Estimate of Radioactivity Production in ^{40}Ar from the NuMI Beam

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At the October 24 review for the NuMI RAW systems, the question of whether to use argon or helium in the surge tanks arose. The lower cost of argon makes it an attractive choice, but a concern was raised about the production of radioactivity from gas venting through the NuMI horn. The following is a very rough estimation of the radioactivity produced.

To date, only three radionuclides produced from ^{40}Ar have been observed in Fermilab stack emissions. These are described in Table 1.

Radionuclide	**Reaction**	**Half-life (seconds)**	**Decay Constant (s^{-1})**
Argon-41	$^{40}Ar(n,\gamma)^{41}Ar$	6588	1.052×10^{-4}
Chlorine-39	$^{40}Ar(\gamma,p)^{39}Cl$	3336	2.078×10^{-4}
Chlorine-38	$^{40}Ar(\gamma,np)^{38}Cl$	2232	3.105×10^{-4}

Table 1 Radionuclides produced on Argon-40 at accelerators.

Argon-41 is commonly seen in accelerator stack emissions. It is formed by capture of thermal neutrons. The chlorine isotopes are seen less frequently, both because of their shorter half-life and because of the tendency for chlorine to combine chemically and thus be removed from the airflow by attachment or filtration. They have, however, been observed at the AP0 production target.[1]

At the review, K. Vaziri presented MARS results for the neutral hadron flux in the target/horn region.[2] I make the following simplifying assumptions to estimate the radioactivity released at the NuMI stack due to one cm^3 of ^{40}Ar in horn 1.

1. The thermal neutron flux is approximately equal to the fast neutral hadron flux of 8000 cm^{-2} s^{-1}. See, e.g., Sullivan.[3]
2. The radionuclides listed in Table 1 are produced in roughly equal amounts and are the only ones produced. It is possible to produce a number of radionuclides by spallation on argon,[4] but these are ignored here since they have not been observed in Fermilab stack emissions.
3. In the absence of information on the length of the irradiation time, the equilibrium activity of the sample is assumed. This is an extremely conservative assumption, since it would take about 8 hours of irradiation for ^{41}Ar to approach equilibrium.

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[1] K. Vaziri, *et al.*, AP0 Stack Montor Calibration, Fermilab Radiation Physics Note 106, May 1993

[2] K. Vaziri, NuMI RAW Systems, October 24, 2001

[3] A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, p 120, Nuclear Technology Publishing, 1992

[4] D. Cossairt, Radiation Physics for Personnel and Environmental Protection, FNAL TM-1834, p 8-3, March, 2001

4. After the radionuclide leaves the horn, it is vented through the NuMI stack one hour later.

The cross section for thermal neutron capture on ^{40}Ar is 610 mb. The number of target atoms in a cm^3 of argon is

$$N = N_A \rho / M = (6.022 \times 10^{23}\ \mathrm{mol}^{-1}) \times (1.784 \times 10^{-3}\ \mathrm{g\ cm}^{-3}) / (39.95\ \mathrm{g\ mol}^{-1})$$

$$= 2.689 \times 10^{19}\ \mathrm{cm}^{-3} \qquad (1).$$

The activation rate is then

$$R = \Phi N \sigma = (8000\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}) \times (2.689 \times 10^{19}\ \mathrm{cm}^{-3}) \times (6.10 \times 10^{-25}\ \mathrm{cm}^{2})$$

$$= 0.131\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1} \qquad (2).$$

The highest possible level of radioactivity is at equilibrium, where the decay rate is equal to the activation rate. The "test sample" of one cm^3 of ^{40}Ar would then contain 0.131 Bq of ^{41}Ar. Assuming the same activity of ^{38}Cl and ^{39}Cl to be present, we now allow the sample to decay for one hour. The activities at the stack are:

$$A(^{41}\mathrm{Ar}) = (0.131\ \mathrm{Bq}) \times \exp[-(1.052 \times 10^{-4}\ \mathrm{s}^{-1}) \times (3600\ \mathrm{s})] = 0.090\ \mathrm{Bq},$$

$$A(^{39}\mathrm{Cl}) = (0.131\ \mathrm{Bq}) \times \exp[-(2.076 \times 10^{-4}\ \mathrm{s}^{-1}) \times (3600\ \mathrm{s})] = 0.062\ \mathrm{Bq},$$

$$A(^{38}\mathrm{Cl}) = (0.131\ \mathrm{Bq}) \times \exp[-(3.105 \times 10^{-4}\ \mathrm{s}^{-1}) \times (3600\ \mathrm{s})] = 0.043\ \mathrm{Bq} \qquad (3),$$

for a total of 0.195 Bq = 5.27 pCi. It is estimated that the annual ^{41}Ar emission from NuMI will be on the order of 10 Ci.[5] In order for radionuclides generated from the use of argon in the RAW system surge tanks to make a significant impact on this number, say 10%, it would require that roughly 190 million liters at atmospheric pressure be irradiated in the course of one year in the manner described here. That would average to an impossibly high flow of over 21,000 l/hr of ^{40}Ar through the target hall.

This calculation is only a rough estimate and a more thorough investigation should be made before choosing a gas for the RAW surge tanks. However, my preliminary conclusion is that the choice of argon does not present a problem from the standpoint of releasing radioactivity to the environment.

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[5] N. Grossman *et al.*, Production and Release of Airborne Radionuclides Due to the Operation of NuMI, FNAL TM-2089, August, 1999