International Cyclotron, Inc. Technical Evaluation Report
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1. Background

International Cyclotron, Inc. (ICI) operated an 11 MeV Eclipse cyclotron in Hato Rey, Puerto Rico to produce fluorine 18 (F-18) for Positron Emission Tomography (PET) imaging studies. ICI operated the cyclotron under U.S. Nuclear Regulatory Commission (NRC) license 52-31352-02, which was granted on August 20, 2009. However, the cyclotron operated prior to NRC licensing because an NRC license was not required prior to the passage of the Energy Policy Act of 2005 (EPAct). Section 651(e) of the EPAct expanded the definition of byproduct material, as defined in Section 11e. of the Atomic Energy Act of 1954, to include certain discrete sources of radium, certain accelerator-produced radioactive material, and certain discrete sources of naturally occurring radioactive material. It thereby placed those materials, including the F-18 produced by ICI, under NRC jurisdiction. Before NRC licensing in 2009, the cyclotron did not have any license because the Commonwealth of Puerto Rico also did not require it to be licensed. In addition to the cyclotron, ICI operated a radiopharmacy at the same location under NRC License No. 52-31-352-01MD. The radiopharmacy distributed the F-18 materials produced with the cyclotron to medical facilities authorized to perform PET imaging studies.

After obtaining an NRC license, ICI did not demonstrate the necessary financial assurance for the cyclotron operations. Consequently, on December 19, 2011, the NRC issued an Order requiring ICI to provide financial assurance within 60 days or to shut down operations of the cyclotron and the radiopharmacy (Accession No. ML11353A417 in the NRC Agencywide Documents Access and Management System [ADAMS]). Financial assurance was not provided and ICI ceased cyclotron activities on February 17, 2012. The NRC later revoked the license for non-payment of fees (ADAMS No. ML12170B066) and imposed civil penalties for failure to decommission (ADAMS No. ML16294A515).

In 2019, the facility Radiation Safety Officer (RSO) ensured that all sealed sources were removed from the facility as part of a “source round-up” coordinated by the Conference of Radiation Control Program Directors (CRCPD). In addition, NRC inspectors verified (ADAMS No. ML19112A147) that no unsealed materials or radioactive waste remained at the facility, other than material that was activated incidental to cyclotron operations. Therefore, the remaining source term at the facility includes activated material in the cyclotron, built-in shields, and the floor under the cyclotron[1]. Because operations ceased by NRC Order rather than through the typical license termination process, the licensee did not do a final status survey to support terminating the cyclotron license. Therefore, the estimated source term is based primarily on possession limits in the license, adjusted as described in Section 3, and information from decommissioning similar cyclotrons. In addition, the licensee submitted a survey of the facility to support a request for termination of license 52-31-352-01MD for the radiopharmacy. That survey has not been verified by the NRC but is described in Section 3 as supplemental information.

The cyclotron apparatus is currently inaccessible because the moveable shields are closed and are too heavy (i.e., 14.5 metric tons) to move without heavy equipment or electrical power.

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[1] Based on experience with another similar cyclotron (Pfizer, 2014) the built-in shields of the Eclipse cyclotron are expected to protect the room walls from activation.

Electrical power has been disconnected from the facility. Therefore, the NRC staff determined the facility does not present a hazard in its current configuration.

2. Regulatory Requirements

The NRC staff evaluated whether the cyclotron and cyclotron facility meet the requirements for license termination with unrestricted release under 10 CFR 20.1402. That requirement states:

> A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA). Determination of the levels which are ALARA must take into account consideration of any detriments, such as deaths from transportation accidents, expected to potentially result from decontamination and waste disposal.

3. Source Term

3.1. Radionuclide Inventories

The cyclotron was licensed to produce F-18 for PET imaging. F-18 is not a contamination concern at the site because of its short half-life. Cyclotron operation, however, also created activation products in the cyclotron apparatus (e.g., magnet, target body, foils), built-in shields, and floor under the cyclotron. The source term created by the cyclotron therefore consists of volumetrically contaminated metals and concrete. Surface contamination from radiopharmaceuticals would have decayed more than ten half-lives since cyclotron production ceased. Furthermore, no decommissioning activities have occurred to disrupt the building concrete surfaces or create dust. Therefore, no removable contamination is expected. In addition to this process knowledge, the licensee has submitted a radiation survey to support termination of the radiopharmacy license 52-31-352-01MD (ICI, 2019; non-public). That survey has not been verified by NRC inspectors or contractor staff. However, the survey results are consistent with the process knowledge-based expectation that there is no removable contamination above background at the site, including in the room that contains the cyclotron.

Table 1 shows the inventory the staff used in its analysis. The NRC staff developed a bounding inventory by adjusting the possession limits in the license based on calculated radioactive decay and process knowledge. Specifically, the staff adjusted for radioactive decay from the date the facility stopped operation (i.e., February 17, 2012) to November 1, 2019. Then, the staff removed all radionuclides listed in the license as sealed sources because all the sealed sources have been removed from the site. Although Cs-137 was listed on the license as both a sealed source and an activation product, Cs-137 is not expected to be a cyclotron activation product and was removed from the analysis.[2] Finally, the staff eliminated radionuclides that would have undergone 15 or more half-lives since the facility stopped operating (e.g., F-18, W-181).

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[2] Cs-137 was listed in the original license (ADAMS No. ML092330012) only as a sealed source. When the licensee later requested the possession limits be updated (ADAMS No. ML110320357; non-public) the licensee implied the Cs-137 was an activation product rather than a sealed source and NRC added it to the revised license as an activation product in addition to the entry as a sealed source. However, the manufacturer later confirmed with NRC staff that Cs-137 is only expected to be present in an 11 MeV cyclotron facility as a sealed source, not an activation product (ADAMS No. ML19303A785).

The possession limits were based on information from the manufacturer (ADAMS No. ML110320357). The manufacturer based those activities on the activity of sealed sources typically used with its 11 MeV cyclotrons and measured activation products in other cyclotrons of the same or similar models. The information supplied by the manufacturer was based on the assumption that the cyclotron had operated consistently until the activation products reached steady state. However, the ICI cyclotron operated intermittently, and the activation products may not have reached steady state. Therefore, the inventory based on those possession limits is expected to be conservative (i.e., to overestimate the actual radionuclide inventory).

Table 1. Radionuclide inventory used in this analysis

Radionuclide	Half-life (years)	Calculated Inventory (Becquerel)	Calculated Inventory (microcurie)
Na-22	2.6	2.3×10^5	6.2
Mn-54	0.85	6.5×10^5	18
Co-57	0.75	2.5×10^5	6.7
Co-60	5.3	1.0×10^7	280
Zn-65	0.67	3.6×10^6	96
Eu-152	13.6	6.2×10^5	17

3.2. Radionuclide Locations

Different exposure scenarios apply to radionuclides distributed in large volumes of waste, such as the 14.5-ton movable shields, as compared to radionuclides concentrated in small parts of the cyclotron apparatus, such as the target body and foils. The NRC staff determined potential radionuclide locations based on literature sources, including information from the manufacturer and published studies of other similar cyclotrons. The staff used those potential locations to develop appropriate exposure scenarios. Potential locations of the radionuclides are provided in Table 2.

Havar is an alloy of cobalt, chromium, iron, nickel, manganese, tungsten, and molybdenum. It is a commonly used foil in F-18 production. Tantalum foils also can be used for F-18 production. Available licensing documents do not specify which type of foil was used by ICI. However, because the manufacturer (Siemens, 2009) stated that Na-22 could be formed in tantalum targets, the NRC staff expects Na-22 could be formed in tantalum foils as well as Havar foils. Documentation from the manufacturer did not indicate that any additional activation products were expected to be formed in tantalum components. Therefore, because the foil type is not known, the staff assumed that Na-22, Mn-54, and Co-57 could be present in a foil based on the activation products expected in a Havar foil.

Table 2 Expected locations and formation reactions for radionuclides listed in Table 1

Radionuclide	Potential Locations	Activation Reaction*	References
Na-22	Havar foil	Mg-25 (p, α)	Sunderland et al. (2012)
Na-22	Tantalum target	Not provided	Siemens (2009) Appendix B
Mn-54	Magnet yoke	Fe-54 (n, p)	Siemens (2009) Appendix B
Mn-54	Concrete in shields and floor	Fe-54 (n, p)	Sunderland et al. (2012)
Mn-54	Havar foils	Cr-54 (p,n)	Sunderland et al. (2012)
Co-57	Havar foil	Fe-57(p, n) Ni-60(p, a)	Sunderland et al. (2012) Siemens (2009) Appendix C
Co-60	Magnet coils	Ni-60 (n, p) Co-59 (n, γ) Cu-63 (n, a)	Siemens (2009) Appendix B Calandrino et al. (2006)
Co-60	Concrete in shields and floor	Co-59 (n, γ)	Sunderland et al. (2012) Calandrino et al. (2006)
Co-60	Concrete and rebar in floor	Not provided	Moroney et al. (2011)
Co-60	Metal components (e.g., screws)	Ni-60 (n, t)	Calandrino et al. (2006)
Zn-65	Target support grid	Cu-65 (p, n)	Siemens (2009) Appendix C
Zn-65	Copper dees	Cu-65 (p,n)	Sunderland et al. (2012)
Eu-152	Concrete in shields and floor	Eu-151(n, γ)	Sunderland et al. (2012) Calandrino et al. (2006)

* activation reactions written in the format of "original atom (incoming radiation, ejected radiation)" where "n" indicates a neutron, "p" indicates a proton, "t" indicates a tritium nucleus, "α" indicates an alpha particle, and "γ" indicates gamma radiation

4. Dose Assessment

The NRC staff expects that residual radioactivity at the ICI facility is confined to areas that are inaccessible unless the movable shields are opened. That expectation is based on process knowledge and information from decommissioning other similar cyclotrons (e.g., Pfizer, 2014; Sunderland, 2012; Moreney, 2011; Calandrino, 2006). In addition, that expectation is supported by the licensee's survey for termination of the radiopharmacy license (ICI, 2019), which does not show removable contamination or areas of elevated gamma radiation at the facility. Because the cyclotron shields are currently closed and can only be opened with heavy equipment or reconnection to electrical power, the NRC staff determined that the ICI facility does not pose a radiation hazard in its current configuration.

The NRC staff evaluated three exposure scenarios in cases in which the movable shields are opened: (1) building occupancy, which would require significant building repairs and reconnection to electrical power, (2) a small-item carry-away scenario, which would require reconnection of the cyclotron to electrical power, and (3) facility demolition.

A building occupancy scenario would require significant repairs to the building to make it habitable (NRC, 2019; non-public) as well as reconnection of the facility to electrical power. Building occupancy with the movable shields open also appears to be unlikely because there does not appear to be a reason an individual would occupy the site with the moveable shields open. However, the scenario provides an idea of the potential hazard from chronic exposure to the facility without close contact with the cyclotron, which was evaluated in other scenarios. Therefore, the NRC staff evaluated the projected dose to an individual in the unexpected case that an individual opens the moveable shielding of the cyclotron without recognizing the hazard and removes cyclotron components and works at the site for 2000 hours annually.

Close contact with scenario components could occur without significant building repairs if the facility is reconnected to electrical power. It appears to be plausible, although unlikely, that an intruder could reconnect power either by illicitly reconnecting to the power grid or by using a generator. An intruder could be motivated to open the equipment to salvage metal; NRC inspectors have observed evidence that other metal at the site (e.g., copper piping) has been taken (ADAMS No. ML19085A237; non-public). Therefore, the NRC staff evaluated the potential dose to an individual who opens the cyclotron and removes easily-removable metal components. The most concentrated areas of residual radioactivity within the cyclotron are expected to be components in the proton beam, such as targets, target bodies, foils, and foil support grids. The RSO indicated that it is possible that a target was left in the cyclotron when ICI ceased operations. In addition, these items are designed to be removed from the cyclotron as part of normal operation and they are small enough to be put in a pocket. Therefore, the NRC staff considered the dose to an individual who removes an item from the cyclotron without being aware of the radioactivity as a plausible exposure scenario if the moveable shields are opened. That scenario is referred to as the “small-item carry-away” scenario.

Because the ICI facility is in a state of significant disrepair, the NRC staff also considered building demolition. The unauthorized use of heavy equipment appears to be unlikely because the facility is in a densely populated part of Puerto Rico. However, it is possible that authorized building demolition could occur by individuals who do not recognize there is residual radioactivity onsite. Therefore, the NRC staff considered the dose to a “downstream” individual who is exposed to contaminated rubble from the concrete cyclotron shields or metal from the cyclotron if the building is demolished. The NRC staff used dose factors from NUREG-1640 to determine whether the projected dose to a downstream individual in a demolition scenario would meet the 0.25 mSv (25 mrem) annual dose limit. The NRC staff used dose factors for the road building scenario because it was the most restrictive applicable scenario considered in NUREG-1640, which includes dose factors for renovation, demolition, recycling, and disposal. If the building is demolished, it is also possible, although unlikely, that an individual could encounter a small cyclotron component that had been in the cyclotron beam pathway and contained a more concentrated level of activation products than the larger cyclotron components. In that case, the small-item carry-away scenario would be applicable.

4.1. Building Occupancy

The NRC staff assumed the individual spent 2000 hours per year at the facility to approximate a working year. Staff assumed a receptor would be located an average distance of 2 meters (m) from the open cyclotron shields and 3 m from the cyclotron apparatus within the open shields.

Table 3 shows the locations and concentrations the NRC staff assumed for the activation products. Those locations are based on the inventories in Table 1 and the potential radionuclide locations in Table 2. For radionuclides that could be present in several locations, the NRC staff assumed the radionuclide was located in the location that would experience the least amount of shielding. For example, the entire Na-22 inventory was attributed to a Havar foil because radionuclides in a thin foil would experience less self-shielding than radionuclides in a tantalum target, which has more mass and is more compact than a foil.

Table 3. Assumed radionuclide distribution in the building occupancy scenario

Radionuclide	Modeled Location	Modeled Configuration	Calculated Concentration (Bq/cm^3)	Assumed Distance from Receptor
Na-22	Havar foil	Cylinder 0.04 cm thickness, 2 cm radius	5.5×10^5	3 m
Mn-54	Havar foil		1.3×10^6	3 m
Co-57	Havar foil		4.9×10^5	3 m
Co-60	Moveable shields*	Cylinder 1.7 m height, 0.75 m radius	3.3	3 m
Zn-65	Target support grid	Cylinder 0.8 cm thickness, 2 cm radius	2.3×10^4	3 m
Eu-152	Moveable shields*	annulus with height of 2.3 m, inner radius of 0.75 m, and outer radius of 120 cm	9.9×10^{-2}	2 m

* Eu-152 and Co-60 could also be present in the floor under the cyclotron but NRC staff conservatively assumed all the Table 1 inventory of those radionuclides is present in the shields because an individual working in the room would have greater exposure to radionuclides in the shields than to the floor under the cyclotron.

The radionuclide that makes the largest dose contribution in the occupancy scenario is Co-60. Because of its importance to dose in the occupancy scenario, NRC staff evaluated the projected dose under the alternative assumptions that the entire Co-60 inventory can be attributed to the magnet or that it can all be attributed to the shielding. The alternative assumptions for the location of Co-60 in the occupancy scenario make approximately a factor of 2 difference in the projected dose. If the inventory of Co-60 is assumed to be in the shields, the projected dose to an individual in the occupancy scenario is 0.13 mSv per year (yr) (13 mrem/yr). Most of that projected dose (i.e., 0.10 mSv/yr [10 mrem/yr]) is due to Co-60. Most of the remainder (i.e., 0.031 mSv/yr [3.1 mrem/yr]) is due to Mn-54 and Na-22 in the foil. If the Co-60 is assumed to occur primarily in the magnet, the projected dose from Co-60 is reduced to 0.019 mSv/yr (1.9 mrem/yr) and the projected dose in the occupancy scenario is 0.055 mSv/yr (5.5 mrem/yr).

4.2. Small Item Carry-Away Scenario

The NRC staff evaluated the projected dose to an individual who removes a small component of the cyclotron and places the item in a pocket (estimated as 1 centimeter [cm] from the body) for 4 hours before selling or disposing of it[3]. In addition to the dose from the small item itself, the NRC staff assumed the individual spends 15 minutes within 10 cm of the cyclotron magnet and movable shields while removing the small item. However, that exposure contributed less than 1 percent to the projected dose.

As shown in Table 2, after the significant decay period the ICI cyclotron has already undergone, the radionuclides that are expected to remain in target bodies, Havar foils, and target support grids are Na-22, Mn-54, Co-57, and Zn-65. Because the licensing documentation did not specify where the incidental activation products were expected to be located, the NRC staff assumed that the entire decayed inventory of those radionuclides is present in one of the small components. That assumption is expected to be bounding for Mn-54 and Zn-65 because both of those radionuclides are also expected to be present in other components (i.e., the entire activity is not expected to be attributable to the target body, foil, or target support grid) (see Table 2).

The foil and support grid both are very thin pieces of metal that would not offer as much self-shielding as a thicker component. Havar foils are reported to weigh less than a gram (O'Donnell et al., 2004) and the foil support grid for an 11 MeV Eclipse cyclotron is reported to have a volume of less than 10 cubic centimeters (Siemens, 2009). To test the sensitivity of the projected dose to assumptions about the geometry of the small components, the NRC staff used MicroShield (Version 12) to model the absorbed radiation at 1 cm from hypothetical small objects with a fixed inventory and different geometries. Specifically, the NRC staff first compared the absorbed radiation from the inventory in Table 1 for Zn-65, Na-22, Mg-54, and Co-57 distributed a point source, which would provide no self-shielding, and a 1.34-cm radius sphere, which would maximize the self-shielding for a 10 cubic centimeter volume. The same inventory distributed in those two geometries caused almost a factor of 10 difference in projected dose. Because the assumed geometry had a significant effect on the projected dose, the NRC staff attempted to use more representative geometries instead of making the simplifying assumption that the geometries could be represented by a point source.
The NRC staff assumed the radionuclides were present either in a foil (i.e., for Na-22, Mn-54, and Co-57) or the support grid (i.e., for Zn-65) based on the locations in Table 2. The NRC staff chose the foil and foil support grid as conservative assumptions because those were the components with the least compact geometries, which would therefore provide the least self-shielding. The NRC staff used a cylinder of thickness 0.04 cm and 2 cm radius to represent a foil, and a cylinder with a thickness of 0.8 cm and a 2 cm radius to represent the foil support grid. For both cylinders, the exposure point was assumed to be one cm from the end of a cylinder along the axis of radial symmetry.

[3] Additional analyses demonstrated that the additional dose from exposure at 2 m for 730 additional hours per year (e.g., if the individual places the item on a shelf) adds less than 2 percent to the dose.

Figure 1 shows the projected dose from a foil if the entire inventory of Na-22, Mg-54, and Co-57 in Table 1 is assumed to be present in the foil. The dashed line in Figure 1 shows the projected dose from a foil support grid if the entire inventory of Zn-65 in Table 1 is assumed to be present in the foil support grid. The time used on the x-axis in Figure 1 is time after November 1, 2019. The decrease in the projected dose is due to radioactive decay. Figure 1 shows the dose from each object individually. If both materials were put in a pocket, the projected doses would be summed.

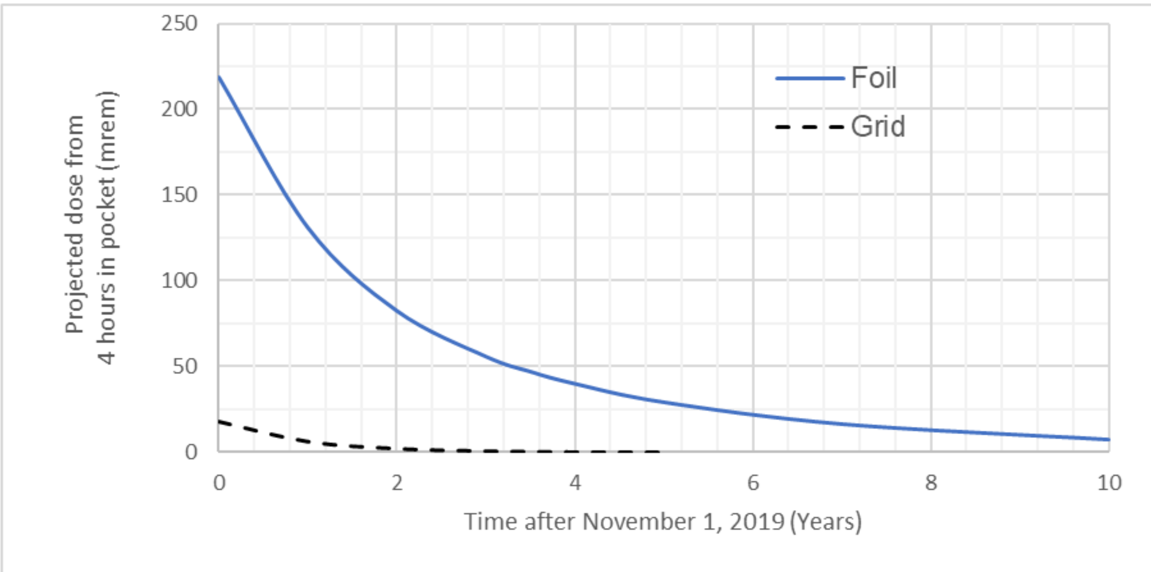

Figure 1. Projected dose to an individual who removes a foil or grid from the cyclotron apparatus and places it in a pocket for 4 hours

The key radionuclides for the foil at time zero (i.e., November 1, 2019) are Mn-54, which causes 51 percent of the projected dose, and Na-22, which causes 46 percent of the projected dose. Because Na-22 has a longer half-life than Mn-54 or Co-57, the relative contribution of Na-22 to the projected dose due to Na-22 will increase with time. Because of the importance of Mn-54 and Na-22 to the projected dose in the carry-away scenario and the uncertainties in the inventories determined from the possession limits, the NRC staff compared the inventory values to published measurements to determine the likelihood that conservatism in the possession limits caused an overly conservative dose projection.

The inventory of activation products will depend on the design, energy, and usage history of the cyclotron. Therefore, comparison of inventory assumptions to values from another cyclotron can only provide a rough indication of the reasonableness of the assumed inventory. However, because possession limits may have been established based on conservative assumptions, a comparison to measured values could provide an indication of whether the assumed inventory is grossly overestimated. The NRC staff did not find evidence of such an overestimation.

For comparison, the NRC staff used a published study of measurements from a cyclotron that included foils and targets, because the NRC does not know if a target was left in the ICI cyclotron when it ceased operation. That type of measurement has been published for the decommissioning of a 17 MeV cyclotron used to produce medical isotopes (Sunderland et al., 2012). Although the energy of the cyclotron is greater, which would tend to increase production of activation products, the energies are roughly similar. In addition, the reported usage history is similar to the ICI cyclotron. The ICI cyclotron is estimated to have been used 1 hour per day for 5 days per week for 16 years. Based on the information from the manufacturer, the Eclipse cyclotron has a single-beam current of 40 or 60 microamperes, depending on whether it is an RD or HP model. Those values would suggest a 10,000 to 15,000 microampere-hour beam usage for the ICI cyclotron. The 17 MeV cyclotron studied by Sunderland et al. was reported to have a 300,000 microampere-hour usage over 20 years, or approximately a 15,000 microampere-hour annual beam usage. The ICI cyclotron was known to have intermittent pauses in usage. However, an estimate of its fraction of time online is not known.

For both Mn-54 and Na-22, the comparison to published results does not indicate a gross overestimate of the radionuclide inventory in this analysis. The inventory of Mn-54 used in this analysis (i.e., 6.5×10^5 Bq) is approximately a factor of 2 greater than the measured value reported for the decommissioning of a 17 MeV cyclotron once that value is adjusted to account for the same time for radioactive decay assumed for the ICI cyclotron (i.e., 7.7 years) (i.e., approximately 2.9×10^5 Bq) (Sunderland et al., 2012). The inventory of Na-22 used in this analysis (i.e., 2.3×10^5 Bq) is similar to the measured value for that cyclotron after adjusting for radioactive decay assumed for the ICI cyclotron (i.e., 7.7 years) (i.e., approximately 2.6×10^5 Bq) (Sunderland et al., 2012). For either Mn-54 or Na-22, the difference between the values assumed for ICI and the values measured for the cyclotron studied by Sunderland et al. (2012) is expected to be smaller than the uncertainty in inventory caused by the possibility that a target and associated small components are still present in the cyclotron. Additional knowledge about the presence of those small components could reduce the projected dose in the small-item carry-away scenario.

If intrusion occurred in November, 2019, the projected dose to an individual who places a grid in a pocket for four hours would be 0.18 mSv (18 mrem) and the projected dose to an individual who places a foil in a pocket for four hours would be 2.2 mSv/yr (220 mrem/yr). Placing a foil in a pocket for four hours is the only scenario analyzed that had a projected dose that exceeds the 10 CFR 20.1402 annual dose limitation of 0.25 mSv (25 mrem). As shown in Figure 1, that projected dose is expected to decrease to less than 1 mSv (100 mrem) in two years and 0.25 mSv (25 mrem) in six years.

4.3 Demolition and Recycling

If the ICI facility is demolished by individuals who do not know there is residual radioactivity in the cyclotron, rubble from the cyclotron could be mixed with rubble from the building and disposed of or recycled. Therefore, the NRC staff evaluated the potential dose from the radionuclides in Table 1 if the radionuclides are in larger cyclotron components, such as the magnet, copper electrodes (called "dees"), or concrete shields. The NRC staff used NUREG-1640, which provides dose factors for a range of scenarios including renovation, demolition, recycling, and disposal. The staff considered steel, copper, and concrete separately. For each material, the staff chose the scenario from NUREG-1640 that yielded the highest dose for each radionuclide (Table 4). The staff then used the scenario dose conversion factor provided in the NUREG to project a dose based on the estimated concentration of each radionuclide in that material.

All of the radionuclides in Table 1 were included in the analysis of demolition scenarios except Na-22. Na-22 was excluded because it is not expected to be formed in large cyclotron components or in the shielding. Because it is expected to be formed by proton activation and not neutron activation, it is only expected to be present in significant concentrations in components directly in the beam pathway, such as targets and foils left in the cyclotron, if any.

The demolition scenario dose factors, which are based on tens to hundreds of thousands of tons of material, depending on the material, are inapplicable to such small components. If the facility is demolished, it is possible, but very unlikely, that an individual could retrieve a small component of the cyclotron from the rubble. In that case, the applicable scenario for that item would be the small-item carry-away scenario (Section 4.2).

Table 4. Bounding Dose for Demolition Scenarios based on Road Building with Volumetrically Contaminated Concrete

Nuclide	Average Activity Concentration		Mass-Based Dose Factor (NUREG-1640)		Projected dose in µSv/yr	
	Bq/g	pCi/g	µSv/yr per Bq/g	mrem/yr per pCi/g	µSv/yr	mrem/yr
Mn-54	0.044	1.2	85	0.60	3.7	0.37
Co-57	0.016	0.44	8.1	0.58	0.13	0.013
Co-60	0.68	18	290	1.1	200	20
Zn-65	0.233	6.3	59	0.22	14	1.4
Eu-152	0.041	1.1	120	0.46	5.0	0.50
				Total	220	22

For the other radionuclides in Table 1, the dose factor for concrete was greater than the dose factor for steel or copper. If the radionuclides in Table 1 are assumed to be in the shields, the calculated concentrations are approximately half of what they would be if the radionuclides were assumed to be present in the cyclotron metal. However, the dose factors for concrete in most cases were approximately five times the value of the dose factor for steel. As a result, assuming the radionuclides were distributed in the shield concrete was conservative in the demolition scenario. The NRC staff used the largest dose factor for concrete, which corresponded to a road building scenario (Table 4). To calculate the radionuclide concentrations to use in the demolition scenario, the NRC staff assumed the entire inventory of the radionuclides in Table 1 (except for Na-22) was distributed in an annular shield with a height of 230 cm, an inner diameter of 75 cm, and an outer diameter of 240 cm. These dimensions were determined from the height and width of the shields and the width of the cyclotron (Siemens, 2011). To convert volumetric to mass-based concentrations, the NRC staff assumed a concrete density of 2.4 g/cm^3.

The dose factors calculated in NUREG-1640 were based on the volumes of concrete and steel resulting from decommissioning a nuclear power plant. Those volumes are much larger than the volumes of contaminated material present in the cyclotron or shields at ICI. For example, the mass of the cyclotron shields is approximately 17,800 kg (Siemens, 2011). For comparison, the calculations of dose factors for volumetrically contaminated concrete in NUREG-1640 are based on an assumed waste stream of 143-281 kilotons of concrete (i.e., a factor of 8,000 to 16,000 greater than the volume of concrete in the ICI cyclotron shields). No adjustment was made to the projected dose in Table 4 to account for that volume difference because the relationship between the projected dose and the volume of material is not known. For example, the projected dose due to recycling the cyclotron magnet into a smaller batch of metal would be different form the projected dose of recycling the magnet into a larger batch of metal. However, although the precise relationship between the projected dose and the contaminated mass of material is not known, it can be assumed that applying the NUREG-1640 dose factors without applying any adjustment for the much smaller volume present in the ICI cyclotron and shields is conservative.

The bounding dose in the demolition scenario if all the radionuclides in Table 1 except for Na-22 are present in the shields is 0.22 mSv/yr (22 mrem/yr). Most of that dose (i.e., 0.20 mSv [20 mrem/yr]) is attributable to Co-60. Although the calculations in NUREG-1640 involve many approximations, because the volume of material that would result from demolition of the cyclotron is significantly smaller than the volumes of material used in the calculations supporting NUREG-1640, adjustments of the approximations involved in the NUREG-1640 scenarios are unlikely to cause the estimated doses to exceed 0.25 mSv (25 mrem/yr) dose limit.

5. As Low As Is Reasonably Achievable (ALARA) Considerations

Removal of sealed sources from the facility as part of the CRCPD “source round-up” in early 2019 was a significant hazard reduction and a significant step toward achieving doses that are ALARA. Region I staff has pursued further reducing risk from residual activation products at the site by pursuing enforcement actions. In addition, Region I staff discussed the site with regional staff of the U.S. Environmental Protection Agency (US EPA) and determined that the US EPA did not intend to devote resources to decommissioning the facility. The NRC has not identified a party with resources to support decommissioning efforts.

6. Conclusions

Because the licensee ceased operation under NRC Order and has not submitted a request for license termination, the NRC staff based its conclusions on independent analyses. The components of the NRC staff review included (1) inventory development; (2) determination of likely radionuclide locations and concentrations; (3) evaluation of occupancy and small-item carry-away scenarios with MicroShield V. 12; (4) evaluation of demolition scenarios using NUREG-1640 dose factors; (5) comparison to literature information from decommissioning other similar cyclotrons; and (6) consideration of whether the projected doses are ALARA.

The NRC staff evaluated three hypothetical exposure scenarios: (1) an occupancy scenario, which would require significant building repairs and reconnection to electrical power, (2) a small-item carry-away scenario, which would require reconnection of the cyclotron to electrical power, and (3) a demolition scenario. The NRC staff has reasonable assurance that the projected dose in the occupancy scenario meets the 10 CFR 20.1402 0.25 mSv (25 mrem) annual dose limit for unrestricted release. The NRC staff also has reasonable assurance the projected dose in the demolition scenarios meets 0.25 mSv (25 mrem) annual dose limit unless an individual carries away a small cyclotron component from the building rubble. The projected dose in the unlikely, but plausible, small-item carry-away scenario exceeds the 0.25 mSv (25 mrem) dose limit. However, the NRC staff has reasonable assurance that the projected dose in the small-item carry-away scenario would be below the 1 mSv (100 mrem) public annual dose limit in two years and the license termination unrestricted release 0.25 mSv (25 mrem) annual dose limit in six years because of radioactive decay.

Because the licensee did not perform a final status survey, the NRC staff developed its best estimate of the inventories and locations of the residual radioactivity based on process knowledge and defensible assumptions. The inventory, therefore, is a significant source of uncertainty in the projected doses. Additional information that could limit the estimated quantities of Co-60, Mn-54, and Na-22 present in the cyclotron could significantly reduce the projected dose. In particular, information about whether a target, foil, or foil grid remain in the cyclotron could significantly reduce the projected dose in the small-item carry-away scenario.

7. References

Anigstein, R., H. J. Chmelynski, D. A. Loomis, S. F. Marschket, J. J. Mauro, R. H. Olsher, W. C. Thurber, and R. A. Meck, 2003. "Radiological Assessments for Clearance of Materials from Nuclear Facilities, Main Report," NUREG-1640, Vol. 1. Prepared by SC&A, Inc. and Gemini Consulting Company for the U.S. Nuclear Regulatory Commission, Washington, D.C., ML032250178.

Banovac, K.L., J.T. Buckley, R.L. Johnson, G.M. McCann, J.D. Parrott, D.W. Schmidt, J.C. Sheperd, T.B. Smith, P.A. Sobel, B.A. Watson, D.A. Widmayer, and T.H. Youngblood, 2006. "Consolidated Decommissioning Guidance: Decommissioning Process for Materials Licensees, Final Report," NUREG-1757, Vol. 1, Rev. 2. U.S. Nuclear Regulatory Commission, Washington, D.C., ML063000243.

Calandrino, R., del Vecchio, A., Savi, A., Todde, S., Griffoni, V. Brambilla, S., Parisi, R., Simone, G., and Fazio, F. 2006. "Decommissioning Procedures for an 11 MeV Self-Shielded Medical Cyclotron After 16 Years of Working Time," Health Physics Journal. Vol. 90(6), p. 588, ML19303A782; non-public.

International Cyclotron, Inc., 2019. "Radiation Safety Closeout Survey." May 17, 2019, ML19226A128; non-public.

Moroney, W.R., Krueger, D.G., Elam, C.L., Plastini, F.L., Chance, A., "Quantification of Induced Radioactivity for a Compact 11 MeV Self-Shielded Cyclotron for Decommissioning Funding Purposes," Health Physics Society Mid-Year Meeting, 2011, ML19303A786.

NRC, "Note to file March 12, 2019 re: site visit on February 25, 2019," ML19085A237; non-public.

O'Donnell, R.G., Vintrtŕo, L.L., Duffy, G.J., Mitchell, P.I., "Measurement of the residual radioactivity induced in the front foil of a target assembly in a modern medical cyclotron," Applied Radiation and Isotopes, v. 60 p. 539-542, 2004. ML19329D943; non-public.

Pfizer, Inc., "Request to Terminate Radioactive Materials License No. 06-05869-03." March 24, 2014. ML14094A54.

Siemens, "Eclipse Cyclotron Radiation Safety Aspects," 2009. ML19303A778; non-public.

Siemens, "Eclipse Cyclotrons," 2011. ML19303A779; non-public.

Sunderland, J.J., Erdahl, C.E., Bender, B.R., Sensoy, L., and Watkins, G.L. "Considerations, Measurements and Logistics Associated with Low-Energy Cyclotron Decommissioning," AIP Conference Proceedings, 1509(16), 2012. ML19330D564; non-public.