Radiological Impact Assessment on a Sabotage of Spent Fuel Handling in a Pyroprocessing Facility

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing a pyroprocessing technology to process nuclear spent fuels. A demonstration facility termed PRIDE (PyRoprocess Integrated inactive DEmonstration facility) has been built to study and prepare for the construction of the active facility. Prior to that, a radiological impact assessment must be conducted to establish a safe and secure facility design.

Research have been done to identify possible accident scenarios and their impact thereof to the surrounding environment [1,2]. However these studies were based on the notion of internal accidents which extent was defined by the process' characteristics. There has yet a study on externally induced radiological consequences, for example by malicious acts launched towards the facility.

This paper attempts to close the gap by analyzing a certain malicious attack scenario and its radiological consequences. It may provide support for identification of vital areas in the facility and to achieve a security-by-design objective.

2. Methods

2.1 Radioactive Release Scenario

A scenario was devised where a group of adversaries obtained a fully loaded petrol truck and portable rocket launchers. The group then launched an attack at the laydown area in the pyroprocess facility during the unloading of spent fuel casks from shipping trucks. Layout of the area inside the facility is shown in Fig. 1 [2]. In this scenario, rockets were shot to a transport cask to breach its physical integrity, which was then followed by colliding a petrol truck into it to cause fire. Previous study mentioned that this type of combined attack could lead to an increased release of radioactive material to the environment [3]. The truck capacity was of 8800 gallons of petrol with a 48000 kJ/kg combustion heat. Fire engulfed the spent fuel casks and fills the laydown area with a radius of 20.2 meters. This fire lasts for two hours and lifted radioactive materials upward in a smoke plume. The radioactive plume was then carried away and dispersed to the surrounding environment by the wind. In this scenario air filtration system, mitigation systems and emergency response team were not considered. A scenario in which multiple fully-loaded casks were attacked was also investigated to compare the consequences.

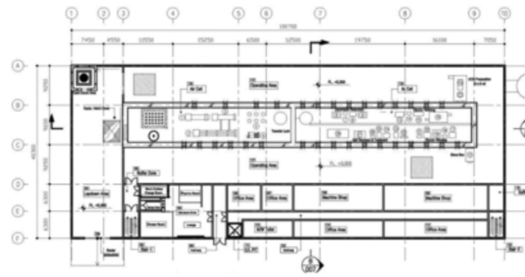

Fig. 1. Layout of pyrofacility's first floor

The transport cask used in this scenario had a configuration as shown in Fig 2 [4]. It was a truck type cask which uses 2.5 depleted uranium gamma shielding and a polypropylene neutron shield. It has a maximum load capacity of four PWR spent fuel assemblies.

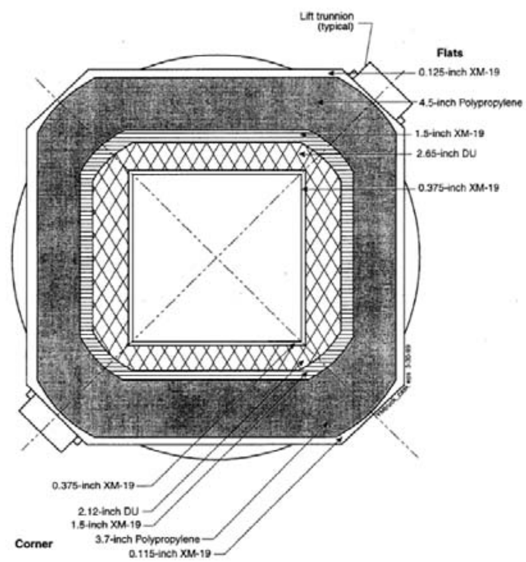

Fig. 2. Cross section of a truck-based spent fuel transport cask

2.2 Source Term

The radioactive material inventory involved in the scenario was computed using ORIGEN-ARP of SCALE code. The feed was based on a 16x16 PWR type fuel with 4.5wt% U-235 enrichment after reaching 55000 MWD/MTU burnup and 10 years of interim cooling for as many as four spent fuel assemblies.

The source term (ST) released to the environment in the scenario is governed by the following equation:

ST = MAR x ARF x RF x DR x LPF (1)

Where MAR is the material at risk which can be released (expressed in grams or curies); ARF is the airborne release fraction in the form of aerosol; RF is the respirable fraction of aerosolized radionuclides which can be inhaled into the human respiratory system; DR is the damage ratio of the total MAR; LPF is the leak path factor, a fraction of airborne materials transported from containment through filtration mechanism. Both DR and LPF were taken as 1 for conservatism.

ARF and RF were taken from previous studies [3,4] and listed in Table 1. These values are conservative estimates in the case of explosions and fire on a spent fuel transport cask.

Table I: Release Fraction Values

Radionuclide / Form group	Parameter	Value
Cesium	ARF x RF	0.1
Pu-241	ARF x RF	3E-4
Sr-90	ARF x RF	1E-4
Matrix form	ARF	0.4
	RF	0.1
Noble gases	ARF	1
	RF	1
Volatile	ARF	0.2
	RF	0.1

2.3 Dispersal Model

Briggs plume rise model was used to characterize the plume from petrol fire. Buoyant plume rise formula was chosen over momentum plume rise due to its relative significance in characterizing the plume in this scenario. Heat emission rate from the petrol fire is determined based on Eq (2)

Q = 3785 V d H (1-f) / t (2)

And the buoyancy flux as a function of the heat emission rate is given by Eq (3)

F = 0.011 Q / T (3)

While the buoyant effective release height is figured out by Eq (4)

$$H = 1.6(F)^{1/3} (X^*)^{2/3} / u(H/2) \quad (4)$$

Note that the abovementioned equation is only applicable in atmospheric stability class A, B, C and D. It is however shown in the results section that this formula sufficiently meets the stability class requirement.

Plume dispersal to the environment was modelled using Gaussian dispersion model as governed by Eq (5). HOTSPOT code version 3.0.1 developed by Lawrence Livermore National Laboratory was used to calculate plume rise and dispersal.

$$\chi = \frac{Q}{2\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{exp\left(-\frac{(H+z)^2}{2\sigma_z^2}\right) + exp\left(-\frac{(H-z)^2}{2\sigma_z^2}\right)\right\} \quad (5)$$

It was assumed that the facility is located at KORI site. A one-year meteorological data of the site was used to as a basis for determining the wind characteristics in the scenario. The meteorological data was processed using the WRPLOT View^{TM} version 7 developed by Lakes Environmental Software. This process produced a windrose representation of the meteorological data from which a dominant wind direction and average speed was selected. The atmospheric stability class was then determined based on Pasquill method according to the wind speed and solar condition as shown in Table 2.

Table II: Pasquill Stability Criteria

Ground wind speed (m/s)	Sun high in the sky	Sun low in the sky or cloudy	Night time
< 2	A	B	F
2 – 3	A	C	E
3 – 4	B	C	D
4 – 6	C	D	D
> 6	C	D	D

2.4 Dose Conversion Factors (DCFs)

The Federal Guidance Report (FGR) 13 was chosen as the dose conversion factor. With this option, the human lung was modeled based on the International Commission on Radiation Protection (ICRP) Publication 66 while dose coefficients were taken from ICRP Publication 60. The reference man was assumed to have a breathing height of 1.5 meter and a breathing rate of 3.47E-4 m^3/s. Radiological dose was then evaluated at various distances away from the facility. Special consideration was paid to the site boundaries and the dose limits thereof as regulated in the Notice of the NSSC No. 2012-03. The site boundaries for KORI site are Exclusion Area Boundary (EAB) at 560 meters, Low Population Zone (LPZ) at 5.7 km, and Population Center Distance (PCD) at 10.4 km. Dose limits for EAB are 25 rem for whole body exposure or 300 rem for thyroid exposure from Iodine within 2 hours. The same numbers apply for LPZ for the whole exposure time.

3. Results and Discussions

There were 54 radionuclides in the source term. The windrose diagram for KORI site is shown in Fig 3. The wind direction in this diagram is coming from each sector. The frequency distribution of wind speed classes is given in Fig. 4.

Based on the meteorological statistics, the wind direction was chosen to move in the direction towards North-North West (NNW) with an average speed of 3.12 m/s. As shown in Table 2, only stability class A, C and F are applicable to this meteorological situation. Class F however was excluded because in this class the wind blows from the land to the sea. Although it may transport radioactive material to the seawater and eventually to the nearby population, the waterborne pathway is beyond the scope of this study. Precipitation was not considered since the statistics showed that over 90% of the time the weather was dry.

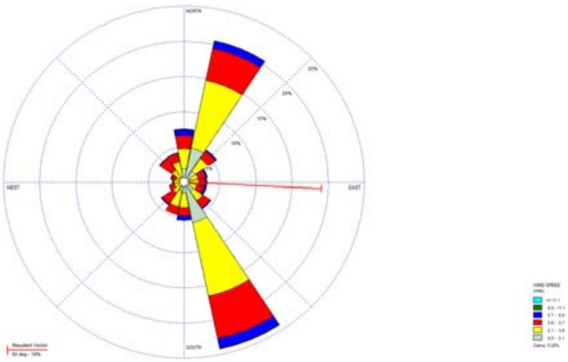

Fig. 3. Windrose for KORI site

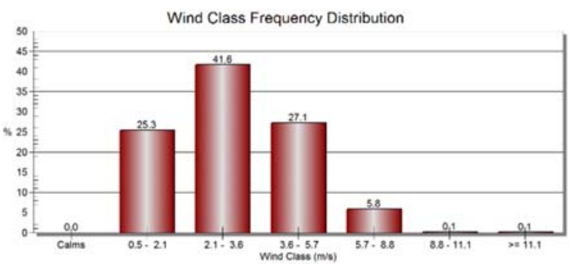

Fig. 4. Frequency distribution of wind speed classes

The plume's effective release height was calculated to be at 702 in stability class C and 734 m in stability class A. Radiation dose expressed in Total Effective Dose Equivalent (TEDE) is shown in Fig 5 for stability class A and C.

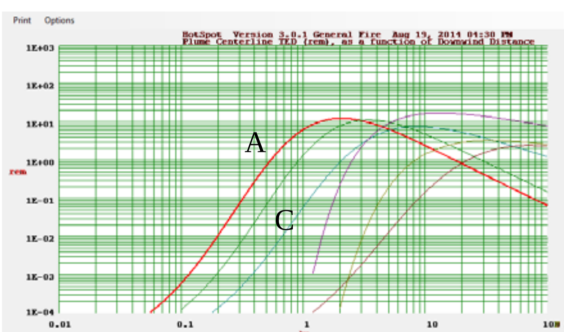

Fig 5. TEDE vs distance for stability class A and C

For stability class A, the maximum TEDE was found to be 13 rem at 2.1 km away from the facility. This maximum TEDE went down to 7.6 rem in stability class C, at a distance of 8.6 km. In both classes, the observed thyroid dose from Iodine intake was considered trivial at the order of 10^{-2} rem in contrast to the dose limits.

A comparison of results between stability class A and C is presented in Table III. In neither of the stability classes did the radiation doses exceed regulatory limits. It was observed however in class C stability scenario, the radiation dose to the population at PCD was 3.2 times larger than that in the class A scenario.

Table III: Radiological Impact in Class A and Class C

Parameter	Class A	Class C
EAB		
TEDE (rem)	1.1	4.7E-03
Land contamination (uCi/m2)	3.3	1.4E-02
Ground shine (rem/hr)	2.7E-5	1.1E-7
Arrival time (seconds)	2	2
LPZ		
TEDE (rem)	5.5	6.6
Land contamination (uCi/m2)	16	19
Ground shine (rem/hr)	1.3E-4	1.6E-4
Arrival time (seconds)	26	24
PCD		
TEDE (rem)	2.3	7.4
Land contamination (uCi/m2)	6.7	22
Ground shine (rem/hr)	5.4E-5	1.8E-4
Arrival time (seconds)	47	44

The remaining inventory of gamma emitters on the site gave rise to an external dose rate of 1188.6 rem/hr at 10 meters away from the fire boundary. This might impede the work of first responders and thus justified the original assumption of excluding them from the scenario.

Although it is questionable whether the attack can similarly breach multiple transport casks altogether, the possibility of more destructive missiles in the future and / or a sufficient number of malicious group members and equipment led to the analysis of the following scenario. Retaining the previous release fraction values, the radiation dose from two and three damaged casks are depicted in Fig 6 and Fig 7 respectively.

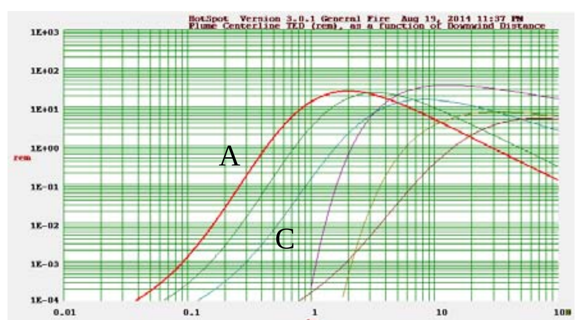

Fig 6. TEDE from 2 damaged transport casks

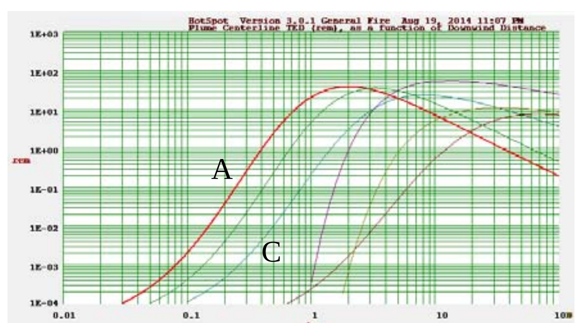

Fig 7. TEDE from 3 damaged transport casks

In 2 transport casks scenario, the regulatory limit was exceeded in stability class A. The maximum dose was 26 rem from the whole exposure time in the LPZ area. Further analysis revealed that this situation encompasses an area of 0.22 km^2 along the plume central line as shown in Fig 8. This dose went up to 39 rem when 3 transport casks are involved. There were not any violation of regulatory limit observed in stability class C. An increase in thyroid dose from Iodine intake was observed, however it is still considered insignificant in the order of 10^{-1} rem compared to the regulatory limit.

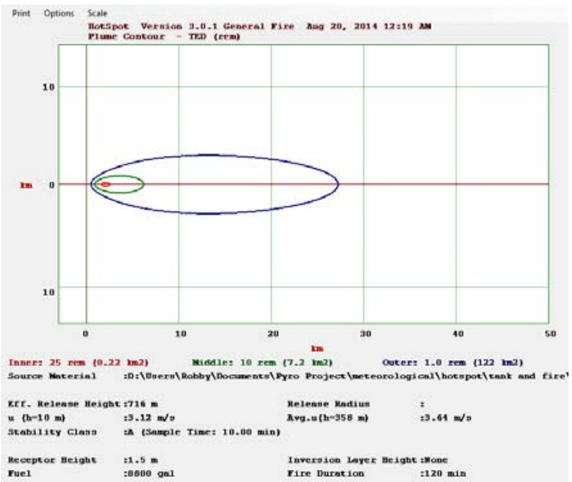

Fig. 8. TEDE contour along the plume centerline

4. Conclusions

Based on the results, an attack launched on a single transport cask fully loaded with spent fuel as described in the scenario did not cause a radiological impact which exceeds regulatory limits. The limits were surpassed when there were two or more spent fuel casks involved. This result might be used as a basis not to aggregate loaded transport casks either during transport or during handling in the laydown area.

Future progress in this research includes assessments on physical integrity of transport casks if the design is different than what was assumed. This will define the release fraction of the radioactive materials. A mechanical finite element analysis might be employed to predict this behavior.

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