Sensitivity of ambient dose equivalent to the concentration of cobalt impurity present in stainless steel

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Abstract. Stainless steels contain nickel in large amounts (about 8%) to improve its corrosion and heat resistance. Traces of cobalt are present in nickel, which are hard to separate because of its chemical similarity. Therefore, cobalt content in steel is restricted to a maximum of 2 parts per mille for applications in nuclear industry as natural cobalt (composed of 100% Co-59) transmutes into highly radioactive Co-60 by absorbing a thermal neutron. Co-60 has a rather long half-life of 5.3 years decaying to stable Ni-60 by emitting 2 gammas of 1.17 MeV and 1.33 MeV during the process. These hard gammas will be mostly responsible for the dose rates seen in the next few tens of years. Therefore, it is important to consider the activation of cobalt in steel and estimate the dose contributed by it. Monte Carlo simulations are performed where stainless steel samples with different cobalt concentrations are irradiated with thermal and epithermal neutrons. The ambient dose equivalent, $H^*(10)$, from irradiated samples is found to be linearly proportional to the concentration of cobalt. This paper explains the motivation, the procedure, and the detailed results of the simulations.

1. Introduction
ELI Beamlines is a high-power laser facility under development, where laser-plasma interactions are expected to produce secondary sources of radiation. The radiation protection group at ELI Beamlines assesses prompt radiation and activation of materials. In order to plan radioactive material handling, activation studies are routinely performed using Fluka [1, 2] simulations for the most commonly used materials. The material composition is obtained from the manufacturers, however it does not account for the contamination. Contamination of stainless steel with cobalt is a major issue in radiation protection, and this paper presents the studies done on the sensitivity of radiation dose to the concentration of cobalt contamination.

Stainless steel is used ubiquitously in particle accelerators for beam pipes, interaction chambers, vacuum chambers, structural materials, nuts, bolts, screws, etc. As an example, figure 1 shows the E2 experimental room at ELI Beamlines. The room hosts the beam transport and interaction chambers that are made of stainless steel.

Stainless steels contain nickel in large amounts (about 8%) to improve its corrosion and heat resistance. Traces of cobalt are present in nickel, which are hard to separate because of their chemical similarity. Therefore, cobalt content in steel is restricted to a maximum of 2 parts per mille for applications in nuclear industry as natural cobalt (composed of 100% cobalt-59) transmutes into highly radioactive cobalt-60 by absorbing a thermal neutron. Cobalt-60 has a
Figure 1. Engineering rendering of E2 experimental room at ELI Beamlines that is hosting laser beam transport and interaction structures made from steel.

![Engineering rendering of E2 experimental room at ELI Beamlines](image)

Figure 2. Decay scheme of cobalt-60.

rather long half-life of 5.3 years decaying to stable nickel-60 by emitting 2 gammas of 1.17 MeV and 1.33 MeV during the process (see figure 2). These hard gammas will be mostly responsible for the dose rates seen in the next few tens of years. Therefore, it is important to consider the activation of cobalt in stainless steel, and estimate the dose contributed by it.

Co-59 has a significant thermal neutron capture cross section. It also has a large resonance for neutron capture around 100 eV as shown in figure 3.

2. Source term and simulation of induced activation
Laser-plasma interactions at ELI Beamlines are expected to produce protons up to 250 MeV and electrons up to 10 GeV. There are other sources of radiation such as X-rays and ions, however these are not important as the former for activation. The intensities of protons and electrons
Figure 3. Co-59(n,γ)Co-60 reaction cross section as in ENDF [3].

Figure 4. Simulation scheme for activation studies.

can reach up to $10^{10}$ particles per shot, with a repetition rate up to about 10 Hz.

For structural material activation studies, a 3 cm thick, very large plane of the material is irradiated with a pencil beam of particles. The ambient dose equivalent, $H^*(10)$ at 30 cm from the material is scored, along with the nuclide inventory (see figure 4 obtained via Flair [4]).

Figure 5 shows the neutron spectra generated by proton and electron projectiles, respectively
Figure 5. Neutron spectra from a 3 cm thick EN14435 type stainless steel target due to 250 MeV protons and 10 GeV electrons.

of 250 MeV and 10 GeV. The upper limit of neutron energy is up to about a few tens of MeV, and the lower limit depends on the thermalization. Thermalization is offered by the thick concrete walls surrounding the neutron source, and the amount of activation of cobalt is directly proportional to the extent of thermalization, as the neutron absorption probability is higher in the thermal region. Therefore the simulations are always run with the concrete walls (cage) present.

The yearly irradiation profile has been assumed as follows. For the first 20 days of the month, there are 4 hours of irradiation each day. The beam is off for the rest of the month. This pattern is repeated for 12 months. The dose and nuclide inventory are scored at the following cooling times: 0 second, 1 day, 1 week, 4 weeks and 26 weeks, after the end of the irradiation.

3. Results

Figure 6 shows the dose rate decay curve for 250 MeV proton irradiation on stainless steel with an intensity of $10^{10}$ particles per second with and without contamination. Immediately after the end of irradiation, the dose rate rises by up to about 20% for steel contaminated with 10 parts per mille of cobalt when compared to dose rate in uncontaminated steel. For other cooling times, the increase in dose rate is up to about 10%, as can be seen in figure 7. The difference in dose rate increase between short and long cooling times can be attributed to the presence of short-lived isotopes such as meta-stable isomers of cobalt-60.

Table 1 shows the concentration of cobalt contamination and the specific activity of cobalt-60. There exists a linear relationship between the two. Hence, and unsurprisingly, in the long-term, the dose is linearly proportional to the concentration of cobalt. Note that the statistical error of the calculated activity is negligible.
Figure 6. Comparison of dose rate decay curves for uncontaminated steel and steel contaminated with 10 parts per mille of cobalt. Error bars are smaller than the markers.

Table 1. Linear relationship between cobalt-59 contamination and specific activity of cobalt-60.

| Co-59 ppm (end of irradiation) | Co-60 Bq/cm² |
|-------------------------------|--------------|
| 0                             | 3.975        |
| 2                             | 8.924        |
| 10                            | 26.03        |
| 20                            | 44.34        |
| 40                            | 74.94        |

4. Conclusions
Natural cobalt contamination in stainless steel is a real problem faced by every particle accelerator laboratories producing neutrons. The paper presented the sensitivity studies performed for activation of cobalt contamination in stainless steel. Even small amounts (2 parts per mille) of cobalt can lead to a systematic increase in the observed dose by up to about 20%, immediately after shutdown, and about 10% thereafter. Hence uncertainty or lack of knowledge of cobalt contamination in steel can lead to a non-negligible systematic error in the observed dose.
Figure 7. Comparison of dose rate decay curves for longer cooling times. Error bars are smaller than the markers.

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