

# **A Summary of Contamination Control Practices at Thomas Jefferson National Accelerator Facility**

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## **Introduction**

It is often the belief that electron accelerators are "clean" machines, producing little or no measurable removable contamination. However, at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), a 200  $\mu$ A continuous wave, 4 GeV electron accelerator, there are several types of contamination that may be found: external contamination of beamline components near high beam loss points, radionuclides produced from the spallation of oxygen in air, and internal contamination of water systems used to cool beamline components. The last two categories, however, are fairly well understood and are not discussed herein. The Jefferson Lab Radiation Control Group has developed a comprehensive set of contamination control practices to identify and control personnel exposure to these radionuclides.

## **Beamline Activation**

Contamination found on the outside of beamline component near high loss points is perhaps the least understood of the three contamination phenomena, so it will be discussed in greater detail in this paper. At Jefferson Lab, the most commonly contaminated beamline components are the flanges and beamline itself. The flanges are made of type 304/304L

stainless steel and the beamlines are type 316 stainless steel. Table 1 identifies radionuclides expected from activation of stainless steel (Saxon, 1969; Barbier, 1969).

**Table 1 Radionuclides Expected from Activation of Stainless Steel**

Nuclide	Reaction	Fractional Abundance of Parent	Half-Life	Integrated Cross-Section ( $\sigma_{2,2}$ ) barn MeV <sup>-1</sup>
Mn-54	Fe-56 ( $\gamma$ , np)	0.917	314 days	$4.5 \times 10^{-5}$
Mn-52	Fe-56 ( $\gamma$ , 3np)	0.917	5.7 days	$2.5 \times 10^{-5}$
Mn-52	Fe-54 ( $\gamma$ , np)	0.058	5.7 days	$4.5 \times 10^{-5}$
Ni-57	Ni-58 ( $\gamma$ , n)	0.678	37 hours	$1.2 \times 10^{-3}$
Co-57	Ni-58 ( $\gamma$ , p)	0.678	267 days	$6.0 \times 10^{-4}$
Co-56	Ni-58 ( $\gamma$ , np)	0.678	77 days	$4.5 \times 10^{-5}$
Co-58	Ni-60 ( $\gamma$ , np)	0.262	71 days	$4.5 \times 10^{-5}$
Co-60	Ni-62 ( $\gamma$ , np)	0.037	5.26 years	$4.5 \times 10^{-5}$
Co-60	Ni-61 ( $\gamma$ , p)	0.012	5.26 years	$6.0 \times 10^{-4}$
Cr-51	Cr-52 ( $\gamma$ , n)	0.838	26.5 days	$1.2 \times 10^{-3}$

Cr-51	Cr-53 ( $\gamma$ , 2n)	0.094	26.5 days	$1.5 \times 10^{-4}$
V-48	Cr-50 ( $\gamma$ , np)	0.045	16 days	$4.5 \times 10^{-5}$
V-49	Cr-50 ( $\gamma$ , p)	0.045	320 days	$6.0 \times 10^{-4}$

The dynamics of activation and decay for induced radioactive material may be described using the following equation:

$$A = A_s (1 - e^{-(\ln 2 / \tau_{1/2}) (t_{up})}) (e^{-(\ln 2 / \tau_{1/2}) (t_{dn})})$$

where:

- A = activity at time t (Bq)
- $A_s$  = saturation activity (Bq)
- $t_{up}$  = time machine has been running (s)
- $t_{dn}$  = time machine has been off (s)
- $\tau_{1/2}$  = half-life of product (s).

Close estimates of saturation activity may be made by assuming that electrons interact with constant cross-sections at the high energy limit with an infinitely thick target, represented by Approximation A of analytical shower theory:

$$A_s (Bq) = \left[ \frac{P}{eE_0} \right] \cdot \left[ \frac{N_0 \rho}{A} \right] \cdot [0.572 E_0 X_0 \sigma_{-2}]$$

where:

- P = power (W)
- e = electron charge (C)
- E<sub>0</sub> = electron energy (MeV)
- N<sub>0</sub> = Avogadro's number
- ρ = density of material (g cm<sup>-3</sup>)
- A = atomic weight (gm)
- X<sub>0</sub> = radiation length (g cm<sup>-2</sup>)
- σ<sub>-2</sub> = second moment of integral cross-section (μb MeV<sup>-1</sup>).

For the typical 0.165 cm thick stainless steel beam line, the above equation should be corrected for target thickness. An angular thickness (at 5° angle of incidence) of 1.9 cm and X<sub>0</sub>/ρ of 1.76 cm yields an X/X<sub>0</sub> of 1.1, and thus an approximate yield correction of 0.017.

The saturation exposure rate (C·kg<sup>-1</sup>·m<sup>2</sup>·h<sup>-1</sup>), then, from any given radionuclide is approximately:

$$\begin{aligned} \dot{X}_s &= 2.15 \times 10^9 P \left( \frac{X_0}{A} \right) \Gamma \sigma_{-2} (0.017) \\ &= 9.17 \times 10^6 P \Gamma \sigma_{-2} \end{aligned}$$

where:

- P = power (kW) deposited to parent nuclide

- $X_0$  = radiation length ( $\text{g}/\text{cm}^2$ ) (13.8 for Fe)  
 $A$  = molar atomic weight (g) (55.85 for Fe)  
 $\Gamma$  = specific gamma-ray constant ( $\text{C}/\text{kg}\cdot\text{h}$ )/( $\text{Bq}/\text{m}^2$ )  
 $\sigma_2$  = second moment of integral cross-section ( $\mu\text{b}/\text{MeV}$ )

Reasonable estimates of  $\sigma_2$  may be made from the data presented by Barbier (Barbier, 1969).

An example of radionuclides expected from a short (120-hour) run, 12 hours after shutoff, for a 0.5 kW loss is represented in Table 2.

**Table 2 Radionuclides Expected from a Short Run, 12 Hours After Shutoff, 0.5 kW Loss**

Nuclide	half-life(h)	parent % in stainless	mGy h <sup>-1</sup> @ 30 cm	Activity (relative)
Cr-51	664.8	14.0%	5.2E-3	0.34
V-48	383.52	0.8%	4.4E-2	0.03
Ni-57	37	6.8%	4.6E-1	0.48
Mn-52	136.8	62.4%	8.1E-2	0.10
Mn-52	136.8	3.9%	9.2E-3	0.01

#### Measured Radionuclides in a Typical Beamline Swipe

Comparing measurements to calculations, Table 3 and Table 4 identify actual radionuclides found in two events. Note that the activity measured by a conventionally calibrated end-window pancake GM tube, or "frisker", in one case overestimates the actual activity and in the other case underestimates it.

**Table 3 Radionuclides Identified in a Swipe 12 Hours After Shutdown**

Major Radionuclides		swipe activity (from gamma spectroscopy)	% total activity
Na-24	( $\beta, \gamma$ )	40 Bq	56 %
Sc-47	( $\beta, \gamma$ )	2.3 Bq	3.2%
V-48	( $\beta^+, \epsilon, \gamma$ )	1.8 Bq	2.6%
Cr-51	( $\epsilon, \gamma$ )	15.1 Bq	21 %
Mn-52	( $\epsilon, \beta^+, \gamma$ )	1.4 Bq	1.9%
Ni-57	( $\epsilon, \beta^+, \gamma$ )	5.7 Bq	7.8%
Total		66.3 Bq	92.5%
Apparent frisker activity		133 Bq	

**Table 4 Radionuclides Identified in a Swipe 113.5 Hours After Shutdown**

Major Radionuclides	swipe activity (from gamma spectroscopy)	% total activity
Na-24 ( $\beta,\gamma$ )	0.52 Bq	3.1%
Sc-47 ( $\beta,\gamma$ )	1.15 Bq	7.0%
V-48 ( $\beta^+,\epsilon,\gamma$ )	0.56 Bq	3.3%
Cr-51 ( $\epsilon,\gamma$ )	11.7 Bq	71.0%
Mn-52 ( $\epsilon,\beta^+,\gamma$ )	1.07 Bq	6.5%
Ni-57 ( $\epsilon,\beta^+,\gamma$ )	1.15 Bq	7.1%
Total	66.3 Bq	98.0%
Apparent frisker activity	6.7 Bq	

### Discussion

Na-24 was found to be a primary removable contaminant at several beam loss locations shortly after shutdown. It is believed to have been caused by activation of concrete dust that had settled on the beamline. Ni-57 contributes to a major portion of the contamination and dose rates from the beam line for days after shutdown. If the Na-24 were not present (a clean beamline), Ni-57 would be the second highest contributor. There is quite a gap in literature

with regard to this nuclide. A major reference (IAEA, 1979) does not mention it at all; in the beamline, it is the second highest contributor to activity from the steel.

Sc-47 contributes about 10% of the activity at about 90 hours after shutdown. It is produced either from Fe-54( $\gamma$ ,sp) or Ti-48( $\gamma$ ,np) reactions. This radionuclide was not listed as a product of electron accelerator interactions in any common literature.

### Rules of Thumb

- From a "point" loss, the removable contamination may be estimated by:

$$A_r (Bq) = 120 \cdot \dot{D} (\mu Sv h^{-1})$$
$$[A_r (dpm) = 5 \cdot \dot{D} (mrem h^{-1})]$$

- Frisker readings overestimate removable activity on swipes for the first few days after shutdown. This overestimate is due to highly efficient detection of positrons from neutron-deficient radionuclides. These same nuclides tend to decay quickly, and the frisker soon underestimates true removable activity. Swipes should be counted on a gamma spectroscopy system to obtain the best estimates of contamination. Use the above rule of thumb until the results are available. Applications to other losses in the machine have shown that the rule is good to within a factor of about two.
- After several days, the radionuclides of interest decay primarily by electron capture (Cr-51, Mn-52, Ni-57).

- Distributed sources (such as from minor scraping along a longer length of beamline) produce small amounts of removable contamination on the beamline that are primarily from reactions in air (Be-7, Cl-39). These are evident shortly after shutdown.
- Losses near a beam dump are characterized by radionuclides from both photoactivation reactions and thermal neutron absorption reactions. Activated lead (Pb-210) and gold (Au-198) are likely when gold connectors or lead shielding are used nearby.

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