might be a good discussion anyway.		Accept. We will add the reference when it is confirmed that the calculation/ECN is finalized. However, it is uncertain if any changes, besides adding the reference can or should be made to the document.	REA	
14.	Moody 1999 should be replaced with design calculation by Mo Islam that calculates 5 inches of crush material. When Mo finishes his ECN, the reference for Mo's calculation will be in: DESH, 1997, <i>Design Analysis Report for the TN-WHC Cask and Transportation System</i> , HNF-SD-SNF-FDR-003, Rev. 0, Duke Engineering and Services Hanford, Richland, Washington.		Accept. We will look at the sentence and try to make it clearer.	REA	
15.	Page B-15, first paragraph, third sentence could use a little help.		Agree, however, the models used in this analysis have been thoroughly reviewed in previous calculations. A statement to this effect will be added in the document.	REA	
16.	Appendix C calculation needs checking.		The calculations in Appendix C were to provide a realistic range of impact energy to the basin concrete floor and the associated floor-wall gap distance. The analysis was never intended to explain why 450,000-pounds was selected as a conservative load to the concrete floor. No changes to the document are required.	REA	
17.	Appendix C, Section 1.0. This calculation is supposed to explain why 450,000 lb. was selected as a conservative load to the concrete floor based on earlier calculations performed by M&D for the IPSS supported from the SLOP floor. The concrete could possibly withstand a higher load based on later calculations that were less conservative.		Agree. Text will be added to Appendix B, Section B.1 further amplifying on the discrepancies in weights throughout document.	REA	
18.	Appendix C, Page 4 of 19, second para. 66,200 lb used but Table 1-1 uses 66,300 lb.		Agree, as noted above a discussion will be added to show the relationship between the 5 drop scenarios and the 12 drop cases.	REA	
19.	Table 1-1, No definition of twelve cases listed. Are the cases consistent with those starting on Page B-6? It would be helpful to tie back to the report done by Marlin Linquist at M&D which identifies all of the drops. Then you don't have to recreate.				
20.					

REVIEW COMMENT RECORD (RCR)

5 Document Number(s)/Title(s) 9904561-001		6 Program/Project/Building Number SNF		7. Reviewer Barclay Lew		8. Organization/Group Nuc Safety		9. Location/Phone 373-2019		1. Date 10-21-99		2. Review No. []	
17 Comment Submittal Approval:		10. Agreement with indicated comment disposition(s)		11. CLOSED		3. Project No. SNF		4. Page 1 of 2					
Organization Manager (Optional)		Date 11/4/99		Reviewer/Point of Contract		Date 11/4/99		Reviewer/Point of Contract					
Author/Originator		Author/Originator		Author/Originator		Author/Originator		Author/Originator					
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status									
1	The appendix on the leak rate section needs to include a discussion of the PNNL work done on the characterization of the soils under the basin. This should be several paragraphs summarizing the findings of PNNL and impact on drainage out of the basin. Bob Winkel of M&D should do this since he is familiar and update on this information. This summary information is intended to provide more basis and background on the range of assumptions used in the uncertainty analysis done for the leak rate.	Y	The soil resistance data has large variations, and most of the data was for the 200 Area, with little data directly adjacent to the K Basin. Therefore, the report specifically states that: "The contribution due to the soil resistance was not included in the uncertainty analysis because the analysis evaluates the initial flow rate thought the floor/wall gap caused by the impact energy of dropping a casks and MCO." One doesn't know what the soil resistance is just next to the basin wall, which may impede the flow from the basin, or directly under the basin floor which may affect the resistance to any drop impact. Because of these reasons, as noted above, the flow resistance was not included. No change will be made to the document.	closed SM									
2	The report should have emphasis on the uncertainties on the leak rate values and less on other parts of the analysis which lead to the leak rate values.	Y	Stronger ties will be made between the Executive Summary, Section 1.0, Section 5.0 and Appendix F.	closed SM									
3	Wording in the appendices needs work to be clearer to what is done to estimate the uncertainties vs what are the uncertainty results. A first time reader of the report is easily confused about what was done in determining the uncertainties versus what do the uncertainty results mean. This has led to confusion to what the report is trying to accomplish and how this was accomplished.	Y	Some text will be re-written to provide stronger ties between the Executive Summary, Section 1.0, Section 5.0 and Appendix F.	closed SM									

REVIEW COMMENT RECORD (RCR)

1. Date 10-20-99		2. Review No. []	
3. Project No. SNF		4. Page 1 of 2	
5. Document Number(s)/Title(s) 9904561-001	6. Program/Project/Building Number SNF	7. Reviewer Roger Webb/Steve Peck	8. Organization/Group Nuc Safety
9. Location/Phone 373-2251		10. Agreement with indicated comment disposition(s) 11. CLOSED	
17. Comment Submittal Approval: Organization Manager (Optional) <i>Roger Webb</i> Reviewer/Point of Contract Date 11/4/99		Author/Originator Date Reviewer/Point of Contact	
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)
1	1 st paragraph of executive summary- delete everything after the word leakage in the second sentence. Then add "Subsequent analysis has shown that preventing a cask drop or basin leakage is not practical and the risk of a cask drop and subsequent leakage is acceptable. Reason 1) this document shows that leakage rates aren't excessive relative to recovery; 2) attempts were made to quantify uncertainties. Similar changes should be made in the introduction to the document.		Partially accept. The recommended changes to the second sentence will be made. However, the rest of this paragraph is a summary of the previous efforts and is not a review of the present study. We think that the suggested sentence to be added is incorrect in that preventing a cask drop is, and should be, the primary defense and is a practical solution.
2	2nd paragraph of Exec Sum - Rewrite to: This analysis: 1) determines the uncertainty that a cask drop has occurred , determines the associated		Accepted. The recommended changes will be made.
3	Change first sentence of 4 th paragraph of exec summ to " ... dropped, the analysis establishes possible leak rates by considering; 1) ...		Accepted. The recommended changes will be made, except leak rates will be replaced by initial volumetric flow rates.
4	Last paragraph of Exec summ and table containing summary of results - The paragraph states that there is a 95.5 confidence at a probability of .95 that the flow rate would be smaller than 400 gpm. Then, it goes on to say that the combined frequency is 1.6 E-5 per year that a load drop would produce a leak GREATER than 400 GPM. The values in the table all are for rate greater than the reference value. It would be much more compelling to show what the frequencies of not exceeding a given flow rate are. For example, at a frequency of 1 E-6 what can we say is the maximum initial flow rate at 95% confidence. This table and discussion point out that the probability of exceeding some flow rate is low as the flow rate increases -- but it doesn't help bound the flow rate to some max value to support with a high confidence that the mitigation will be effective and timely.		One needs to remember to objectives of this analysis. The objectives were; (1) to show that the likelihood of dropping a cask is small, and (2) given that a cask load drop has occurred the likelihood of exceeding a specified flow rate is small. The operative sentence in the executive summary is: "The results of the uncertainty analysis demonstrated that even if a cask and MCO were to be dropped the possible initial volumetric flow rate through the opened floor/wall joint would be small. There is a 95% confidence that the initial volumetric flow rate would be smaller than 400 gpm." No changes will be made to the document.
5	The title and discussion should not be limited to KW basin. This analysis should be applicable to either basin. Delete K-West from title and elsewhere as appropriate.		Do not accept. The analysis was specifically for the K-West Basin. Since the K-East basin SLOP crane is different and the K-East Basin IPSS has not been installed we cannot at present assume that the analysis would apply to both.

Attachment F-2
Checked Calculations and Calculation Notes

Formulas Used For Model Verification

The following formulas were used in verifying the model calculations.

The velocity of the Cask and MCO falling in air just prior to impact with the bottom of the Immersion Pail is given by;

$$V_1 = \sqrt{2 g H_1}$$

The velocity of the Cask and MCO immediately after impact with the bottom of the Immersion Pail is given by;

$$V_2 = \sqrt{V_1^2 - \frac{2 U}{m}}$$

where U is the energy lost due to shearing the Immersion Pail pins.

The velocity of the Cask, MCO and Immersion Pail just prior to impacting the bottom of the Immersion Pail Support Structure is calculated by;

V_3 calculated using Equation A-14 of Appendix A.

The kinetic energy of the Cask, MCO and Immersion Pail just prior to impacting the bottom of the Immersion Pail Support Structure is given by;

$$KE_1 = \frac{1}{2} m V_3^2$$

The remaining kinetic energy after the energy lost by crushing the impact limiter and shearing the legs of the Immersion Pail Support Structure is calculated from;

$$KE_2 = KE_1 - U_{\text{impact limiter}} - U_{\text{bottom plate}}$$

This is the impact energy to the K Basin SLOP concrete floor.

The following equations are used to calculate the initial volumetric flow through the K Basin SLOP floor / wall gap which results from the impact energy of dropping a cask, MCO and Immersion Pail.

Referring to Equation D-6 in Appendix 6, the superficial velocity through the floor/wall gap is given by;

$$U = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

where the constants a, b, and c are calculated using Equation D-8 in Appendix D.

With the superficial velocity through the floor/wall gap and the floor/wall gap height, the initial volumetric flow through the floor/wall gap is given by;

$$Q = A U - d p U F$$

Table F-1. Parameters For Model Hand Calculations.

Drag Coefficient	1.2	
Density of Water	1000	kg/m
Gravitational Const	9.81	m/sec ²
Frontal Area of IP	1.2464	m ²
Volume of Cask & IP	4.9128	m ³
Constant k	747.85	kg/m
Cask, MCO; Mass 1	58885	lb
Cask, MCO, IP; Mass 2	66191	lb
Drop Height (m)	9.217	m
Height 1	4.46	m
Height 2	4.76	m
Mass 1	26710	kg
Mass 2	30024	kg
Velocity at Impact to IP	9.350	m/sec
Energy absorbed to yield pins	36000	nt-m
Velocity after Impact with IP	9.20	m/sec
Velocity at Impact to Bottom	11.679	m/sec
KE	2047503	nt-m
Foam	270000	nt-m
IPSS	20000	nt-m
Remain	1757503	nt-m
Viscosity of Water	1.00E-03	kg/m-sec
Roughness Parameter	2.5	
Porosity	0.7	dl
SLOP Basin Height	7.600	m
SLOP Basin Wall Thickness	0.4064	
SLOP Basin Perimeter	5.900	m
Residual Gap	1.0000	mm
Residual Gap	1.00E-03	m
a =	1.09E+06	
b =	1.18E+04	
c =	-183455	
Superficial Velocity	4.04E-01	m/sec
Water Stop Effectiveness	1	
Volumetric Flow Rate	2.39E-03	m ³ /sec
Volumetric Flow Rate	3.79E+01	gpm

PROJECT NO.: 9904500.54 CALC. NO.: 001 REVISION NO.: 0 SHEET NO.: 1
 PREPARED BY: C. M. CONSELMAN DATE: 11/11/99 REVIEWED BY: N/A DATE: _____

HAND CALCULATION VALIDATING MODEL CALCULATIONS

$$V_1 = \sqrt{2gH_1} = \sqrt{2(9.81)4.46} = 9.35 \text{ m/sec}$$

$$V_2 = \sqrt{V_1^2 - \frac{2U}{m}} = \sqrt{9.35^2 - \frac{2(36,000)}{26,710}} = 9.20 \text{ m/sec}$$

$$V_3 = \sqrt{V_0^2 e^{\frac{-1k}{m}(h-z)} - \frac{pgV_0}{k} \left(1 - e^{\frac{-1k}{m}(h-z)}\right) + \frac{mg}{k} \left(1 - e^{\frac{-1k}{m}(h-z)}\right)}$$

$$V_3 = \sqrt{9.20^2 e^{\frac{-1(747.85)}{30,024}(4.76-0)} - \frac{1000(9.81)4.9128}{747.85} \left(1 - e^{\frac{-1(747.85)}{30,024}(4.76-0)}\right) + \frac{30,024(9.81)}{747.84} \left(1 - e^{\frac{-1(747.85)}{30,024}(4.76-0)}\right)}$$

$$V_3 = 11.68 \text{ m/sec}$$

$$KE_1 = \frac{1}{2} m V_3^2 = \frac{1}{2} (30,024) 11.68^2 = 2,047,503 \text{ NT-M}$$

$$KE_f = KE_1 - U_{\text{IMPACT LIMITED}} - U_{\text{BOTTOM PLATE}} = 2,047,503 - 270,000 - 10,000$$

$$KE_f = 1,757,503 \text{ NT-M}$$

PROJECT No.: 9904500.54 CALC. No.: 001 REVISION No.: φ SHEET No.: 2
 PREPARED BY: C.M. CONSELMAN DATE: 11/11/99 REVIEWED BY: N/A DATE: _____

$$U = \frac{-b + \sqrt{b^2 - 4ac}}{2a} = \frac{-1.18 \times 10^4 + \sqrt{1.18 \times 10^4 - 4(1.09 \times 10^6)} - 183,455}{2(1.09 \times 10^6)}$$

$$U = 0.404 \text{ m/sec}$$

$$Q = AV = dp UF = \left(\frac{1.0}{1000}\right) 5.9 (0.404) 1.0$$

$$Q = 2.39 \times 10^{-3} \text{ m}^3/\text{sec} = 37.9 \text{ GPM}$$