Appendix 5

Structural Integrity of Spent Fuel Pool Structures Subject to Heavy Loads Drops

A heavy load drop into the spent fuel pool, or onto the spent fuel pool wall, can affect the structural integrity of the spent fuel pool. A loss-of-inventory from the spent fuel pool could occur as a result of a heavy load drop. Heavy loads were evaluated by the staff as Generic Technical Activity A-36, which resulted in the publication of NUREG-0612, "Control of Heavy Loads at Nuclear Power Plants," U.S. Nuclear Regulatory Commission, July 1980. Cask handling is expected to be the dominate heavy load operation at a decommissioning plant.

The staff has revisited NUREG-0612 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 are summarized in Table 1 by incident type and incident 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: (a) 70% were identified as rigging errors and (b) 30% were rigging-related failures resulting from the crane operation. Reported load drops occurred in about 9% of the accidents, 3% related to the crane and its operation and 6% to improper rigging. The fault trees used to assess a heavy load drop leading to a loss-of-inventory are shown in Figure 1. Table 1 includes the grouping of the incidents type for use in the fault tree quantification.

Based on the July 1999 SFP workshop, it was assumed that there will be a maximum of 100 cask lifts per year. Using the new 1990s Navy database, for 100 lifts, about 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, about 6 lifts may lead to a load drop for the evaluation of the "failure of rigging" event (CR). In NUREG-0612, which was based on 200 lifts per year, the range of lifts leading to a load drop was estimated by the staff to be between 10 and 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} incidents per year based on the 1970s Navy crane incident data and a staff estimate of the total number of lifts per year. The staff's evaluation included a factor of 0.5 reduction for the estimates range 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 incidents over the same time span. It was assumed that the estimated number of lifts per year has about doubled and therefore the same handling system failure rate range was used in this assessment. Failure of the lifting equipment and failure to secure the load are addressed separately.

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The base data used in this evaluation considered a range of values comprised of a high estimate and a low estimate to represent an initiator rate or a demand rate. The method used to describe the result was based on the geometric mean of these ends points — the likelihood of being higher or lower than the geometric mean is equal, and is the median value for the range. For example, the median value for the handling system failure rate would be computed as 3.9×10^{-5} incidents per year. As a results of the uncertainties in the base data, the possibility of interdependencies of conditional failure (demand) rates, and their confidence limits, this median value was used for this evaluation.

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 quantification of the fault tree is summarized in Table 2. Table 2 presents the results for a release fraction of 1.0. When heavy loads were evaluated in NUREG-0612, low density storage racks were in use and after 30 to 70 days no release was expected (gap noble gas inventory decayed and no zircaloy fire). Table 2 represents the "Releases exceed guidelines due to loads handled over spent fuel," event 3.1(A) branch of Figure B-3 in NUREG-0612. The companion branch, "Releases exceed guidelines due to loads handled near spent fuel," event 3.1(B) branch was not considered in this evaluation for cask handling. (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 of crane" is the "failure due to random component failure," for a primary component with a backup component, event CF2.

The same fault tree was re-quantified using the new Navy data (from Table 1), as summarized in Table 3. It is again noted that the dominant contributor to failure is the "failure due to random component failure," for a primary component with a backup component, event CF2. In this re-quantification, 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 (CRANE) for a single-failure proof handing system (median value) was estimated to be 7.5×10^{-7} per year for the 1980 data and 8.2×10^{-7} per year for the 1999 data.

The purpose of the WIPP evaluating 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 2.0×10^{-5} per demand value used in the preliminary WIPP report. A value of 2.5×10^{-6} per demand was used in the final WIPP report. 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 median failure frequency of a component without a secondary device (for example, a crane cable/hook failure) was estimated in NUREG-0612 to be 8.8×10^{-7} per demand (based on Table 2, event CF4). This estimate was further reduced by the staff, based on conformance with NUREG-0554 ("Single-Failure Proof Cranes for Nuclear Power Plants") and based on the expected increase in design safety factors to reduce the failure probability, by an additional factor of 10. 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, this median frequency was estimated to be 5.8×10^{-8} per year (Table 3, CF4), as compared to the NUREG-0612 median of 8.8×10^{-8} per year (Table 2, CF4).

Failure to Secure the Load

The second cause of a dropped load is failure of the load rigging. In NUREG-0612 (see Table 2, RIGGING), the median failure of the rigging was estimated to be 3.0×10^{-7} 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 were from improper rigging. The total handling system failure rate (crane plus rigging) remains about the same but the apportionment between the crane and the rigging drop rates are different. The 1999 (see Table 3) evaluation resulted in an improper rigging median failure rate estimate of 9.2×10^{-7} per year, based on the NUREG-0612 method.

The improper rigging evaluation as presented in NUREG-0612 may be overly conservative. In addition, the frequency of improper rigging incidents identified in the 1990s Navy data may not be representative of a single-failure proof load handling design which conforms to the guidelines in NUREG-0612. 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 WIPP report for the Trudock crane. 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 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 ("Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications," August 1983) information, the mean failure rate due to improper rigging was estimated in the WIPP report to be 8.7×10^{-7} per lift. The re-quantification of the fault tree using the WIPP improper rigging failure rate is summarized in Table 4. The WIPP evaluation for the human error probabilities is summarized in Table 5. The 1999 (see Table 4) evaluation resulted in an improper rigging median failure rate estimate of 8.7×10^{-7} per year, based on the WIPP method.

Drop Summary

Current studies for the failure of a crane are dominated by the "failure due to random component failure," for a primary component 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 summarized in Table 4, provides the basis for developing the estimate of a loss-of-inventory from a heavy load (cask) drop into a decommissioning plant's spent fuel pool.

The estimated median value for a load drop was 7.9×10^{-6} per year for 100 lifts (CFCR). The median crane failure contribution was 2.6×10^{-6} per year (CF) for 100 lifts, with the operator-related contribution estimated to be 5.2×10^{-8} per year (3 times (CF1 + CF3), Table 4) for 100 lifts. The median improper rigging contribution was estimated to be 5.3×10^{-6} per year for 100 lifts (CR).

Load Path

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% (event P in Tables 2, 3, and 4) 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% (event P' in Tables 2, 3 and 4) of each respective path length, a release could occur. If the cask is dropped from its maximum height (about 40 feet above the pool floor — with a range of between 30 feet to 36 feet) it is felt likely that, without a specific load drop analysis, damage to the pool floor could occur resulting in a loss-of-inventory. 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 on the pool wall (from a height of 6 to 10 inches above the wall), there is a 10% likelihood that damage to the wall could result in a loss-of-inventory based on Generic Safety Issue 82 studies (NUREG-1353, "Regulatory Analysis for the Resolution of Generic Issue 82, 'Beyond Design Basis Accidents in Spent Fuel Pools').

Loss-of-Inventory

For a single-failure proof handling system, the median probability of a loss-of-inventory was estimated to be 1.2×10^{-7} per year for 200 lifts based on the 1980 evaluation presented in NUREG-0612 (Table 2, LOI-S). The range was estimated to be between 6.9×10^{-6} to 2.2×10^{-9} per year.

Based on the 1990s Navy data for evaluating crane failures and the WIPP method for evaluating improper rigging, the median probability of a loss-of-inventory was estimated to be 2.4×10^{-7} per year for 100 lifts for a single-failure proof handling system (Table 4, LOI-S). The range was estimated to be between 2.1×10^{-6} to 2.8×10^{-8} per year. Using the NUREG-0612 rigging method (Table 3), the range was estimated to be between 4.8×10^{-6} to 4.4×10^{-9} per year.

For a non-single-failure proof handling system, the median probability of a loss-of-inventory was estimated based on NUREG-0612. In NUREG-0612, an alternate fault tree (Figure B-2, page B-16) was used to estimate the probability of exceeding the release guidelines (loss-of-inventory) for a non-single failure proof system. The median value was estimated to be about 2.7×10^{-6} per year (event 2.1.1) when corrected for the new Navy data and 100 lifts per year (Table 4, LOI-N). The range was estimated to be between 7.5×10^{-5} to 1.0×10^{-7} per year.

Incident Rate

The incidents per year range was estimated to be on the order of 1.5×10^{-4} to 1.0×10^{-5} incidents per year. This range was used in the NUREG-0612 evaluation. There have been about 150 casks loaded for dry storage at commercial reactor sites (LWRs) in the past 14 years. There have been about 250 cask loaded at the Fort St. Vrain gas-cooled reactor site (GCR). There have been no reportable incidents related to heavy loads per 10CFR 72.75, "Reporting requirements for special events and conditions."

Point estimates of the incident rate may be calculated with the following equations for those events not observed (zero occurrence — no drops or any other reportable event) in C number of components (lifts) for T years:

$$\lambda_{95\%\ \text{confidence limit}} = 3.0/(C \times T) \text{ incidents per year}$$
$$\lambda_{50\%\ \text{confidence limit}} = 0.69/(C \times T) \text{ incidents per year}$$

For the current experience base for LWRs, $\lambda_{95\%} = 7.1 \times 10^{-4}$ incidents per year (assuming each cask load requires two lifts). At the 50% confidence limit, $\lambda_{50\%} = 1.6 \times 10^{-4}$ incidents per year. If the GCR data is considered and added to the LWRs data, then $\lambda_{95\%} = 2.7 \times 10^{-4}$ incidents per year and $\lambda_{50\%} = 6.2 \times 10^{-5}$ incidents per year. The cask handling data indicates that the incident rate range used in this assessment is reasonable, 1.5×10^{-4} to 1.0×10^{-5} compared to the $\lambda_{50\%}$ range of 1.6×10^{-4} to 6.2×10^{-5} per year.

The dominate contributor to a heavy load drop is the "failure due to random component failure," for a primary component with a backup component, event CF2, when combined with a conditional failure rate of the backup component given the failure of the primary component in the range of 0.1 to 0.01 per demand (CF22). If the upper and lower bound estimate for this conditional failure were reduced by a factor of 10 (either better quality backup components or an additional, second backup component), and if the failure of a component without a secondary device (event CF4) was also reduced by an additional factor of 10, and if operator errors were not considered (events CF1 and CF3), the median crane failure rate would be reduced from about 8.2×10^{-7} to 5.8×10^{-9} per year. The overall median failure rate (including rigging failure, with a median value of 8.7×10^{-7} per year) would be reduced from 1.7×10^{-6} to 8.8×10^{-7} per year. The median probability of a loss-of-inventory, based on the load path estimates from NUREG-0612, would be reduced to 9.4×10^{-8} per year for 100 lifts, from 2.4×10^{-7} per year for 100 lifts.

Summary of Other Heavy Load Drop Studies

Heavy load drops were evaluated as part of Generic Safety Issue 82. In NUREG/CR-4982 ("Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82) the total human error rate associated with cask movement was estimated to be 6.0×10^{-4} incidents per lift. It was further assumed that only 1-in-100 human errors would result in a cask drop. It was also estimated that the cask was above the pool edge (wall) about 25% of the lift time. Based on two shipment per week with two lifts per shipment (208 lifts), the estimate for a load drop on the spent fuel pool wall was 3.1×10^{-4} per year. Damage to the pool wall sufficient to cause a loss-of-inventory was further estimated to have a 1-in-10 probability, for an estimate of a loss-of-inventory from a heavy load drop on the spent fuel pool wall of 3.1×10^{-5} per year (for a non-single-failure proof handling system). Based on 100 lifts per year, the NUREG/CR-4982 evaluation would estimate the loss-of-inventory from a heavy load drop on the spent fuel pool wall to be about 1.5×10^{-5} per year (for a non-single-failure proof handling system).

In NUREG-1353, conformance with NUREG-0612 was estimated to reduce the probability of a load drop as presented in NUREG/CR-4982 by a factor of 1,000. Based on Table 2, the fault tree method indicated that the expected reduction was in the 10 to 100 range. For 100 lifts per year, the NUREG/CR-4982 evaluation would estimate the loss-of-inventory from a heavy load drop on the pool wall to be 1.5×10^{-8} per year. This value should be increased by a factor of 10, to 1.5×10^{-7} per year, for use for comparison to this current evaluation for a load drop on the pool floor (a drop onto the pool floor may likely cause sufficient damage to result in a loss-of-inventory). Based on the fault tree quantification (Table 4), the median probability for the loss-of-inventory from a heavy load drop was estimated to be 2.4×10^{-7} per year for 100 lifts (for a single-failure proof handling system).

Conclusion

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 a loss-of-inventory from the spent fuel pool is in the range of 2.1×10^{-6} to 2.8×10^{-8} per year for 100 lifts, with a median value of 2.4×10^{-7} per year. A heavy load (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 uncertainties is this evaluation include:

(1) Incident rate. The range used in this evaluation (1.5×10^{-4} to 1.0×10^{-4} incidents per year) was based on the Navy data originally assessed by the staff in NUREG-0612. The 1999 Navy data, like the 1980 data, did not include the number of lifts made and only provided information about the number of incidents. The cask loading experience at LWRs and the GCR tends to support use of the incident range.

(2) Drop rate. The drop rate, about 1-in-10, was based on the 1999 Navy data. Previous studies used engineering judgement to estimate the drop rate to be as low as 1-in-100.

(3) Load path. The load path fraction over which a load drop may cause sufficient damage to the spent fuel pool to result in a loss-of-inventory was estimated to be between 6.25% and 0.5% of the total path needed to lift, move and set down the load. This range was developed by the staff for the NUREG-0612 evaluation.

(4) Load handling design. The benefit of a single-failure proof load handing system to reduce the probability of a load drop was estimated to be about a factor of 10 to 100 improvement over a non-single-failure proof load handling system, based on the fault

tree quantifications in this evaluation. Previous studies have used engineering judgement to estimate the benefit to be as high as 1,000.

The guidelines for the control of heavy loads, Section 5 of NUREG-0612, should be followed for a decommissioning plant. Specifically, if a decommission plant does not have a single-failure proof handling system then 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.

A sensitivity evaluation was performed assuming no interdependencies in the base data. The results are shown in Table 6. The loss-of-inventory range remains the same, $2.1x10^{-6}$ to $2.8x10^{-8}$ per year. A mean value for a loss-of-inventory, assuming no interdependencies in the base data, was estimated to be $5.2x10^{-7}$ per year. The median value for a loss-of-inventory, assuming no interdependencies in the base data, was estimated to be $2.5x10^{-7}$ per year.

A comparison of the four fault tree quantifications (Tables 2,3,4 and 6) is provided in Figure 2. Note that the results for the new Navy data with the WIPP rigging model differ because the rigging model used a single median estimate for the contribution from rigging to a loss-of-inventory from a heavy load (cask) drop.

Table 1 - Summary of the 1996-1999 Navy crane data

		ID	Non-rigging Fraction	Rigging Fraction	Total Traction
	Summary by Incident Type (fraction of events)				
	Crane collision	CC	0.17	0.00	0.17
	Damaged crane	DC	0.20	0.08	0.27
	Damaged load	DL	0.02	0.03	0.05
	Dropped load	DD	0.03	0.06	0.09
	Load collision	LC	0.11	0.03	0.14
	Other	OO	0.02	0.00	0.02
	Overload	OL	0.08	0.05	0.12
	Personnel injury	PI	0.03	0.05	0.08
	Shock	SK	0.00	0.02	0.02
	Two-blocking	TB	0.05	0.00	0.05
	Unidentified	UD	0.02	0.00	0.02
	Totals		0.70	0.30	1.00
	Summary by Incident Cause (fraction of total events)	ID	Fraction		
	Improper operation	IO	0.38		
	Procedures	PROC	0.20		
	Equipment failure	EQ	0.05		
	Improper rigging(1)	IR	0.30		
	Others	OTHER	0.08		
	Totals		1.00		
Fault Tree ID(2)	**Application of new Navy data to heavy load drop evaluation**	Fraction		NUREG-0612 Fraction	
F1	OL + 0.5*(DL+LC)	0.14		0.05	
F2	CC + DC + 0.5(DL+LC) + DD + OO + PI + SK + UD + 0.3*IR	0.61		0.53	
F3	TB	0.05		0.35	
F4	Assume next incident	(0.01)		(1/44)	
F5	Rigging 0.7*IR	0.21		0.07	
	Totals	1.00		1.00	

Notes:

(1) Based on database description, 30% or "improper rigging" by incident cause were rigging failures during crane movement, and 70% of "improper rigging" by incident cause were rigging errors.

(2) F1 - Load hangup resulting from operator error (assume 50% of "damaged load" and "load collision" lead to hangup)
F2 - Failure of component with a backup component (assume 50% of "damaged load" and "load collision" lead to component failure)
F3 - Two-blocking event
F4 - Failure of component without a backup
F5 - Failure from improper rigging

Table 2 - Summary of NUREG-0612 heavy loads evaluation (for cask drop) with NUREG-0612 original values and 1.0 release fraction

Event	Description	Units	High	Low	Median
N0	Base range of failure of handling system	/year	1.5E-04	1.0E-05	3.9E-05
	Crane Failure				
F1	Fraction of load hangup events (2/43 1970s Navy data)	---	0.05	0.05	
CF11	Operator error leading to load hangup (N0*F1))	/year	7.0E-06	4.7E-07	
CF12	Failure of the overload device	/demand	1.0E-02	1.0E-03	
CF1	Load hangup event (CF11*CF12)	/year	7.0E-08	4.7E-10	5.7E-09
F2	Fraction of component failure events (23/43 1970s Navy data)	---	0.53	0.53	
CF21	Failure of single component with a backup (N0*F2)	/year	8.0E-05	5.3E-06	
CF22	Failure of backup component given CF21	/demand	1.0E-01	1.0E-02	
CF2	Failure due to random component failure (CF21*CF22)	/year	8.0E-06	5.3E-08	6.6E-07
F3	Fraction of two-blocking events (15/43 1970s Navy data)	---	0.35	0.35	
CF31	Operator error leading to Two-blocking (N0*F3)	/year	5.2E-05	3.5E-06	
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*CF32*CF33)	/year	5.2E-08	3.5E-11	1.4E-09
F4	Fraction of single component failure (1/44 1970s Navy data)	---	0.02	0.02	
F4'	Credit for NUREG-0554	/demand	0.10	0.10	
CF4	Failure of component that doesn't have backup (N0*F4*F4')	/year	3.4E-07	2.3E-08	8.8E-08
CRANE	**Failure of crane (CF1+CF2+CF3+CF4)**	**/year**	**8.5E-06**	**7.7E-08**	**7.5E-07**
D1	Lifts per year leading to drop (200 lifts per year, 5% to 2% are dropped)	No.	10	4	7
CF	**Failure of crane leading to load drop (CRANE*D1)**	/year	**8.5E-05**	**3.1E-07**	**5.1E-06**
	Rigging failure - Based on NUREG-0612 method				
F5	Fraction of improper rigging events (3/43 1970s Navy data)	---	0.07	0.07	
CR11	Failure due to improper rigging (N0*F5)	/year	1.0E-05	7.0E-07	2.7E-06
CR12	Failure of redundant/alternate rigging	/demand	0.25	0.05	
RIGGING	**Failure due to improper rigging (CR11*CR12)**	**/year**	**2.6E-06**	**3.5E-08**	**3.0E-07**
D2	Lifts per year leading to drop (200 lifts per year, 5% to 2% are dropped)	No.	10	4	7
CR	**Failure of rigging leading to a load drop (RIGGING*D2)**	**/year**	**2.6E-05**	**1.4E-07**	**1.9E-06**
FHSL	**Failure of heavy load (crane and rigging) system (CRANE+RIGGING)**	**/year**	**1.1E-05**	**1.1E-07**	**1.1E-06**
CFCR	**Total failures (crane and rigging) leading to a load drop (CF+CR)**	**/year**	**1.1E-04**	**4.5E-07**	**7.0E-06**
	Loss-of-inventory for a single-failure proof crane				
RF	Fraction of year over which a release may occur	---	1.00	1.00	1.00
P	Fraction of path near/over pool	---	0.25	0.05	0.11
P'	Fraction of path critical for load drop	---	0.25	0.10	0.16
LOI-S	**(CFCR) * P * P' * RF**	**/year**	**6.9E-06**	**2.2E-09**	**1.2E-07**
	Loss-of-inventory for a non single-failure proof crane				
CFCRNON	Failures leading to a dropped load (NUREG-0612 Fig B-2, Event 2.1.1)	No.	1.5E-04	2.0E-07	5.5E-06
RF	Fraction of year over which a release may occur (current configuration)	---	1.00	1.00	1.00
LOI-N	**(CFCRNON) * RF**	**/year**	**1.5E-04**	**2.0E-07**	**5.5E-06**
	Risk reduction for a single-failure proof crane (LOI-N /LOI-S)	---	**22**	**90**	

Table 3 - Summary of NUREG-0612 heavy loads evaluation (for cask drop) with new 1996-1999 Navy crane data values and NUREG-0612 rigging method

Event	Description	Units	High	Low	Median
N0	Base range of failure of handling system	/year	1.5E-04	1.0E-05	3.9E-05
	Crane Failure				
F1	Fraction of load hangup events (new 1990s Navy data)	---	0.14	0.14	
CF11	Operator error leading to load hangup (N0*F1))	/year	2.0E-05	1.4E-06	
CF12	Failure of the overload device	/demand	1.0E-02	1.0E-03	
CF1	Load hangup event (CF11*CF12)	/year	2.0E-07	1.4E-09	1.7E-08
F2	Fraction of component failure events (new 1990s Navy data)	---	0.61	0.61	
CF21	Failure of single component with a backup (N0*F2)	/year	9.1E-05	6.1E-06	
CF22	Failure of backup component given CF21	/demand	1.0E-01	1.0E-02	
CF2	Failure due to random component failure (CF21*CF22)	/year	9.1E-06	6.1E-08	7.4E-07
F3	Fraction of two-blocking events (new 1990s Navy data)	---	0.05	0.05	
CF31	Operator error leading to Two-blocking (N0*F3)	/year	6.8E-06	4.5E-07	
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*CF32*CF33)	/year	6.8E-09	4.5E-12	1.8E-10
F4	Fraction of single component failure (new 1990s Navy data)	---	0.01	0.01	
F4'	Credit for NUREG-0554	/demand	0.10	0.10	
CF4	Failure of component that doesn't have backup (N0*F4*F4')	/year	2.2E-07	1.5E-08	5.8E-08
CRANE	**Failure of crane (CF1+CF2+CF3+CF4)**	**/year**	**9.5E-06**	**7.7E-08**	**8.2E-07**
D1	Lifts per year leading to drop (100 lifts per year, drops from non-rigging)	No.	3	3	3
CF	**Failure of crane leading to load drop (CRANE*D1)**	/year	**2.9E-05**	**2.3E-07**	**2.6E-06**
	Rigging failure - Based on NUREG-0612 method				
F5	Fraction of improper rigging events (new 1990ss Navy data)	---	0.21	0.21	
CR11	Failure due to improper rigging (N0*F5)	/year	3.2E-05	2.1E-06	8.2E-06
CR12	Failure of redundant/alternate rigging	/demand	0.25	0.05	
RIGGING	**Failure due to improper rigging (CR11*CR12)**	**/year**	**8.0E-06**	**1.1E-07**	**9.2E-07**
D2	Lifts per year leading to drop (100 lifts per year, drops from rigging)	No.	6	6	6
CR	**Failure of rigging leading to a load drop (RIGGING*D2)**	**/year**	**4.8E-05**	**6.4E-07**	**5.6E-06**
FHSL	**Failure of heavy load (crane and rigging) system (CRANE+RIGGING)**	**/year**	**1.7E-05**	**1.8E-07**	**1.7E-06**
CFCR	**Total failures (crane and rigging) leading to a load drop (CF+CR)**	**/year**	**7.7E-05**	**8.8E-07**	**8.2E-06**
	Loss-of-inventory for a single-failure proof crane				
RF	Fraction of year over which a release may occur	---	1.00	1.00	1.00
P	Fraction of path near/over pool	---	0.25	0.05	0.11
P'	Fraction of path critical for load drop	---	0.25	0.10	0.16
LOI-S	**(CFCR) * P * P' * RF**	**/year**	**4.8E-06**	**4.4E-09**	**1.5E-07**
	Loss-of-inventory for a non single-failure proof crane				
CFCRNON	Failures leading to a dropped load (0.5 * NUREG-0612 Fig B-2, Event 2.1.1)	No.	7.5E-05	1.0E-07	2.7E-06
RF	Fraction of year over which a release may occur (current configuration)	---	1.00	1.00	1.00
LOI-N	**(CFCRNON) * RF**	**/year**	**7.5E-05**	**1.0E-07**	**2.7E-06**
	Risk reduction for a single-failure proof crane (LOI-N /LOI-S)	---	**16**	**23**	

Table 4 - Summary of NUREG-0612 heavy loads evaluation (for cask drop) with new 1996-1999 Navy crane data values and WIPP rigging HEP method

Event	Description	Units	High	Low	Median
N0	Base range of failure of handling system	/year	1.5E-04	1.0E-05	3.9E-05
	Crane Failure				
F1	Fraction of load hangup events (new 1990s Navy data)	---	0.14	0.14	
CF11	Operator error leading to load hangup (N0*F1))	/year	2.0E-05	1.4E-06	
CF12	Failure of the overload device	/demand	1.0E-02	1.0E-03	
CF1	Load hangup event (CF11*CF12)	/year	2.0E-07	1.4E-09	1.7E-08
F2	Fraction of component failure events (new 1990s Navy data)	---	0.61	0.61	
CF21	Failure of single component with a backup (N0*F2)	/year	9.1E-05	6.1E-06	
CF22	Failure of backup component given CF21	/demand	1.0E-01	1.0E-02	
CF2	Failure due to random component failure (CF21*CF22)	/year	9.1E-06	6.1E-08	7.4E-07
F3	Fraction of two-blocking events (new 1990s Navy data)	---	0.05	0.05	
CF31	Operator error leading to Two-blocking (N0*F3)	/year	6.8E-06	4.5E-07	
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*CF32*CF33)	/year	6.8E-09	4.5E-12	1.8E-10
F4	Fraction of single component failure (new 1990s Navy data)	---	0.01	0.01	
F4'	Credit for NUREG-0554	/demand	0.10	0.10	
CF4	Failure of component that doesn't have backup (N0*F4*F4')	/year	2.2E-07	1.5E-08	5.8E-08
CRANE	**Failure of crane (CF1+CF2+CF3+CF4)**	**/year**	**9.5E-06**	**7.7E-08**	**8.2E-07**
D1	Lifts per year leading to drop (100 lifts per year, drops from non-rigging)	No.	3	3	3
CF	**Failure of crane leading to load drop (CRANE*D1)**	/year	**2.9E-05**	**2.3E-07**	**2.6E-06**
	Rigging failure - Based on WIPP method				
F5	Fraction of improper rigging events (new 1990ss Navy data)	---	0.21	0.21	
CR11	Failure due to improper rigging (from WIPP report)	/year	8.7E-07	8.7E-07	8.7E-07
CR12	Failure of redundant/alternate rigging (considered as part of CR11)	/demand	1	1	
RIGGING	**Failure due to improper rigging (CR11*CR12)**	**/year**	**8.7E-07**	**8.7E-07**	**8.7E-07**
D2	Lifts per year leading to drop (100 lifts per year, drops from rigging)	No.	6	6	6
CR	**Failure of rigging leading to a load drop (RIGGING*D2)**	**/year**	**5.3E-06**	**5.3E-06**	**5.3E-06**
FHSL	**Failure of heavy load (crane and rigging) system (CRANE+RIGGING)**	**/year**	**1.0E-05**	**9.5E-07**	**1.7E-06**
CFCR	**Total failures (crane and rigging) leading to a load drop (CF+CR)**	**/year**	**3.4E-05**	**5.5E-06**	**7.9E-06**
	Loss-of-inventory for a single-failure proof crane				
RF	Fraction of year over which a release may occur	---	1.00	1.00	1.00
P	Fraction of path near/over pool	---	0.25	0.05	0.11
P'	Fraction of path critical for load drop	---	0.25	0.10	0.16
LOI-S	**(CFCR) * P * P' * RF**	**/year**	**2.1E-06**	**2.8E-08**	**2.4E-07**
	Loss-of-inventory for a non single-failure proof crane				
CFCRNON	Failures leading to a dropped load (0.5 * NUREG-0612 Fig B-2, Event 2.1.1)	No.	7.5E-05	1.0E-07	2.7E-06
RF	Fraction of year over which a release may occur (current configuration)	---	1.00	1.00	1.00
LOI-N	**(CFCRNON) * RF**	**/year**	**7.5E-05**	**1.0E-07**	**2.7E-06**
	Risk reduction for a single-failure proof crane (LOI-N /LOI-S)	---	**70**	**7**	**11**

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	3.75×10^{-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	1.25×10^{-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	5.2×10^{-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	3.75×10^{-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	1.25×10^{-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	3.5×10^{-7}	Failure rate if first pin improperly connected	$a_1 * A_2 * B_2 * C_2 * D_2$
F_T	8.7×10^{-7}	Total failure due to human error	F1 + F2

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

Table 6 - Sensitivity study assuming no interdependencies in the data base (new Navy data and WIPP rigging HEP method)

Event	Description	Units	High	Low	Mean	Median
N0	Base range of failure of handling system	/year	1.5E-04	1.0E-05		
	Crane Failure					
F1	Fraction of load hangup events (new 1990s Navy data)	---	0.14	0.14		
CF11	Operator error leading to load hangup (N0*F1))	/year	2.0E-05	1.4E-06		
CF12	Failure of the overload device	/demand	1.0E-02	1.0E-03		
CF1	Load hangup event (CF11*CF12)	/year	2.0E-07	1.4E-09	6.0E-08	1.7E-08
F2	Fraction of component failure events (new 1990s Navy data)	---	0.61	0.61		
CF21	Failure of single component with a backup (N0*F2)	/year	9.1E-05	6.1E-06		
CF22	Failure of backup component given CF21	/demand	1.0E-01	1.0E-02		
CF2	Failure due to random component failure (CF21*CF22)	/year	9.1E-06	6.1E-08	2.7E-06	7.6E-07
F3	Fraction of two-blocking events (new 1990s Navy data)	---	0.05	0.05		
CF31	Operator error leading to Two-blocking (N0*F3)	/year	6.8E-06	4.5E-07		
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*CF32*CF33)	/year	6.8E-09	4.5E-12	1.1E-09	2.6E-10
F4	Fraction of single component failure (new 1990s Navy data)	---	0.01	0.01		
F4'	Credit for NUREG-0554	/demand	1.0E-01	1.0E-01		
CF4	Failure of component that doesn't have backup (N0*F4*F4)	/year	2.2E-07	1.5E-08	1.2E-07	1.2E-07
CRANE	**Failure of crane (CF1+CF2+CF3+CF4)**	**/year**	**9.5E-06**	**7.7E-08**	**2.8E-06**	**8.9E-07**
D1	Lifts per year leading to drop (100 lifts per year, drops from non-rigging)	No.	3	3		
CF	**Failure of crane leading to load drop (CRANE*D1)**	/year	**2.9E-05**	**2.3E-07**	**1.5E-05**	**1.5E-05**
	Rigging failure - Based on WIPP method					
F5	Fraction of improper rigging events (new 1990s Navy data)	---	0.21	0.21		
CR11	Failure due to improper rigging (N0*F5)	/year	8.7E-07	8.7E-07	8.7E-07	8.7E-07
CR12	Failure of redundant/alternate rigging	N/A				
RIGGING	**Failure due to improper rigging (CR11*CR12)**	**/year**	**8.7E-07**	**8.7E-07**	**8.7E-07**	**8.7E-07**
D2	Lifts per year leading to drop (100 lifts per year, drops from rigging)	No.	6	6		
CR	**Failure of rigging leading to a load drop (RIGGING*D2)**	**/year**	**5.3E-06**	**5.3E-06**	**5.3E-06**	**5.3E-06**
FHSL	**Failure of heavy load (crane and rigging) system (CRANE+RIGGING)**	**/year**	**1.0E-05**	**9.5E-07**	**3.7E-06**	**1.8E-06**
CFCR	**Total failures (crane and rigging) leading to a load drop (CF+CR)**	**/year**	**3.4E-05**	**5.5E-06**	**2.0E-05**	**2.0E-05**
	Loss-of-inventory for a single-failure proof crane					
	Fraction of year over which a release may occur	---	1.00	1.00		
P	Fraction of path near/over pool	---	0.25	0.05		
P'	Fraction of path critical for load drop	---	0.25	0.10		
LOI-S	**(CFCR) * P * P' * RF**	**/year**	**2.1E-06**	**2.8E-08**	**5.2E-07**	**2.5E-07**

Figure 1 (sheet 1 of 2) - Heavy load drop fault trees

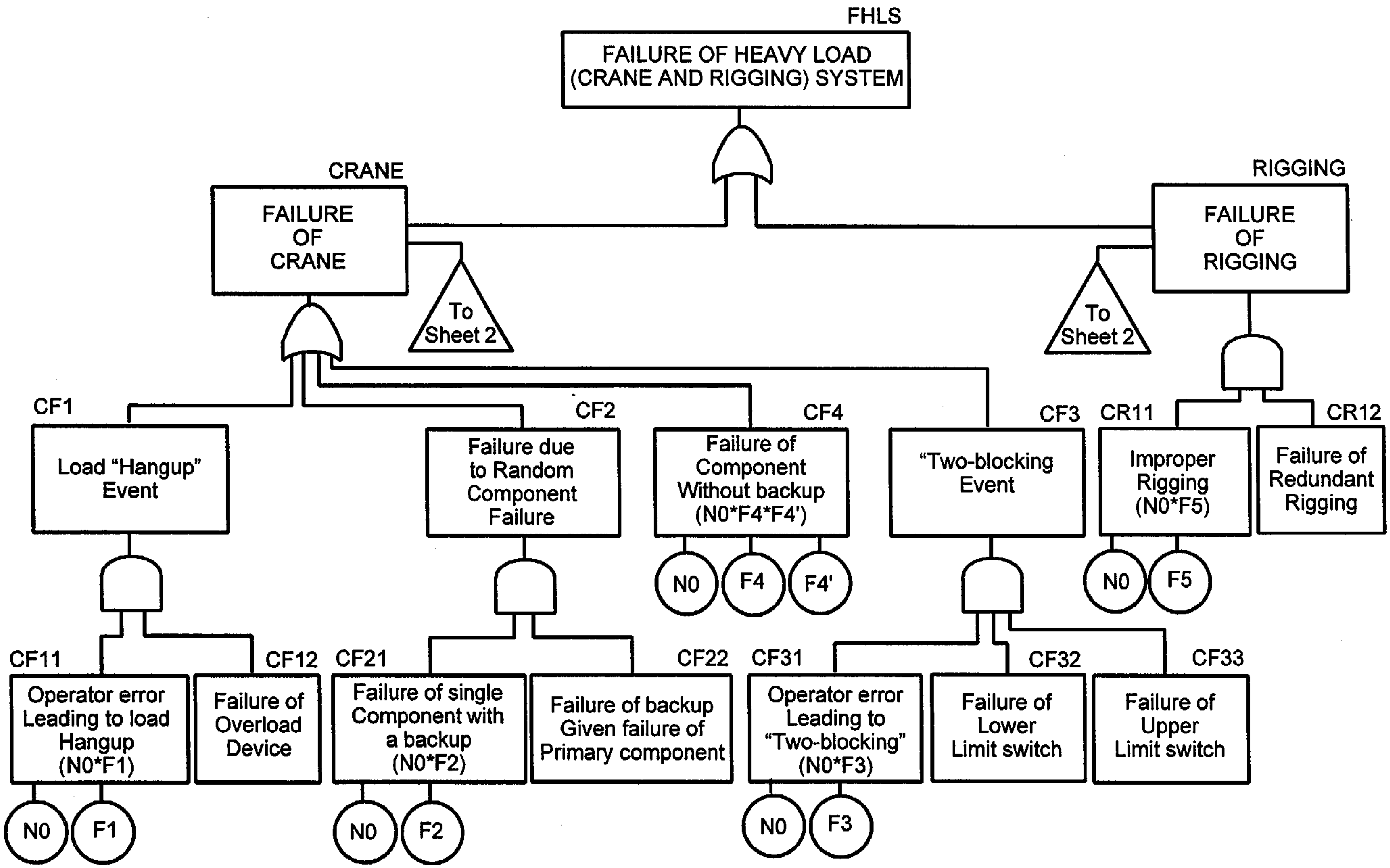

Figure 1 (sheet 2 of 2) - Heavy load drop fault trees

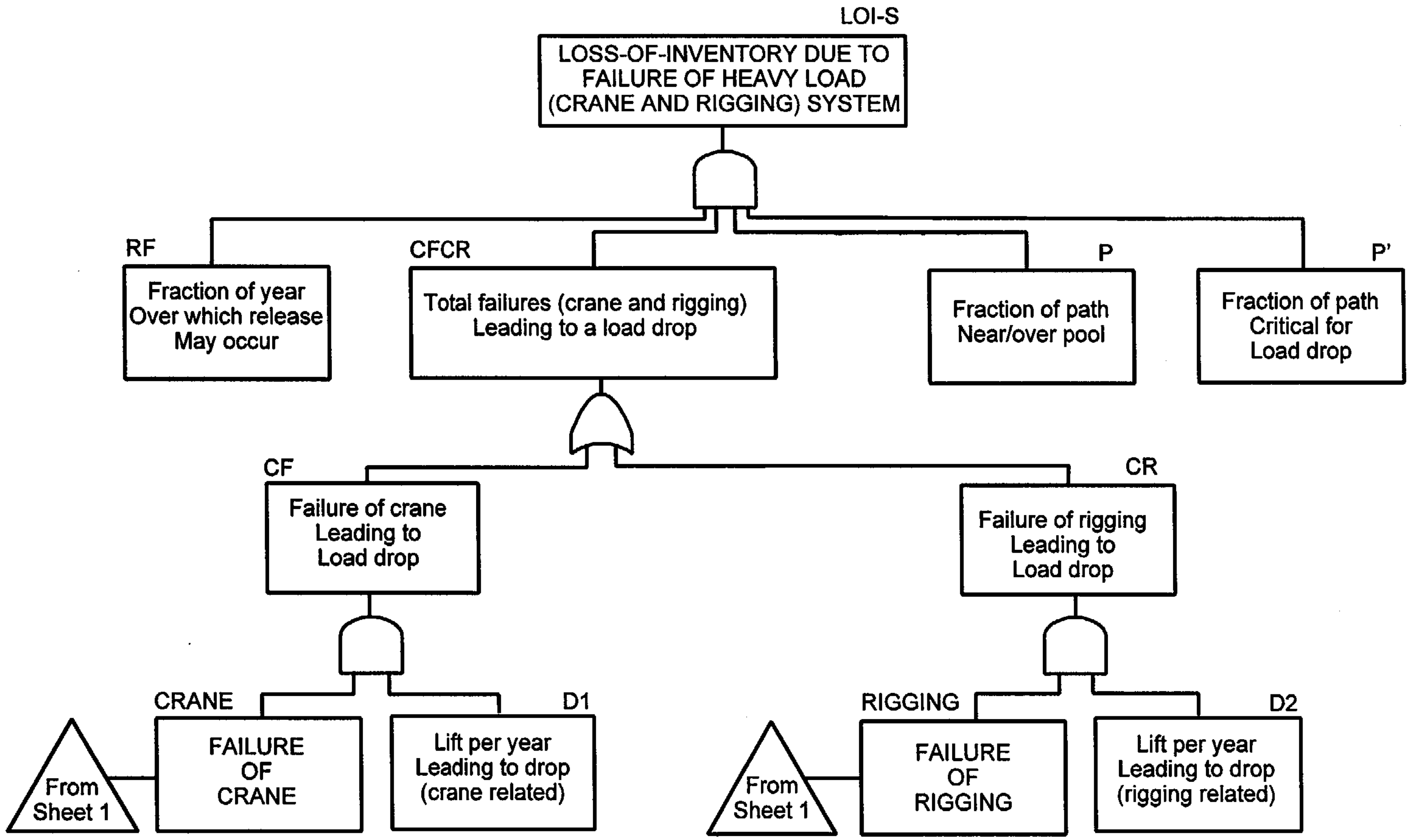

Figure 2 - Loss-of-inventory for a single-failure proof crane