Engineering project
Deconstruction of cell 241B,
Batch 01 of the ARRONAX cyclotron

1. Site background and history

ARRONAX, the renowned Nantes-based cyclotron, is deconstructing a building containing obsolete effluent storage and transfer lines at its Saint Herblain site. Cell 241B is an active effluent storage and transfer station. It essentially comprises 3 storage tanks for effluents from the target cooling system used during irradiation for the manufacture of 82Sr and 99mTc radionuclides, which are used in nuclear medicine for imaging. These three tanks contain effluents and active deposits in different concentrations, depending on the irradiation histories of the targets during the periods concerned. These radioactive elements originate either from recoil nuclei produced during target irradiation, or from incidents linked to target breakthroughs during irradiation.

2. Call for tenders and services

ARRONAX wishes to dismantle the 3 tanks mentioned above. The work is due to start between t0 and t0+2 months (when the tanks will cease operating). As part of the initial study phase of the project, ARRONAX has launched a call for tenders (RFQ) with leading engineering firms to obtain proposals for dismantling scenarios. The aim is to put several companies in competition with each other in order to select the best one able to provide the service. The selection criteria are :
- Technical aspects (weighting 40%)
- Financial aspects (weighting 40%)
- Impact on site activity (weighting 20%)

The company with the best overall score will be selected.

3. Project organization and task allocation

Your company MARS, with teams of engineers specializing in decommissioning and the prevention of risks of exposure to ionizing radiation, has decided to respond to this invitation to tender. Remember, winning a tender requires both teamwork and robust project management.

To maximize your chances of winning this tender, Mr. Plouf, MARS' engineering department manager, asks you to form teams of four students. Each team must contain two students from each course. You'll also need to set up mixed teams of former Nantes University students and newcomers. He reminds you that you must set up a project management organization in each team.

Each team will first have to carry out a zoning study of the site to be deconstructed, based on information supplied by ARRONAX, in particular the composition of the contents of each tank, which will have to be validated by an independent calculation. **Given the steel thickness of the tank walls, only electromagnetic radiation needs to be taken into account. The effects of the Bremsstrahlung radiation due to the interaction of electrons on the vessel walls will be neglected.** Explain your methodology and calculations, and list the measuring and control equipment used. In addition, each team will compare the mapping carried out with that provided by the DEM+ software for batch 01 of cell 241B. A comparison with a Monte-Carlo simulation tool will be a plus (e.g. the tools used in practical work).

In addition, ARRONAX has provided the geometric characteristics of the tank room, as well as the production conditions for the radioactive elements present in the tanks (see appendices to this document). This information will enable the teams to estimate the composition of the contents of each tank. This estimation must be carried out with a view to being as representative as possible of the actual composition, while ensuring the safety of the employees who will be out in the field. In order to optimize the cost of dismantling, it is important to validate the data supplied by Arronax.

The members of each team are expected to exchange information regularly, for example at project progress meetings held between scheduled sessions. The radiation protection experts from each team will then provide their dismantling experts with joint feedback on the estimated composition of the 3 tanks, so that they can finalize the dismantling scenarios envisaged. At the same time, the dismantling experts in each team will use the DEM+ software, based on the compositions given a priori by ARRONAX, to establish different dismantling scenarios, taking into account the customer's selection criteria: cost, ALARA principle, site duration, quantity of waste to be minimized and treatment channels. This list is not exhaustive, and may be expanded in the specifications. **Mr. Plouf also asks that the presence of tritium in the tanks, particularly number 3, be taken into account in the dismantling scenarios, particularly in terms of site conditions.**

4. Milestones and Deliverables

Milestones and deliverables respect the collective nature of the project. Teams of experts will be invited to respond to the call for tenders.

The deadline for responding to the call for tenders is 11:30pm on april 13, 2026. Before this date, you must send a document (in word or pdf format) detailing your proposals and the methodology used to arrive at this result, by e-mail to eric. moreno@cea.fr with acknowledgement of receipt. We emphasize that this response is a joint deliverable for each team, requiring the different members of each team to interact throughout the project to prepare it. The defense of your proposal will take place on February 20, 2026.

During the first session, a meeting is scheduled with Mr. Plouf to present the specifications, and for the teams to get to grips with the project for the first time. At the next meeting, you are expected to give a powerpoint presentation of the specifications and the Gantt chart (phases, milestones, estimated dates of intermediate deliverables) you have drawn up for your respective assignments. The project structure should also be presented (entities, responsibilities). It is important for the success of the project that the phases of exchanges between the members of each team (who does what? and when?) are identified from this date. For example, you need to ensure that the radiation protection experts are in sync with each other in providing the team's decommissioning experts with the actual composition of the tanks, sufficiently in advance to give them time to revise their scenarios accordingly before issuing their final conclusions. **Similarly, the joint response to the call for tenders requires coordination to draw up the final document, so that participants' contributions are ready in good time to be incorporated.**

In the final session (April 20, 2026), each team will present its results and methodology. You will also be asked to report on the project management you have put in place, as well as the points for improvement you are considering for your next engineering project. This presentation will last 30 minutes per team.

The intermediate milestones will be as follows (they will be assessed):
- Session 1 (Sept. 13, 2025): presentation of work, definition of groups and start of group work.
- Session 2 (Sept. 27, 2025): **powerpoint presentation of your understanding of the specifications and the Gantt chart you've constructed.**
- Session 3 (Oct. 8, 2025): group work
- Session 4 (Nov 4, 2025): **milestone 1:** results for tank 1 (or at least the methodology to be used): oral presentation with written support to be handed in to supervisors;
- Session 5 (Dec. 9, 2025) **milestone 2:** zoning presentation (with written support to be handed in - if the calculated composition is not ready, use the one given by Arronax),
- Session 6 (Dec. 10, 2025): **milestone 3:** presentation of first dismantling scenario(s) (with written support due).
- Session 7 (Dec. 12, 2025): **final milestone**: finalization of all estimates and dismantling scenarios with definitive input data.
- Feb. 13, 2025 at 11:30pm: **project submission** to mars-ingenierie@subatech.in2p3.fr
- Session 8 (Feb. 20, 2025): **Oral presentation** of the project at the final session.

All team members are responsible for the results presented. However, in the event of under-participation in the work carried out by one or more members of a team, the supervisors reserve the right to differentiate marks between members of the same team.

Annexe 1 : Presentation of the cell241B

Dimensions:

Hall: 21.598 x 10.2m; height 3.749m; wall thickness: 1.375m

Tank 1: steel, thickness 4mm placed under the wall diameter 2.04 length 4.495m

Tank 2: steel, 4mm thick diameter 1.428m, H 2.289

Vessel 3 (tritium): steel, 4mm thick (see appendix 2)

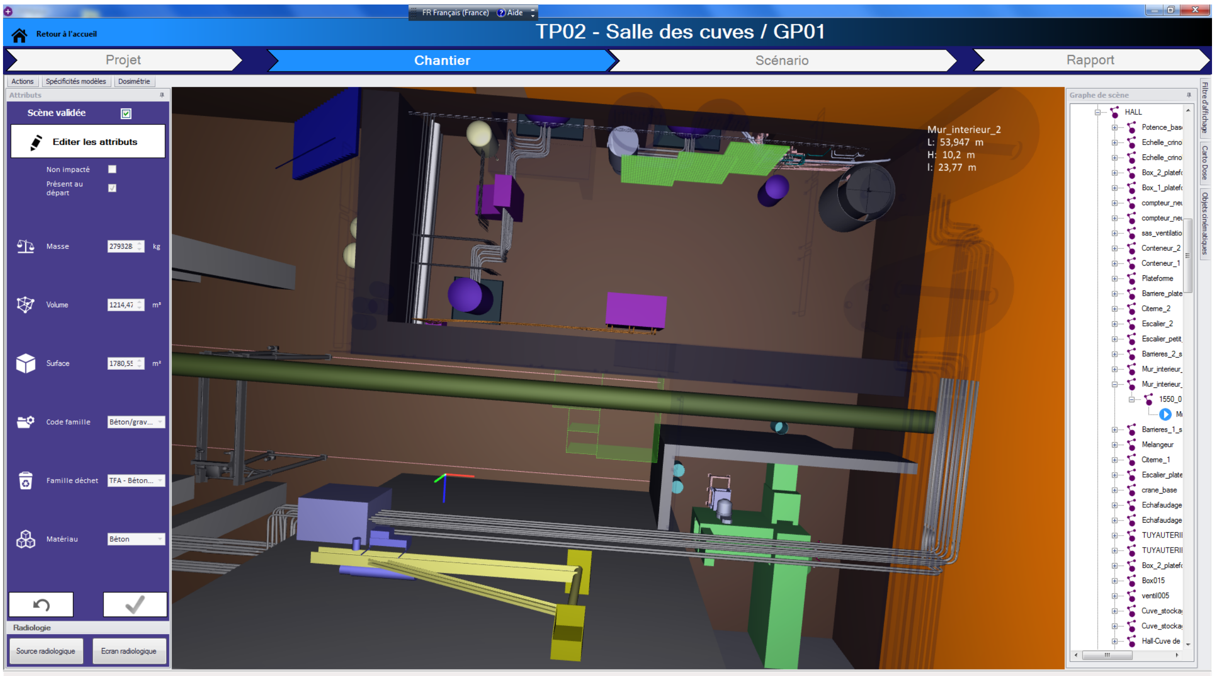


Figure 1 : View of the tank room.

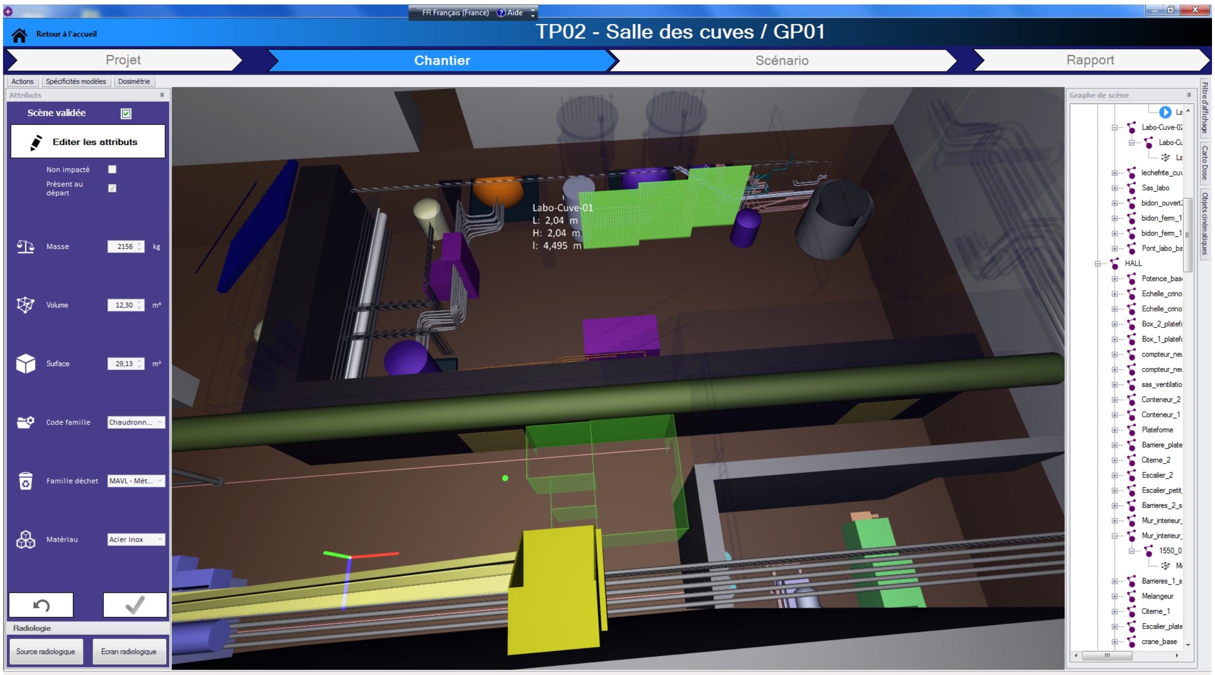


Figure 2 : Tank number 1 is colored orange.

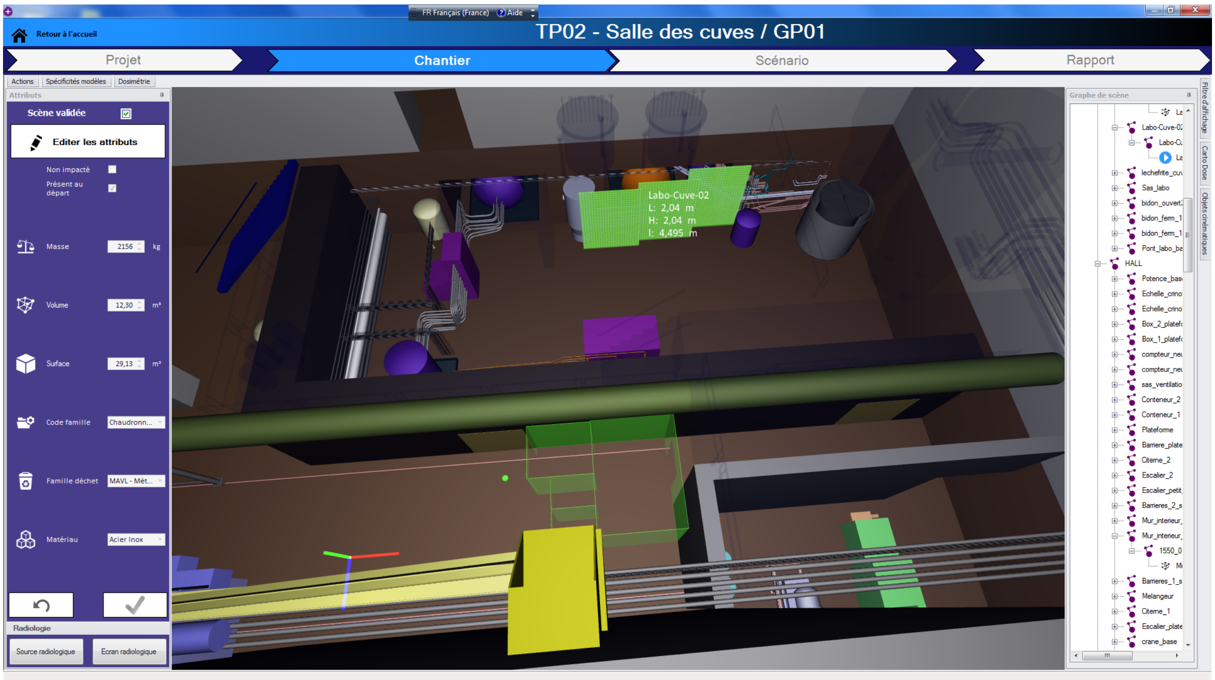


Figure 3 : Tank number 2 is colored orange.

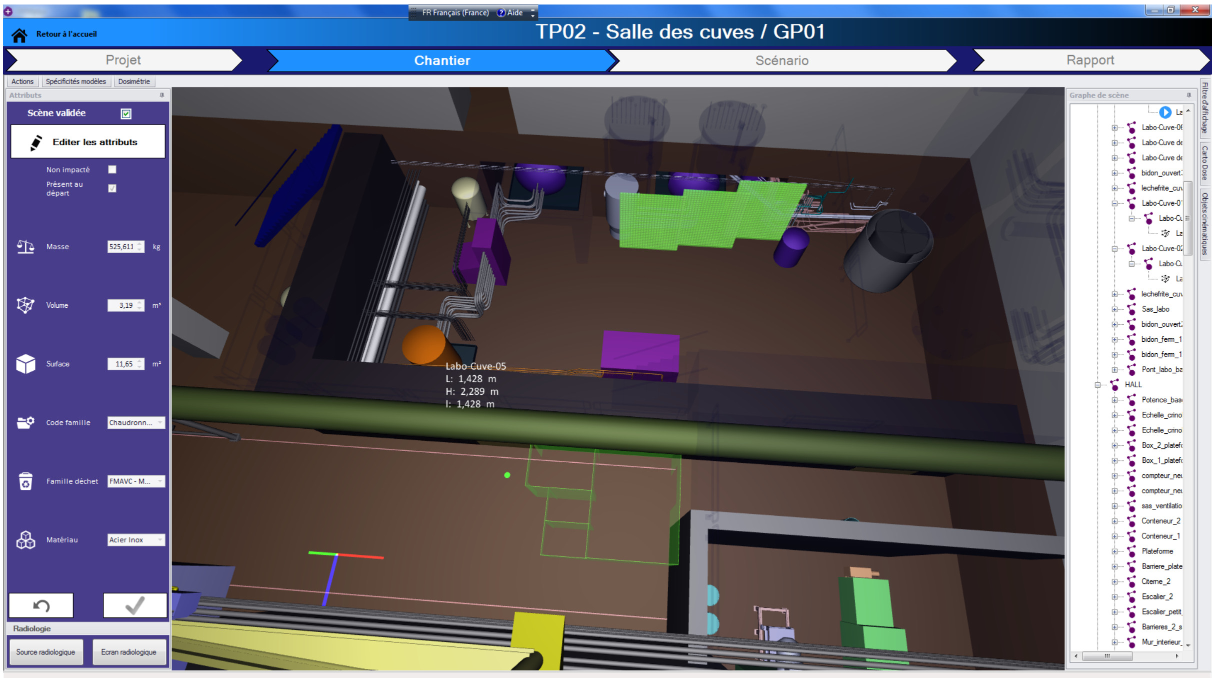
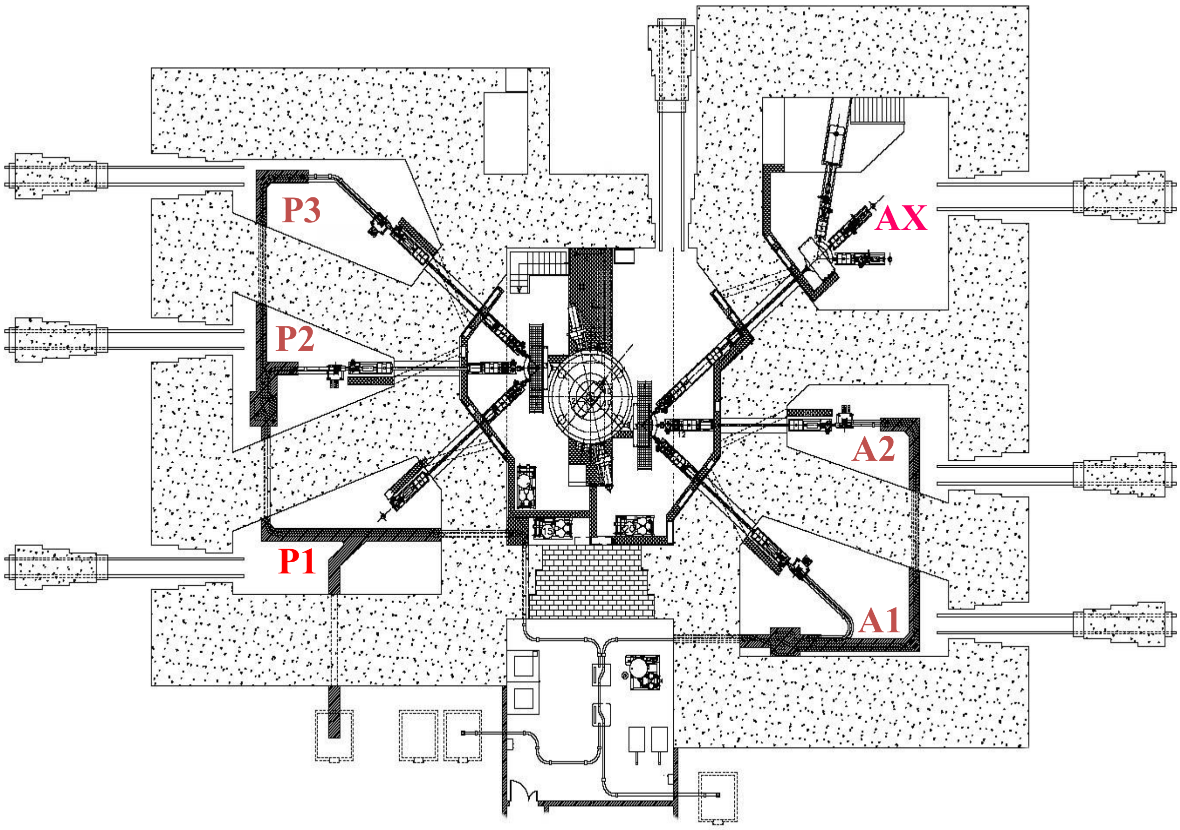


Figure 4 : Tank number 3 is colored orange.

Annexe 2 : Composition of the sources contained in the tanks

The Arronax cyclotron has 3 cooling tanks, each holding 100 L of deionized water. These are used to cool the targets in casemates P2 and P3, to cool the tanks in casemates A1 and A2, and to cool the system's measuring elements and magnets.



Tank 1 : cooling of targets in casemates P2 and P3

The P side (casemates P2 and P3) is used exclusively for strontium 82 production. This is achieved by bombarding a rubidium target in metallic form contained in a thin steel capsule (0.1mm thick, 316L steel). The entire target is immersed in cooling water to ensure optimum cooling. The protons have an energy of 70 MeV and, given the shape of the effective production cross-section, the thickness of the target is defined so that the protons leave the target with an energy of 40 MeV. The beam is then stopped in the cooling water.

Under normal operating conditions, only a few recoil nuclei (which will be neglected) and tritium are present in the cooling circuit (this choice will have to be justified). In an accident situation, where a target is pierced, the entire contents of the target are dissolved in the cooling water. In these situations, we will consider the production of the following elements: ^{82}Sr, ^{83}Sr, ^{85}Sr, ^{86}Rb, ^{84}Rb, ^{83}Rb, ^{82}Rb et le ^{83m}Kr. You'll need to justify the relevance of this choice.

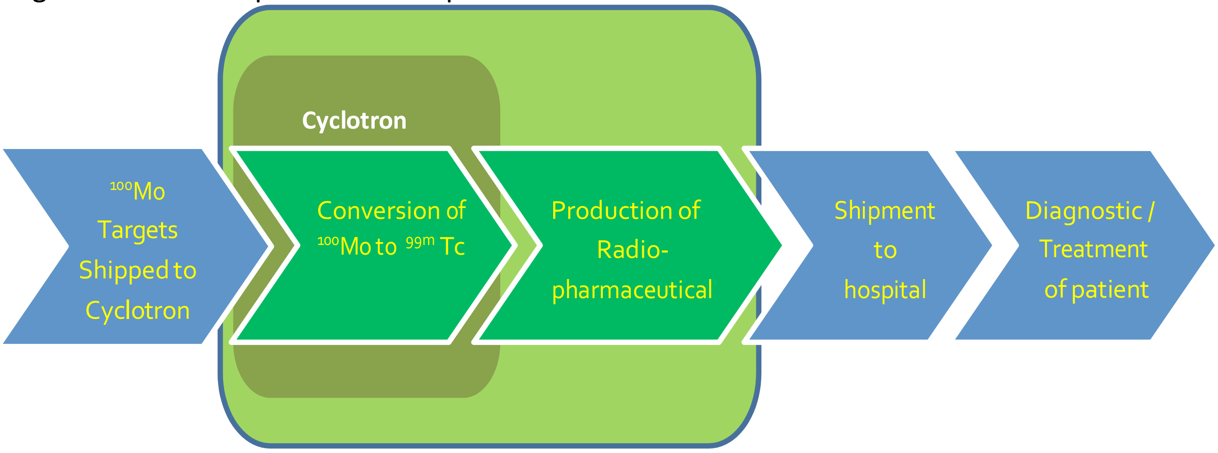
A typical irradiation "run" corresponds to one week's uninterrupted irradiation (120 hours) with 100µA of 70 MeV protons. There is one irradiation per month. The tanks have been in operation for 5 years. T0 will be the date on which the tanks cease operation. There have been 3 target piercing incidents during this period:

T0 - 40 months, T0 - 23 months, T0 - 3 months

Estimated composition (to be validated): ^{82}Sr=343mCi, ^{83}Sr=0, ^{85}Sr=504mCi, ^{86}Rb=15mCi, ^{84}Rb=762mCi, ^{83}Rb=490mCi,^{82}Rb=343mCi et le ^{83m}Kr=490mCi

Tank 2 : cooling of targets in casemates A1 and A2.

The A side is used exclusively for ^{99m}Tc production by irradiating a 100% enriched ^{100}Mo target with 24 MeV protons at 100µA.



The cooling circuit is not, a priori, in contact with the beam, except in the event of a target rupture, when it is assumed that the entire production output ends up in the beam. A typical irradiation corresponds to 6 hours.

There are 3 irradiations per week and an average loss of 2 targets per month.

Tank 3 : cooling beam line elements

This tank is used to cool the diagnostic elements and, in particular, the Faraday cups used for beam adjustment. During these operations, the beam is sent into the Faraday cage with the shot energy and intensity required to work out the beam shape. The thickness of the water in the Faraday cup is such that the beam is stopped in the Faraday cup. This operation takes 1 hour and is carried out systematically before each shot.

Annexe 3 : Project Management :

- The Master lecture about project management
- https://mooc.gestiondeprojet.pm/
- référence dans le domaine : le MOOC Gestion de Projet de Remi Bachelet (Centrale Lilles) http://www.lemonde.fr/campus/article/2017/01/05/gestion-de-projet-le-mooc-a-grand-succes-de-centrale-lille_5058190_4401467.html
- Gantt diagram with excel: https://www.excel-exercice.com/diagramme-de-gantt/

Annexe 4 Nuclear Data

Decay characteristics of nuclei: Use the databases of the "national nuclear data center" (nndc of the US Department of Energy).

- https://www.nndc.bnl.gov/
- nudat2: https://www.nndc.bnl.gov/chart/
- decay radiation search: https://www.nndc.bnl.gov/nudat2/indx_dec.jsp
- Particle/matter interaction calculations: SRIM (free software) - http://www.srim.org/
- production cross-section data: https://www.nndc.bnl.gov/exfor/exfor.htm

If these data are not available, the TENDL database can be used.

Calculating the production of a radioactive element from its effective production cross-section:

In the case of a thick target, to calculate the activity produced, we need to take into account the energy dependence of the effective cross-section and the linear energy loss of the incident particles over the thickness of material crossed. The relationship is shown below:

$$Act = \phi.\chi.\frac{N_A.\rho}{A}.(1 - exp(-\lambda.t_{irr})).\int_{E_{fin}}^{E_{in}} \frac{\sigma(E)}{\frac{dE}{dx}} dE$$

– Act : the activity of the radioisotope produced (Bq), referred to the irradiation end time
– χ : isotopic abundance in the target
– ϕ : incident particle flux (particles.s-1)
– N_A : Avogadro constant (mol-1)
– A : atomic number of the target (g.mol-1)
– λ : decay constant of the produced isotope (s-1)
– t_{irr} : irradiation duration (s)
– ρ : volumic mass of the irradiated target ($g.cm^{-3}$)
– E_{in} : projectile energy at the entrance of the target (MeV)
– E_{fin} : projectile energy at the exi of the target (MeV)
– σ(E) : the production cross section of the radioisotope of interest at energy E (cm^2)
– dE/dx : the linear energy loss of the projectile in the target ($MeV.cm^{-1}$)

For calculation purposes, the effective cross-section is assumed to be constant and equal to the average value of the effective cross-section over the thickness of the target under consideration. You can also use the RYC software available on the arronax website (https://www.arronax-nantes.fr/outil-telechargement/outils-radionuclide-yield-calculator/). This calculation does not take account of filiations.

In the case where the mother nucleus decays on a daughter radioactive nucleus, the equations change (inspired by http://iopscience.iop.org/article/10.1088/0031-9155/56/17/002/pdf

Calculating photon dose for a given radiation source

To determine dose rates, the source is considered as a point source. For each photon line, the contribution to the dose received can be determined.

$$\frac{dD}{dt} = \frac{1.3E-10 * A * E * I}{d^2}$$

- $\frac{dD}{dt}$: instantaneous dose rate (mSv/h)
- A : source activity (Bq)
- E : radiation energy (MeV)
- I : branching ratio
- d : distance from the source (m)

The total dose rate received is then calculated by adding up the contribution of each radiation source.

Linear attenuation of photons in matter :

Linear Attenuation Shielding Formula With Buildup:

$$I_B = I_A \times b \times e^{-\mu x}$$

Where:

- I_B : the shielded dose rate
- I_A : the initial dose rate
- b : the buildup factor for one energy at the shield thickness x
- μ : the linear attenuation coefficient in cm^{-1}
- x : the shield thickness in cm

For attenuation coefficients, use the NIST tables:

https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

The build-up factor should be specified (http://www.radprocalculator.com/Files/ShieldingandBuildup.pdf).

Pn can provide a table for steel and lead if shielding elements are used.

Units :1 Ci = 1 Curie = $3{,}7.10^{10}$ Bq