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Activation analysis of the water cooling system of the LIPAc beam dump

Francisco Ogando [a], Patrick Sauvan [a], Daniel López [a], Javier Sanz [a], Beatriz Brañas [b], Fernando Arranz [b]
[a] *UNED, Madrid, Spain*
[b] *CIEMAT, Madrid, Spain*

Abstract

LIPAc stands for Linear IFMIF Prototype Accelerator. LIPAc generates a 9MeV deuteron beam, which is stopped at a beam dump, depositing over 1 MW of thermal power. A water cooling system has been devised for extracting this energy while keeping operational temperatures within range. The existing high neutron fluxes in the beam dump during operation produce activation of both coolant and beam stopper, which also suffers from corrosion into the coolant. The presence of radioisotopes in the cooling water leads to a radiological hazard. Water purification systems are located outside the accelerator vault and accumulate activated products during filtration, requiring a specific radiological shield to comply with target dose rates. Also devices containing large volume of activated cooling water, like N-16 decay pipes, require specific radioprotection analysis and design. This work identifies the most relevant radiation sources due to the activated cooling fluid, which may result in radiation doses to workers, and propose radioprotection measures into the design to mitigate their effect.

Keywords:

LIPAc; Radioprotection; Material activation

1. Introduction.

The LIPAc accelerator [1] will be a 9 MeV, 125 mA CW deuteron accelerator, identical to the low energy section of one of the IFMIF accelerators, which will be tested to verify the validity of the design before launching the IFMIF construction. It is actually under construction in Rokkasho (Japan).

LIPAc beam is stopped at a beam dump [2], depositing over 1 MW thermal power onto a copper conical beam stopper. This power is extracted by means of a water based cooling circuit [3],and transported to heat exchangers outside the accelerator vault.

Deuteron interactions with copper at the beam dump produce an intense secondary neutron and gamma radiation field, which is partially attenuated with a beam dump shield [4]. The accelerator vault is not accessible during beam operation due to the existing high radiation levels, but vault walls have been designed to allow human access to neighboring rooms at all times. There is a dose rate limit of 12.5 μSv/h in these rooms.

Cooling water penetrates into the beam dump shield in order to reach the beam stopper, and it is therefore immersed in an intense neutron field, which produces transmutation and eventually activation of composing materials due to neutron induced nuclear reactions. These activated materials in the cooling fluid are

transported out of the accelerator vault to the heat exchangers and purifications systems, resulting in decay gamma sources inaccessible areas.

This work determines the most relevant radioisotopes produced in the cooling circuit of the beam dump due to two main pathways: (a) corrosion of activated materials containing the cooling water,(b) activation of both water and corroded materials in water. Radiation doses rate at the purification system due to radioisotope decay gammas is estimated.

2. Assumptions and methodology.

2.1. Cooling system schematics.

Detailed schematics and operation mode of the water cooling system can be found in Ref [3]. A water flow of 108 m^3/h is circulating in a 4 m^3 cooling circuit, including a 0.465 m^3 cartridge inside the beam dump, where water is mostly irradiated. Outside the beam dump shield, the neutron field is strongly attenuated. After exiting the beam dump, water is taken to a decay pipe in order to delay its exit of the accelerator vault and to let short-lived radioisotopes decay.

Outside the accelerator vault there is a resin-based filtering system, after which water returns into the accelerator vault. Water circulation time in the system is 2.2 min.

2.2. Corrosion and water purification.

Corrosion rates for the expected operation mode were calculated in detail in [5], resulting in these main conclusions:

•Corrosion of steel water pipes is negligible, and only copper corrosion at the beam stopper may be considered for the analysis. A conservative value for copper corrosion is 4.0 g/(m^2 year) for only the surfaces contacting high speed water at the cooling channels of the beam stopper. This results in 10.8 g/year of dissolved copper.

•Water conductivity is to be kept between 0.5 and 2 μS/cm, which is turn limits copper concentration in water between 210 and 900 mg/m^3.

Considering the high efficiency of purification resins, only a small fraction of the circulating water should be purified in permanent mode, in order to stay over the minimum copper concentration values. Permanent purification of more than 0.002 m^3/h would result in too low copper steady-state concentration, leading to higher corrosion rates.

Since the water purification bypass is also designed for the circuit filling operation, a minimum of 1 m^3/h has been proposed for the system. Under these conditions, the purification system cannot work in permanent mode and must operate in pulses, where copper concentration is quickly reduced from the highest to lowest tolerated values. The purification cycle consists of 93 days of operation without purification, with linear increase of copper concentration and 6 h of purification, with exponential decay of concentration. The purification phase will be taken as instant for the analyses.

2.3. Determination of the radiation field.

The neutron field inside the beam dump is key factor for the activation process of the cooling water and its solutes. Relevant analysis of the nuclear data for the LIPAc beam dump can be found in [6].The main relevant conclusion was that none of the nuclear models embedded in MCNPX [7] behaved accurately for this application with low energy deuterons [8], and TENDL libraries [9] provide the most accurate nuclear data for the task.

MCUNED [10] was used for the analysis, since it is the only MCNPX-based code capable of handling external libraries for deuterons, like TENDL. Both copper beam stopper and water in the beam dump cartridge, the only considered high flux areas (Fig. 1), were tallies for energy dependent neutron flux calculation.

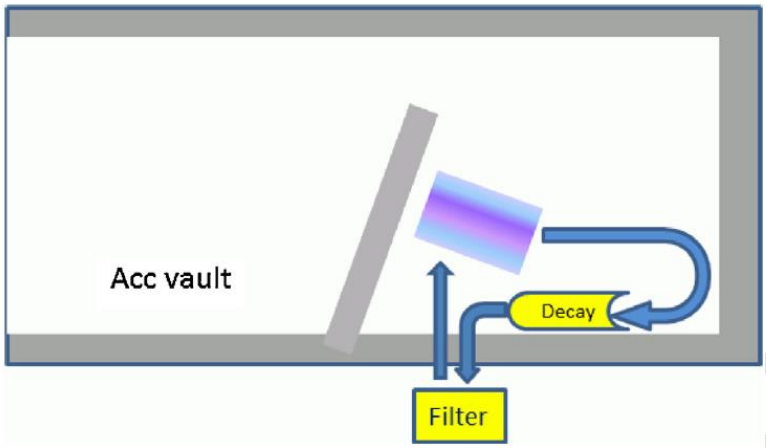

Fig. 1 Schematics of beam dump cooling system.

2.4. Determination of most relevant radioisotopes.

The ACAB code [11] with EAF-2007 nuclear data [12] with Vita-minJ + energy group structure was used in order to compute the isotopic inventory of the cooling water. This code was accepted within the LIPAc project for activation calculations.

For the initial estimation of most relevant radioisotopes, a continuous irradiation was set for copper and water inside the beam dump cartridge, assuming no water flow. Irradiation time was taken as the corresponding fraction of irradiation time (water receives suffers from pulsed irradiation) multiplied by the 0.5 fpy expected lifetime of the facility. The fraction of irradiation time is one for copper in the beam stopper, but in water is the volume fraction between cartridge and whole cooling circuit. The impurity composition for copper beam stopped was taken from [13], although impurities turned out to play a minority role (~3%) in this analysis.

Activated products in water may arise from direct activation of water and from dissolution of increasingly activated copper at the beam stopper. Analytical calculations are performed in order to take into account both effects. Isotope activity is assessed in pipes exiting the accelerator vault and in the filtering resins during water purification.

Out of the obtained radioisotopes, two classes were considered:(a) at 10 s cooling time, the short lived that may live enough to be carried away outside the accelerator vault to the purification filters and, (b) at 1 y cooling time the medium and long-lived isotopes that may result in significant radioactive waste. The most important radioisotope was selected for each class and its inventory evolution and impact analyzed.

Table 1 contains the results of material activation for the previously described calculations, in terms of semi-infinite contact dose rate (CDR). This magnitude is only good here for qualitative evaluation, so no absolute figures are shown.

•N-16 is produced in water through O16(n,p)N16 reaction. This isotope has short half-life (7 s) but decays to O-16 with emission of a beta particle and a 7 MeV gamma.

•Cu-64 is produced in natural copper irradiated by neutrons through a capture reaction. Since copper is constantly being dissolved into cooling water, it contributes to its activity. With short half-life of 12.7 h, it has high specific activity.

•Co-60 is directly produced in copper by Cu-63(n,α)Co-60 reaction. It does not decay significantly during all operation period, but with a relatively short half-life, has strong specific activity.

Table 1 Contribution to CDR of most relevant isotopes.

	Copper	Water
10 s	Cu-64 (90%)	N-16 (100%)
1 y	Co-60 (100%)	Negligible

2.5. Concentration balances.

The coupled activation of beam stopper and water, with transfer of activated matter goes beyond the normal operation mode of ACAB, so a semianalytical model is created to take into account all processes.

The evolution of atomic fraction (F) for any considered isotope in irradiated copper follows the equation:

$$\frac{dF}{dt} = \langle \sigma\phi \rangle_{BS} - \lambda F \quad (1)$$

Where $\{\sigma\phi\}$ stands for average specific production rate, which is returned by the activation code, and λ for the disintegration constant. For times of interest, *F(t)* is a constant value for Cu-64, and a linear function for Co-60.

The evolution of isotope atomic contents Cu-64 and Co-60 in all cooling water follow the equation:

$$\frac{dN_i}{dt} = \beta \cdot F_i(t) + \langle \sigma\phi \rangle_w \frac{V_{BD}}{V_T} \cdot N_0(t) - \lambda N_i \quad (2)$$

where β stands for copper atomic dissolution rate into water, V_{BD} the irradiated water volume water in beam dump, V_T the total volume in the circuit, and N_0 the atomic contents of copper in the cooling circuit. The first term of the RHS represents the dissolution of activated products, the second the activation of copper in water, and the last the decay of the isotope.

N-16 is only produced from oxygen in water, and due to its short half-live, it is considered to decay completely before the cooling water completes a cycle. However it may take significant activity outside the accelerator vault. The N-16 produced in the beam dump has time to decay significantly before exiting it. Assuming constant irradiation in time, the specific activity of N-16 in water at the outlet of the beam dump is

$$a_{16} = \langle \sigma\phi \rangle_w \cdot n_0 \cdot (1 - e^{-\lambda V_{BD}/Q}) \quad (3)$$

where Q stands for the cooling circuit flow current, and n_0 for the atom concentration of oxygen in water. After exiting the beam dump, specific activity decays exponentially.

3. Activity results.

Once obtained with ACAB (or simple product of flux times crosssection data) the specific production rates of the different isotopes, activity values can be obtained by solving the differential equations stated in previous section.

3.1. N-16

Nitrogen 16 specific activity when exiting the beam dump is computed to be a_{16}= 35 kBq/cm^3, but the isotope decays while circulating in the cooling pipes. This activity value is constant during all operation times, since it is independent of copper activation.

The activity of N-16 in water exiting the accelerator vault depends on the time it takes water to get there after exiting the beam dump. This free parameter allows for the design of decay pipes which simply delay the water flow before exiting the vault.

3.2. Cu-64.

This element is produced in copper, and is analyzed separately from Co-60, since because of its short half-live, its content in the beam stopper reaches saturation level in short time in comparison to the purification cycle period. Considering Eq. (2) after saturation of atomic fraction *F(t)*, the total isotope activity in the circuit is at end of any purification cycle is

$$\lambda N_i(\Delta T) = \beta \cdot \frac{\langle \sigma\phi \rangle_{BS}}{\lambda} + \langle \sigma\phi \rangle_w \frac{V_{BD}}{V_T} \cdot N_0 \left(\Delta T - \frac{1}{\lambda} \right) \quad (4)$$

The total activity value in the cooling circuit is 605 MBq, of which 1 % comes from dissolution of activated copper, and the 99 % rest from the activation of dissolved natural copper. At the end of the purification cycle, this activity is partially retained in the filtering resins. The fraction of retained Cu-64 is assumed to be the same as of natural copper which is computed from copper concentration before and after purification. After filtering 464 MBq of Cu-64 are retained in the filtering resins.

3.3. Co-60.

Due to the long half-life of this isotope in comparison to the purification cycle period, its decay may be neglected for the analysis. Solving a simplified version of Eq. (2) leads to the expression

$$N_i(t) = \frac{1}{2} \beta \langle \sigma\phi \rangle_{BS} \cdot t^2 + \langle \sigma\phi \rangle_w \frac{V_{BD}}{V_T} \cdot \langle N_0 \rangle \cdot t \quad (5)$$

The initial condition for this integration is zero only for the first purification cycle. Assuming conservatively that the filtering resins are not replaced, and letting N_i be the total activity including resins and water, Eq. (5) still holds after the purification process.

Considering a maximum of 2 purification periods in the 0.5 fpy estimated lifetime of the facility, the maximum Co-60 activity in all cooling circuit is 24 kBq, much smaller than Cu-64 activity.

4. Radioprotection measures.

The filtering system is located outside the accelerator vault, where a 12.5 μSv/h dose rate limit applies.

The resin bed is a 1-m tall cylinder of 15 cm diameter, and the resulting dose rate measured at 50 cm distance from its surface in its equatorial plane. Numerical calculation with MCNP and using the decay gamma source spectrum provides the ambient equivalent dose per disintegration at this distance by such source geometry.

d(N-16) = 3.37 × 10^{-16}Sv/(Bq s)

d(Cu-64) = 2.75 × 10^{-17}Sv/(Bq s)

d(Co-60) = 2.41 × 10^{-16}Sv/(Bq s)

The dose rates due to Cu-64 and Co-60 are determined by the activity of these isotopes in the resins ("*t*" is time since last water purification).

D(Cu-64) = 46 μSv/h·$2^{(-t/12.7\ h)}$

D(Co-60) = 3.80 nSv/h

The dose rate due to Cu-64 is too high for immediate unrestricted access, so a lead shield is proposed around the resin for shielding. A cylindrical layer of 15 mm of lead reduces the initial dose rate due to Cu-64 to 3.6 μSv/h, therefore complying with dose rate objectives at all times. This shielding cylindrical layer weighs around 88 kg.

This expected dose of Cu-64 requires that the contribution fromN-16 be less than 3 μSv/h in order to comply with dose rate limits in uncontrolled area (an additional dose rate of about 5 μSv/h is expected due to neutron and gamma radiation from beam dump).

This dose rate limitation defines the required decay time *T* before N16 from the beam dump reaches the resins.

$$A = \frac{V}{T} \cdot \int_0^T a(t) \cdot dt = \frac{a(0) \cdot V}{\lambda T}(1 - e^{-\lambda T}) \quad (6)$$

which leads to *T* = 57 s.

This required decay time defines the minimum pipe water volume between beam dump and purification resins ($V = Q \cdot T = 1.7$ m^3). This water volume of the decay pipe is stored inside the vault since it contains large amount of N-16 during operation. There are two main radiological hazards from this tank: (a) N-16 producing doses outside the accelerator vault during operation, (b) doses from Cu-64and Co-60 during maintenance.

For the first issue, the total activity of N-16 in the decay pipe has to be calculated and transport calculations provide the doses outside the vault. The total activity is related to the pipe volume and also to the time it takes the water to go through it.

$$A = \frac{V}{T} \cdot \int_0^T a(t) \cdot dt = \frac{a(0) \cdot V}{\lambda T}(1 - e^{-\lambda T}) \quad (7)$$

In the most conservative case, we assume that activated water reaches the decay pipe immediately after exiting the beam dump, and that it is all contained in a cylindrical volume of 1 m diameter (instead of a more detailed pipe layout). Taking previous values, the total activity of N-16 in the decay pipe during operation of the accelerator is 7.47 GBq. With these values, the maximum radiation dose outside the accelerator vault during operation is 0.07 μSv/h.

During accelerator shutdown, the decay pipe may still contain large amount of Cu-64 and Co-60. The radiation doses at 50 cm from the decay pipes due to Cu-64 and Co-60 are 2.3 and 0.04 μSv/h immediately after shutdown, but considering the waiting time required to enter the room, both values are well within accepted limits. There is no need to shield the decay pipe.

5. Conclusions.

The ambient equivalent dose rate evolution has been calculated for a filtering system of the EVEDA beam dump cooling water. This water becomes activated by neutrons, receives radioactive products from corrosion of the activated copper beam stop, and also suffers from activation of its dissolved copper.

The results of the analysis lead to the following conclusions concerning the cooling system:

•N-16 is produced in the beam dump and a decay pipe has to be used in order to delay 57 s its exit from the accelerator vault. The volume of the pipe water between beam dump and filters has to be no less than 1.7 m^3. No special shield is needed for the decay pipe.

•Cu-64 poses are relatively low radiological risk and a moderate radiological shield in the filtering resins is sufficient to keep its radiation field within limits of a controlled area. The maximum expected activity of Cu-64 in water during operation is 650 MBq.

•Co-60 poses no short term radiological risk since, considering 6 month continuous irradiation (containing 2 water purification cycles), it would contribute to local doses at the filters with less than 0.6 μSv/h. The maximum expected activity of Co-60 in water circuit is 24 kBq.

The filtering resins may therefore be safely placed in controlled areas outside the accelerator vault.

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