

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

Summary

A heavy load drop into the spent fuel pool (SFP) 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. For single failure proof systems where load drop analyses have not been performed at decommissioning plants, the mean frequency of a loss-of-inventory caused by a cask drop was estimated to be 2.0×10^{-7} per year (assuming 100 lifts per year). For a non-single failure proof handling system where a load drop analysis has not been performed, the mean frequency of a loss-of-inventory event caused by a cask drop was estimated to be 2.1×10^{-5} per year. The staff believes that performance and implementation of a load drop analysis that has been reviewed and approved by the staff will substantially reduce the expected frequency of a loss-of-inventory event from a heavy load drop for either a single failure proof or non-single failure proof system.

Analysis

The staff revisited NUREG-0612¹ [Ref. 1] to review the evaluation and the supporting data available at that time to determine its applicability to and usefulness for evaluation of heavy load drop concerns at decommissioning plants. In addition, three additional sources of information were identified by the staff and used to reassess the heavy load drop risk:

- (1) U.S. Navy crane experiences (1990s Navy data) for the period 1996 through mid-1999,
- (2) WIPP/WID-96-2196, "Waste Isolation Pilot Plant Trudock Crane System Analysis," October 1996 (WIPP), and
- (3) NEI data on actual spent fuel pool cask lifts at U.S. commercial nuclear power plants [Ref 2]

The staff's first area of evaluation was the frequency of heavy load drops. The number of occasions (incidents) where various types of faults occurred that potentially could lead to a load drop was investigated. Potential types of faults investigated included improper operation of equipment, improper rigging practices, poor procedures, and equipment failures. Navy data from the 1990s were compared to the data used in NUREG-0612. The data gave similar, but not identical, estimates of the various faults leading to heavy load drops (See Table A2c-1.) The NEI cask handling experience also supported the incident data used in this evaluation, and in NUREG-0612. Once the frequency of heavy load drops was estimated (i.e., load drops per lift), the staff investigated the conditional probability that such a drop would seriously damage the spent fuel pool (either the bottom or walls of the pool) to the extent that the pool would drain very rapidly and it would not be possible to refill it using onsite or offsite resources. To do this the

¹ NUREG-0612 documented the results of the staff's review of the handling of heavy loads at operating nuclear power plants and included the staff's recommendations on actions that should be taken to assure safe handling of heavy loads.

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staff used fault trees taken from NUREG-0612 (See Figure A2c-1.) By mathematically combining the frequency of load drops with the conditional probability of pool failure given a load drop, the staff was able to estimate the frequency of heavy load drops causing a zirconium fire at decommissioning facilities.

Frequency of Heavy Load Drop

The database used in this evaluation (primarily the 1990s Navy data) considered a range of values for the number of occasions where faults occurred, the frequency of heavy load drops and the availability of backup systems. The reason that there is a range of values is that while the number of equipment failures and load drops were reported, the denominator of the estimate, the actual total number of heavy load lifts, was only available based on engineering judgement. High and low estimates of the ranges were made, and it was assumed that the data had a log normal distribution with the high and low number of the range representing the 5th and 95th percentile of the distribution. From this the mean of the distribution was calculated. Data provided by NEI on actual lifts and setdowns of spent fuel pool casks at commercial U.S. nuclear power plants (light water and gas-cooled reactors) gave a similar estimated range for the incidents at the 95 percent confidence level.

Load drops were broken down into two categories: failure of lifting equipment and failure to secure the load.

Crane failures (failure of lifting equipment) were evaluated using the fault tree shown in Figure A2c-1, which comes from NUREG-0612. At the time that heavy loads were evaluated in NUREG-0612, low density storage racks were in use and after 30 to 70 days (a period of about 0.1 to 0.2 per year), no radionuclide releases were expected if the pool were drained. It was assumed in NUREG-0612 that after this period, the fuel gap noble gas inventory had decayed and no zirconium fire would have occurred. Today, most decommissioning facilities use high density storage racks. This analysis evaluates results at one year after reactor shutdown. Our engineering evaluations indicate that for today's fuel configurations, burnup, and enrichment, a zirconium cladding fire may occur if the pool were drained during a period as long as five years.

A literature search performed by the staff searching for data on failure to secure loads identified a study (WIPP report) that included a human error evaluation for improper rigging. This study was used by the staff to re-evaluate the contribution of rigging errors to the overall heavy load (cask) drop rate and to address both the common mode effect estimate and the 1990s Navy data. Failure to secure a load was evaluated in the WIPP report for the Trudock crane. The WIPP report determined that the most probable human error was associated with attaching the lifting legs to the lifting fixture. In the WIPP report, the failure to secure the load (based on a 2-out-of-3 lifting device) was estimated based on redundancy, procedures, and a checker. The report assumed that the load could be lowered without damage if no more than one of the three connections were 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. Our requantification of the NUREG-0612 fault tree using the WIPP improper rigging failure rate is summarized in Table A2c-2. The WIPP evaluation for the human error probabilities is summarized in Table A2c-3.

These estimates provided a rate for failures per lift. Based on input from the nuclear industry at the July 1999 SFP workshop, we assumed in our analysis that there will be a maximum of 100 cask lifts per year at a decommissioning plant.

Evaluation of the Load Path

Just because a heavy load is dropped does not mean that it will drop on the spent fuel pool wall or on the pool floor. It may drop at other locations on its path. A load path analysis is plant-specific. In NUREG-0612 it was estimated that the heavy load was near or over the spent fuel pool for between 5% and 25% of the total path needed to lift, move, and set down the load. It was further estimated that if the load were dropped from 30 feet or higher (or in some circumstances from 36 feet and higher depending on the assumptions) when it is over the pool floor, and if a plant-specific load drop analysis had not been performed², then damage to the pool floor would result in loss-of-inventory. In addition we looked at the probability that the load drop occurred over the pool wall from eight to ten inches above the edge of the pool wall. In our analysis we evaluated the chances the load was raised sufficiently high to fail the pool and evaluated the likelihood that the drop happened over a vulnerable portion of the load path. Table A2c-2 presents the results for a heavy load drop on or near the spent fuel pool. Based on NUREG-0612, if the cask were dropped on the spent fuel pool floor, the likelihood of a loss-of-inventory given the drop is 1.0. Based on the evaluation presented in NUREG/CR-5176, if the load were dropped on the spent fuel pool wall, the likelihood of a loss-of-inventory given the drop is 0.1.

Conclusion

Our heavy load drop evaluation is based on the method and fault trees developed in NUREG-0612. New 1990s Navy data were used to quantify the failure rate of the lifting equipment. The WIPP human error evaluation was used to quantify the failure to secure the load. We estimated the mean frequency of a loss-of-inventory from a cask drop onto the pool floor or onto the pool wall from a single failure proof system to be 2.0×10^{-7} per year for 100 lifts per year.

However, only some of the plants that will be decommissioning plants in the future currently have single failure proof systems. Historically, many facilities have chosen to upgrade their crane systems to become single failure proof. However, this is not an NRC requirement. The guidance in NUREG-0612, phase 2 calls for systems to either be single failure proof or if they are non-single failure proof to perform a load drop analysis. The industry through NEI has indicated that it is willing to commit to follow the guidance of all phases of NUREG-0612.

² If a load drop analysis were performed, it means that the utility has evaluated the plant design and construction to pick out the safest path for the movement of the heavy load. In addition, it means that the path chosen has been evaluated to assure that if the cask were to drop at any location on the path, it would not catastrophically fail the pool or its support systems. If it is determined that a portion of the load path would fail if the load were dropped, the as-built plant must be modified (e.g., by addition of an impact limiter or enhancement of the structural capacity of that part of the building) to be able to take the load drop or a different safe load path must be identified.

For a non-single failure proof handling system, we based the mean frequency of a loss-of-inventory event on the method used in NUREG-0612. In NUREG-0612, an alternate fault tree than that used for the single failure proof systems was used to estimate the frequency of exceeding the release guidelines (loss-of-inventory) for a non-single failure proof system. We calculated the mean frequency of catastrophic pool failure (for drops into the pool, or on or near the edge of the pool) for non-single failure proof systems to be about 2.1×10^{-5} per year when corrected for the 1990s Navy data and 100 lifts per year. The staff assumes that the load drop analysis as performed and implemented by the utility will be sufficient to provide confidence that there is less than a 1-in-1000 chance that a cask drop to the pool wall or floor will result in catastrophic failure. This would make the single failure proof system loss-of-inventory estimate bounding.

Attachment 2C-1

Uncertainties

(1) Incident rate.

The range used in this evaluation (1.0×10^{-4} to 1.5×10^{-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 report the number of lifts made and only provided information about the number of incidents. The cask loading experience at light water reactors and Ft. St. Vrain tends to support values used for 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 fraction of the load path 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 0.5% and 6.25% 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. No time motion study was performed to account for the fraction of time the load is over any particular location.

(4) Load handling design.

The benefit of a single-failure proof load handling 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.

(5) Load drop analysis

The benefit of a load drop analysis is believed to be significant, but is unquantified. A load drop analysis involves mitigation of the potential drop by methods such as changing the safe load path, installation of impact limiters, or enhancement of the structure, as necessary, to be able to withstand a heavy load drop at any location on a safe load path. It is the engineering judgement of the staff that implementation of such an analysis should reduce the estimated frequency of catastrophic failure of the pool by at least an order of magnitude if the load drop analysis were submitted by the utility and then were reviewed and approved by the NRC staff.

Table A2c-1 - Summary of the 1996-1999 Navy crane data

Summary by Incident Type (fraction of events)		ID	Non-rigging Fraction	Rigging Fraction	Total Traction
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 A2c-2 - Summary of NUREG-0612 heavy loads evaluation (for cask drop) with new 1990s Navy crane data values and WIPP rigging HEP method

Event	Description	Units	High	Low	Mean
N0	Base range of failure of handling system	/year	1.5e-04	1.0e-05	5.4e-05
	Crane Failure				
F1	Fraction of load hangup events (new 1990s Navy data)	---	0.14	0.14	0.14
CF11	Operator error leading to load hangup (N0*F1))	/year	2.0e-05	1.4e-06	7.4e-06
CF12	Failure of the overload device	/demand	1.0e-02	1.0e-03	4.0e-03
CF1	Load hangup event (CF11*CF12)	/year	2.0e-07	1.4e-09	3.0e-08
F2	Fraction of component failure events (new 1990s Navy data)	---	0.61	0.61	0.61
CF21	Failure of single component with a backup (N0*F2)	/year	9.1e-05	6.1e-06	3.3e-05
CF22	Failure of backup component given CF21	/demand	1.0e-01	1.0e-02	4.0e-02
CF2	Failure due to random component failure (CF21*CF22)	/year	9.1e-06	6.1e-08	1.3e-06
F3	Fraction of two-blocking events (new 1990s Navy data)	---	0.05	0.05	0.05
CF31	Operator error leading to Two-blocking (N0*F3)	/year	6.8e-06	4.5e-07	2.5e-06
CF32	Failure of lower limit switch	/demand	1.0e-02	1.0e-03	4.0e-03
CF33	Failure of upper limit switch	/demand	1.0e-01	1.0e-02	4.0e-02
CF3	Two-blocking event (CF31*CF32*CF33)	/year	6.8e-09	4.5e-12	4.0e-10
F4	Fraction of single component failure (new 1990s Navy data)	---	0.01	0.01	0.01
F4'	Credit for NUREG-0554	/demand	0.10	0.10	0.10
CF4	Failure of component that doesn't have backup (N0*F4*F4')	/year	2.2e-07	1.5e-08	8.1e-08
CRANE	Failure of crane (CF1+CF2+CF3+CF4)	/year	9.5e-06	7.7e-08	1.4e-06
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	4.4e-06
	Rigging failure - Based on WIPP method				
F5	Fraction of improper rigging events (new 1990s Navy data)	---	0.21	0.21	0.21
CR11	Failure due to improper rigging, mean from WIPP study	/year	8.7e-07	8.7e-07	8.7e-07
CR12	Failure of redundant/alternate rigging	N/A			
RIGGING	Failure due to improper rigging (CR11)	/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
	Failure of heavy load (crane and rigging) system (CRANE+RIGGING)				
FHLS	Failure of heavy load (crane and rigging) system (CRANE+RIGGING)	/year	1.0e-05	9.5e-07	2.3e-06
CFCR	Total failures (crane and rigging) leading to a load drop (CF+CR)	/year	3.4e-05	5.5e-06	9.6e-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	0.13
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	2.0e-07
	Loss-of-inventory for a non single-failure proof crane				
CFCRNON	Total failures leading to a dropped load (est. from NUREG-0612)	No.	7.5e-05	1.0e-07	2.1e-05
RF	Fraction of year over which a release may occur	---	1.00	1.00	1.00
LOI-N	(CFCRNON) * P * P' * RF	/year	7.5e-05	1.0e-07	2.1e-05
	Risk reduction for a single-failure proof crane (LOI-N /LOI-S)	---	35	4	104

Table A2c-3 - 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	F ₁ + F ₂

(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.

Figure A2c-1 (sheet 1 of 2) - Heavy load drop fault trees

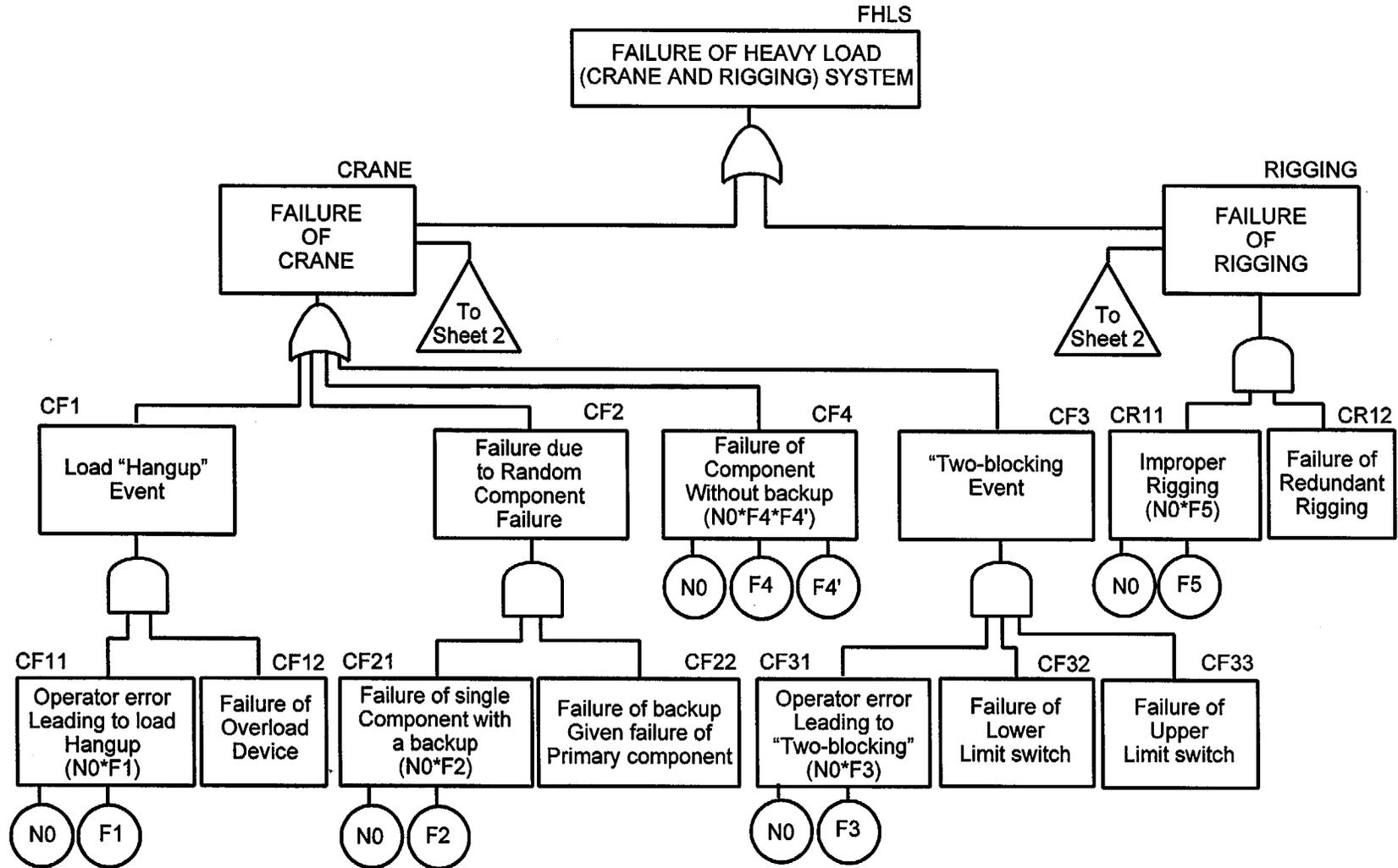


Figure A2c-1 (sheet 2 of 2) - Heavy load drop fault trees

