Activation Levels, Handling, and Storage of Activated Components in the Target Hall at FRIB

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Abstract. The Facility for Rare Isotope Beams (FRIB) is a major new scientific user facility under construction in the United States for nuclear science research with beams of rare isotopes. 400 kW beam operations with heavy ions ranging from oxygen to uranium will create a high radiation environment for many components, particularly for the beam line components located in the target hall, where approximately 100 kW of beam power are dissipated in the target and another 300 kW are dissipated in the beam dump. Detailed studies of the component activation, their remote handling, storage, and transport, have been performed to ensure safe operation levels in this environment. Levels of activation are calculated for the beam line components within the FRIB target hall.

1. Radiation Transport Scope within the FRIB Target Facility

The FRIB scope is shown in figure 1. The Target Facility encompasses a pre-target beam delivery system area, production target systems located in the target hall, and the fragment separator. The fragment separator (figure 2) is designed for production and delivery of rare isotopes with high rates and high purities to maximize FRIB science reach. It is planned to accept a primary beam power of 400 kW, with beam energies of more than 200 MeV/u.

The target hall will have a high radiation environment, with two major sources of radiation: beam power dissipated in the target (~100 kW) and beam power dissipated in the beam dump (~300 kW). Both target and beam dump will be periodically replaced. The highest activated component will be post-target magnet shield located downstream of the target module.

Radiation transport analysis supports technical design and safe operation of the entire project. The scope of this paper is the description of some analysis specific to the Target Facility (see figure 1). The radiation transport model of the target hall and its components is based on engineering models developed from mechanical and facility designs that were converted using code MCAM [1] and geometry visualization software VISED [2] for use by the Monte-Carlo codes PHITS [3] and MCNP [4] to evaluate the radiation environment. High level of detail in the model supports construction and preparation for operations.
Figure 1. FRIB scope. The Target Facility contains the target hall.

Figure 2. Target hall fragment separator. On the right: Three vacuum vessels with beam line components such as target, beam dump, and magnets; multi-colored, multi-shaped blocks represent re-entrant shielding above the vessels that house the beam line components.
2. Radiation Transport Analysis of Activated Beam Line Components

Activation calculations are performed for all beam line equipment. Conservative beam variety and energy choices are employed. As an example, table 1 shows unshielded dose rates for the highest activated components at 30 cm distance, calculated for a $^{48}$Ca beam at 549 MeV/u (a conservative beam/energy assumption), and at 400 kW total power. Irradiation and cooling times are based on planned component service lifetimes and estimated times for preparation activities prior to removal, respectively: targets will be replaced every one to two weeks, depending on experiment, while beam dump will be replaced once a year. The post-target magnet shield, a bronze block with a 40 mrad conical aperture, placed right after the target module to shield the magnets downstream of the target, is planned to last for 30 years, the nominal facility lifetime.

Table 1. Unshielded dose rates from highest activated components at 30 cm.

| Component                | Irradiation Time | Cooling Time | Dose Rate, rem/h |
|--------------------------|------------------|--------------|-----------------|
| Target Module            | 14 days          | 4 hours      | 13              |
| Beam Dump Module         | 1 year           | 16 hours     | 51              |
| Post-Target Magnet Shield| 30 years         | 2 days       | 1547            |

The high dose rates impact operational scenarios. Highly activated components need to be adequately shielded in order to maintain hands-on access to the target hall when shielding is in place and the beam is off. FRIB minimizes radiation exposure to levels as low as reasonably achievable (ALARA) and well below regulatory limits, and uses engineering and administrative controls to maintain safe radiation exposures in occupied areas. Table 2 lists regulatory limits and MSU ALARA limits for general public and radiation workers applicable to FRIB and used in the present analysis. For reference, 1 mSv = 100 mrem.

Table 2. Radiation protection limits and goals at FRIB.

| Radiation Dose – Worker | Standard*: 5,000 mrem/yr | MSU ALARA Goal**: 500 mrem/yr |
|-------------------------|---------------------------|-------------------------------|
| Radiation Dose – Public | Standard*: 100 mrem/yr and < 2 mrem/(any one hour) | MSU ALARA Goal**: 10 mrem/yr and < 2 mrem/(any one hour) |
| Air - maximum exposure to nearest receptor | Standard*: 10 mrem/yr | MSU ALARA Goal**: 1 mrem/yr |
| Groundwater – effluent  | $^3$H Standard*: 1,000 pCi/ml | FRIB Design Goal: 20 pCi/ml (drinking water standard***) |
|                         | $^{22}$Na Standard*: 6 pCi/ml | FRIB Design Goal: 0.4 pCi/ml (drinking water standard***) |

3. Remote Handling

A remote handling system is used to handle highly activated components. The systems consists of a remotely operated bridge 20 ton crane, a window workstation with master-slave-manipulators, a remote viewing system (cameras), a remote handling equipment lift, and tooling for handling. When the beam is off and re-entrant shielding (see figure 2) of the vacuum vessels is in place, hands-on access to the target hall is possible. The estimated 80 hours/year time allowed for personnel access to the target hall for target changes results in personnel doses below MSU ALARA limit of 500 mrem/year. Operations also can include manual utility disconnect, re-entrant lid bolting, as well as general cell maintenance. Whenever the beam is on, or the re-entrant shielding is removed, operations
are remote and use the crane and/or window workstations, and include shielding removal, component removal, and waste handling. The window workstation is used for all dexterous operations, such as component maintenance.

3.1. Dose rates to personnel
Activated components in the target hall will be brought to the Master Slave Manipulator (MSM) gallery’s lead glass window for inspection and repair. The MSM gallery is located on the other (“cold”) side of a target hall wall, and working personnel will be present there. Dose rates in the MSM gallery due to activated components help decide whether adequate measures, such as better local shielding or limited access, should be implemented to protect working personnel from radiation exposure. Table 3 shows dose rates in the MSM gallery, 30 cm from the window, resulting from highest-activated components. The components are assumed to be placed 1 m away from the lead glass window on the target hall (“hot”) side. The size of the lead glass is 70 cm x 56 cm, and the thickness is designed to provide radiation protection equivalent to that of the surrounding concrete wall. Irradiation time of 30 years (lifetime of the facility) is assumed. Resulting dose rates are compared to 0.1 mrem/h (this number is the FRIB shielding design goal and it comes from table 2, Radiation Dose to Workers, assuming 5000 operational hours per year). Dose rates are higher than 0.1 mrem/h for the post-target magnet shield; but the shield is expected to last for lifetime of facility. Dose rates are ~ 0.1 mrem/h for the beam dump module, and < 0.1 mrem/h for the target module. The assumptions are conservative; dose rates for the same irradiation and cooling times are calculated to be smaller for heavier beams.

Table 3. Dose rates in the MSM gallery from highest activated components.

| Beam/energy | 48-Ca, 240 MeV/u | 48-Ca, 549 MeV/u |
|-------------|------------------|------------------|
| Component   | Magnet Shield    | Target Module    | Magnet Shield | Target Module | Beam Dump |
| Cooling time| Dose rate, mrem/h|                  | Dose rate, mrem/h|                  | Dose rate, mrem/h|
| 4 hours     | 0.79             | 1.5e-2           | 3.2           | 4.2e-2         | 0.125     |
| 16 hours    | 0.71             | 1.2e-4           | 3.0           | 3.2e-4         |           |
| 24 hours    | 0.67             | 3.3e-5           | 2.9           | 9.3e-5         |           |

3.2. Waste Storage
The beam line components have modular designs. When a module fails, it is removed from the component, packed in a “waste basket”, and placed in a canyon (area next to the target hall vacuum vessels) for temporary storage. When enough failed modules are accumulated, shipment to a disposal site is scheduled. The failed modules are then removed from the canyon, and packed in a shipping container. The shipping container is then placed in a cask for shipment.

3.2.1. Target hall canyon shielding
Since activated components and waste, such as target assemblies, wedge assemblies, target disk modules, as well as scrap cryostats, are planned to be temporarily stored in target hall canyon, the canyon radiation environment was assessed for a conservative beam/energy combination: 48Ca beam at 549 MeV/u. Irradiation time of 30 years and cooling time of 4 hours were assumed. Resulting dose maps show that the canyon needs to be shielded when personnel are present (figure 3). The canyon cover shield thickness was optimized so that dose equivalent rates above the cover are below 5 mrem/h (dose rate of 5 mrem/h and higher to 100 mrem/h is the definition of a radiation area). This is at or below the level of activation expected from general target hall activation. If the post-target...
magnet shield (life-of-facility component) is not present in the canyon, then a 2-ft thick concrete cover is needed. If the magnet shield is stored in the canyon, 2-in thick local steel shield is needed in addition to the 2-ft thick concrete cover to keep the dose equivalent rates outside of the canyon below 5 mrem/h.

**Figure 3.** Dose equivalent rates due to activated components placed in the target hall canyon, an area next to the vacuum vessels.

4. **Conclusions**

FRIB is being designed and established at MSU as a national user facility to provide fast, stopped, and reaccelerated beams of rare isotopes. High radiation environment in the project target hall demands analysis of beam line component activation. Highly activated components that need to be fixed or disposed will be temporarily stored for cooling and/or disposal. Levels of activation and dose rates have been studied to minimize personnel doses during handling and storage.

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