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To cite this article: A Lee et al 2018 J. Phys.: Conf. Ser. 1046 012019

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Leakage of radioactive materials from particle accelerator facilities by non-radiation disasters like fire and flooding and its environmental impacts

A Lee, N S Jung, L Mokhtari Oranj and H S Lee*

Pohang Accelerator Laboratory, POSTECH, Pohang, 37673, Republic of Korea

*Email: lee@postech.ac.kr

Abstract. The leakage of radioactive materials generated at particle accelerator facilities is one of the important issues in the view of radiation safety. In this study, fire and flooding at particle accelerator facilities were considered as the non-radiation disasters which result in the leakage of radioactive materials. To analyse the expected effects at each disaster, the case study on fired and flooded particle accelerator facilities was carried out with the property investigation of interesting materials presented in the accelerator tunnel and the activity estimation. Five major materials in the tunnel were investigated: dust, insulators, concrete, metals and paints. The activation levels on the concerned materials were calculated using several Monte Carlo codes (MCNPX 2.7+SP-FISPACT 2007, FLUKA 2011.4c and PHITS 2.64+DCHAIN-SP 2001). The impact weight to environment was estimated for the different beam particles (electron, proton, carbon and uranium) and the different beam energies (100, 430, 600 and 1000 MeV/nucleon). With the consideration of the leakage path of radioactive materials due to fire and flooding, the activation level of selected materials, and the impacts to the environment were evaluated. In the case of flooding, dust, concrete and metal were found as a considerable object. In the case of fire event, dust, insulator and paint were the major concerns. As expected, the influence of normal fire and flooding at electron accelerator facilities would be relatively low for both cases.

1. Introduction

In Korea, particle accelerator facilities are classified as radiation generators (RG) in accordance with Nuclear Safety Act. Therefore, to satisfy the location standard of the radiation generator use and storage facility, the particle accelerator facility should be installed at a place with the less risk of a fire, inundation or ground subsidence [1]. There are also design criteria for reactor facilities with detailed requirements related to fire and flooding. In applying the current regulation, small radiation generators do not pose a serious problem because of the limited parts and areas where radiation can be generated. However, in order to apply the criteria to the licensing process of large accelerator facilities, it is required to adopt a somewhat excessive law that is not related to the degree of radioactivity of each facility. For this situation, detailed and reasonable requirements that can be used by regulators, builders and operators of large accelerator facilities are needed.

In this study, fire and flooding at particle accelerator facilities were considered as the non-radiation disasters which result in the leakage or spread-out of radioactive materials. To analyse the expected effects due to each disaster, the case study on fired and flooded particle accelerator facilities was carried
out with the property investigation of interesting materials presented in the accelerator tunnel and the activity estimation. Five major materials in the tunnel were considered: dust, insulators, concrete, metals and paints. Additionally, the activation levels on the concerned materials were calculated using three different Monte Carlo codes: MCNPX 2.7+SP-FISPACT 2007, FLUKA 2011.4c and PHITS 2.64+DCHAIN-SP 2001. Those estimations were carried out and compared each other for the different beam particles (electron, proton, carbon and uranium) and the different beam energies (100, 430, 600 and 1000 MeV/nucleon). This work aimed to evaluate the impacts to the environment, considering the leakage path of radioactive materials due to fire and flooding, and the activation level of selected materials.

2. Materials and methods

2.1. Case study of fire and flooding in particle accelerator facilities

2.1.1. Fire. Seven cases of fire accidents occurred in particle accelerator facilities were summarized in table 1. The fire accident that occurred in the underground accelerator room of Moscow nuclear institute, which had not been reported for its causes. All of other fire cases occurred on the electrical equipment. For J-PARC (Japan Proton Accelerator Research Complex) fire case, there was no leakage of radioactive material, taking into consideration the incident region of fire..

Table 1. List of fire case in particle accelerator facilities.

| Facilities (Nation) | Cause | Incident region | Progress and action | Leakage of radioactive material |
|---------------------|-------|-----------------|---------------------|---------------------------------|
| Fermilab (U.S.) [2] | Over-current in a cable | 34 wire ribbon cable | - Date: Oct. 3, 1987 - Fire spread along cable trays to eventually involve 4 particle detectors. - 5 sprinklers were activated. | Not described |
| Cornell's Particle Accelerator (U.S.) [3-5] | Power supply equipment used for 30 years | Wilson Synchrotron Laboratory | - Date: Sep. 16, Oct. 14, 2009 - Fire was quickly put out. - The laboratory is located in the north section of the underground accelerator ring | Not described |
| Moscow nuclear research centre (Russia) [6,7] | - | Alikhanov Institute of Theoretical and Experimental Physics | - Date: Feb. 5, 2012 - A non-operational 60-year-old reactor and the collider shut off on Dec. 25 were located. - No radiation sources in collider area. - No flames and only smoke came from an area with power cables and could not affect any nuclear materials. | Not described |
| SLAC (U.S.) [8-11] | Electrical fire from switchgear cabinet | Sector 26 of the klystron gallery | - Date: Jun. 25, 2014 - Power to the switchgear was de-energized by SLAC high voltage electricians. - Fire was extinguished in 45 minutes. | Not described |
| J-PARC (Japan) [12-14] | Diesel generator | - | - Date: Jul. 2014 | No |
| | Circuit design of newly installed transformer | Muon D-line area in the 2nd Experimental Hall | - Date: Jan. 16, 2015 - The place is located in the Materials and Life Science Experimental Facility - Fire was immediately extinguished with a fire extinguisher - No radiation exposures and no injuries | No |
2.1.2. Flooding (Inundation). Flooding events at Fermilab and J-PARC facilities were investigated and table 2 shows the details. Fermilab has a pond where the rainwater is collected and used as cooling water. When a large amount of rainfall occurred, Fermilab was flooded because of the pond [15,16]. Two cases of flooding that occurred in J-PARC were investigated. The earthquake that struck Japan in March 2011 cut off the power supply to the pump used to discharge the groundwater in the accelerator tunnel, and the linear accelerator tunnel was flooded. It should be noted that the groundwater infiltrated by concrete during the weekly immersion period was measured as a strong alkaline (pH 11) at the center of linear accelerator tunnel. This caused the aluminium pre-amplifier box located at the bottom of the tunnel to be corroded. Therefore, not only water but also alkali solvents were considered in the flooded situation. The flooding that occurred in 2014 was caused by the problem with the valve connection in the leak test for the new cooling water line (CW line). After the incident, radiation survey were carried out but no leakage of radioactive material was observed [18-22].

| Facilities         | Cause                              | Incident region                                                                 | Progress and action                                                                                     | Leakage of Radioactive material |
|--------------------|------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|-------------------------------|
| Fermilab (U.S.) [15,16] | Rainfall (46.72 cm)                | Main ring tunnel (Linac, booster, anti-proton source: not flooded)            | - Date : Jul. 17-18, 1996  
- Tevatron accelerator was shut down.  
- Water was pumped on Jul. 18  
- Recovery efforts at the laboratory were under way by Jul. 22.  | Not described |
| J-PARC (Japan) [17-22] | Loss of power for water pumping system | Inside of accelerator tunnel                                                   | - Date : Later than Mar. 11, 2011  
- 1 cm deep water was on the floor (Mar. 17) and Max. depth of water reached 10 cm (Mar. 24)  
- pH 11 of water in the tunnel.  
- Aluminum pre-amplifier boxes were corroded.  
- Radiation survey work at the RCS and MR tunnel were carried out.  | No |
| Mis-connected valve, Muon facility | Rainfall                           | - Date : Sep. 2014                                                            | -                                                                                                     | - |

2.2. Selection of interesting material inside the particle accelerator tunnel
The materials that could leak to the outside of the accelerator tunnel when fire or flooding occurred inside the accelerator tunnel were selected in the case study. Five major materials in the tunnel were investigated: dust, insulators, concrete, metals and paints.

- Dust normally exists on the accelerator devices and the tunnel wall. According to the IAEA report (Technical Reports Series No. 188), exposure due to activated dust can be done when an operator enters a tunnel after a shutdown of the accelerator and an evaluation of dust should be performed in such a situation. [34].
- Concrete is the most basic material that constitutes the accelerator tunnel, and plays an important role as a structure safety and radiation shield [35].
Many kinds of metals are commonly used as constituent of accelerator devices. Residual radiation from metal devices is a major contributor to exposure to maintenance worker. Four types of metals were considered: aluminium, iron, stainless steel, and copper.

Carbon compounds are often used in the accelerator tunnels as insulators like control and signal processing cables and wires. Three types of carbon compounds were considered in this study: polyvinylchloride (PVC), polytetrafluoroethylene (Teflon), and polyimide (Kapton).

A few kinds of paints coat the accelerator tunnel wall, floor and components. The concerned kinds of paint were acrylic resin-based paints used for coating accelerator tunnel walls and epoxy-based paints used for the accelerator tunnel flooring and metal parts painting. The paint type used for Pohang Accelerator Laboratory was investigated [36].

2.3. Activation calculation of the material inside the accelerator tunnel

The activation levels of the concerned materials were calculated using several Monte Carlo codes, FLUKA 2011.4c [37], MCNPX 2.7 [38] + SP-FISPACT 2007 [39] and PHITS 2.64 [40] + DCHAIN-SP 2001 [41]. In this calculations, several conditions of the beam particle, the target condition and the geometry were analyzed. The activation levels of each material were estimated in the cases of different beam energies of 100, 430, 600 and 1,000 MeV/nucleon and different beam particles of electron, proton, carbon and uranium. The shape of all particle beams was assumed to be flat_R with 1 cm diameter, and the target was a cylindrical copper with a radius of 2 inches (= 5.08 cm) and a thickness of 20 cm. The target was surrounded by disk-shaped samples with a volume of 10 cm³ (diameter: 2.52 cm, thickness: 0.5 cm), shown as figure 1, and the materials of activation samples were ST-37 and ST304L for metals, ANSI-ANS concrete for concrete, and Kapton for insulators. For paint, it is assumed to be epoxy resin based on the fact that the paint used for the tunnel floor and metal painting is epoxy resin type.

![Figure 1. Schematic view of the target and samples-cross-sectional view (left) zy axis. (right) xy axis](image)

3. Results and discussion

3.1. Characteristics of materials to be considered in case of fire and flooding at the tunnel

3.1.1. For fired particle accelerator tunnel. According to the case study, electric fire is probable by a short circuit, and an overcurrent, etc. and the carbon-compound based insulator was assumed as an ignition source. The characteristics of three insulators (PVC, Teflon and Kapton) were investigated and described in table 3. The flash point and the spontaneous ignition temperature measured according to the ASTM D1929 standard of material test and material specifications were used [42-44] at this study. There are two situations that can cause a fire. The first is when the temperature of the insulator reaches
the flash point by the heat. And the second is when spontaneous ignition may occur because it reaches the ignition point.

Considering the characteristics of the insulator, the insulator will be the material difficult to be burnt in general circumstances. However, in other studies, a combustion in tunnel were reported at situations which a large amount of insulators and cables are placed in the tunnel. The temperature inside the tunnel when a fire occurs due to the combustion of the insulator inside the accelerator tunnel is good reference to consider the combustion of the cable placed in the cable tray. The maximum temperatures measured by the thermocouples which were arrayed at a distance of 1.5 m from the cable tray were about 150 °C for a 0 mm spacing of the cable and 200 ~ 250 °C for a 9.2 mm spacing [45]. The experimental results on combustion temperature of the cable were also found in a study on the functional failure temperature of cables in a nuclear power plants. As a result of the cable combustion test, it was confirmed that most of the cables start to be burned at 450 °C of tunnel fire temperature. [46]. Based on the characteristics of the cable and the experimental results of these studies, it is assumed that insulator was burned at 450 °C and the temperature inside the tunnel that can be reached through the combustion of the insulator is 150 ~ 250 °C.

Table 3. Properties related with fire of insulators (PVC, Teflon, and Kapton).

| Material          | Maximum service temperature, Air (°C) | Flammability, UL94 a [68,69] | Melt temperature (°C) | Flash-ignition a (°C) [42-44] | Self-ignition a (°C) [42-44] |
|-------------------|--------------------------------------|-----------------------------|-----------------------|-------------------------------|------------------------------|
| Polyvinylchloride (PVC) | 40~100 | HB b ~ 5VA c | 154~213 | 330~400 | 385~450 |
| Teflon (PTFE)     | 482   | V-0 d         | -        | 560   | 580   |
| Kapton (polyimide)| 400   | V-0           | -        | -     | -     |

a Flammability, UL94 : “The Standard for Flammability of Plastic Materials for Parts in Devices and Appliances”, is one of the most widely accepted flammability performance standards for plastic materials.

b HB : slow burning on a horizontal specimen less than 76 mm·min⁻¹ for thickness less than 3mm.

c 5VA : After flame or afterglow time ≤60 seconds after 5th flame application, specimen may not have a burn-through

d V-0 : burning stops within 10 seconds, no drips allowed.

The effect of fire on the concrete was investigated in terms of temperature change and summarized in table 4. Considering the temperature at which the explosive fracture and melting occurs (1,200 °C) and the temperature at which the insulator can ignite (330 ~ 580 °C), the possibility of explosion and melting of concrete is low at the particle accelerator tunnel. In addition, concrete is a nonflammable material, so the possibility of leakage of radioactive material from concrete when a fire occurs is considered to be relatively low [47].

Table 4. Property-changes of concrete depending on temperature [47].

| Property-changes                                      |
|------------------------------------------------------|
| 100°C or higher - Free pore water release             |
| 100~200°C - Physically adsorbed water is released and concrete is shrunk. |
| 300°C or higher - Safety is ensured.                 |
| 400°C or higher - Cement hydrate in the concrete chemically altered |
| 500°C or higher - Release chemical combined water     |
500°C or higher - Calcium hydroxide(Ca(OH)$_2$) is thermally decomposed (pyrolysis), durability significantly reduced and 50% reduction in strength by heating
600–800°C - Cement paste is shrunk and aggregate has blowout.
- 80% reduction in strength by heating
1,000–1,200°C - Explosive fracture (Spalling failure) occurs
1,200°C - Melting occurs

The characteristics of the metal were investigated in terms of melting point, boiling point and vapor pressure shown in table 5 [48-51]. These temperatures are much higher than the temperature that can be reached by the combustion of the insulator inside the tunnel. It is expected that the possibility of burning and the effect of fire on metal in the event of fire will be significantly low and the leakage of radioactive material rarely occurs.

| Melting Point (°C) | Boiling Point (°C) | Vapor pressure (°C) |
|-------------------|-------------------|--------------------|
| Aluminum [48]     | 660.37            | 2,519              |
| Steel (iron) [49] | 1,535             | 2,861              |
| Stainless-steel [50] | 1,400–1,455     | 2,750              |
| Copper [51]       | 1,083.2–1,083.6   | 2,562              |

The paint is assumed to be ignited by the contact of flames generated on insulator. The flash point is mainly considered. Both acrylic resin-based paints and epoxy-based paints have a flash point of about 30 °C and the conditions are summarized in table 6 [52-63].

| Coating place | Flash-ignition (°C) | Self-ignition (°C) |
|---------------|---------------------|--------------------|
| Acrylic resin-based paint | Accelerator tunnel wall | 36 | 480 |
| - ACRYDIC A-846 [52] |                      |                   |
| Epoxy resin-based paint | Accelerator tunnel floor | 24 | - |
| - NUKOPOX PRIMER EP103, NUKOPOX TOPCOAT ET597 | Metal component (magnet, support) | EP103 : 25–26 | EP103 : 343–464 |
| | | ET597 : 23–25 | ET597 : 343–464 |

3.1.2. For flooding particle accelerator tunnel. In the case of flooding, the materials placed inside the tunnels were analysed with respect to the solubility and corrosiveness to water and alkali solvents, and to water absorption rate and reactions with water. Dust on the tunnel wall and accelerator devices would be easily rinsed off with water when the flooding occurs inside the accelerator tunnel. Concrete can react with water and the hydration reaction occurs. Among the compounds of the cement, C$_2$S reacts with water to form calcium hydroxide (Ca(OH)$_2$) and calcium silicate hydrate (C-S-H), and then the liquid phase becomes highly alkaline [64]. This phenomenon was confirmed in the J-PARC accelerator tunnel flooding case. The solubility and corrosiveness of metals in water and alkali solvents were investigated and summarized in table 7 [48-51]. Four types of metals are not dissolved or corroded in water, but are soluble in alkaline solvents. So the immersion is important issue to be considered.
Table 7. Solubility for Water and Alkaline of Metals (aluminum, steel, stainless-steel, and copper).

| Solubility (Corrosiveness) | Water | Alkaline |
|---------------------------|-------|----------|
| Aluminum [48]             | Insoluble | Dissolved |
| Steel (iron) [49]        | Insoluble | Dissolved |
| Stainless-steel [50]    | Insoluble | Dissolved |
| Copper [51]               | Insoluble | Dissolved (slowly) |

In the case of insulators, the water absorption, the resistance to water and alkali solvents, and insolubility were considered and summarized in table 8 [32, 65-67]. The water absorption rate of the insulators was used to determine the possibility that the radionuclides produced in the insulators were leaked to the outside through the absorption and re-emission of water. The water absorption rates of three kinds of insulators (PVC, Teflon, Kapton) were found to be as low as 0 ~ 1.3% [32]. PVC and Teflon have low solubility and good chemical resistance to strong alkaline solvent. It is likely to dissolve in a flooded environment because of its good resistance to most cast of acids and alkalis.

Table 8. Absorption and resistance for water and alkaline of insulators (Polyvinylchloride, Teflon and Kapton) [32,33-46].

| Water Absorption (%) [32] | Resistance | Solubility |
|--------------------------|------------|------------|
| Polyvinylchloride (PVC) [65] | 0.06 | Good resistance | Good resistance | Insoluble |
| Teflon (PTFE) [66] | 0 (<0.01) | Excellent chemical resistance | Excellent chemical resistance | Insoluble |
| Kapton (polyimide) [67] | 1.3 | Greater resistance | - | Insoluble |

Paint was classified into the acrylic resin type paint and the epoxy type paint. Characteristics of each type of paints were investigated and this is shown in table 9. Acrylic resin-based paints (Aekyung Chemical, ACRYDIC A-846) have excellent chemical resistance against 5% NaOH and 5% H2SO4, respectively [52]. Epoxy-based paint (Epocop 210 from Samwha paint) is used for coating the bottom of accelerator tunnel. This paint has excellent adhesion and durability for water and alkali solvents, as well as excellent abrasion resistance, rust prevention, chemical resistance, water resistance, water insolubility, water resistance, acid resistance and alkali resistance [53]. Paint used for coating the electronic devices (KCC NUKOPOX PRIMER EP103, NUKOPOX TOPCOAT ET597) has excellent water resistance, acid resistance and alkali resistance. Therefore, paint is less likely to react with water and dissolve, so it is unlikely that radioactive materials will leak out in flood situations [52-63].

Table 9. Properties of paints (acrylic resin-based paint and epoxy resin-based paint).

| Coating place | Resistance | Solubility |
|---------------|------------|------------|
| Accelerator tunnel wall | Resistant (Excellent for 5% NaOH) | - |

Acrylic resin-based paint - ACRYDIC A-846 [52]
3.1.3. Flow of influence on material during fire-flooding event. The influences on the material were designed in various cases based on the characteristics of the materials in the event of fired or flooded particle accelerator tunnel, shown in figure 2 and 3. First, it is assumed that fire in the accelerator tunnel is an electric fire caused by leakage of current, overcurrent (overload), etc., and that ignition occurs on the insulator. In addition, due to the ignition of the insulator, the paint on the accelerator device will also burn, which is expected to raise the temperature of the surrounding materials. Concrete is a non-flammable material so will not be directly combusted. With the consideration on the property change due to temperature rise, it is expected that the effect of fire on concrete will be relatively low since the tunnel temperature will be considerably lower than the temperature at which explosion or melting occurs.

Considering that the melting point, boiling point and vapor pressure of metals are mostly over 2,000 °C, the possibility of leakage of radioactive materials is expected to be ignorable. Dust will not burn significantly since there is generally a small amount of dust around the cable. However, there is a possibility of leaking into the outside environment due to activated dust floating through air. If there is a large amount of dust accumulated for several years, accidents such as ignition and dust explosion may occur, so that dust management should be performed regularly.

In the case of flooded accelerator tunnel, dust located near the floor and devices can be easily washed away by water, hence consideration of the amount of dust and the activation level are needed. Concrete is supposed to produce alkali solvent by the hydration reaction and this can affect other materials. But additional consideration is needed, such as the immersion duration and hydration reaction speed. Metals are expected to dissolve and corrode by alkali solvent, but this will be determined according to flood (water) level. According to the case study, the water level was below the girder height in the general flood situation and the accelerating devices were not flooded. Insulators and paints are less likely to leak radioactive materials due to their reaction with water, according to the properties of Teflon and PVC and paint. However, the degradation of insulators caused by radiation damage is also a factor to be considered.

![Figure 2. Assumed flow of affection on materials and leakage of radioactive material.](image)
3.2. Calculation result of the interesting material inside the accelerator tunnel

3.2.1. Comparison of Monte Carlo codes and activated materials. Figure 4 shows the specific activities generated in the metal (ST304L) calculated by Monte Carlo codes. For the proton beam, the calculation results of the three Monte Carlo codes were similar, but the results of MCNPX code were the largest. However, the calculation results of FLUKA code were the highest for heavy ion beams (carbon and uranium). The radionuclides generated in the disk-shaped metal (ST304L), concrete (ANSI-ANS), insulator (Kapton) and paint (epoxy) around the target when the carbon beam of 430 MeV energy enters the copper target are shown in table 10. Radionuclides generated in each material after 1 day cooling time were analysed to reduce the effects on the short-lived radionuclides (less than 1 day). ST304 contains 69.5% of $^{56}\text{Fe}$ and 17.8% of $^{52}\text{Cr}$ as well as other impurities such as $^3\text{C}$ and $^{14}\text{Si}$. As result of activation calculation, $^{44,44m}\text{Sc}$, $^{48,49}\text{V}$, $^{51}\text{Cr}$, $^{52,54}\text{Mn}$, $^{55}\text{Fe}$, $^{58,58m}\text{Co}$ and $^{57,60}\text{Ni}$ were mainly produced. In ANSI-ANS concrete, $^3\text{H}$, $^7\text{Be}$, $^{22,24}\text{Na}$, $^{37}\text{Ar}$, $^{54}\text{Mn}$, $^{55,56}\text{Fe}$ and $^{57,60}\text{Co}$ were produced and most of the radionuclides are long-lived (several hundred to several decades). For Kapton and Epoxy, the main radionuclides produced are $^3\text{H}$, $^7\text{Be}$, and $^{11,14}\text{C}$ and can contribute to residual radiation as a long-lived radionuclides. In addition, the ratio between calculated specific activities of each radionuclides in interested materials are shown in figure 5. As a result, FLUKA code produced more radionuclides than MCNPX and PHITS code.
Figure 4. Total specific activities calculated by three Monte Carlo codes.

Table 10. Specific activity of major materials in accelerator tunnel (cooling time: 1 day).

| Material          | Dominant radionuclides from FLUKA code calculation |
|-------------------|---------------------------------------------------|
| Metal (ST304L)    | $^{44,44m,4}$Sc, $^{48,49}$V, $^{51}$Cr, $^{52,54}$Mn, $^{55}$Fe, $^{58,58m}$Co, $^{57}$Ni |
| Concrete (ANSI-ANS)| $^{7}$Be, $^{24}$Na, $^{31}$Si, $^{32}$P, $^{37}$Ar, $^{42,43}$K, $^{45,47}$Ca, $^{51}$Cr, $^{55,59}$Fe |
| Insulator (Kapton)| $^{3}$H, $^{7,10}$Be, $^{11,14}$C                  |
| Paint (Epoxy)     | $^{3}$H, $^{7,10}$Be, $^{11,14}$C                  |
Figure 5. Ratio between calculated specific activities of each radionuclides in interested materials irradiated by 430 MeV·n⁻¹ ¹²C using different Monte Carlo codes.

The specific activities in terms of arbitrary unit according to the cooling time was calculated and shown in figure 6. The specific activities of the interested materials decreased in the form of stairs and decreased by a factor of more than 10 times in 24 hours after the irradiation.

Figure 6. Specific activity of each radionuclide produced in insulator (Kapton) irradiated by 430 MeV·n⁻¹ ¹²C.
3.2.2. *Comparison of the specific activities for the beam energy and particles.* Figure 7 shows the clearance index of interested materials for various beam energies and particles. The higher beam energy and the atomic number of the beam particles, the higher specific activities and the higher ratio to the clearance index were calculated. Total specific activity of interested material was high in the order of uranium, carbon, proton and electron beam. The highest specific activity of ST-37 was calculated for uranium beam and is 5,200 times higher than for electron beam. In the case of the same incident beam, the specific activity is high in the order of metal, concrete, insulator and paint, and calculated to be 800 times higher than the clearance level. Therefore, it is necessary to consider the activation level for the different beam energy, particle and the material inside the tunnel.

![Figure 7](image)

**Figure 7.** Clearance index of interested materials for different beam energy and particle.

3.3. *Comparison of impacts on external environments in fired and flooded particle accelerator facilities*  
According to the assumed influence on materials, it was found that three materials can be affected by fire, which are dust, insulation and paint. Dust is expected to be negligible in general situations. However, it will be necessary to continuously manage the emission of dust in a region where dust can be accumulated and the beam loss region. Insulators and paints can be burned, but the activation level is significantly lower than those of other materials. For flooding, it is assumed that dust, concrete, and metal are likely to be affected by inundation. However, the amount of dust accumulation can be controlled by cleaning, and the activation level is low. It was expected that the exposure by activated dust and the influence on the external environment will be insignificant. Concrete is expected to elute alkaline ions by the reaction with water, and there is a possibility that radioactive nuclides will escape from this reaction. However, in the case of flooding occurred at the J-PARC facility, radioactive nuclides were not detected in the water. Metal is one of the main materials to be activated in the tunnel and activation level is 4 ~ 5 times higher than insulator according to the activation calculation. Metal can be corroded by alkaline water, however, it is considered that the metal device are placed on the girder so that the flooded water level must be evaluated together. Following the case study on flooding, the flooded water level was limited to below the girder so the possibility of leakage of radioactive material due to flooding of radioactive metal parts is expected to be low. In the case of insulator, it is assumed that the insulator needs to be considered depending on the degree of degradation due to activation.
4. Conclusion
In this study, fire and flooding at particle accelerator facilities were considered as the situation which results in the leakage or spread-out of radioactive materials. To analyze the possibility of leakage of radioactive materials, case studies on fired and flooded particle accelerator facilities, the property investigations of interesting materials, and the activity estimation were performed. In the case of fire, dust, insulator, and paint can burn and float into the air, so there is a possibility of leakage of radioactive material. However, considering the activation level of the interested material, the influence on the external environment is confirmed to be low. In the case of flooding, there is a possibility of leaking of radioactive material presented in dust and metal. If considering the amount of dust in the general situation, the influence on the external environment may be small. Metals are highly radioactive but additional considerations are needed to ensure that the level of flooded water to reach the activated metal devices. Only the alkaline water due to the reaction of water with concrete can be considered seriously.

The activation calculations for concrete, metal, insulator and paint were performed for the various conditions of different beam energies and particles. When the same beam energy and beam particles were irradiated to each material, the activation level was different depending on the materials and high in the order of metal, concrete, insulator and paint. When irradiated with the same beam energy, different kinds of incident beam particles, the activation level was high in the order of uranium, carbon, proton, and electron. Therefore, to develop more practical regulation, it is necessary to consider the difference depending on the beam energy, beam particle, and the area where activation is produced in the accelerator facility.

References
[1] Korea Institute of Nuclear Safety 2014 Regulations on technical standards for radiation safety control, Etc
[2] Hinds S S 2011 Fire lessons learned in the nuclear industry. American Glovebox Society
[3] http://cornellsun.com/blog/2009/09/17/electrical-unit-catches-fire-at-synchrotron-laboratory/
[4] http://cornellsun.com/blog/2009/10/14/old-equipment-sparks-fire-at-synchrotron/
[5] http://bilmes.blogspot.kr/2009/09/fire-in-cornells-particle-accelerator.html
[6] http://www.reuters.com/article/2012/02/05/us-russia-fire-nuclear-idUSTRE8140J520120205
[7] http://bellona.org/news/nuclear-issues/accidents-and-incidents/2012-02-update-fire-breaks-out-at-central-moscow-nuclear-research-institute
[8] http://news.stanford.edu/news/2014/june/slac-fire-story-062714.html
[9] http://www.dailymail.co.uk/wires/ap/article-2670554/Fire-shuts-Stanford-linear-accelerator.html
[10] http://www.almanacnews.com/news/2014/06/27/menlo-park-fire-temporarily-shuts-down-slac-linear-accelerator
[11] https://news.slac.stanford.edu/announcement/electrical-fire-sector-26
[12] https://j-parc.jp/en/topics/20150219press.html
[13] http://j-parc.jp/en/topics/20150116press.html
[14] Saito N 2015 Overview of recovery efforts from the incident. The 2nd Int. Symp. on Safety in Accelerator Facilities (Tokai)
[15] Fermi National Accelerator Laboratory 1996 FermiNews 19 pp 1-4
[16] U.S. Department of Energy 2013 Annual Laboratory Planning Fermilab 22
[17] MIURA A 2011 Progress of beam instrumentation in J-PARC linac. Int. Beam Instrumentation Conf. (Ibaraki)
[18] Yamamoto K 2012 J-PARC recovery status. Institute of High Energy Physics
[19] Hasegawa K 2012 Recovery of the J-PARC linac from the earthquake. Linear Accelerator Conf. (Tel Aviv)
[20] Hasegawa K, Kinsho M and Koseki T 2011 Status of J-PARC accelerator facilities after the great east Japan earthquake Int. Particle Accelerator Conf. (San Sebastian)
[21] Yamamoto K 2012 Comparison of the residual doses before and after resumption of user operation in J-PARC RCS. *Int. Particle Accelerator Conf.* (New Orleans Louisiana)

[22] Oguri H, Ikegami K, Ohkoshia K, Koizumia I, Namekawab Y, Unnoa A, Takagia A and Yamazakia S 2013 Operation status of the J-PARC negative hydrogen-ion source. *American Institute of Physics Conf.* 379-85

[23] Charalambus S T and Rindi A 1967 *Nuc. Instr. and Meth.* 56 125-35

[24] U.S. Department of Energy 1979 *Radiological environmental impact of high-energy accelerators.* LBL-6169 pp 82-3

[25] Pohang Accelerator Laboratory 1997 *Dust radioactivity in the tunnel of Pohang light source.* PAL-PUB-97-017 pp 1-5

[26] GSI Proposal for experiment S291 Residual radioactivity induced by U ions - experimental investigation and lifetime predictions.

[27] GSI *Decontamination and surface properties of the controlled areas of FAIR* 2012

[28] Masumoto K, Toyoda A, Eda K, Izumi Y, Shibata T J. *Radioanal. Nucl. Chem.* 465-9

[29] Sonck M, Buls N, Hermande A and Eggermont A G 2000 Radiological and economic impact of decommissioning charged particle accelerators. *Waste Management Conf.* (Tucson)

[30] Fasso A, Silari M and Ulrici L 2000 *Nucl. Sci. Tech.* 827-34

[31] Eggermont G X, Buls N and Hermande A 1996 *Decommissioning analysis of a university cyclotron*

[32] CERN European Organization for Nuclear Research 1979 *Compilation of radiation damage test data - Part 1: Cable insulating materials* pp 5-8

[33] KCC. Heavy duty coating technical data sheets

[34] International Atomic Energy Agency 1979 *Radiological safety aspects of the operation of electron linear accelerators. Technical reports series no.* 188 pp 131-6

[35] Korea Atomic Energy Research Institute 2008 *Proton engineering frontier project - Radiation shielding and safety design.* KAERI/RR-2888/2007 pp 64-5

[36] Pohang Accelerator Laboratory 2011 *Painting specifications for linear accelerator and storage ring* pp 1-17

[37] Fasso A, Ferrari A, Ranft J and Sala P R 2005 *The FLUKA Code: a multi-particle transport code.* CERN-2005-10, INFN/TC_05/11, SLAC-R-773

[38] Los Alamos National Laboratory 2011 *MCNPXTM user’s manual version 2.7.0.* LA-CP-11-00438 pp 5-56 - 65

[39] Forrest R A 2007 *FISPACT 2007 User Manual EASY 2010, UKAEA FUS* 534

[40] Niita K, Sato T, Iwase H, Nose H, Nakashima H and Sihver L 2006 *Radiat. Meas.* 41 1080-90

[41] Takata H and Kosako K 1999 Development of the DCHAIN-SP Code for Analyzing Decay and Build-up Characteristics of Spallation Products, *JAERI-DATA/Code 99-008*

[42] American Society for Testing and Materials International 2016 *Standard test method for determining ignition temperature of plastics D1929-16* pp 1-6

[43] Occupational Safety and Health Research Institute 2003 A study on the characteristics of fire hazard for plastic materials pp 11-23

[44] Poly Marketing. PVC and fire 2

[45] Xianjia H, Kun B, Xiaoshuang L, Jianxin Y and Xi J 2015 A model for predicting temperature produced by upward spreading cable fire under natural ventilation, *Energy Procedia* 66 177-80

[46] Kim D H and Lim H S 2011 *J. KOSOS* 26 41-45

[47] Lee C H, The impact of fire on buildings 2-3

[48] https://ko.wikipedia.org/wiki/%EC%95%8C%EB%A3%A8%EB%AF%B8%EB%8A%84

[49] https://ko.wikipedia.org/wiki/%EC%B2%A0

[50] https://ko.wikipedia.org/wiki/%EC%8A%A4%ED%85%8C%EC%9D%B8%EB%A6%AC%E C4%EA%B0%95

[51] https://ko.wikipedia.org/wiki/%EA%B5%AC%EB%A6%AC
[52] Aekyung Chemical Co, LTD. ACRYDIC A-848-RN, ACRYDIC A-837/A-846 2003
[53] Samhwa Paints Industrial Co. LTD. Material safety data sheet(MSDS)-3100247 2014
[54] KCC. Material safety data sheet (MSDS) - EP103PTB 2013
[55] KCC. Material safety data sheet (MSDS) - EP103PTA-N.7.0 2013
[56] KCC. Material safety data sheet (MSDS) - ET597PTB 2013
[57] KCC. Material safety data sheet (MSDS) - ET597PTA-VQ63G 2013
[58] KCC. Material safety data sheet (MSDS) - ET597PTA-5Y7/6 2013
[59] KCC. Material safety data sheet (MSDS) - ET597PTA-2.5Y8.5/2 2013
[60] KCC. Material safety data sheet (MSDS) - ET597PTB 2013
[61] KCC. Material safety data sheet (MSDS) - EP103PTA-N.7.0 2013
[62] KCC. Material safety data sheet (MSDS) - EP103PTA-N.7.0 2013
[63] KCC. Material safety data sheet (MSDS) - ET597PTA-2.5G7/2 2014
[64] http://www.tycement.co.kr/kor/develop/data/cement_09.pdf
[65] Occupational Safety and Health Research Institute 2003 A study on the characteristics of fire hazard for plastic materials pp 11-23
[66] DuPont. Properties handbook - Teflon PTFE. (7/96) 220313D pp 1-34
[67] Ministry of Economy, Trade and Industry 1992 High-tech industry technical dictionary. Gyeomjisa p 158
[68] http://ulstandards.ul.com/standard/?id=94
[69] http://www.thermon.com/ThermoTips/Flammability%20Testing.pdf