A STUDY ON ACCIDENT SEQUENCE ANALYIS FOR A HEAVY ION ACCELERATOR, RAON

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RAON will be the only accelerator complex in the world that has both Isotope Separation On-Line (ISOL) and In-flight Fragmentation (IF) for the production of various rare isotopes. Since accelerators are defined as radiation generating devices, strict operate procedures and safety assurance are required to prevent radiation exposure. To satisfy this condition, there is a need for evaluating potential risks of the accelerator facility from the design stage itself. Radiation generating devices, e.g., accelerators are one of the types of non-reactor nuclear facilities where PRA can be of benefit. The objective of this study is to conduct accident sequence analysis for the accelerator facility using the PRA approach. The analysis embraces identification of initiating events, system analysis, and accident sequences development. As RAON is in the design stage where various configurations are under consideration now, only qualitative accident sequence analysis was conducted. When the detailed design is finalized, quantitative accident sequence analysis will be conducted.

I. INTRODUCTION

In recent years, producing rare isotopes has been essential worldwide. It is expected that there will be conspicuous progress in a broad range of fields in both basic and applied science by using them. Hence, construction of the accelerator complex for the rare isotope science named RAON was approved by the Korean government in 2009. RAON will be the only accelerator facility in the world that has both Isotope Separation On-Line (ISOL) and In-flight Fragmentation (IF) for the production of various rare isotopes. A wide range of rare isotopes can be produced since the ISOL and IF systems are used at the same time. The accelerator complex will be located in Sindong area in the northern part of Daejeon city.

The concept of the accelerator complex is shown in Fig. 1 and the beam specifications are summarized in TABLE I (Ref. 1). It consists of a heavy ion linear accelerator as the driver, called the Driver Linac, for the IF system, a proton cyclotron as the driver for the ISOL system, and a post-accelerator for the ISOL system. The ISOL and the IF systems can be operated separately and independently. In addition, the rare isotopes produced in the ISOL can be injected into the Driver Linac for accelerating the RI beam to even higher energies or for use in the IF system to produce even more exotic rare isotopes. In the future, a proton beam in the Driver Linac can be used for the ISOL system with higher power. A large number of rare isotopes with high intensity and various beam energies will be available.

Accelerators are defined as radiation generating devices according to the Nuclear Safety Act. Thus, strict operate procedures and safety assurance are required to prevent radiation exposure. To satisfy this condition, there is a need for evaluating potential risk of the accelerator facility from the design stage itself. The probabilistic risk assessment (PRA) approach offers a formal structured procedure for defining the functional logic of complex systems, assessing the consequences of failure and deriving numerical estimates of risk from the operation of a plant. In addition, PRA allows an explicit demonstration of safety that is comparable across different types of systems and different industries. PRA can also support enhancement of plant safety. For example, it can provide plant designers with an unbiased benchmark against which to rank the safety significance of alternative design options, and enable them more easily to decide on the best option. These benefits of PRA can be applied to simpler and less hazardous nuclear facilities or systems and are judged to be particularly beneficial to non-reactor nuclear facilities. Radiation emitting devices, e.g., accelerators are one of the types of non-reactor nuclear facilities where PRA can be of benefit (Ref. 2).

The objective of this study is to conduct accident sequence analysis for the accelerator facility using PRA techniques. The analysis embraces identification of initiating events, system analysis, and accident sequences development. As RAON is in the design stage where various configurations are under consideration now, only qualitative accident sequence analysis rather than quantitative analysis was conducted using the conceptual design information. When the detailed design is finalized, quantitative accident sequence analysis will be conducted.

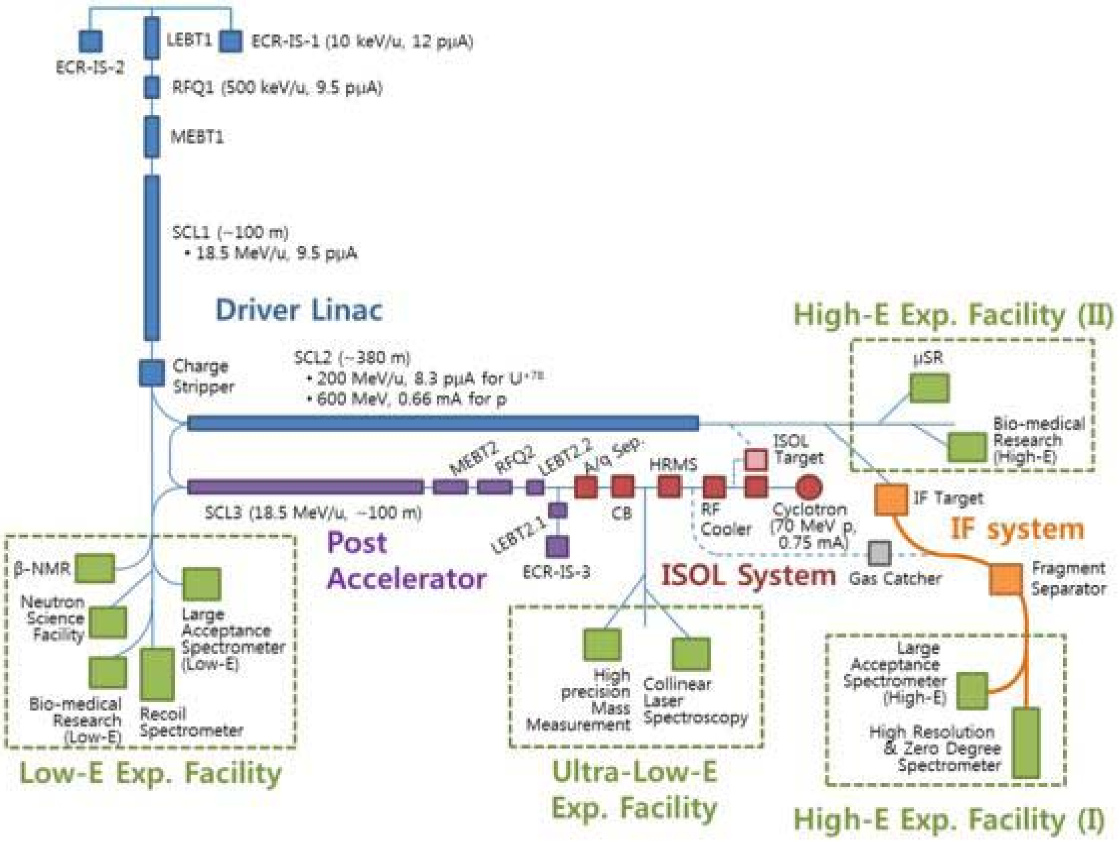

Fig. 1. Schematic diagram of RAON

TABLE I. Beam parameters of RAON

Accelerator	Driver Linac				Post Accelerator	Cyclotron
Particle	proton	$^{16}O^{+8}$	$^{124}Xe^{+54}$	$^{238}U^{+79}$	RI beam	Proton
Beam energy (MeV/u)	600	300	240	200	18.5	70 MeV
Beam current (pμA)	660	83	13	8.3	-	1 mA
Power on target (kW)	400	400	400	400	-	70 kW

II. INITIATING EVENTS SELECTION

A master logic diagram (MLD) was used to identify the possible initiating events occurring in RAON. A MLD is similar to a fault tree. It presents a model of a plant in terms of individual events and their combinations. It develops into a plant level logic structure whose basic input events are the initiating events. The particular advantage of the MLD method is that the issue of completeness is put into a more tangible perspective compared to other methods (Ref. 3). The top event was defined as undesired radiation exposure to personnel and the initiating events taken into consideration in this study are restricted to only internal initiating events. As a result of the meeting with experts on accelerators, some initiating events such as cryogenic system failure and ventilation system loss were excluded. The MLD used for identifying initiating events considered in this study is depicted in Fig. 2.

The five initiating events identified through the MLD method:

1. Abnormal beam losses;
2. Vacuum system failure;

3. Shielding material rupture;
4. Beam window rupture;
5. Access control failure.

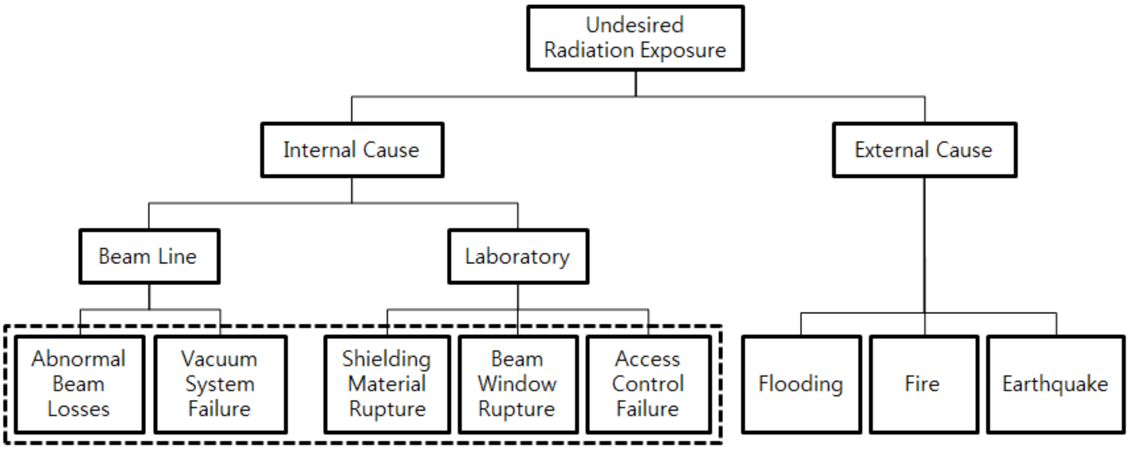

Fig. 2. MLD used for identifying initiating events

III. SYSTEM ANALYSIS

System analysis is to model key components and failure modes contributing to the function of safety systems expected to operate in accident sequences. Among safety systems devised and installed in RAON for assuring safety of personnel from radiation exposure, the most important system is the interlock system that trip the accelerator when get a trip signal from other systems. Several systems that give a signal to the interlock system are descripted below.

Radiation Monitoring System (RMS) is to monitor prompt radiation and radiation from radioactive materials. The RMS is composed of both an area monitoring system to observe the radiation level in the facility of the accelerator and experiment and environmental radiation monitoring system in the site boundary. When the monitors detect the higher level of radiation than normal, it gives a trip signal to the interlock system. Beam diagnostics including Beam Loss Monitor (BLM), Beam Current Monitor (BCM), Beam Position Monitor (BPM), Phase Monitor (PM), and Faraday Cup (FC) detects and measures beam parameters for a wide range of beam intensities. It also gives a trip signal to the interlock system when they find irregular beam status. There are beam boxes regularly placed for necessary beam diagnostics. The configuration of the beam diagnostics of the driver SCL and a plot of a beam box are shown in Fig. 3 as an example.

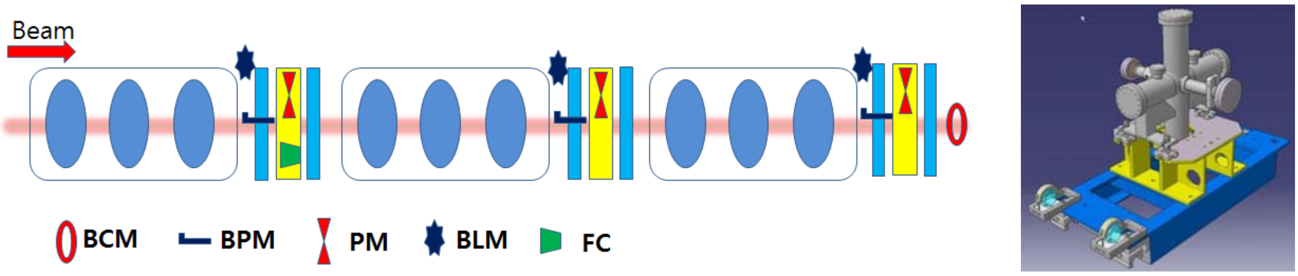

Fig. 3. Configuration of beam diagnostics of the driver SCL and plot of a sample beam box (Ref. 4)

An Emergency Stop Button (ESB) is placed at certain locations that persons in a high radiation area could easily access. When persons press the ESB, the accelerator will instantaneously stop through the interlock system. Also, there are sensors such as motion sensors, temperature sensors, and door sensors that can shutdown the accelerator when they detect an abnormal situation. Vacuuming Monitoring System (VMS) is mainly to check if the vacuum conditions are maintained. If not, it will impart a trip signal to the interlock system. The configuration diagram of RAON safety systems is shown in Fig. 4.

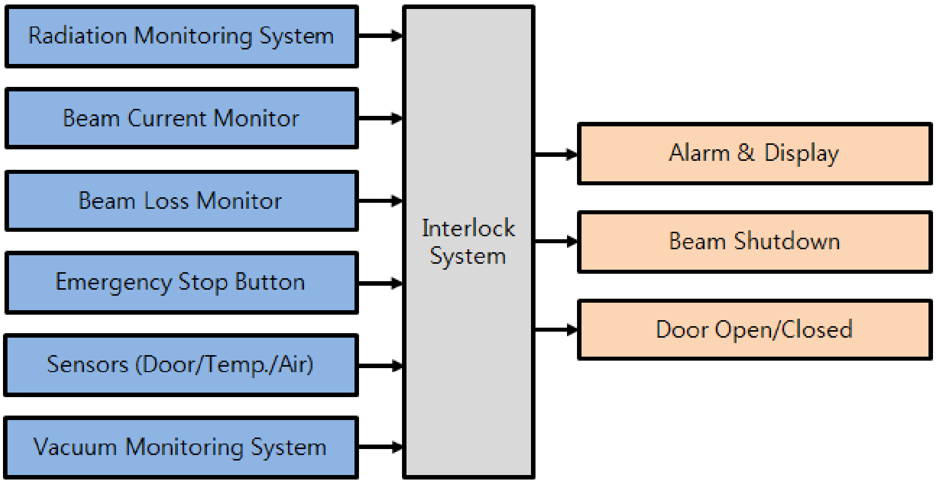

Fig. 4. Configuration diagram of RAON safety systems

IV. ACCIDENT SEQUENCES DEVELOPMENT

Event tree analysis (ETA) was used for the development of accident sequences from the initiating events that were identified. ETA is a method used to model an accident as a sequence of events, with various safety systems or human actions that can succeed or fail.

IV.A. Abnormal Beam Losses

It is inevitable that controlled beam losses happen while the beam is accelerated and transported to the target. However, there could be abnormal beam losses caused by several reasons. One of the reasons is a loss of power to dipoles. Dipoles reflect heavy ion beam in bending sections. Fig.5 shows the most probable area where the loss of power to dipoles happens. When there is no sufficient electric power, dipoles lose their original function. It makes the beam go in different directions from that originally designed.

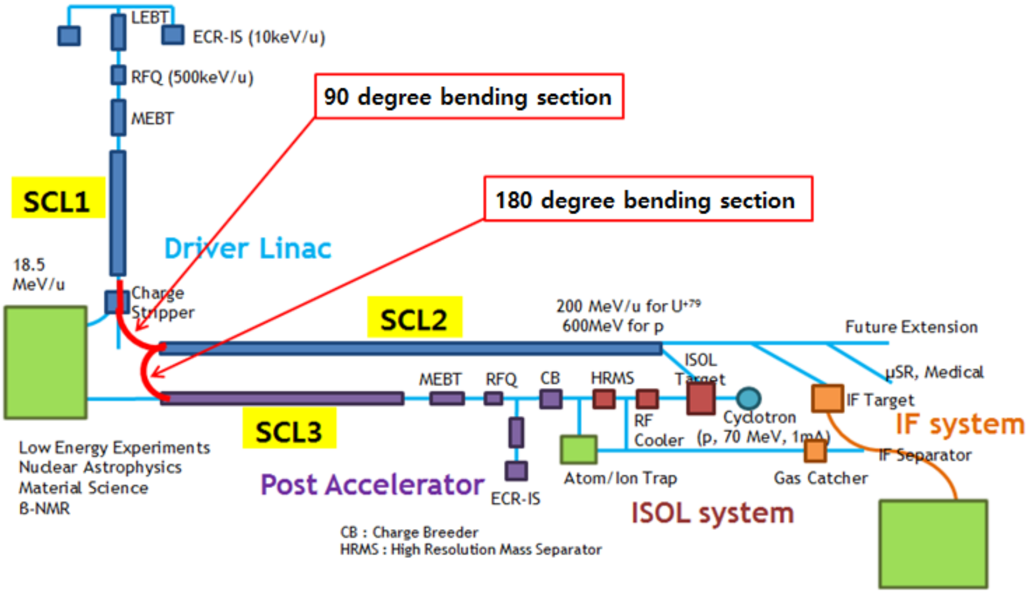

Fig. 5. The most probable areas where the loss of power to dipoles happen

The abnormal beam losses also arise from misalignment of accelerator components and the operator setting improper beam parameters. In case of the beam losses, the beam collides with nearby systems and could lead to the production of bremsstrahlung radiation and neutron activating the accelerator parts and shielding materials. This causes higher radiation exposure to personnel nearby and maintenance workers. Once beam losses occur, the beam diagnostics (BLM, BCM) installed along the beam line detect the beam losses and give a trip signal to the interlock system. If the beam diagnostics fail to detect the beam losses and make a trip signal, the operator should shutdown the beam using the ESB. The event tree for abnormal beam losses is shown in Fig. 6.

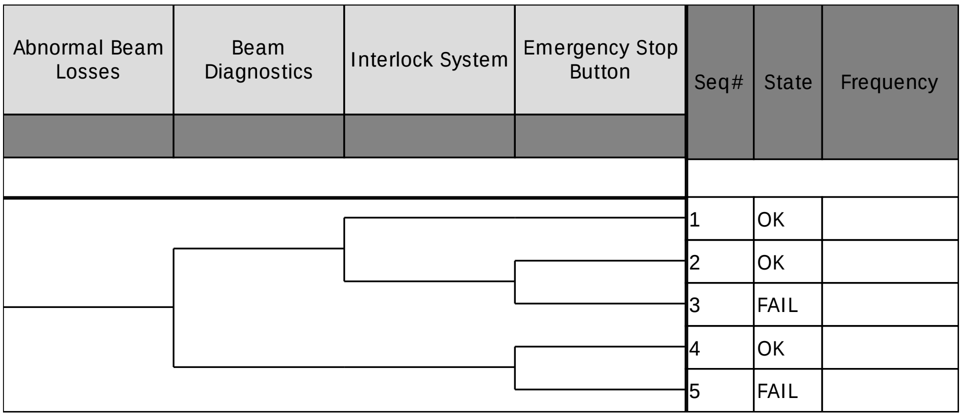

Fig. 6. Event tree for abnormal beam losses

IV.B. Vacuum System Failure

Vacuum system can be divided into ultra-high vacuum (UHV) system (10^{-8}~10^{-9} torr) for the beam line and high vacuum (HV) system (~10^{-6} torr) for cryogenic insulation and preliminary pumping of the design. The vacuum system is to prevent contaminations on superconducting cavities which can cause field emission and lower the accelerating voltage. Vacuum system failure can considerably increase the bremsstrahlung dose rates in the beam lines. During beam operation, if any pump in the vacuum system presented in Fig. 7 fails to run or vacuum leaks, the vacuum system fails and cannot maintain a vacuum in the beam line and reduce beam losses.

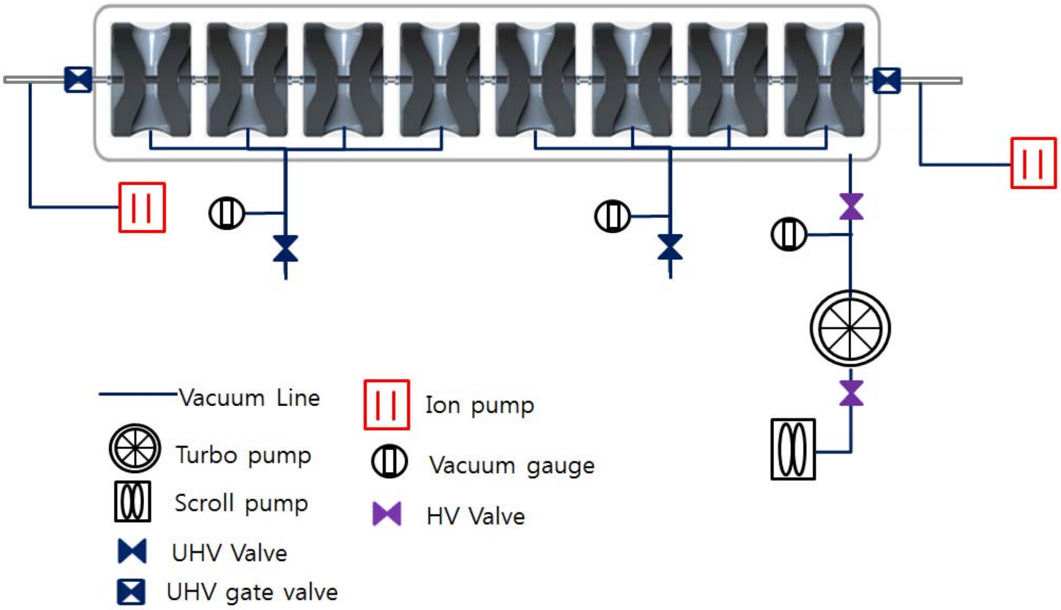

Fig. 7. Schematics of vacuum system in a cryomodule of SCL (Ref. 4)

When the vacuum system fails, the VMS that checks the quality of the vacuum will detect the failure and the operator will close the gate valves. Even though the VMS fails to detect the failure, the beam diagnostics could detect beam losses due to the vacuum system failure and trip the accelerator. If both the VMS and the beam diagnostics fail, the operator should manually trip the accelerator through the ESB by reading the vacuum gauge. The event tree for vacuum system failure is shown in Fig. 8.

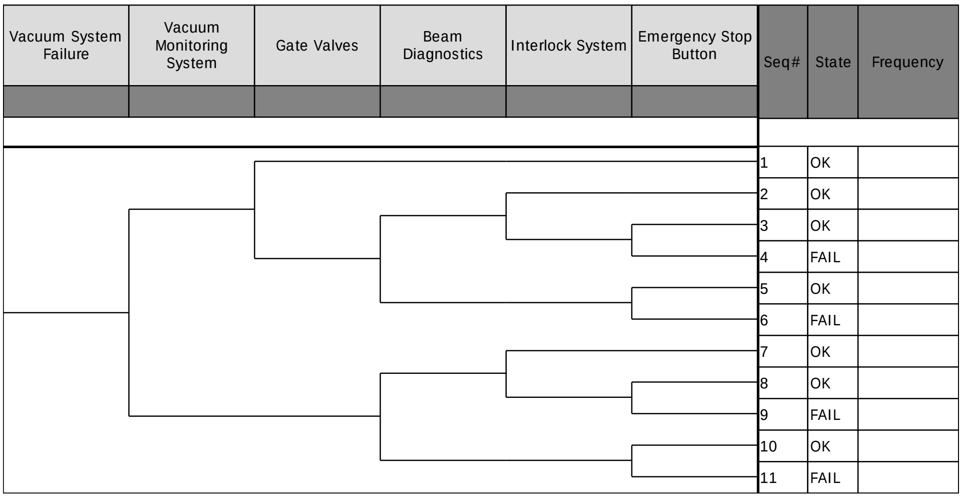

Fig. 8. Event tree for vacuum system failure

IV.C. Shielding Material Rupture

An area where there is the possibility of radiation exposure is designated as the radiation controlled area. There are multiple barriers such as shielding walls and shielding doors located in the radiation control area in order to prevent the radiation exposure. Shielding material rupture can be resulted from an incomplete construction of shielding materials such as a shielding wall and a shielding door, an inappropriate installation of shielding blocks, or an aging of shielding materials. The shielding material rupture leads to the radiation exposure. The RMS incessantly checks the level of radiation and makes the accelerator shutdown through the interlock system when detecting the higher level of radiation than it should be. If not tripped by the interlock system, the accelerator must be shutdown by the operator action using the ESB. Fig. 9 presents the event tree for shielding material rupture.

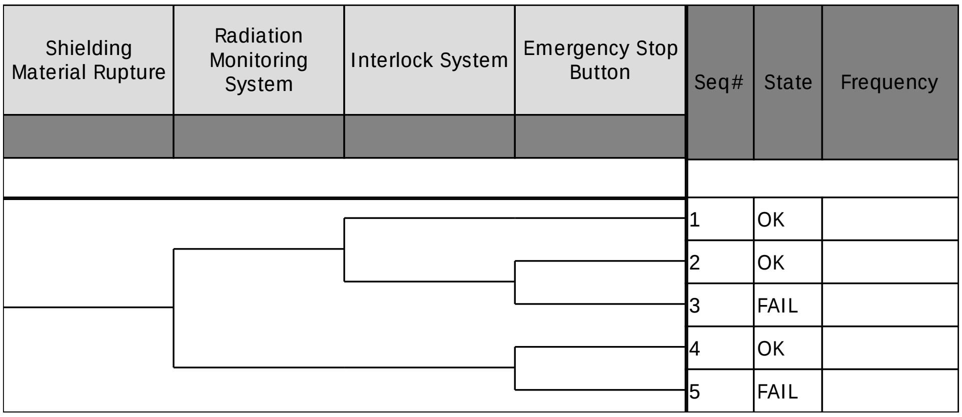

Fig. 9. Event tree for shielding material rupture

IV.D. Beam Window Rupture

Accelerated heavy ion beam is transported to experiment areas along with beam line. At the end of beam line, there is a beam window used to extract the beam for experiments. It must be designed to be able to withstand the high temperature and pressure difference caused by high current beam and the atmospheric pressure. When there is any faulty design or a use of excessive beam current, beam window rupture could happen. In case of beam window rupture, vacuum pumps can be damaged due to loss of vacuum and accelerator components can be activated. There is secondary beam window in case that primary beam window ruptures. Even if the secondary beam window fails to block radiation, the operator should obstruct the radiation using a fast closing valve. If the radiation obstruction using the secondary beam window and the fast closing valve fails, beam diagnostics can detect the beam status changes and then trip the accelerator. Fig. 10 shows the event tree for beam window rupture.

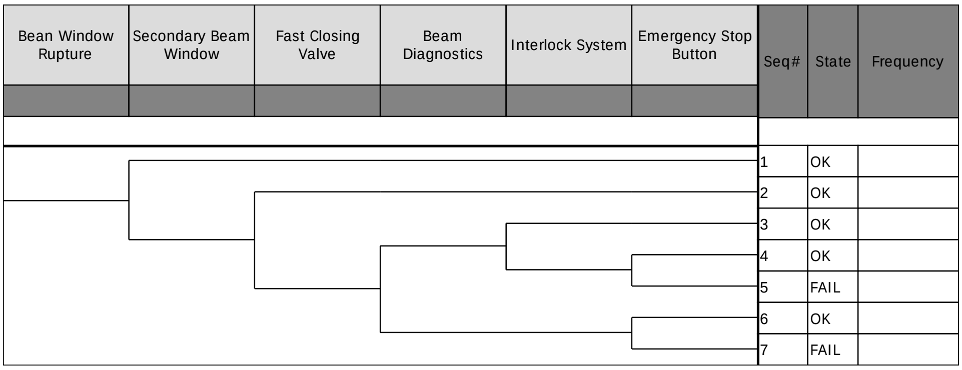

Fig. 10. Event tree for beam window rupture

IV.E. Access Control Failure

Access control system is the engineered safety system providing protection by assuring that no persons may occupy or enter an area where prompt radiation may be present. The system also restricts beam generation when improper access is gained. In addition, the operator runs the accelerator after confirming that no one is present there. If the access control system fails and any person gets inside a radiation area during accelerator operation, the person will be exposed to high radiation and get significantly injured. To prevent this, there is motion detecting sensors that disable the accelerator operation through the interlock system when they detect movement in the area. If the motion detecting sensors fail to detect, the operator has to stop the accelerator as soon as possible to minimize the radiation exposure. The event tree for access control failure is shown in Fig. 11.

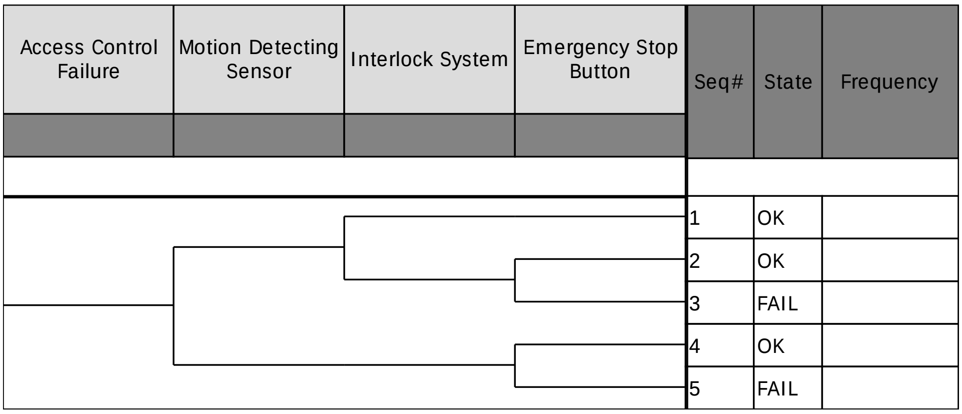

Fig. 11. Event tree for access control failure

V. CONCLUSIONS

In order to evaluate the potential risks of RAON, accident sequence analysis was performed. Accident sequences from the five internal initiating events identified through the MLD method were analyzed using the PRA techniques. As the accelerator facility is in the design stage where various configurations are under consideration now, only qualitative accident sequence analysis was conducted using the conceptual design information. After the detailed design is finalized, quantitative analysis will be done. Since there are several sections that all have different beams, targets, and designs, the analysis should also be conducted differently depending on each area. For example, when shielding material rupture occurs in the injector area and the IF area, different accident sequences may progress. The results of this study might contribute to assessing the accelerator system for future full probabilistic risk assessments.

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