Probabilistic Risk Assessment of Cask Drop Accident considering Human Errors during on-site Spent Nuclear Fuel Transportation

Jaehyun Ham[1], Belal Al Momani[1], Robby Christian[2], Hyun Gook Kang[2],

[1] *291 Daehak-ro, Daejeon, 34141, Republic of Korea, Korea Advanced Institute of Science and Technology*
Turbulent@kaist.ac.kr, Balmomani@kaist.ac.kr
[2] *110 Eighth Street, Troy, NY USA 12180 (518) 276-6000, Rensselaer Polytechnic Institute*
Rckkms@kaist.ac.kr, Hyungook@kaist.ac.kr

PRA (Probabilistic Risk Assessment) of cask drop accident during on-site SNF (Spent Nuclear Fuel) transportation between SFP (Spent Fuel Pool) and wharf in NPP site was done in this research. Modified process of cask storage system was used. Based on modified process with height and state of cask, drop accident scenarios were invented. Bolted metal cask is selected as a target cask, which is composed of four parts: 21 fuel assemblies, cask body, 2 cask lids, and 2 impact limiters. Based on the results of FDR (Fuel Damage Ratio) and Release Fraction from cask to environment (RFc-e) from the simulation of ABAQUS, source term from cask drop accident was calculated. For all stages, side drop was applied. With the source term, risk to each person in LPZ (Low Population Zone) was calculated by Hotspot code. The total risk in LPZ with 45,000 MWD/MTU burn-up SNFs was calculated as 1.906E-06 man-person/transport for rubber o-ring case, and 8.413E-06 for metal o-ring case.

I. Introduction

In Republic of Korea, a handling method of SNF is not determined yet, SNFs stacked in SFP on NPP (Nuclear Power Plant) site. But within several years, some SFPs will be full of SNFs. If alternative is determined such as installing a cask storage on NPP site before SFPs are filled with SNFs, that will be the best situation. However, it’s not easy to determine the handling method because it is sensitive issue to public. The best way to handle this situation for a while is transferring the SNF from relatively placeless SNP to other SNPs. There are two ways to transfer the SNF from a site to other site, one is land transportation and the other is maritime transportation. Maritime transportation might be used because this way uses more safe route which is far from populated area. The whole transportation process can be divided in two parts: transferring the SNF between SNP and wharf on-site by truck, and transferring the SNF from the wharf to the other wharf by ship. In this research, on-site SNF transportation between SNP and wharf was considered.

Two kinds of single accident can occur during this type of SNF transportation, impact and fire, caused by internal events and external events. Among these, PRA was done for impact accident on cask caused by drop only because it was analyzed as almost the whole risk of cask storage system by PRA reports about cask storage system which has similar process with that of on-site SNF transportation.

II. Research Method

II.A. Process of on-site SNF transportation

When the SNF is moving, it should be inside of the SNF cask which can prevent the leakage of radioactive materials. Bolted metal cask was selected as a target cask. Figure 1 shows the example of bolted metal cask, KN-12. It is composed of four parts: 21 fuel assemblies, cask body, 2 cask lids, and 2 impact limiters which made of wood to absorb the impact energy.

The detailed process of on-site SNF transportation will be almost similar to the process of cask storage system which transfer the SNF from SNP to cask storage system. Because detailed operation sequence of on-site SNF transportation is not determined yet, modified process of cask storage system which is from NUREG-1864 report was used [1]. Table I shows the modified process. Based on the modified process, drop accident scenarios were invented. There are two variables for each scenario, height and state of cask. During the whole process, SNF assemblies can be existed in three states: only SNF assemblies, SNF assemblies inside the cask without impact limiter, and SNF assemblies inside the cask with impact limiter. Every stages can be divided in two kinds of operation: horizontal and vertical operation of crane. By each stage, a specific height range is determined.

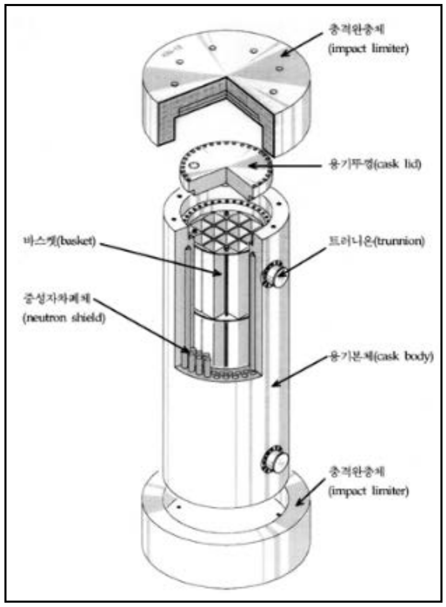

Fig. 1. Overview of bolted metal cask

TABLE I. Modified process of in-site transportation

Stages	Contents	Height (m)		State
		Before	After	
1	Loading fuel assemblies into the cask	4.8	0	SNF assemblies
2	Lifting the cask out of the cask pit	0	13	SNF assemblies + Cask
3	Moving the cask to the railing area	0	13	
4	Lowering the cask over a railing of the spent fuel pool	13	0.3	
5	Moving the cask to the preparation area	0.3	0.3	
6	Lowering the cask onto the preparation area	0.3	0	
7	Preparing the cask (draining, drying, inerting, sealing)	0	0	
8	Lifting the cask	0	0.6	
9	Moving the cask to the equipment hatch	0.6	0.6	
10	Inspection and maintaining the cask	0.6	0.6	
11	Lowering the cask onto the equipment hatch	0.6	0	
12	Equipping the impact limiter to cask body	0	0	
13	Lifting the cask	0	0.6	SNF assemblies + Cask
14	Moving the cask to the shipment area	0.6	0.6	
15	Inspection and maintaining the cask	0.6	0.6	
16	Lifting the cask	0.6	3	

17	Moving the cask to the truck	3	3	+ Impact limiter
18	Lowering the cask on the truck	3	1	
19	Transferring the cask to wharf by truck	1	1	
20	Inspection and maintaining the cask	1	1	
21	Lifting the cask	1	5	
22	Moving the cask to the ship	5	5	
23	Lowering the cask onto ship	5	0	

II.B. Risk Analysis Method

Risk can be calculated by multiplying probability and consequence.

$$Risk = Probability \times Consequence \qquad (1)$$

Probabilities of each scenario for drop accident are used as a same data from U.S.NRC and EPRI reports. Details are discussed in chapter II.C.

To get the consequence, the same approach which is used for level 3 PSA of NPP was used. With wind history data and source term, the consequence by person (man-person/transport) can be calculated. Hotspot code was used to calculate the consequence based on source term, using the simple Gaussian plume model. Source term can be calculated by multiplying the MAR (Material-At-Risk), RF, and LPF (Leak Path Factor).

$$Source\ term = MAR \times RF \times LPF \qquad (2)$$

MAR is the initial amount of interested radiation, which can be calculated by Origen code. Under the impact accident situation, gas and volatiles can be released to the environment. So Kr and Cs are considered as target radioactive materials in this research. There are two barriers to prevent the radioactive materials in SNF are released to environment: fuel rod and the cask. So, RF which means released fraction of radioactive materials from fuel rod to environment, can be calculated by multiplying FDR, RFr-c, RFc-e.

$$RF = FDR \times RF_{r-c} \times RF_{c-e} \qquad (3)$$

FDR is ratio of damaged claddings of fuel rod by impact. RFr-c is released fraction of radioactive material from rod to cask, and RFc-e is released fraction of radioactive material from cask to environment. Details are discussed in chapter II.D, II.E, and II.F. LPF is attenuation coefficient in the environment, it was considered as 1 conservatively in this research.

II.C. Probability

There are three states for SNF assemblies. For each state, different probability was used. 3.2E-05 was used for fuel assembly drop during loading. It is a state before SNF assemblies are put into the cask. 5.6E-05 was used for cask drop during a single crane action. Whether the impact limiter is installed or not, this probability was used if the SNF assemblies are located inside of cask. 3.3E-08 was used for cask drop during transferring by truck. All probability data were referred from NUREG-1864 and EPRI-1009691 [2].

II.D. Fuel Damage Ratio

In this research, 21 assemblies are assumed to be inside of the cask. Figure 2 shows the FEM model of 21 fuel assemblies. Each fuel assembly is expressed in a simple dummy model, which has same weight with real fuel assembly.

The method of calculating fuel damage ratio is used as the same method in SAND90-2406 [3]. Table II shows the peak strains in fuel rods resulting from a 100G impact. From 55 to 60 GWDt/ MTU spent fuel is assumed to fail at 1 percent strain, from 40 to 45 GWDt/ MTU spent fuel fails at 4 percent strain, and from 0 to 25 GWDt/ MTU spent fuel fails at 8 per cent strain. Based on the accelerations of each fuel assembly dummy, fuel damage ratio can be calculated by linear extrapolation.

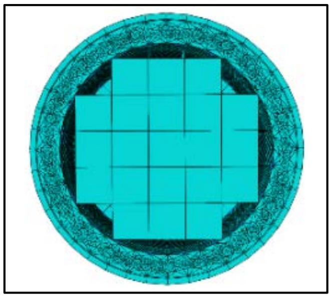

Fig. 2. FEM model of 21 fuel assemblies inside the cask

TABLE II. Peak strains in fuel rods resulting from a 100 G impact

Fraction of PWR Rods	Peak Strain, %
1/15	3.3
2/15	2.9
3/15	2.2
4/15	2
5/15	1.7
6/15	1.5
7/15	1.4
8/15	1.4
9/15	1.4
10/15	1.3
11/15	1.3
12/15	1.2
13/15	1.2
14/15	1.1
15/15	1.1

II.E. RF$_{r\text{-}c}$

Same method from NUREG-6672 was used to calculate the released fraction of radioactive material from cask to environment [4]. Figure 3 shows the relationship between release fraction from cask to environment depends on leak area. After cask is pressurized to 5 atm by the failure of all fuel rods due to collision, radioactive materials are released to environment until pressure of the inner cask reaches to 1 atm. Large leak area is equal to short depressurization time, little time for fission product deposition to cask interior surfaces.

The cask is sealed with lid, and it is fastened by bolts. By the impact, the impacted part is deformed like in figure 4. Although the lid is still fastened on cask body, leak area on lid can be made because of deformation. Four node pairs which are point of contact between lid and cask body around the lid bolts are selected as reference pairs. Average value of displacements in the same direction with cask body between nodes in each pair is considered as lid gap. By multiplying the lid gap and circumference of lid, total leak area can be calculated.

Two kinds of o-ring seal were applied for each cases in this research: rubber, and metal. Recovery of lid gap by o-ring seal which is located between lid gap and cask body is considered as a constant, 2.5 mm for rubber and 0.25 mm for metal.

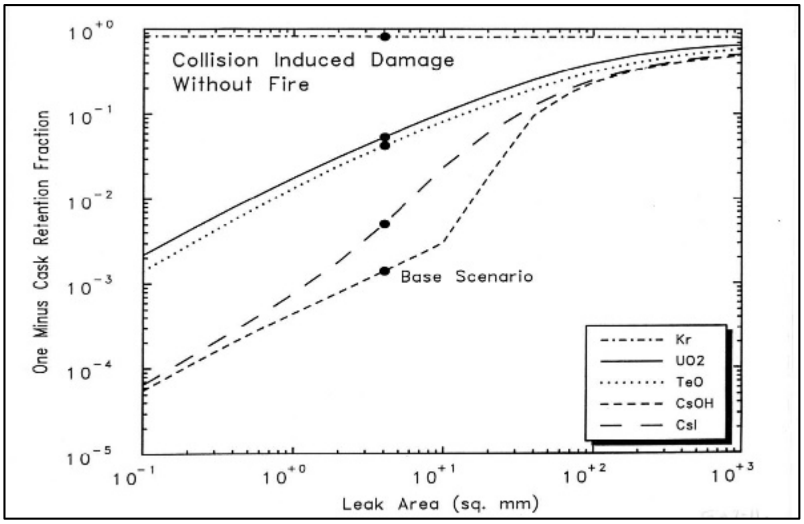

Fig. 3. Dependence of Cask-to-Environment release fractions (1.0-Rention) on the size of the cask failure (leak area)

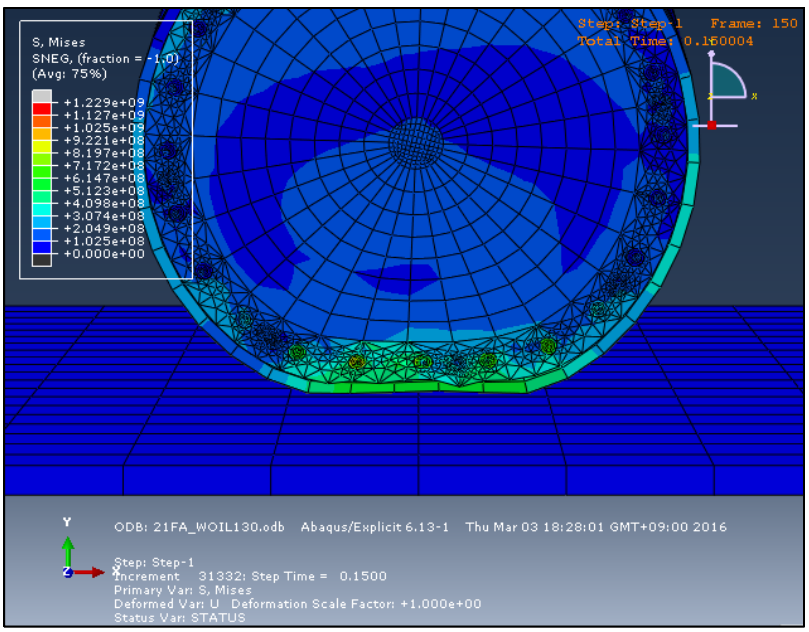

Fig. 4. Stress distribution on impacted part

II.F. $RF_{c\text{-}e}$

Radioactive materials are released under room temperature condition because drop accident was only covered in this research. Under this condition, radioactive materials which are in gas and volatile form can only be released to environment. These gas and volatiles are released with depressurization of fuel rod due to failure. Release fraction from rod to cask for gas and volatiles were applied as 0.12 and 3.0E-05 each, based on experimental data from NUREG-2125 [5].

II.G. FEM simulation

To calculate the impact energy from drop accident, ABAQUS which is FEM (Finite Element Method) software was used. There are three states of cask during whole process: SNF without cask, cask without impact limiter, and cask with impact limiter. There is only one stage for SNF without cask, which is loading the SNF into the cask. Because this stage is occurred under the water, the consequence of this stage is treated as 0 in this research. All other stages which are consist of two states, side drop was applied for the drop accident condition conservatively based on the simulation result which is in figure 5 and 6. Floor was considered as a rigid body. 1, 3, 5 m drop cases of SNF assemblies only and the cask with impact limiter, 1, 4, 7, 10, 13 m drop cases of the cask without impact limiter were done in FEM simulation. Linear interpolation was used to get the risk in other scenarios with other heights.

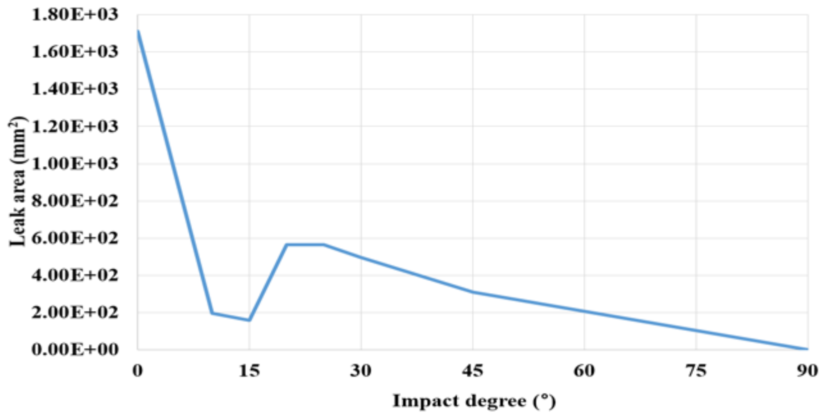

Fig. 5. Leak area under the different impact degree condition for cask without impact limiter

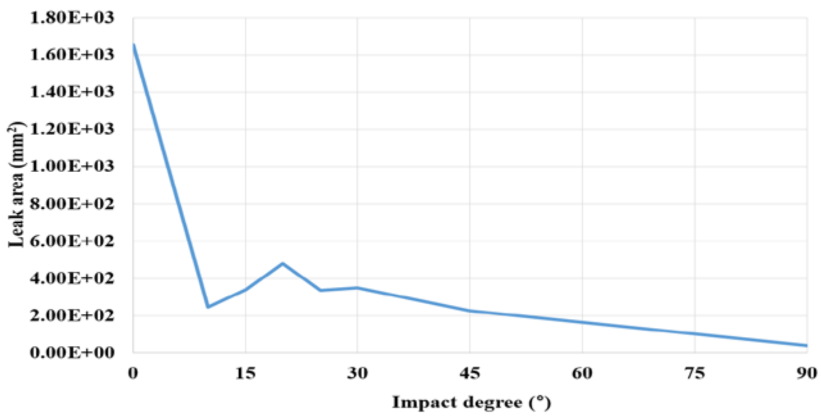

Fig. 6. Leak area under the different impact degree condition for cask with impact limiter

III. RESULTS

There are 5 conditions to calculate the risk from on-site SNF transportation: burn-up, enrichment, cooling year, wind data with direction, and distance from accident place. Specific conditions were used in this research. Burn-up and enrichment of SNF were used as 45,000 MWD/MTU, and 4.5wt% each. Cooling year of SNF was assumed to 10 years. With these condition, MAR was obtained from Origen code. Total 5 kinds of radioactive isotopes were considered, Cs-134, Cs-135, Cs-137, Kr-81, and Kr-85. Initial amount of radiation from radioactive isotopes are 3.91E+03, 1.72E-01, 5.24E+04, 1.37E-07, and 3.35E+03 Curie each. Wind history data of 2012 near a site was used to calculate the consequence based on source term. 16 directions were considered, and the risk was calculated as an average value of all directions. 5.7 km was considered for the result, the LPZ. Based on these conditions and FEM simulation data, event tree for rubber and metal o-ring case were constructed in figure 7 and 8. There are three state of each sequence: OK, ND (No Damage), and F (Failure). OK means no accident during whole process, ND means that there’s no damage on cask under the accident, and F means that there’s damage on cask under the accident. Total risk for rubber o-ring case is calculated as 1.906E-06 man-person/transport, and 8.413E-06 man-person/transport for metal o-ring case.

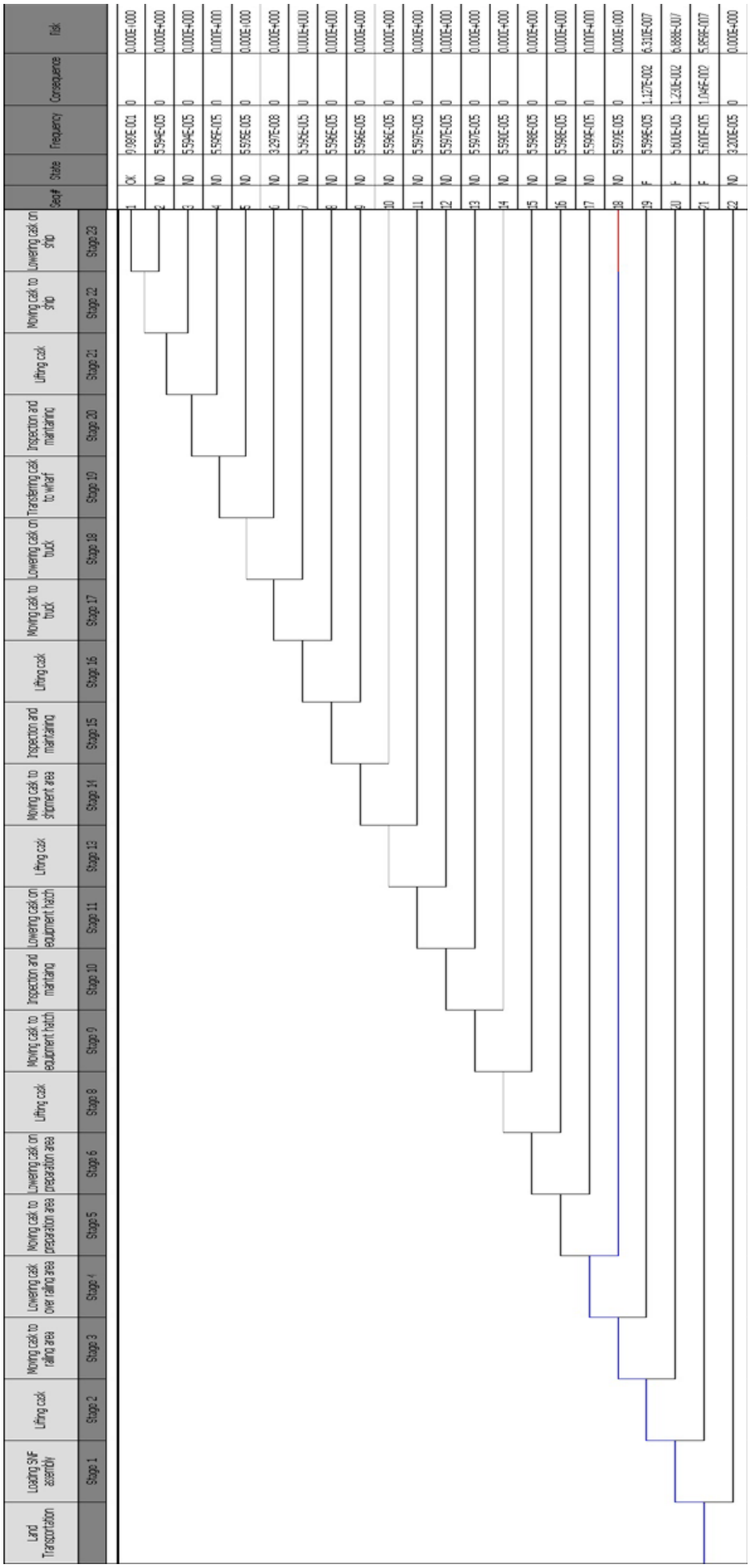

Fig. 7. Event tree of cask drop accident with rubber o-ring

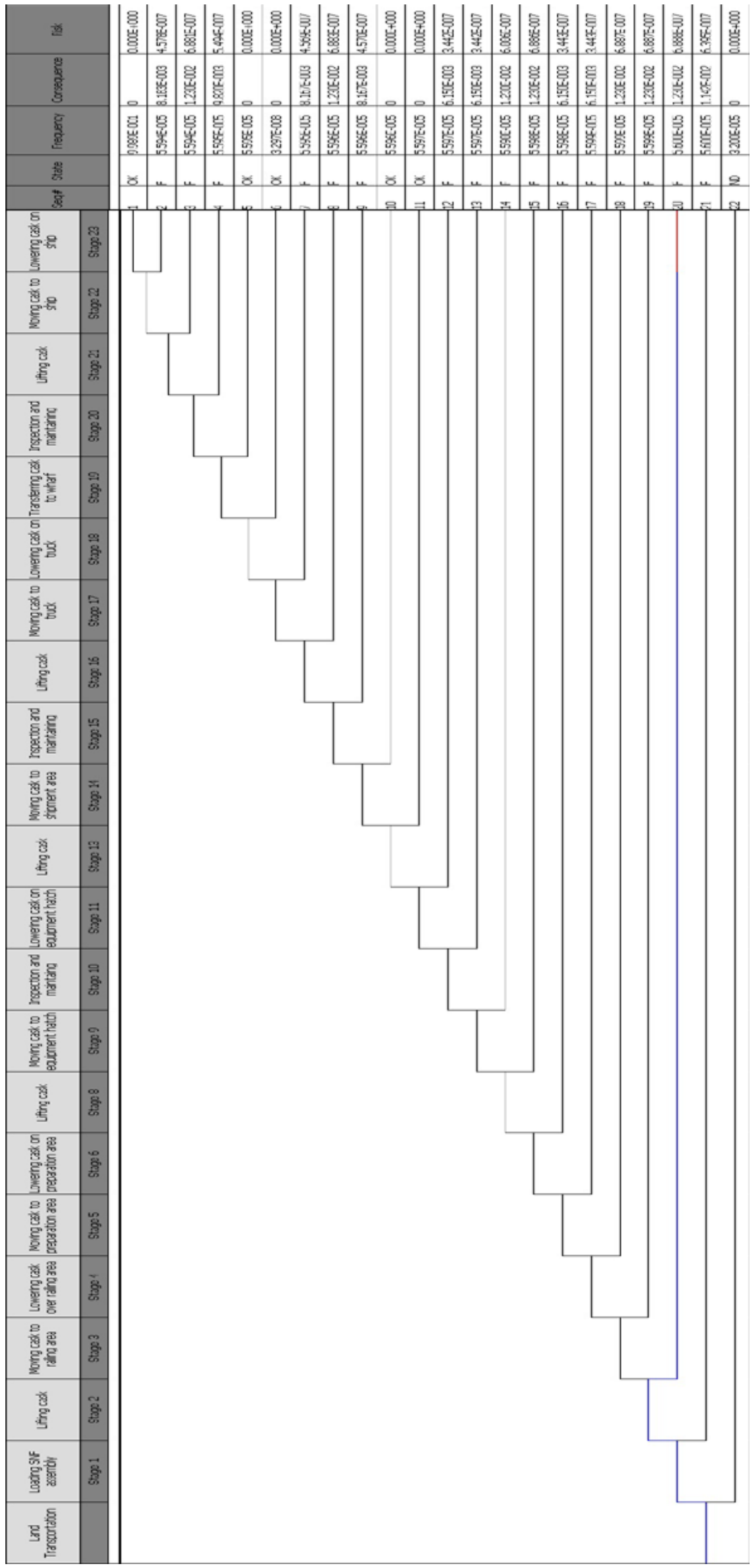

Fig. 8. Event tree of cask drop accident with metal o-ring

IV. CONCLUSIONS

In this research, PRA of cask drop accident during on-site SNF transportation was done, risk to a person (man-person/transport) from a case with specific conditions was calculated. For all stages of SNF cask during whole process, side drop was applied as the most conservative drop condition based on FEM simulation data. With rubber o-ring, no consequence for every stages except 2, 3, and 4 that are operated on 13 m. With rubber o-ring, total risk can be reduced more than 4 times than that of metal o-ring. To get more accurate risk, detailed model of inside cask structure and o-ring should be used. Also, floor should be applied with realistic model instead of rigid body.

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