Reassessment of Heavy Loads

The staff has revisited NUREG-0612 ("Control of Heavy Loads at Nuclear Power Plants") and identified two additional sources of information:

(1) 1990s Navy crane experiences for the period 1996 through mid-1999, and

(2) WIPP/WID-96-2196, "Waste Isolation Pilot Plant Trudock Crane System Analysis," October 1996 (WIPP).

The 1990s Navy data encompassed primarily bridge cranes with lift capacities of 20,000 lb. to 350,000 lb., at both shipyards and non-shipyard sites. The data is summarized in Table 1 by accident type and accident cause. Improper operation caused 38% of the events, improper rigging 30%, procedures 20%, equipment failures 5%, and other causes 8%. Improper rigging was further divided into two parts: (1) 70% were identified as rigging errors and (b) 30% were rigging-related failures resulting from the crane operation. Reported load drops occurred in 9% of the accidents, 3% related to the crane and its operation and 6% to improper rigging. The fault tree used to assess a heavy load drop leading to a loss-of-inventory is shown in Figure 1. Table 1 includes the grouping of the accidents type for use in the fault tree requantification.

Based on the July 1999 SFP workshop, it will be assumed that there will be a maximum of 100 cask lifts per year. Using the new 1990s Navy database, for 100 lifts, 3 lifts may lead to a load drop for the evaluation of the "failure of crane" event (CF). Using the new Navy database, for 100 lifts, 6 lifts may lead to a load drop for the evaluation of the "failure due to improper rigging" event (CR). In NUREG-0612, based on 200 lifts per year, the range of lifts leading to a load drop was estimated to be 10 to 4 (5% to 2%).

The handling system failure rate was estimated in NUREG-0612 to be in the range of 1.5×10^{-4} to 1.0×10^{-5} per year (mean value of 8.0×10^{-5} per year) based on the 1970s Navy crane incident data and a staff estimate of the number of lifts per year. The staff's evaluation included a factor of 0.5 reduction for the estimates range of drops per lift based on improved procedures and conformance with the guidelines presented in Section 5.1.1 of NUREG-0612. The 1990s Navy data identified about twice as many events over the same time span. It will be assumed that the number of lifts per year has doubled and therefore the same handling system failure rate range will be used in this assessment. Failure of the lifting equipment and failure to secure the load are addressed seperately.

Failure of Lifting the Equipment

The only available fault tree (Figure 1) describing the failure of a crane comes from NUREG-0612, and the staff's previous evaluation is summarized in Table 2. (Note: The WIPP report does contain fault trees but they are illegible. The Trudock crane appears to be a non-single failure proof handling system.) It is noted that the dominant contributor to the "Failure

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of crane" is the "Failure due to random component failure," with a backup component, event CF2.

The same fault tree has been requantified using the new Navy data (from Table 1), as shown in Table 3. It is again noted that the dominant contributor to failure is the "Failure due to random component failure," with a backup component, event CF2. In this requantification, improper rigging was evaluated using the NUREG-0612 method.

A comparison of Table 2 to Table 3 shows, with some minor differences, that the 1980 evaluation (NUREG-0612) and the 1999 evaluation (new Navy data) results are about the same. The crane failure component for a single-failure proof handing system leading to a load drop (mean value) is 4.3×10^{-5} per year for the 1980 data and 1.5×10^{-5} per year for the 1999 data. Based on Tables 2 and 3, the estimate of the crane failure component for a non-single-failure proof handling system's failure leading to a load drop (mean value) is 7.2×10^{-4} per year for the 1980 data and 5.9×10^{-4} per year for the 1999 data. Using the NUREG -0612 method, a single-failure proof handling system reduces the crane failure component for a drop by an order of magnitude (a reduction factor of about 20 to 40).

Failure to Secure the Load

The second cause of a dropped load is failure of the load rigging. In NUREG-0612 (see Table 2), this was estimated to be 2.6×10^{-5} to 1.4×10^{-7} per year (mean value 1.3×10^{-5} per year). The 1970s Navy data indicated that about 7% of failures (drops) were from improper rigging. The 1990s Navy data indicates that 21% of failures are from improper rigging. The total drop rate remains about the same but the apportionment between the crane and the rigging drop rates are different. The 1999 data results (see Table 3) in an improper rigging drop rate (mean value) estimate of 2.4×10^{-5} per year, based on the NUREG-0612 method.

The improper rigging evaluation as presented in NUREG-0612 may be overly conservative and a literature search performed by the staff identified a study (WIPP report) which included a human error evaluation for improper rigging. This study was used to re-evaluate the contribution of rigging errors to the overall heavy load (cask) drop rate.

Failure to secure a load was evaluated in the Trudock (WIPP) report. It was determined that failure to attach the load to the lifting mechanism, considering two trained personnel, numerous feedbacks and verifications, was incredible. The more probable human error was for attaching the lifting legs to the lifting fixture using locking pins. In the Appendix 4 of the WIPP report, the failure to secure the load (based on a 2-out-of-3 lifting device) was estimated (a mean point estimate) based on redundancy, procedures and a checker. It was assumed that the load could be lowered without damage if only one of the three connections was not properly made. Using NUREG/CR-1278 information, the mean failure was estimated in the WIPP report to be 8.7×10^{-7} per lift, similar to lower bound value of 7.0×10^{-7} per lift in NUREG-0612. The requantification of the fault tree using the WIPP improper rigging failure rate is shown in Table 4. The WIPP evaluation, including the human error probabilities, is summarized in Table 5.

Summary

Current studies for the failure of a crane are dominated by the "Failure due to random component failure," with a backup component, event CF2 in the fault trees summarized in Tables 2, 3 and 4. The staff evaluation, based on the 1990s Navy crane data with the WIPP improper rigging evaluation, as shown in Table 4 provides the basis for developing the estimate of a loss-of-inventory from a heavy load (cask) drop into a decommission plant's spent fuel pool.

The estimated mean value for a load drop is $2.0.x10^{-5}$ per year for 100 lifts. The mean crane failure contribution is $1.5x10^{-5}$ per year for 100 lifts, with the operator-related contribution estimated to be $3.2x10^{-7}$ per year (CF1 + CF3) for 100 lifts. The mean improper rigging contribution is $5.3x10^{-6}$ per year for 100 lifts (CR).

Crane operation errors and rigging errors (CF1, CF3 and CR) are secondary contributors based on the current studies, accounting for about 10% of the overall frequency of a heavy load (cask) drop.

The purpose of the WIPP reevaluating of NUREG-0612 was to estimate the crane cable/hook failure contribution to the overall failure of the crane. It was determined that this contribution was less than the $2.0x10^{-5}$ per demand value used in NUREG-0612 and a value of $2.5x10^{-6}$ per demand was used in that study. It was further stated in the WIPP report that "there appears to be sufficient evidence to demonstrate that the design conservatism and operating environments associated with the WIPP cranes is much better than that of the Navy cranes which formed the databases for the NUREG-0612 analysis. However, the impact of this evidence is extremely difficult to quantity and no additional credit has been taken for this potential improvement."

The mean frequency of a crane cable/hook failure (a component without a secondary device, event CF4) was estimated in NUREG-0612 to be $1.8x10^{-6}$ per year (Table 2). This estimate was based on conformance with NUREG-0554 ("Single-Failure-Proof Cranes for Nuclear Power Plants") and included a reduction by a factor of 10 based on the expected increase in design safety factors to reduce the failure probability. It is noted that the 1990s Navy data supports the NUREG-0612 estimate of 1-in-44 events being the result of equipment failure (2% versus about 1% for the 1990s Navy data). Using the 1990s Navy data and 100 lifts per year, this mean frequency is estimated to be $3.6x10^{-7}$ per year (Table 4).

Load Path

At this point the path of the lift, and the portion of the path interval over which significant damage is likely to occur given a cask drop, needs to be factored into an overall estimate of a loss-of-inventory.

The load path assessment is plant specific. In NUREG-0612 it was estimated that the heavy load was near, or over, the spent fuel pool for between 25% and 5% of the total path needed to lift, move and set down the load. It was further estimated that if the load were dropped over 25% and 10% of that each respective path length, a release could occur. Therefore a heavy load (cask) drop over between 6.25% and 0.5% of the path length could result in a loss-of-inventory. If the cask is dropped from its maximum height it is felt likely that, without a specific load drop analysis, damage to the pool floor could occur resulting a loss-of-inventory. If the cask is dropped on the pool wall, there is a 10% likelihood that damage to the wall could result in a loss-of-inventory.

For a single-failure proof handling system, the probability of a loss-of-inventory (mean value) is 3.5×10^{-6} per year for the 1980 data and 2.4×10^{-6} for the 1999 data.

Conclusion

This reassessment has determined that, based on available — although questionable as to its suitability to NSSS SFP handling systems — data, the drop per year values presented at the July 1999 SFP workshop are of the correct order of magnitude. Given uncertainties in load path characteristics, but assuming only 10% of the path to be critical to rapid pool draining, the likelihood of the rapid loss of inventory values presented in the workshop are also of the correct order of magnitude (absent a specific load drop evaluation to determine structural damage).

It is important to note that operator errors have been determined to be of secondary importance and component failures dominate the current risk estimates.

The drops per lift range is estimated to be on the order of 1.0×10^{-4} to 1.0×10^{-5} per lift. This range was used in the NUREG-0612 evaluation and is supported by the Savannah River report. There have been about 150 casks loaded for dry storage at commercial reactor sites in the past 14 years. Point estimates of failure rates may be calculated with the following equation for those events not observed (zero occurrence - no drops or any other reportable event) in C number of components (lifts) for T years:

$$\lambda_{95\%\ \text{confidence limit}} = 3.0/(C \times T)$$

For the current experience base, $\lambda_{95\%} = 7.0 \times 10^{-4}$ per year (assuming each cask load requires two lifts). At the 50% confidence limit, $\lambda_{50\%} = 1.6 \times 10^{-4}$ per year.

The dominate contributor is the "Failure due to random component failure," with a backup component, event CF2, combined with the conditional failure of the backup component given the failure of a component with a backup in the range of 0.1 to 0.01. If the upper and lower bound estimate for this conditional failure are reduced by a factor of 10, and if the failure of a component without a secondary device (event CF4) is also reduced by a factor of 10, and if operator errors are not considered, the mean crane failure rate is reduced from about 4.0×10^{-5} to 4.0×10^{-6} per year, with a range of 8.6×10^{-6} to 7.6×10^{-8} per year. The overall mean drop rate (including rigging failure, with a mean value of 5.0×10^{-6} per year) would be reduced from 4.5×10^{-5} to about 1.0×10^{-5} per year.

Recommendation

This generic assessment of a heavy load (cask) drop which may result in significant damage to the spent fuel pool indicates that the likelihood of the uncovery of spent fuel is on the order of $1.0x10^{-6}$ per year, given 100 lifts per year and 1-in-10 drops results in significant damage to the spent fuel pool. A heavy load (shipping cask) drop leading to the uncovery of spent fuel in a decommissioning plant's spent fuel pool appears to be a credible event, even for a plant with a single-failure proof handling system. A segregated cask transfer area, a plant specific load drop analysis confirming acceptable consequences, or a load drop limiter (for example, cask crash pads) would most likely demonstrate that the heavy loads event need not be considered as a significant contributor to the risk.

The guidelines for the control of heavy loads, Section 5 of NUREG-0612, should be followed for a decommissioning plant. Specifically, if a detailed evaluation of the specific plant heavy load handling system cannot be shown to be significantly better than the generic assessment described above, a plant specific load drop analysis should be performed to demonstrate Item III of Section 5.1 of NUREG-0612, "Damage to the reactor vessel or the spent fuel pool based on calculations of damage following accidental dropping of a postulated heavy load is limited so as not to result in water leakage that could uncover the fuel, (makeup water provided to overcome leakage should be from a borated source of adequate concentration if the water being lost is borated); ..." Alternatively, mitigation of damage with load impact limiters (for example, cask crush pads) to reduce the likelihood of the uncovery of spent fuel should be considered, as appropriate, on a plant specific basis.

In the staff's evaluation of heavy loads presented in NUREG-0612, one of the underlying assumptions was that between 42 and 74 days was a safe decay time if a full core were damaged (Ref: NUREG-0612, page B-1) — negligible release of radioactivity. Therefore an 0.1 to 0.2 multiplier (38 to 72 days out of 365 days per year) was included in the assessment to estimate the per year frequency of a release exceeding the guidelines. This multiplier is no longer applicable with high density storage racks in a spent fuel pool. It is appropriate to reconsider the acceptance of a single-failure proof without a load drop analysis for a decommissioning plant since the NUREG-0612 evaluation would show a log-mean value of $2.0x10^{-6}$ per year of exceeding the release guidelines. The mean value would be $5.0x10^{-5}$ per year.

Table 1 - Summary of Navy crane data (1996 through mid-1999)

Event	Percent of events	Cause	Percent of event by cause
Dropped load	9	Equipment	33
		Improper rigging	66
Overload	12	Improper operation	25
		Improper rigging	38
		Procedure	37
Crane collision	17	Improper operation	46
		Procedure	18
		Other	27
Damage crane	27	Improper operation	50
		Improper rigging	28
		Procedure	22
Damage load	5	Equipment	33
		Improper rigging	67
Load collision	14	Improper operation	56
		Improper rigging	22
		Procedure	11
		Other	11
Personnel injury	8	Improper operation	20
		Improper rigging	60
		Procedure	20
Two-blocking	5	Improper operation	67
		Procedure	33
Other	3	Improper operation	33
		Improper rigging	33

		Procedure	33

Table 2 - NUREG-0612 Failure of crane (from Figure B-3, sheet 2(a))

Event	Description	Units	High	Low	Mean(1)	LogMean(2)
CF11	Operator error leading to load hangup	/Year	7.0e-05	2.0e-06	3.6e-05	1.2e-05
CF12	Failure of the overload device	/demand	1.0e-02	1.0e-03		
CF1	Load hangup event (CF11 and CF12)	/Year	7.0e-07	2.0e-09	3.5e-07	3.7e-08
CF21	Failure of single component with a backup	/Year	8.0e-04	2.0e-05	4.1e-04	1.3e-04
CF22	Failure of backup component given CF21	/demand	1.0e-01	1.0e-02		
CF2	Failure due to random component failure (CF21 and CF22)	/Year	8.0e-05	2.0e-07	4.0e-05	4.0e-06
CF31	Operator error leading to Two-blocking	/Year	5.0e-04	1.0e-05	2.6e-04	7.1e-05
CF32	Failure of lower limit switch	/demand	1.0e-02	1.0e-03		
CF33	Failure of upper limit switch	/demand	1.0e-01	1.0e-02		
CF3	Two-blocking event (CF31 and CF32 and CF33)	/Year	5.0e-07	1.0e-10	2.5e-07	7.1e-09
CF4	Failure of component that doesn't have backup	/Year	3.0e-06	9.0e-08	1.5e-06	5.2e-07
CF	Failure of crane (CF1 or CF2 or CF3 or CF4)	/Year	8.4e-05	2.9e-07	4.2e-05	5.0e-06

(1) - (High + Low)/2
(2) - $\exp^{((\ln(high) + \ln(low)) / 2)}$

Table 3 - WIPP Failure of crane (from WIPP/WID-96-2196, Appendix A5)

Event	Description	Units	High	Low	Mean[1]	LogMean[2]
CF11	Operator error leading to load hangup	/lift	7.0e-06	4.7e-07	3.7e-06	1.8e-06
CF12	Failure of the overload device	/demand	1.0e-02	1.0e-03		
CF1	Load hangup event (CF11 and CF12)	/lift	7.0e-08	4.7e-10	3.5e-08	5.7e-09
CF21[3]	Failure of single component with a backup	/lift	8.0e-05	5.3e-06	4.3e-05	2.1e-05
CF22	Failure of backup component given CF21	/demand	1.0e-01	1.0e-02		
CF2	Failure due to random component failure (CF21 and CF22)	/lift	8.0e-06	5.3e-08	4.0e-06	6.5e-07
CF31	Operator error leading to Two-blocking	/lift	5.2e-05	3.5e-06	2.8e-05	1.3e-05
CF32	Failure of lower limit switch	/demand	1.0e-02	1.0e-03		
CF33	Failure of upper limit switch	/demand	1.0e-01	1.0e-02		
CF3	Two-blocking event (CF31 and CF32 and CF33)	/lift	5.2e-08	3.5e-11	2.6e-08	1.3e-09
CF4[4]	Failure of component that doesn't have backup	/lift	3.4e-07	2.3e-08	1.8e-07	8.8e-08
CF	Failure of crane (CF1 or CF2 or CF3 or CF4)	/lift	8.5e-06	7.7e-08	4.3e-06	8.0e-07

(1) - (High + Low)/2

(2) - $\exp^{((\ln(\text{high}) + \ln(\text{low}))/2)}$

(3) - Based on 1970s Navy data, about 50% of incidents resulted from random material failure, personnel errors, design deficiencies, improper maintenance or inadequate inspection. The 1990s Navy data indicates about the same percentage.

(4) - After conformance with NUREG-0554 (Ref: NUREG-612, page B-11)

Table 4 - Failure of crane based on 100 lift per year (with Navy drop data 1-in-10 drops)

Event	Description	Units	High	Low	Mean(1)	LogMean(2)
CF11	Operator error leading to load hangup	/Year	7.0e-05	4.7e-06	3.7e-05	1.8e-05
CF12	Failure of the overload device	/demand	1.0e-02	1.0e-03		
CF1	Load hangup event (CF11 and CF12)	/Year	7.0e-07	4.7e-09	3.5e-07	5.7e-08
CF21	Failure of single component with a backup	/Year	8.0e-04	5.3e-05	4.3e-04	2.1e-04
CF22	Failure of backup component given CF21	/demand	1.0e-01	1.0e-02		
CF2	Failure due to random component failure (CF21 and CF22)	/Year	8.0e-05	5.3e-07	4.0e-05	6.5e-06
CF31	Operator error leading to Two-blocking	/Year	5.2e-04	3.5e-05	2.8e-04	1.3e-04
CF32	Failure of lower limit switch	/demand	1.0e-02	1.0e-03		
CF33	Failure of upper limit switch	/demand	1.0e-01	1.0e-02		
CF3	Two-blocking event (CF31 and CF32 and CF33)	/Year	5.2e-07	3.5e-10	2.6e-07	1.3e-08
CF4	Failure of component that doesn't have backup	/Year	3.4e-06	2.3e-07	1.8e-06	8.8e-07
CF	Failure of crane (CF1 or CF2 or CF3 or CF4)	/Year	8.5e-05	7.7e-07	4.3e-05	8.0e-06

(1) - (High + Low)/2
(2) - $\exp^{((\ln(high) + \ln(low)) / 2)}$

Table 5 - WIPP evaluation for failure to secure load (improper rigging estimate)

Symbol	HEP	Explanation of error	Source of HEP (NUREG/CR-1278)
A_1	$3.75x10^{-3}$	Improperly make a connection, including failure to test locking feature for engagement	Table 20-12 Item 13 Mean value (0.003, EF[(1)] = 3)
B_1	0.75	The operating repeating the actions is modeled to have a high dependency for making the same error again. It is not completely independent because the operator moves to the second lifting leg and must physically push the locking balls to insert the pins	Table 20-21 Item 4(a) High dependence for different pins. Two opportunities (the second and third pins) to repeat the error is modeled as 0.5+(1-0.5)*0.5 = 0.75
C_1	$1.25x10^{-3}$	Checker fails to verify proper insertion of the connector pins, and that the status affects safety when performing tasks	Table 20-22 Item 9 Mean value (0.001, EF = 3)
D_1	0.15	Checker fails to verify proper insertion of the connector pins at a later step, given the initial failure to recognize error. Sufficient separation in time and additional cues to warrant moderate rather than total or high dependency.	Table 20-21 Item 3(a) Moderate dependency for second check
F_1	$5.2x10^{-7}$	Failure rate if first pin improperly connected	$A_1 * B_1 * C_1 * D_1$
a_1	0.99625	Given first pin was improperly connected	
A_2	$3.75x10^{-3}$	Improperly make a connection, including failure to test locking feature for engagement	Table 20-12 Item 13 Mean value (0.003, EF = 3)
B_2	0.5	The operating repeating the actions is modeled to have a high dependency for making the same error again. It is not completely independent because the operator moves to the second lifting leg and must physically push the locking balls to insert the pins	Table 20-21 Item 4(a) High dependence for different pins. Only one opportunity for error (third pin)
C_2	$1.25x10^{-3}$	Checker fails to verify proper insertion of the connector pins, and that the status affects safety when performing tasks	Table 20-22 Item 9 Mean value (0.001, EF = 3)
D_2	0.15	Checker fails to verify proper insertion of the connector pins at a later step, given the initial failure to recognize error. Sufficient separation in time and additional cues to warrant moderate rather than total or high dependency.	Table 20-21 Item 3(a) Moderate dependency for second check
F_2	$3.5x10^{-7}$	Failure rate if first pin improperly connected	$a_1 * A_2 * B_2 * C_2 * D_2$
F_T	$8.7x10^{-7}$	Total failure due to human error	F1 + F2

(1) Note: The EF (error factor) is the 95^{th} percentile/50^{th} percentile (median). For an EF of 3, the mean-to-median multiplier is 0.8.