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# Politecnico di Torino

## **Deuterium and Tritium dynamic management in the Sorgentina-RF plant**

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# 1. Introduction

The SORGENTINA-RF facility is a project developed by ENEA Brasimone and their partners that aims to develop and optimize the  $^{99}\text{Mo}$  production routes that are alternative and complementary to those presently adopted. This radionuclide is the precursor of  $^{99m}\text{Tc}$ , one of the tracers used in *single photon emission computed tomography (SPECT)*, a diagnostic technique that covers more than 80% of all the nuclear medicine diagnostic procedures worldwide [1].

SPECT is a nuclear imaging scan that integrates computed tomography (CT) and a radioactive tracer (it is different depending on the organ analysed) which allows the doctors to see how blood flows to tissues and organs. It may be used to help diagnose seizures, stroke, stress fractures, infections and tumours. Before the SPECT scan, a tracer is injected into your bloodstream, where it emits gamma rays that can be detected by the CT scanner. The computer collects the information emitted by the gamma rays and displays it on the CT cross-sections. These cross-sections can be added back together to form a 3D image of the tissue or organ of interest [2].

Nowadays, the gold standard for  $^{99}\text{Mo}$  production is the irradiation of samples containing highly enriched  $^{235}\text{U}$  with the neutrons generated at research fission reactors. But in 2009, the simultaneous and unpredicted temporary shutdown of the two main fission reactors (i.e. HFR in Holland and the NRU in Canada) that were providing a large fraction of the world demand of  $^{99}\text{Mo}$  caused a global crisis of this radionuclide supply, which instigated different international organisations to request unexplored production methods without using uranium.

In SORGENTINA-RF (SRF) the nuclear reaction involved in the production of  $^{99}\text{Mo}$  is the inelastic reaction  $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$ . The facility will assess the chain that starts with the irradiation of the natural molybdenum (where  $^{100}\text{Mo}$  has an isotopic abundance of about 10%) up to the production of the so-called mother solution, a liquid solution named sodium molybdate. The innovation of Sorgentina is the production of 14 MeV neutrons from fusion reactions between deuterium and tritium (D-T reactions are the same as the ones in future fusion reactors like ITER or DEMO) to irradiate stable molybdenum and produce  $^{99}\text{Mo}$  [1].

The whole project is subdivided in different activities, denominated *Tasks*, each of them carried out by a different team that focus on particular aspects and components of the plant:

- Task 1–Civil works
- Task 2–Rotating target
- Task 3–Ion source
- Task 4–Neutronics
- Task 5–Tritium facility
- Task 6–Radiochemistry facility
- Task 7–Radiation protection
- Task 8–Safety
- Task 9–Titanium facility

This Master Thesis is centred around the work of Task 5. Before describing the different aspects considered for the design of the tritium facility and the systems analysed in this work, a brief overview on the other Tasks' projects is here presented.

Task 1 main works will be those related to the building that will host the plant, which will be installed at the ENEA Brasimone Research Centre. In particular: remaking of the deteriorated partial coverage, demolition of partitions, adaptation of conventional and non-conventional systems (water supply, electricity supply, gas supply), reinforcement of the attic on the ground floor, realization of the stack and the biological shield.

The goal of Task 2 is the design of the rotating target of the neutron source and of its auxiliary components, in particular the vacuum chamber and heat transfer system. The rotation of the device is designed to fulfil two different functions: it will permit a suitable deposition and implantation of deuterium and tritium into a thin titanium layer (about 3  $\mu\text{m}$ ) properly deposited on the target surface; at the same time, it has to dissipate the thermal power (250 kW) delivered by the accelerator by acting as a sort of heat pipe. In order to perform this double scope, the rotating device material is required to have some particular characteristics: high thermal conductivity to keep the temperature of the titanium layer below 200 °C, low neutron activation to keep shutdown periods as short as possible, good mechanical properties and chemical compatibility with water. Aluminium alloys were selected as the best compromise to fulfil these criteria. A scheme of the target is showed in Figure 1.

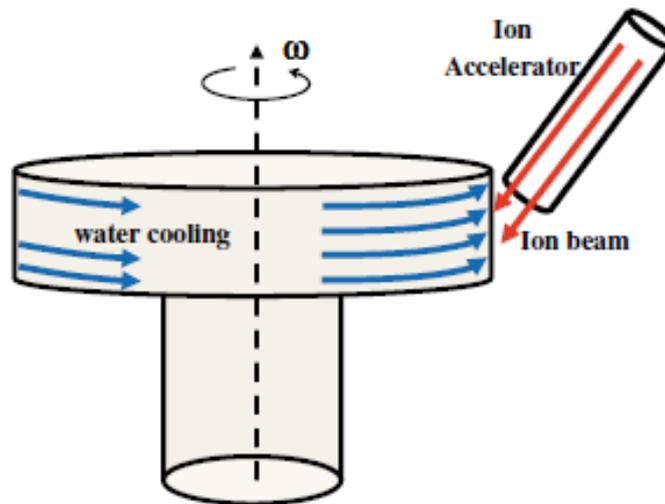


Figure 1. Rotating target and ion accelerator scheme [1].

Task 3 focuses on the accelerator that drives the D-T ion beam toward the rotating target, where the thin titanium layer acts as a “neutron sponge”. The beam power of 250 kW at the target was fixed after evaluating a number of general aspects of the project, such as the maximum power input of the facility, the electrical consumption and the desired neutron yield for the production of a given activity of the radionuclide. The design of the ion beam, which is the source of the neutrons that irradiates the molybdenum, is based on some critical aspects:

- To demonstrate continuous and sustainable operation, it has to work on a continuous and long cycle between two consecutive maintenance services.
- To preserve the neutron production, it has to control the composition of the deuterium and tritium ion beam.
- Since it manages tritium gas, which is radioactive, some components must be properly designed to solve the issues related to tritium contamination.

Task 4 handles everything related to neutron analysis. It studies the optimization of the radionuclide production, it evaluates the nuclear loads on the components in the facility and therefore designs proper shielding elements to mitigate radiation effects. In particular, the bio-shield embedding the neutron source presents a peculiar solution obtained after Monte Carlo simulations: the structure (see Figure 2) surrounding the radiative source is made of 1m thick concrete and the access corridor presents a labyrinthine shape in order to mitigate the flux directed to the entrance door. Objective of this Task is also the estimation of the radiation damage on sensitive elements (such as grids, insulators and magnet of the ion source) in order to prevent the degradation of the physical properties of the materials. Finally, the radioactive waste produced

during operation by all the equipment and components is evaluated and taken into account for the future decommissioning of the plant.

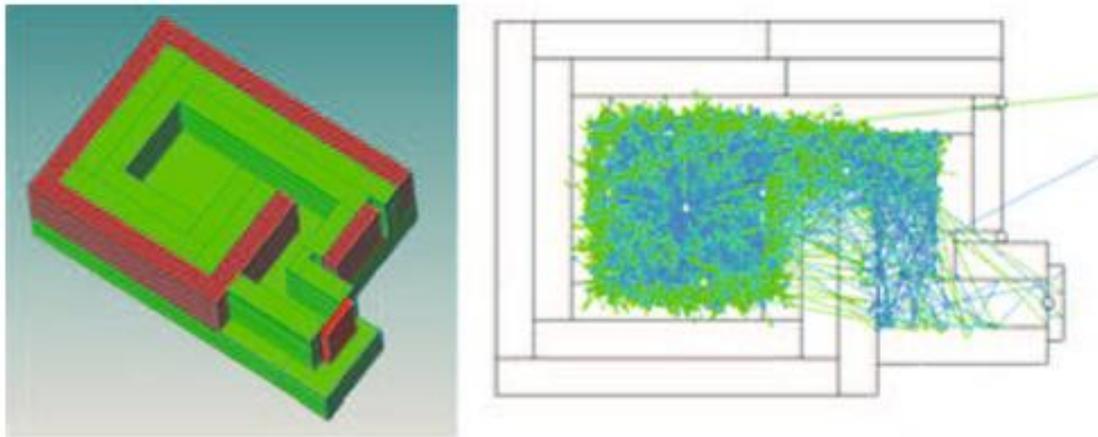


Figure 2. Left side: 3D representation of the geometry. Right side: Monte Carlo simulation for neutrons (blue line) and gamma rays (green line) respective fields inside the bio-shield labyrinth [1].

Task 6 main activity is the design, development and implementation of the chemical processes by means of due components for the production of the sodium molybdate  $\text{Na}_2\text{MoO}_4$ , the so-called mother solution from which  $^{99m}\text{Tc}$ , is obtained. Object of the Task is then to model and experimentally validate the chemical reactions related to the dissolution of the target. Therefore, the required systems must be designed and built to permit continuous operation, which comprehend a fast production of the solution to minimise the specific activity decrease of the target. Finally, another object is the quality control of the target, performed with an impurity assessment of the material before irradiation done by mass spectroscopy with a quadruple spectrometer.

Task 7 performs a preventive safety analysis of SORGENTINA-RF and of the related activities in order to identify ways in which potential exposures could occur. The sources of ionizing radiation present in the facility are direct radiation from fusion reactions, gamma radiation due to material activation, tritium diffusion and environmental contamination. Workers and population can face both external exposure and internal contamination: in order to solve this issue, Task 7 has to precisely characterize every form of radioactive source, producing technical and organisational procedures, managing and monitoring the various exposure pathways, and finally made a report of the quantity of neutron emission rate in order to obtain Category A License needed to run the whole plant.

Task 8 performs a safety assessment in order to identify any hazard related to the operation of the facility, possibly leading to accident events under any of the foreseen plant states. This assessment is performed by a combination of Probabilistic and Deterministic Safety Analyses: the former aims to identify the so-called Initiating Event with a top-down approach, while the latter studies the accidental sequences that results from different Initiating Events. Since tritium is recovered from the rotating target, one of the main safety analyses is dedicated to avoiding any criticality of the recycling process which might release tritium. Finally, the activities carried out by this Task must support and integrate the work produced by Task 7 in order to provide both occupational and radiological safety.

Task 9 aim is to recycle the titanium sputtered away by deuterium and tritium ion beam in order to keep the thickness of the titanium layer constant. The restoration is carried out by means of a sputtering-based Ti deposition relying on an ion source delivering argon ions on a titanium target. The rate of erosion, and in turn the sputtering yield of the material depends on different quantities, such as the ion energy and their density, as well as the relative mass between ions and target atoms.

As previously mentioned, this Master Thesis focuses on the Task 5 work, which is the design and the management of the Tritium Facility. The main objective of Tritium Facility (TF), and the Tritium Processing System (TPS) contained within the former, is to process and recycle deuterium and tritium used in the vacuum chamber for the high-energy neutrons production in the SORGENTINA-RF project. In particular, the ion beam, which is the source of both deuterium and tritium, has to be fuelled by a pure D-T gas mixture with a stoichiometric ratio of 50:50 within a tolerance of  $\pm 5\%$ . The two isotopes are sent to the ionization chamber through two different tubes, each containing one of the two gases. They return back to the tritium facility inside a larger pipe and mixed together with residual elements from the chamber. Therefore, the other impurities from the vacuum chamber as titanium, helium, argon, oxygen, etc., have to be removed from the stripping gas before to route the  $Q_2$  (where  $Q = D, T$ ) isotopes to the fuel management system. The system is foreseen to handle the exhaust gas with an impurity composition of about 1 at. %, while the concentration of hydrogen in the purified gas should be less than 2%. Finally, the Tritium Facility is constituted by four different subsystems strictly interacting:

- The vacuum system
- The tritium control system
- The Pd/Ag permeator system
- The tritium getter storage system

The vacuum system operates at a pressure of  $10^{-3}$  Pa generated by means of a turbo-molecular pump backed by a dry scroll pump or rotary vane pump. Its function is to pump the D-T mixture coming from the vacuum chamber. A filtering system is needed in order to remove impurities from the gas stream before directing it to the tritium control system.

The tritium control system is designed to allow a dynamic control of the deuterium and tritium inventories. In particular, the deuterium and tritium mixture coming from the vacuum system is accumulated inside a pressurized storage tank which sends the gas mixture to the permeator. The ion accelerator is fed by the D-T mixture collected in other two smaller pressurized tanks contained in this system. These tanks are filled by means of external sources as well as by the gas flow coming from the permeator system. Inside the three different tanks, the gas composition is evaluated by a dedicated mass spectrometer and an ionization chamber.

The Pd/Ag permeator system aims to remove tritium and deuterium from the exhaust gas coming from the vacuum chamber, before redirecting the purified D-T mixture to the storage tanks and in turn to the ion accelerator. At the same time the impurities removed are then sent to the so-called impurities removal system. The permeator system technology is based on the phenomenon of tritium permeation through a membrane towards a secondary side where vacuum is present.

The tritium getter storage system is one of the external sources for the two tanks mentioned before. It is a separate system from the others due to the particular nature of the gas, being it radioactive, and therefore it is placed inside a reserved glovebox. The tritium is stored inside a getter bed, which is complemented by a dedicated heating system, which allows the solubilized tritium to be desorbed, and by a control valve, which opens once the desired pressure is reached.

The work presented in this Master Thesis focuses on the tritium control system, on the Pd/Ag permeator system and on the tritium getter storage system (which combined form the Tritium Processing System, TPS) and does not design the vacuum system, despite being still placed inside the tritium facility. In Figure 3, a scheme of the process of SRF fuel cycle is provided:

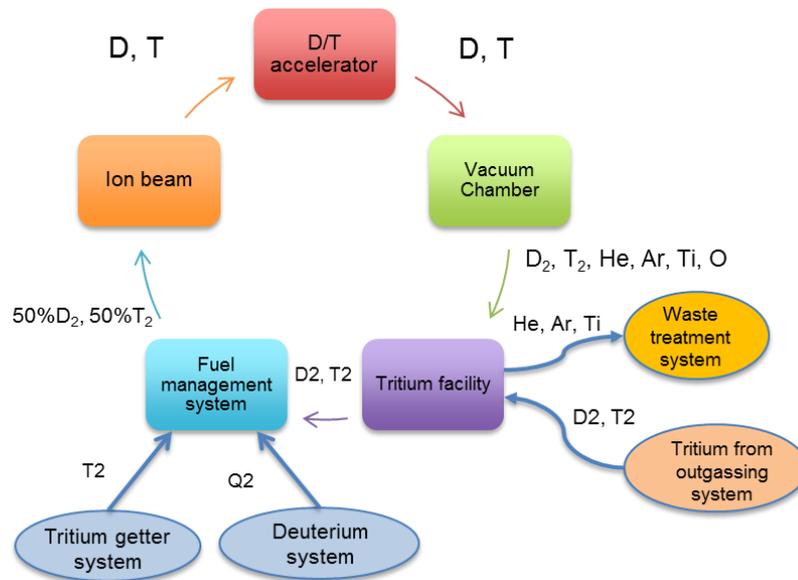


Figure 3. Scheme of the deuterium and tritium cycle inside Sorgentina-RF [1].

This Master's Thesis focuses on the design of the TPS: an initial Process Flow Diagram is defined, highlighting the relations between the different subsystems of the TPS. The main components of the system are designed, such as the storage tanks and the tritium piping. For the pipes, a transport model is developed in order to find the most suitable material for its realization, and a CAD for the tubes' arrangement is proposed. The tritium is initially stored in a uranium getter, and the getter beds are designed in accordance with international standards. All the tritium-facing components, getter included, are contained in gloveboxes specifically designed: the containment barriers must respect international regulations. A preliminary design of the gloveboxes is performed determining the most appropriate material to reduce gas permeation and estimating the required minimum thickness. Thereafter, a better design is presented considering the safety features of the gloveboxes required by legislation and the dimensions of the contained components. Finally, the TPS is simulated with Simulink to optimize its operational framework and to represent the logic that regulates the whole system. This model shows the dynamic management of the fuel, describes the alternate filling of the tanks and how the external sources of tritium and deuterium intervenes. It is a fundamental part in the whole Sorgentina project, being the starting point for the future development of the plant.

In particular, Chapter 2 provides a general design of the TPS, specifying some parameters and constraints of the facility; an initial PFD of the system is produced and additional safety measures and systems are described, such as the ventilation system needed; the main processes carried out in the TPS are listed and discussed with the creation of a proper functional analysis and finally, the systems that interface the Tritium Processing System are described. Chapter 3 is dedicated to the design of the main components: initially, the theoretical background supporting the calculations is provided, and after that the components are analysed one by one; their design must be in compliance with safety international standards since tritium is a radioactive gas. Finally, Chapter 4 is dedicated to the modelling of the TPS: a simplified version that describes the filling and successive discharging of the gas tanks is presented.

## 2. Design of the Tritium Facility

Sorgentina-RF will be installed in the CPC1 building at ENEA Brasimone Research Centre, Figure 4. **L'origine riferimento non è stata trovata.** (last update of the drawing: 4 Nov 2021), and in particular, the Tritium Facility will be located in the northern part of the building, in the rooms closest to the main entrance door. The objective of the TF is to process and recycle deuterium and tritium used in the vacuum chamber for the high-energy neutrons production in the SORGENTINA-RF project. The ion beam, which is the source of both deuterium and tritium, has to be fuelled by a pure D-T gas mixture with a stoichiometric ratio of 50:50 within a tolerance of  $\pm 5\%$ . The design of tritium system has to allow the continuous of Sorgentina RF with a constant refuelling of the ion beam. The fuel cycle takes into account:

- Deuterium and tritium requirements of ion beam.
- D/T acceleration and implantation in the vacuum chamber.
- D-T reactions in the vacuum chamber.
- Vacuum chamber operative conditions.
- Feed gas downstream the vacuum chamber to be processed ( $D_2$ ,  $T_2$ , HD, He, Ar, Ti, O).
- D/T losses in the loop.
- Deuterium and tritium monitoring and management in the tritium facility.
- Refuelling of D and T and the composition control before re-entering in the ion beam.

The schematic representation of the fuel cycle was previously described and reported in Figure 3.

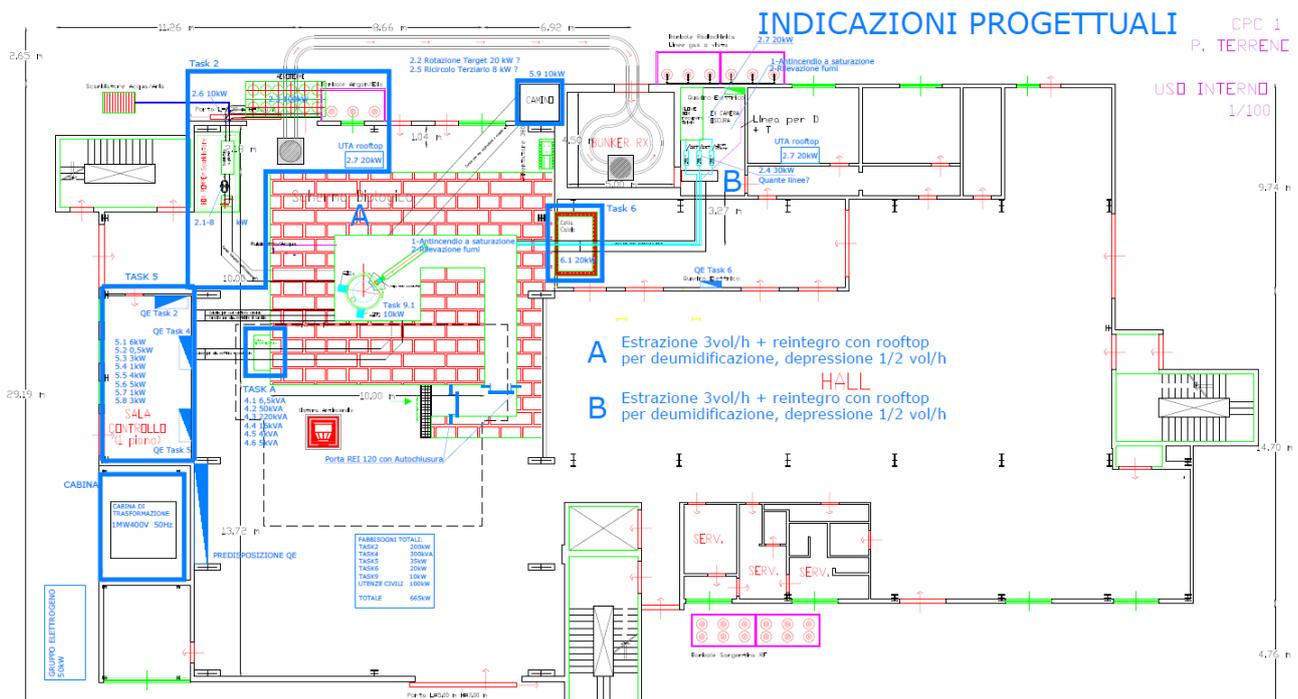


Figure 4. Layout of CPC1 building at ENEA Brasimone Research Centre.

Some input data useful to the design Tritium Facility but coming from to other systems (e.g. the ionization chamber and the vacuum chamber) are:

- Ion accelerator efficiency: 20 %
- Tritium and deuterium partial pressure in vacuum chamber:  $10^{-3}$  Pa
- Tritium and deuterium partial pressure in plasma chamber: 0.2-0.3 Pa

The main operative conditions of the Tritium Processing System are reported in Table 1:

Table 1. Operative conditions of the TPS.

Parameter	Value	Units
T <sub>2</sub> and D <sub>2</sub> pressure in tubes	100	Pa
T <sub>2</sub> pressure in glovebox	10000	Pa
Tritium inventory	5	g d <sup>-1</sup>
Tritium molar rate required	0.09	mol h <sup>-1</sup>
Deuterium molar rate required	0.09	mol h <sup>-1</sup>
Temperature range in tubes	20-120	°C
Temperature range in glovebox	20-50	°C

Fundamental aspect to consider in the design of the Tritium Processing System is that the deuterium and tritium mixture fed to the ionization chamber must be pure (with a tolerance of the purified gas of 0.1 at. %, with heavy ions less than 10 ppm and H less than 2%), meaning that the impurities generated by the fusion reactions on the rotating target must be eliminated and the pure D-T cannot be contaminated inside the TPS after the purification. The first process is carried out by a particular system (the permeator), while the second issue is solved generating vacuum inside the system handling the deuterium and tritium, which in turn means that design of the TPS requires every component suitable for vacuum applications.

## 2.1 Process Flow Diagram

Generally speaking, a Process Flow Diagram (PFD) is a simplified scheme that characterizes the processes of a certain plant. In order to highlight the general flow of these processes, it adopts graphical symbols to represent the main components of the system, as well as the instrumentation and the connections with other systems. A PFD is considered a basic document of a project because it is required during each stage and it is constantly updated to represent the evolution of the system design, ultimately functioning as the starting document to produce the more complete P&ID diagram.

The PFD representation of the Tritium Processing System is reported in Figure 5. It depicts the three different subsystems forming the TPS, showing every different component that constitutes them, as well as the connection pipes linking them. As already mentioned, the subsystems are the tritium control system (represented by the index 200), the Pd/Ag permeator system (index 300) and the tritium getter storage system (index 400). All the components in the TPS work under vacuum conditions, which are guaranteed by the external vacuum system.

The PFD also shows the relation between the TPS and other external systems, like the impurity removal system or the ionization chamber, and especially the vacuum system, which is not part of the TPS even though it is placed inside the Tritium Facility. As of now, the design for the vacuum system foresees a redundant filtering subsystem in which two filters are necessary in order to remove possible solid particles, and the pumping group constituted by a diaphragm pump and a turbomolecular pump, which are both dry pump due to the need of avoiding any oil contaminant in the loop.

The Q<sub>2</sub> (Q = D, T) flow rate coming from the vacuum system is sent to the storage tank V1, which has the function of storage before routing the mixture gas to the permeator system. This vessel has an additional penetration to allow the analysis of the mixture in the ion chamber/mass spectrometer and the pressure inside is monitored by the pressure transducer 200-PT-1101. The Q<sub>2</sub> stream exiting from V1 passes through the pressure reducing valve 300-FCV-1101 (necessary in order to have a suitable inlet pressure for the permeator, ~200 Pa) and then through the permeator system, which is redundant for both safety reasons

and maintenance procedures, allowing a continuous operation of the system. The main objective of the permeator is to separate the D-T hydrogen isotopes from impurities, which are sent to the impurity removal system. The purified  $Q_2$  stream, exiting the permeators with a hydrogen isotopes partial pressure of about 10 Pa, is then pumped by means of a roots pump to two separated buffer tanks, V2 and V3, which are refilled and emptied alternatively. The pressure of the tanks is read by the pressure transducers 200-PT-1102 and 200-PT-1103. The gas pressure inside V1, V2 and V3 is assumed to be 10 kPa in order to have compact sizes of the vessels. Looking back at the value of the tritium pressure inside the glovebox reported in Table 1, that quantity is conservatively assumed equal to the maximum pressure inside the tanks. The  $Q_2$  mixture is integrated by the external deuterium cylinder and by the tritium getter storage system. The former is constituted by a simple tank regulated by a control valve and a pressure transducer, while the latter system uses a getter bed to store tritium; its release is controlled by a dedicated heating system which increase the temperature, allowing the tritium to be desorbed from the getter. The outlet pressure is regulated by the pressure reducing valve 400-FCV-1101 in order to compensate the pressure in the V2 and V3 buffer tanks. Both the vessels V2 and V3 foresee penetrations to route the  $Q_2$  mixture to the ion chamber and to the mass spectrometer.

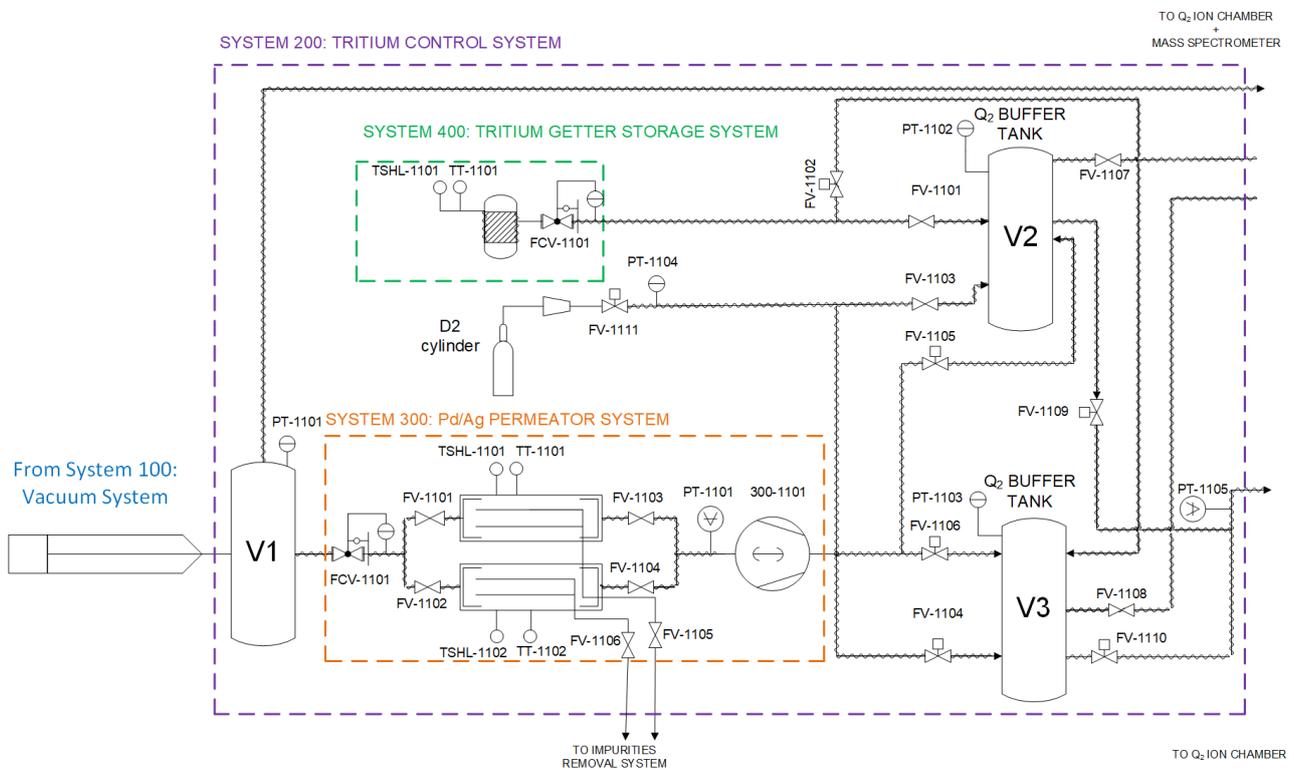


Figure 5. Process Flow Diagram of the TPS.

It has to be observed that all the piping lines are heat traced to allow the degassing of water vapor from the steel, which is performed at 120 °C. Only the two pipes directed to the impurities removal system are simple tubes: the reason is that they only process impurities and therefore there is no issue about the absorption of hydrogen isotopes inside the pipes.

On a surface exposed to vacuum, gas particles can be dissolved in the bulk by means of absorption reactions with the material of the wall. This process is called outgassing and it is an important factor when the gas balance inside the system is considered. The opposite process is the degassing, generally defined as the deliberate removal of gas from a solid or a liquid, which in Sorgentina-RF plant is performed when the system operations are stopped by heating the tubes and enhancing the natural release of gases from the material. Moreover, hydrogen is contained from the beginning inside the tubes due to the manufacturing process and is slowly discharge in the system once vacuum is created in the piping.

Finally, in this Process Flow Diagram, two different types of valve are represented: the simpler design, like the one for the valve 200-FV-1101 at the entrance of V2, indicates On-Off valves. They are simple valves that cannot regulate the flow rate passing through them, just allowing unimpeded flow or preventing it altogether. The other type of valve, such as the 200-FV-1104 at the entrance of V3, is a Control valve. These are more sophisticated valves that control the flow rate varying the size of the flow passage; this operation is executed by means of actuators which are directed by a signal from a controller. The reason behind the choice to include two types of valves is to guarantee the same flow to V2 and V3, without losses after the tubes bifurcation; if future analyses guarantee no differences between the flows coming from the external sources and going to the tanks, the design will be revised to install the same type of valve. The valves at the exit of the tanks to fuel the ionization chamber are the control type to properly accommodate the needs of the accelerator, while the valves related to the permeator system, as well as the mass spectrometer are On-Off since there is no need to control the flow.

## 2.2 Tritium containment and confinement

The general rule to handle tritium is to design suitable containment and confinement systems which protect both the workers and the environment, in addition to high velocity ventilation of the spaces occupied by workers, high velocity air hoods, and elevated release techniques. To enhance worker protection, the use of single-pass ventilation systems is foreseen, with the aim of rapidly removing the tritium released in the breathing space from the area where workers are present. Ventilation gasses are normally introduced at high velocity through an elevated stack to greatly dilute the gasses before they could reach the ground. Single-pass ventilation systems and high velocity hoods are also used extensively. The room or building where the tritium activity takes place is equipped with a one-way ventilation system that does not return air to the facility. Outside air is drawn in by the fans, conditioned for comfort, passed once through the building spaces, and then discharged to the environment through an elevated stack. The air exchange rate generally accepted as adequate for worker protection is 6 to 10 room air changes per hour. The tritium apparatus can be enclosed in a high velocity air hood, and the worker works with gloves in the doors or reaches through the hood openings to operate the equipment. The high velocity air hood is maintained at a negative pressure to the room, and natural airflow passes from the room through the hood opening and then up through the ventilation ducts to the environment.

The DOE [3] draws a distinction between containment and confinement. With *containment*, a collection of passive barriers that can satisfy a specified leak criterion without operation of any ancillary equipment is meant. An example of a containment system is a series of pipes and containers that enclose the tritium gas operations. An example of a simple double containment system is one pipe within another pipe, with each tube acting as a separate and independent containment system. The definition of *confinement* is a collection of barriers that can satisfy a specified leak criterion contingent upon operation of its ancillary (active) system. Examples of confinement systems include a glovebox and its associated clean-up system, and a room with its associated clean-up system. In simpler words, containment consists of an arrangement of physical barriers that do not require other devices or operator actions to satisfy a leak rate criterion, while confinement consists of an arrangement of barriers that require an active system or action to satisfy the leak rate criterion. Note that in the context of these definitions, a glovebox with an associated glovebox clean-up system is a confinement system. A glovebox structure itself is a containment system if and only if the specified leakage criterion can be satisfied by the structure itself. Containments and confinements can be classified as *primary* or *secondary*, depending on whether the tritium is directly in contact with a certain component or not.

On the other hand, ITER [4] distinguishes between first and second confinements. *First confinements* are process enclosures and other spaces normally containing radioactive material. This confinement is typically provided by piping, tanks, gloveboxes, encapsulating material, and the like, along with any off-gas systems that control effluent from within the primary confinement. The *second confinement* surrounds one or more

primary confinement systems. The first confinement system has the function of limiting and minimizing the release of tritium in the secondary confinement system. This one instead diminishes the consequences and the damage in case of failure of the first confinement system. Both the systems are comprised of many different barriers and consider prevention and mitigation effects reported in beyond design basis events considered by the Safety Analysis.

In addition to these two confinements, the DOE [3] adds also the definition of *tertiary confinement*, which is typically provided by walls, floor, roof, and associated ventilation, exhaust systems of the facility, providing a final barrier against the release of hazardous materials into the environment. Within this Thesis, the DOE classification will be adopted as a reference.

In SRF-TF, tritium flows directly inside the pipes that link the facility to the accelerator, therefore safety measures have to be carefully implemented and the system is classified as primary containment; at the same time these tubes are placed inside an external enclosure pipe which constitutes the secondary containment. Otherwise, inside the glovebox, the gas is not free: it is stored inside a uranium getter, which is encapsulated by a proper barrier, while the glovebox ensures to avoid leakage of the already contained gas in the outside room. The glovebox is then classified as secondary containment while the getter is primary containment. A sketch of the different containments is given in Figure 6 below.

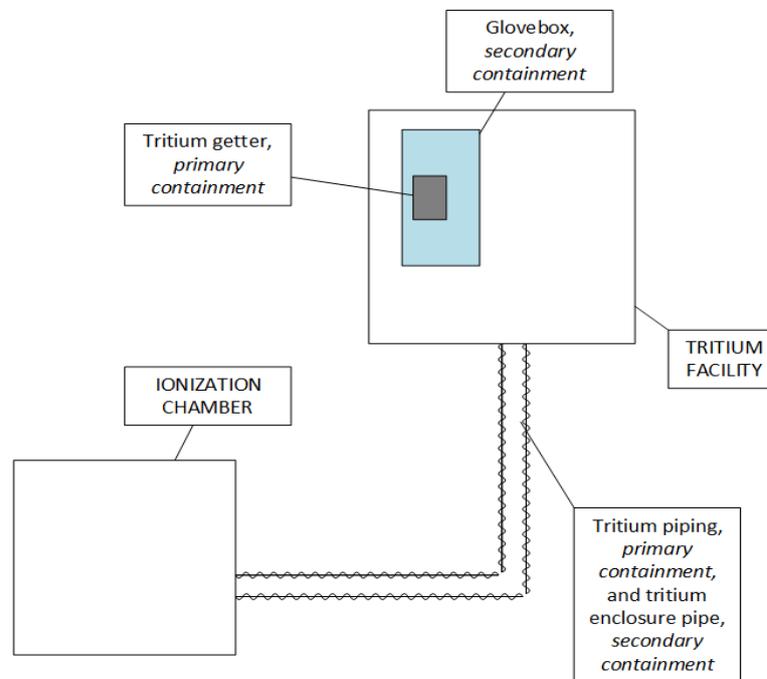


Figure 6. Scheme of tritium containment in SRF-TF.

The proposed scheme foresees, for the moment, to not have a dedicated purification/clean-up system either in the glovebox or in the room hosting the glovebox, which implies the actual classification of containment instead of confinement. It is not excluded that during future development of the design an active purification system will be included, therefore modifying the classification to secondary confinement.

When tritium is released into a secondary confinement, the associated clean-up system starts, and the gases containing tritium are circulated through the clean-up system, and the tritium is removed. According to DOE, the transfer of tritium to another container can take several days without a significant release of tritium to the environment if the purification system is associated with a high-quality barrier (leak rate of less than 1 Ci of tritium over a period of 4 to 40 days). If the purification system is associated with a medium-quality barrier (leak rate of less than 1 Ci in 3 to 30 hours), the flow rate of the purification system must be high enough to remove the tritium within a few hours to prevent a significant release of tritium to the

environment. If the purification system is associated with a low-quality barrier (leak rate of 8 Ci or more per minute), the flow rate of the purification system must be very high to remove the tritium from the gas before it is released to the environment.

### **2.2.1 Building ventilation system**

The ventilation system is designed to guarantee a safe expulsion of the tritium once the gas has penetrated its barriers. In particular, this system has different objectives: first, it has to move the released tritium from the worker breathing space as soon as possible. The second aim is to minimize the contamination of other areas while moving the tritium. Finally, the tritium contaminated gases must be expelled with particular condition such that the tritium is sufficiently diluted before it reaches ground level.

The ventilation system works following several design guidelines. In fact, the ventilation system is a single-pass ventilation system. Outside air is brought in through a supply fan and it passes through the ductwork to the ventilated spaces one time, goes through the exhaust ductwork to an exhaust fan, and is released to the environment through the facility stack. Room recirculation designs can also be used in conjunction with single - pass ventilation systems. Both the air supply system and the exhaust system are designed to eliminate dead air spaces where tritium can accumulate.

A possible issue of the ventilation system is the cross-contamination between different parts. To minimize this effect from one room to another, the exhaust gas from each place is collected by a central exhaust duct, avoiding the gases from several rooms to combine before being dumped into the central exhaust duct. To reduce cross-contamination from one ventilation function to another, the gases in each room for every type of function, such as room ventilation, high velocity air hood ventilation and glovebox ventilation, are not combined before they reach the central exhaust duct. Another way the system minimizes the cross-contamination is the pressure control of each zone in contact with tritium. In particular, the ventilation control system is designed to keep the spaces occupied by the tritium operations at a negative pressure relative to the spaces surrounding the facility, letting external air continuously entering the tritium operating areas from the surrounding environment. Therefore, it is important to always monitor the temperature and the humidity conditions to reduce the in-leakage of moisture to inert atmosphere gloveboxes.

The walls separating adjacent rooms should be sealed to minimize tritium released from contaminating an adjacent room, with particular attention to penetrations such as conduit and piping. The inside and outside doors and airlocks need to be used properly and equipped with automatic door closures. Also, some personal protective equipment, like respiratory protection and passing exhaust through particulate filters, is required when dealing with stable metal tritide.

Finally, the ventilation rate should be based on analysis of the hazards of the operations and future designs of the ventilation system can consider variable flow rate that is a function of the time of day and the measured tritium concentration in the rooms. In this possible design, a higher initial cost would be balanced by the decrease of the long-term operating costs without significant impact on the safety of the facility.

### **2.2.2 Seismic and other natural phenomena design**

To mitigate the effects on the tritium systems produced by earthquakes, extreme winds, and other natural phenomena (NPH) is necessary to understand the loads produced by them on each part of the facility.

Earthquakes produce vibration in ground, which affects the entire facility and its contents. It is important to specifically design the anchorage and connection details for every structure, system, and component. Earthquakes may also cause ground displacement if the facility is near a fault. Loss of ground stability may also occur due to settlement or liquefaction and depends on the soil types and the location of the ground water table.

Extreme winds affect mainly the structural shell of the system and its external components. In particular, the wind produces pressure and suction on walls and roofs with increased loading at corners, eaves, and ridges. If some debris are present near the facility, they can become missiles and damage the nearby structures. Moreover, in case of tornadoes, the atmospheric pressure will change resulting in a pressure drop below ambient pressure as the tornado passes over a facility. This effect can damage wall and roof openings and ventilation system filters. Flooding or extreme precipitation events can also have a deleterious effect on structures.

A possible solution to counter the damage resulting from NPHs is to store the resources inside specially designed cases that are resistant to extreme conditions, specifically metal cabinets designed to store tritium reservoirs and Hydride Storage Vessels. This cabinet is designed to protect the pressure boundary integrity of stored reservoirs in case of strong impacts from the surroundings.

Employing mitigation efforts before natural hazards occur is a very cost-effective method to provide life safety, to minimize damages and losses and to reduce the impact on the facility and operations. It is extremely important to pay attention to all the details because natural phenomena will find the weaknesses in the protection systems and cause damage to the facility and possibly to the workers.

## 2.3 Functional Analysis

Functional Analysis (FA) is a top-down process of translating system-level requirements into detailed functional and performance design criteria. It is performed to define the requirements of the system, to map its functions to physical components, guaranteeing that every necessary element is considered, as well as to highlight the relationships between the various system parts and components.

Basically, what the Functional Analysis wants to accomplish is to break a complex system into smaller and simpler parts, allowing the individual design of each of them. In turn, as the design of the system, via its smaller subsystems, progresses, also the FA will evolve and be updated.

The primary result of Functional Analysis is the development of physical block diagrams both the whole system and of each subsystem: the former identifies the basic functions the system has to be able to perform, while the latter individuates all system physical components, which are able to carry out the basic functions described in the first diagram [5].

Regarding Sorgentina-RF, this Master Thesis produced the block diagrams related to the plant: first, the whole system is analysed and divided in its subsystems, then the focus of the functional analysis is directed on the functions performed by the Tritium Processing System and their necessary components.

### 2.3.1 General Functional Analysis

The General FA is the first step performed in the development of a Functional Analysis for Sorgentina-RF. During this stage the whole plant is defined in terms of its purpose and then it is broken down in the different subsystems composing it. The conceptual design of SRF is schematized in Figure 7, where the Functional Analysis is built along three different levels: level 0 (L0) represents the foundation behind the design of the whole Sorgentina-RF facility, which is the final objective of the plant; level 1 (L1) indicates and describes the methodology used to achieve L0, which is the production of high energy neutrons by means of nuclear fusion reactions between tritium and deuterium; lastly, in the second level (L2) the SRF system is divided in its different parts, which they correspond to the Tasks described before, and their general main scope is mentioned. For example, Task 7 (T7) aims to design a suitable radiation protection system for every possible radioactive source, while Task 9 (T9) handles the recycle of the titanium that constitutes part of the rotating target (which is designed by Task 2).

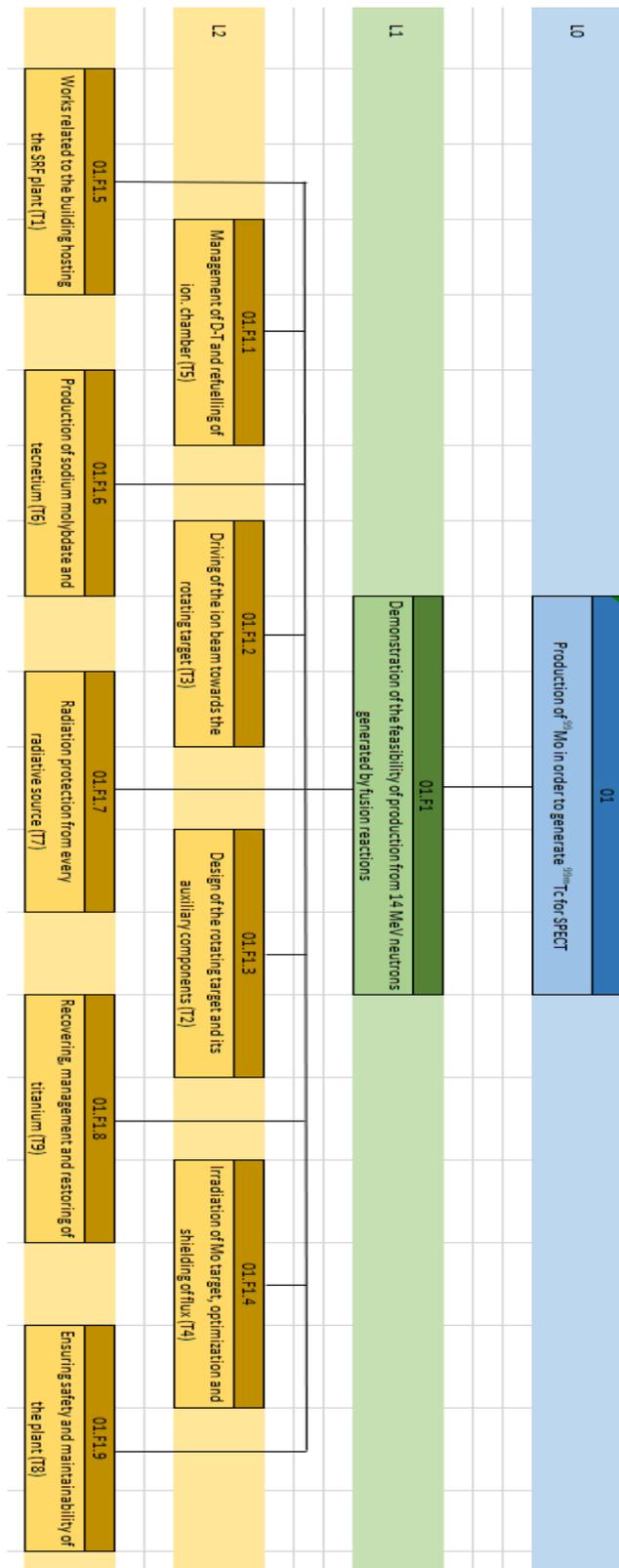


Figure 7. General FA of the Sorgentina-RF facility.

Every single block of the diagram is identified by an individual code that distinguishes that specific block from the others belonging to the same level, and at the same time it allows to recognise the higher levels from which that block is derived. In this particular case, every block in level 2 is generated by the same block in level 1 and in level 0, but in other systems with more ramifications this identification can prove very beneficial.

Finally, what is represented in L2 of the General FA are only the subsystems of Sorgentina-RF and their main objectives; all the different solutions, processes and systems devised by the Tasks to accomplish their particular scopes belong to lower levels of the Functional Analysis and are reported in different diagrams. For this purpose, a second diagram is produced to describe more specifically the procedures carried out inside the Tritium Processing System.

### 2.3.2 Tritium Processing System Functional Analysis

This second part of the FA describes all the functions performed by the Tritium Processing System in order to properly manage the deuterium and the tritium before routing them toward the ionization chamber. Each function is described in terms of what it wants to accomplish and shows the different processes needed to achieve that (lower-level functions), and for each process the components required are highlighted.

The recognized main functions needed to achieve the scope of the Tritium Processing System, and therefore implemented as level 3 (L3) functions of the TPS FA are:

- To guarantee a 50-50 stoichiometry for deuterium and tritium.
- To separate D and T from impurities.
- To control D-T stoichiometry ratio.
- Tritium permeation reduction towards environment.

In TPS FA for each listed function, other functions of inferior level are needed to achieve the higher function, and are subdivided in the necessary actions (like the valves involved and their state).

The first one, “To guarantee a 50-50 stoichiometry for deuterium and tritium”, describes the actions necessary to fill the tanks V2 and V3 and to fuel the ion beam. The lower-level functions (L4) are basically the different scenarios that solve this function, and they are:

- External sources refuelling.
- Initial tanks filling.
- V2 fuelling and V3 tanks filling.
- V3 fuelling and V2 tanks filling.

As it is possible to see from the L4 functions, the two tanks are foreseen to work alternatively, which means that when one of them is filling up the other is feeding the ionization chamber and vice versa. Only the first filling of the two tanks is done at the same time, and once they are completely full one of them starts emptying and supplying the ion beam.

Here below in Figure 8, the “external sources refuelling” scheme is shown:

L0	L1	L2	L3	L4
01	Production of 99Mo in order to generate 99mTc for SPECT			
	01.F1	Demonstration of the feasibility of production from 14 MeV neutrons generated by fusion reactions		
		01.F1.1	Management of D-T and refuelling of ion. chamber (T5)	
			01.F1.1.1	To guarantee a 50-50 stoichiometry for Deuterium and Tritium
			01.F1.1.1.1	External sources refuelling
				200-FV-1101 (open)
				200-FV-1102 (open)
				200-FV-1103 (open)
				200-FV-1104 (open)
				200-FV-1105 (closed)
				200-FV-1106 (closed)
				200-FV-1107 (closed)
				200-FV-1108 (closed)
				200-FV-1109 (open)
				200-FV-1110 (open)
				200-FV-1111 (open)
				300-FCV-1101 (closed)
				300-FV-1101 (closed)
				300-FV-1102 (closed)
				300-FV-1103 (closed)
				300-FV-1104 (closed)
				400-FCV-1101 (open)

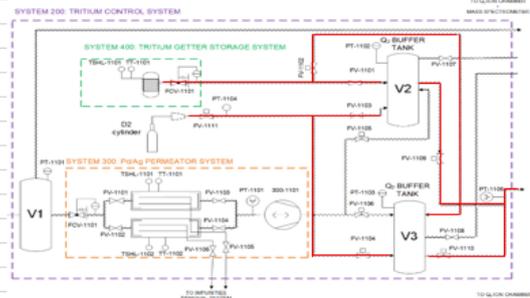


Figure 8. External source refuelling function for the stoichiometric control of the fuel.

The level 4 function is displayed and properly identified by its code, which recalls the higher functions from where it is derived. As it is possible to notice, the valves solving the process are reported with their nomenclature from the PFD (Figure 5) and their status (either open or closed).

The schematic for the Functional Analysis of this function, as well as the others, is coupled with a small picture of the TPS PFD on the side. Highlighting the specific pathways where the deuterium and the tritium flow through helps to visualize and to identify the exact valves and components involved in the solution of the process.

On a side note, this particular process is carried out only at the very beginning of the facility operation (and if the plant is completely stopped due to abnormal accidents, when it is restarted) or after a bake-out operation: all the tanks are completely empty and no deuterium nor tritium flows inside the whole SRF plant; the only sources for the fuel are the external tank and the getter, and so they start to feed the ionization chamber, bypassing the V2 and V3 tanks since the same  $Q_2$  flow entering them is completely routed to the beam. The deuterium and the tritium reach the rotating target, they cause fusion reactions and the fuel cycle begins; only after the gas flows is processed by the permeator and sent to the tanks, V2 and V3 start filling. Therefore, the deuterium and tritium external sources become auxiliary sources to balance out the composition inside the tanks and the inevitable small losses of the gas flowing out the system.

The second L3 function, which is “To separate D and T from impurities”, is performed entirely by the Pd/Ag permeator system and it considers the flux of impurities present in the gas stream from the vacuum system rather than the flow of deuterium and tritium.

The two permeators are designed to be redundant and work alternatively, meaning that while one of them is working the other discharges the accumulated impurities. Therefore, the level 4 functions that carry out the separation of the fuel from the impurities are:

- Initial P1 working and accumulation.
- Disposal P1 and accumulation P2.
- Disposal P2 and accumulation P1.

Again, at the beginning of the SRF operation the permeators do not treat any gas stream and so they are also empty of any type of impurity. Only the first permeator (P1) initially accumulates impurities once the gas stream comes from the ionization chamber and the alternate operation condition begins.

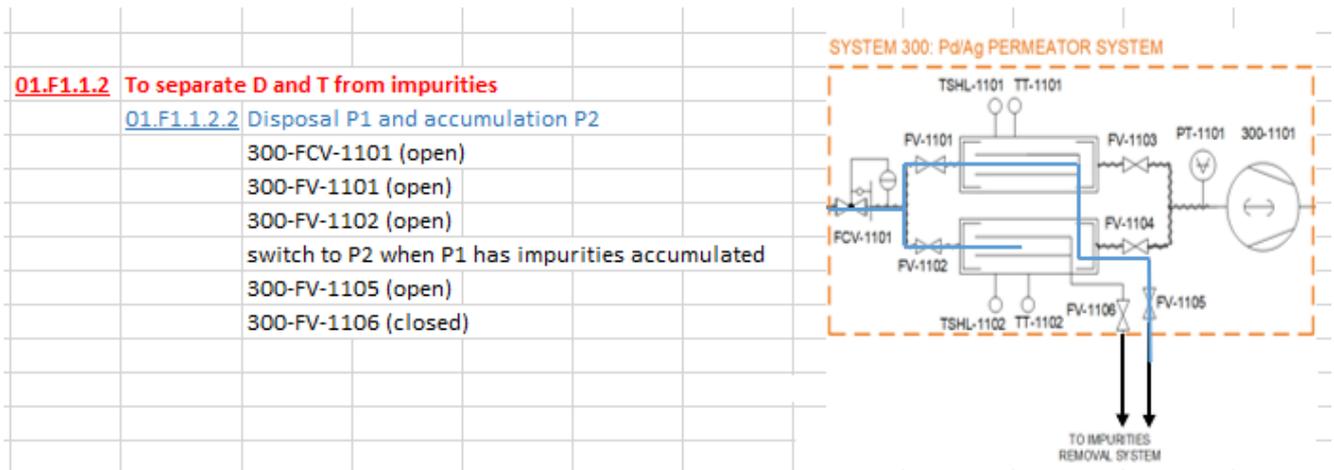


Figure 9. FA for the impurity disposal from one permeator.

Figure 9 shows the disposal process of the impurities accumulated inside the first permeator while the second one is processing the gas stream and separating its own impurities from the deuterium and tritium.

Regarding the L3 function “To control D-T stoichiometry ratio” the focus of the analysis shifts back to the deuterium and tritium processed inside the tritium control system (in the PFD of Figure 5 the system with index 100). The control on the stoichiometry of the mixture is done only on the gas contained inside the two pressurized storage tanks V2 and V3, and in particular the control on V2 is performed when it is accumulating and V3 is refuelling the ionization chamber, and vice versa. The reason is that it is important to feed the ion beam with a 50-50 mixture of D and T, and verifying the composition during the tank accumulation allows to fix eventual disproportions with the external sources of deuterium and tritium. The two function of level four individuated for this case are:

- Control on V2 while V3 fuels the system.
- Control on V3 while V2 fuels the system.

This process is done by spilling a small quantity of the gas mixture from the tank of interest and send it to the mass spectrometer, which will analyse the sample and report the data obtained; depending on the result of the analysis the two external sources get involved.

In Figure 10 the process to control the gas composition in V2 is displayed:

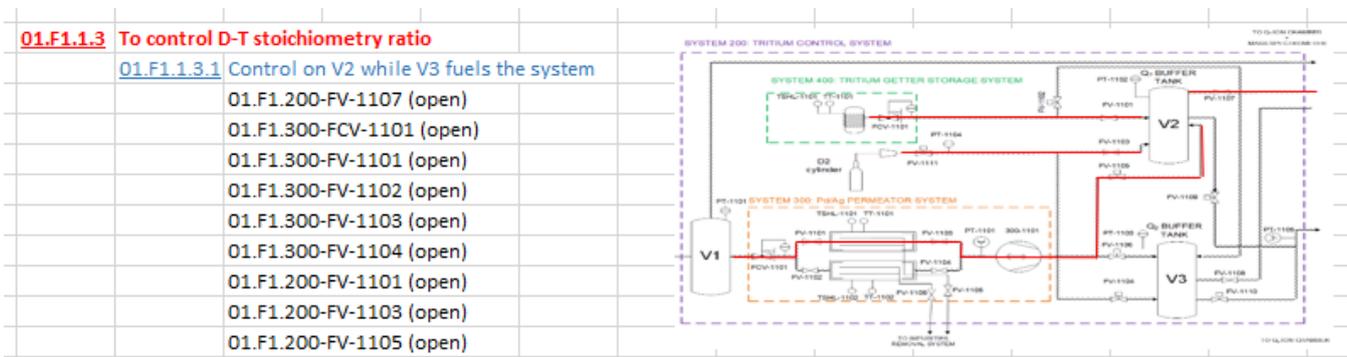


Figure 10. FA for stoichiometric control of the gas mixture in the V2 tank.

The last L3 function that the Tritium Processing System must resolve is the “Tritium permeation reduction towards environment”. Different from the other functions of the same level, this one is not related to a specific flow path that the tritium pass through, but it puts emphasis on the design of the systems inside the TPS so that they could guarantee performance of safety conforming international standards. It aims to identify

the necessary measures to adopt, proper materials for the enclosures, as well as the dimensions of barriers and piping.

The level 4 functions that compose this process are listed here and more explicitly defined in the Figure 11 below, showing for each part the hot point that necessitates of particular attention:

- Tritium getter storage system (TGSS).
- Tritium control system.
- Tritium tubes linking tritium facility (TF) and ionization chamber (IC).

<b>01.F1.1.4</b>	<b>Tritium permeation reduction towards environment</b>		
<b>01.F1.1.4.1</b>	<b>Tritium getter storage system</b>		
	Encapsulate the system in a glovebox		
	Proper choice of the glovebox case materials		
	Additional features of glovebox to respect safety standards		
	Control of temperature to extract tritium		
<b>01.F1.1.4.2</b>	<b>Tritium control system</b>		
	Encapsulate the whole system in a glovebox, except TGSS		
	Proper choice of the glovebox case materials		
	Additional features of glovebox to respect safety standards		
	Proper choice of the piping materials inside system 200		
	Proper choice of the piping dimensions inside system 200		
<b>01.F1.1.4.3</b>	<b>Tritium tubes linking TF and IC</b>		
	Proper choice of the piping materials		
	Proper choice of the piping dimensions		
	Additional external tube as protection barrier		
	Secondary confinement space for tubes placing		

Figure 11. FA for the reduction of tritium permeation toward environment and workers as well.

## 2.4 Tritium Processing System Interfaces

Many different systems are connected and interact with the TPS; they constitute the TPS Interfaces and are listed here:

- The vacuum chamber.
- The ion beam.
- The tritium storage.
- The waste treatment system.
- The building.
- The electrical cabinet.

Each interface is represented in Figure 12 with its connections to or from the Tritium Facility. The vacuum chamber and the tritium storage constitute the two main inputs of the TF since they collect the main  $Q_2$  sources to be processed in the tritium control system (system 200 of the PFD in Figure 5). The outputs are constituted by the ion beam and waste treatment system. The last two interfaces are the electrical cabinet which gives the necessary electrical power to the system and the tritium building where the tritium facility is located.

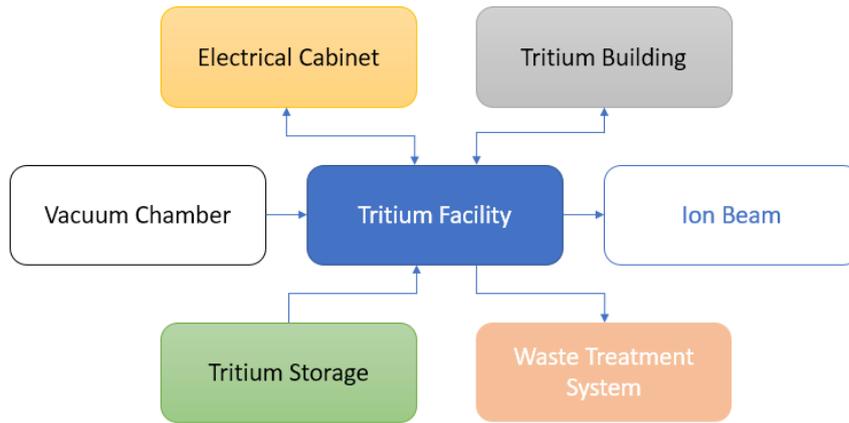


Figure 12. Schematic representation of the main interfaces of the Tritium Facility.

## 2.4.1 Vacuum chamber and ion beam interfaces

The interface of the Tritium Processing System with the vacuum chamber, which constitutes one of the inputs for the tritium control system in terms of deuterium and tritium, is constituted by the subsystem 100, reported in Figure 13.

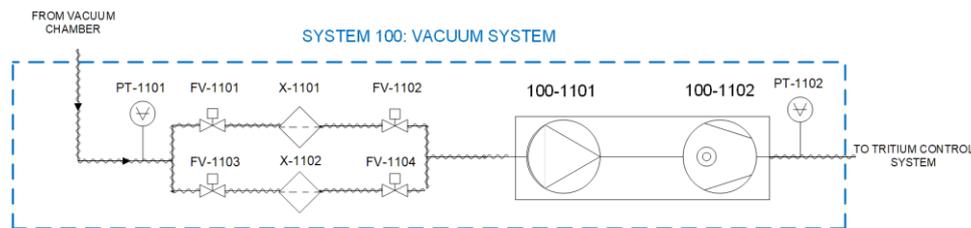


Figure 13. Subsystem 100: vacuum system. This system constitutes the main interface with the vacuum chamber.

Before entering the pumping group, the  $Q_2$  mixture flow rate coming from the vacuum chamber is routed to a redundant subsystem in which two filters are foreseen in order to remove possible solid particles. The 100-X-1101 and 100-X-1102 filter can be sintered metal filters which are commonly available on the market up to 4  $\mu\text{m}$  pore size diameter; PORAL filters can reach 0.2  $\mu\text{m}$  and are suitable for very thin solid impurities.

The pumping group is constituted by a diaphragm pump 100-1101 and a turbomolecular pump 100-1102. The use of a dry pump as a baking solution is due to the need of avoiding any oil contaminant in the loop. If HTO is present, even in small quantities, the use of a chemical version with gas ballast valve is suggested due to excellent chemical resistance and condensate tolerance.

The pressure in the vacuum system is read by the capacitive pressure transducers 100-PT-1101 and 100-PT-1102 which are able to guarantee a very high accuracy on the measured value. It is foreseen that a single 1/2 inches tube goes from the Ionization Chamber to the Tritium Facility, while another 1/4 inches tube goes from the Tritium Facility to the Ionization Chamber. In order to comply with the concentration limit of 740 Bq/l [3], an external tube that encapsulates both the 1/2 in. tube and the 1/4 in. is foreseen to provide an ulterior barrier for the permeation of tritium.

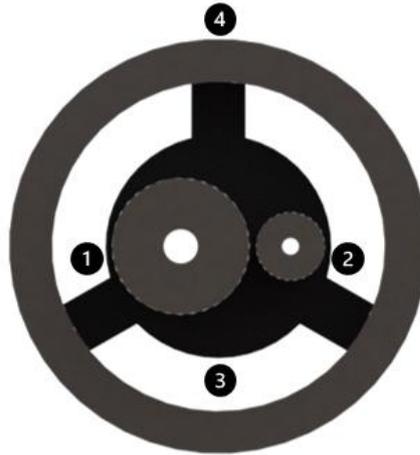


Figure 14. 2D tubes scheme 1) Pipe from Ionization Chamber to Tritium Facility, 2) Pipe from TF to IC, 3) Spacer, 4) Second containment pipe.

The two tritium pipes run next to each other and are inserted in the spacer, which is the black device in the middle of Figure 14. The preliminary dimensions of the pipes are reported in Table 2.

Table 2. Dimensions of tritium piping.

	1/2 inches diameter	1/4 inches diameter
Outer Diameter (mm)	12.7	6.35
Schedule (mm)	4.78	2.41

A more comprehensive description of the tritium pipes, detailing also the materials that compose them and the analyses carried out on the tritium permeation fluxes, is described in the Chapter 3.2, where the design of the main components is presented.

The ion beam is placed inside the ionization chamber, thus the interface on the output side of the TPS with it, and in turn with the chamber, is the same system of tritium pipes without the need for a filtering system, since the D-T stream is already purified from impurities inside the Tritium Processing System.

## 2.4.2 Tritium storage system

The Tritium Storage interface is basically constituted by the tritium getter storage system, which serves as an external storage and source when a resupply of tritium to the plant is necessary. Due to the radioactive nature of the tritium, the getter interface is placed inside a dedicated glovebox.

This glovebox is placed inside the Tritium Building and it encapsulates the uranium getter with its containment. Uranium is currently the most useful material for general purpose tritium storage beds. Uranium beds are used successfully to pump, store and purify tritium gas. Uranium tritide not only has a high tritium capacity but also a low dissociation pressure at room temperature. Such tritides provide an attractive alternative to compressing and storing tritium in pressure containers. At room temperature, tritium in the presence of uranium powder forms uranium tritide. The tritium partial pressure in the bed is very low, thus at room temperature the bed acts as a vacuum pump that absorbs all the hydrogen isotopes.

Again, a more exhaustive design of the tritium getter, as well as the glovebox, is presented in Chapter 3.6.

### 2.4.3 Waste treatment system

The exhausted gas stream coming from the Vacuum Chamber of Sorgentina-RF is not composed by only deuterium and tritium, but it is composed by many impurities coming from the chamber like helium, argon, oxygen, titanium and even some compounds of every hydrogen isotope.

An initial separation is carried out in the vacuum system by particular filters that remove particulate, like TiD and TiT, from the flow stream, but the majority of the impurities are managed by the Waste Treatment System (WTS). Tritium and deuterium are separated from the stream by the permeators in order to recycle fuel, while the rest of the particles like Ti, Ar and O are disposed in the WTS. The  $Q_2$  species can permeate through the membrane wall of the permeator and reach the shell side of the module while the impurities do not permeate across the membrane and forms the so-called “retentate” stream. This retentate stream accumulates in the membrane lumen and along the pipe until a dedicated valve, which allows the impurity flow to be collected in a dedicated tank and, depending on its activity, further processed or freely discharged. The details of the Pd/Ag permeator system are given in Chapter 3.4.

As of now, the Waste Treatment System is yet to be designed, but it already foresees the impurity content representing only the 1% of the whole gas stream, therefore the discharge valve is designed to stay close until the pressure reaches 200 Pa, then open and let the impurities be discharged in the WTS.

### 2.4.4 Building

The CPC1 Building, see Figure 4, constitutes one of the most important interfaces for the Tritium Facility. The installation of all the equipment and all the subsystems has to be carried out taking into account the space availability and the safety requirements. For the last point, one important issue is the safety system for accidental tritium release in the room (i.e. failure of the glovebox or rupture of the tritium piping second containment). Up to now, the safety system is constituted by a saturation fire protection system and a smoke detection system. In addition, a dedicated purification/clean-up system either in the glovebox or in the room hosting the glovebox can be foreseen. In case during future development of the design an active purification system will be included, and the secondary confinement will have the scheme proposed in Figure 15.

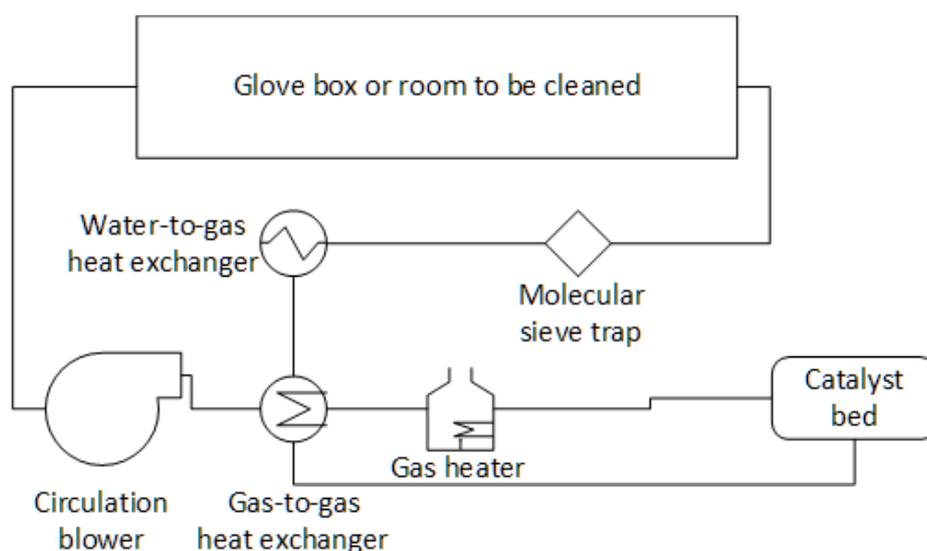


Figure 15. Scheme of second confinement for SRF-TF.

## 2.4.5 Electrical cabinet

The electrical cabinet, placed inside the CPC1 building, hosts all the necessary power supplies for the functioning of the Tritium Facility. A first estimation of the electrical power needed is reported in Table 3 along with the function of the different items.

Table 3. Power supplies for TF in CPC1 building.

ID	Description	Function	Type	Power
1	Pd/Ag permeator heating system	Heating up to 500°C Pd/Ag permeator	230V	6KW
2	Pd/Ag - valves and instrumentation	Control tritium and deuterium release to Pd/Ag membrane	tbd	0,5KW
3	Vacuum pumping system	Pump the vacuum in the Pd/Ag permeator	230V	3KW
4	Tritium heating system	Heating of tritium getter	230V	1KW
5	Pipes heating system	Heating up to 200°C pipes for degassing	230V	4KW
6	Tritium and deuterium monitoring system-Instrumentation	Measure tritium and deuterium concentration in the tritium facility	230V	5KW
7	DACS	Data acquisition and control system of the tritium facility	230V	1KW
8	Impurities removal system	System dedicated to remove impurity from stripping Pd/Ag permeator gas	230V	3KW
9	Exhaust extractor	Send exhaust to chimney	AC 400V 50Hz	10 KW

### 3. Sizing of the main components

This chapter is dedicated to the design of the main components present inside the Tritium Permeation System; analyses are carried out on their dimensioning as well as on the proper material choices from the point of view of safety against tritium permeation. These components, previously shown graphically on the Tritium Processing System PFD in Figure 5, are the following:

- Tritium pipelines.
- Tanks.
- Permeators.
- Uranium getter bed.
- Gloveboxes.
- Other auxiliary components.

Prior to the description of the designs of all these components, it is defined the theoretical background supporting the models utilized for the analyses on the gas permeation through the materials: deuterium and tritium tend to penetrate the surfaces of their confinement and permeate toward the environment. Both for safety reasons and to avoid wasting resources, it is necessary to limit as much as possible this phenomenon, designing in a proper way the barriers against these two isotopes. In order to achieve this objective, a proper transport model that can evaluate and quantify the processes between the gas and the surface is required.

#### 3.1 Theoretical Background

It is necessary to adopt a suitable transport model for the tritium passing through a solid surface in order to properly design all the tritium-facing components. Obviously, the model is also effective for the transport of deuterium, nonetheless the future calculations are carried out with respect to the tritium because it is the only radioactive hydrogen isotope and greatly impacts the safety of the plant: assuming that the whole permeating gas is tritium, the calculation results will be more conservative from a safety point of view. If the international regulations are respected in this extreme case, then they will also be during the plant operations where the gas is not pure tritium but a D-T mixture.

The permeation of tritium through a membrane is called *gas-driven permeation* because the permeation is induced by the pressure gradient of the tritium gas between upstream (high-pressure side) and downstream (low-pressure side) [6]. A simple scheme is shown in Figure 16, which highlights the different possible phenomena [7].

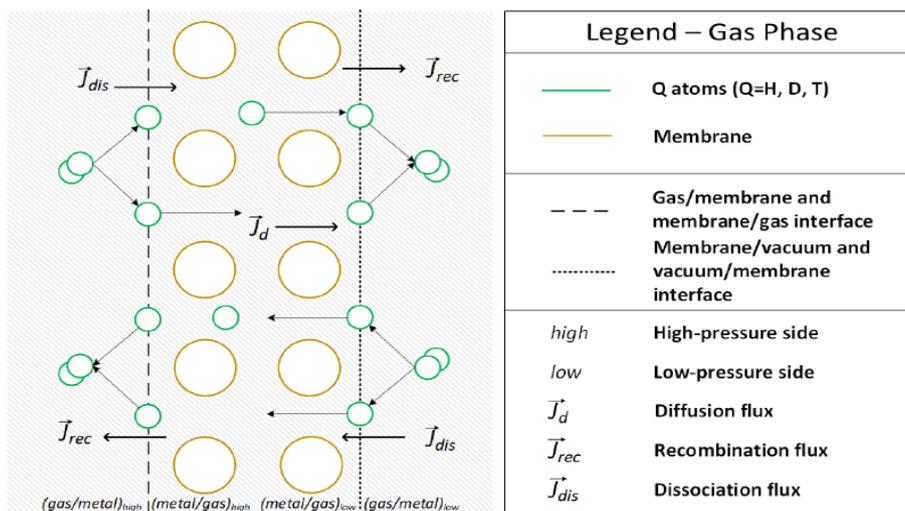


Figure 16. Permeation scheme with its different phenomena.

The hydrogen permeation through a dense metal layer is a mass transfer mechanism which consists of the several steps, including:

- Adsorption of the molecular hydrogen on the first metal surface.
- Dissociation of the hydrogen into two protons at the first metal surface (dissociation flux).
- Diffusion of the protons through the metal lattice (diffusion flux).
- Recombination of the two protons at the opposite side of the metal wall (recombination flux).
- Desorption of the molecular hydrogen from the metal surface.

Diffusion and surface phenomena are fundamental in the description of the model because they permit to simplify the conditions under which the transport happens: permeation can be defined by different regimes, depending on which process, between diffusion and surface phenomena, is the limiting (slowest) one. This slowest process determines the permeation regime, which is related to the permeation parameter  $W$  (-). An ulterior simplification of the transport model is assuming the low pressure is equal to zero, which is an acceptable hypothesis for the Sorgentina-RF plant. Under this premise the parameter  $W$ , according to [8], can be evaluated as:

$$W = \frac{k_r \cdot k_s}{D} \cdot t \cdot \sqrt{p_T} \quad (1)$$

where  $k_r$  ( $\text{m}^4/\text{mol/s}$ ) is the recombination constant,  $k_s$  ( $\text{mol}/\text{m}^3/\text{Pa}^{1/2}$ ) is Sievert's constant,  $D$  ( $\text{m}^2/\text{s}$ ) is the diffusion constant,  $t$  (m) is the thickness of the membrane and  $p_T$  (Pa) is the pressure of tritium. The value of  $W$  determines the permeation regime: the three possible regimes permit to evaluate with different equations the flux ( $\text{mol}/\text{m}^2/\text{s}$ ) permeated through the membrane. Diffusion limited regime (DLR) and Surface limited regime (SLR) are two limiting cases of the mixed regime, and in particular, the former is for  $W \rightarrow \infty$  while the latter is for  $W \rightarrow 0$ .

Both the flux evaluated in Diffusion-Limited,  $J_{DL}$ , and in Surface-Limited,  $J_{SL}$ , are simplification of the general equations from mixed regime.

$$J_{DL} = \frac{Dk_s}{t} \sqrt{p_T} \quad (2)$$

$$J_{SL} = \frac{1}{2} k_s^2 k_r p_T \quad (3)$$

The calculation in mixed regime is more complex because it is necessary to solve different equations. The general flux balance at each surface is expressed by a system of two equations.

$$\begin{cases} k_s^2 k_r p_T - k_r c_1^2 = -D(c_2 - c_1)/x \\ -\frac{D(c_2 - c_1)}{x} = k_r c_2^2 \end{cases} \quad (4)$$

where  $c_1$  and  $c_2$  are the concentrations ( $\text{mol}/\text{m}^3$ ) at the two sides of the membrane. The limit of application of equations (2) and (3) can be set by fixing a maximum error to 5% with respect the full solution of the above set of algebraic equations (4).

A dedicated study on the validity of the solution obtained using the mixed regime or the two approximations has been conducted by [8] and the results are shown in Figure 17, where it is clear that moving toward the possible extremity values of the permeation parameter, the differences in results between the approximations and the complete model are negligible, especially for Surface Limited Regime.

This assumption leads to a partition of the permeation regimes based on the value of the permeation parameter. Dividing this system by  $J_{DL}$ , it is possible to obtain a new system of dimensionless equations that depends on two dimensionless parameters:

$$v = \frac{c_1}{k_s \sqrt{p}} \quad (5)$$

$$u = \frac{c_2}{k_s \sqrt{p}} \quad (6)$$

The dimensionless system is:

$$\begin{cases} W(1 - v^2) = v - u \\ v - u = Wu^2 \end{cases} \quad (7)$$

The equations are then rearranged to create the final dimensionless system:

$$\begin{cases} v = \sqrt{1 - u^2} \\ W^2 u^4 + 2Wu^3 + 2u^2 - 1 = 0 \end{cases} \quad (8)$$

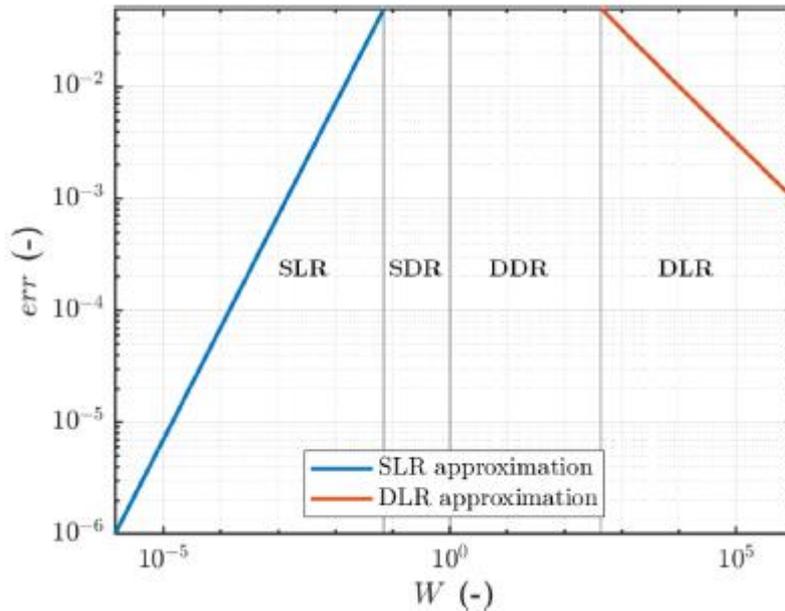


Figure 17. Relative error (-) between the limit regimes solution and the full solution, cut at  $err = 0.05$ .

## 3.2 Design of tritium piping

In the Sorgentina-RF facility, the gas flows from the Tritium Facility to the Ionization Chamber and backwards. It is necessary to evaluate the permeation flux and the activity of tritium that permeates through stainless steel tubes. A single 1/2 inches tube goes from the Ionization Chamber to the Tritium Facility, while another 1/4 inches tube goes from the Tritium Facility to the Ionization Chamber. They both are contained inside an external protection tube and are kept in place by a spacer component (the black one in Figure 18) every two meters.

The reason behind the different sizes is related to the conductance of the tritium tubes. In particular, the gas mixture is sent to the TPS from the vacuum chamber by vacuum pumps, therefore a higher conductance is necessary, which is in turn enhanced by larger diameters. On the other hand, the gas fuelling the ionization chamber is at higher pressures, thus it is possible to adopt tubes with a smaller diameter.

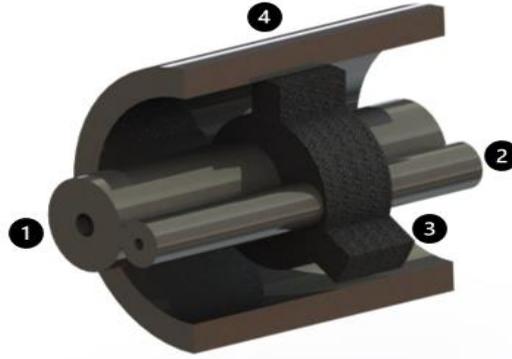


Figure 18. 1) Pipe from Ionization Chamber to Tritium Facility, 2) Pipe from TF to IC, 3) Spacer, 4) Second containment pipe.

The two pipes in which the D-T mixture flow are tubes produced by Swagelok [9], with their dimensions well defined by their catalogue and already provided before in Table 2: specifically the 1/2 inches pipe has an outer diameter of 12.7 mm and a schedule (the thickness of the tube) of 4.78 mm, while the 1/4 inches one has an outer diameter of 6.35 mm and a schedule of 2.41 mm. The total length of the tubes is estimated between 20 m and 50 m.

### 3.2.1 Possible choices for the piping material

The possible materials selected for the tritium tubes are all martensitic stainless steels because they are less permeable to tritium than the austenitic ones. For this project, four stainless steels are considered: AISI 316, AISI 316L, AISI 304 and AISI 304L. Low carbon concentration steels are selected because they have better performances in vacuum application than higher carbon concentration steels [10]. In order to select the better material for the construction of the tubes among the ones explored, a comparison of their performances is carried out based on the permeation model described before in Chapter 3.1.

An approximation is made in order to simplify the problem and to assure conservative results: the gas flowing inside the pipeline considered for the calculus is pure tritium at 100 Pa, while in reality a part of it is deuterium with its partial pressure (100 Pa is the mixture pressure). Moreover, the pressure outside the tubes is supposed to be 0 Pa, which is impossible, and overestimates the permeation flux.

In order to compare the performance of the aforementioned materials, it is necessary to evaluate the permeation flux through each one of them. As shown in the model described before, the first thing needed to calculate this quantity is to determine the permeation regime, and thus the permeation parameter. The transport parameters (diffusivity  $D$ , Sieverts' constant  $k_s$ , recombination constant  $k_r$  and permeability  $\Phi = D \cdot k_s$ ) depend on the gas and the material of the membrane, as well on the temperature. For the calculation, the temperatures selected are from 20 °C to 400 °C (400 °C is selected because is a relevant value in standard applications as in ITER or DEMO).

Due to a lack of data, the recombination constant is taken equal for every steel and derived from the work [11], which provides an experimental-derived value for AISI 316:

$$k_r = 2.35 \cdot \exp[-70000/(R \cdot T)] \quad (9)$$

where  $R$  is the gas constant and is equal to 8.3145 J/mol/K. In Table 4, Table 5, Table 6 and Table 7 the transport parameters and their correlation for all the four stainless steels are collected.

Table 4. AISI 316 transport parameters.

AISI 316	Correlation	Temperature range	Ref.
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Diffusivity (m <sup>2</sup> /s)	$7.30 \cdot 10^{-7} \cdot \exp(6300/T)$	T=300-550 °C	[12]
Sievert's constant (mol/m <sup>3</sup> /Pa <sup>0.5</sup> )	$1.11 \cdot \exp(-1890/T)$	T=300-550 °C	[12]
Permeability (mol/m/s/Pa <sup>0.5</sup> )	$D \cdot k_s$ (derived)	T=300-550 °C	[12]

Table 5. AISI 316L transport parameters.

AISI 316L	Correlation	Temperature range	Ref.
Diffusivity (m <sup>2</sup> /s)	$3.82 \cdot 10^{-7} \cdot \exp[-45500/(R \cdot T)]$	T=250-600°C	[13]
Sievert's constant (mol/m <sup>3</sup> /Pa <sup>0.5</sup> )	$1.50 \cdot \exp[-18510/(R \cdot T)]$	T=250-600°C	[13]
Permeability (mol/m/s/Pa <sup>0.5</sup> )	$D \cdot k_s$ (derived)	T=250-600°C	[13]

Table 6. AISI 304 transport parameters.

AISI 304	Correlation	Temperature range	Ref.
Diffusivity (m <sup>2</sup> /s)	$2.72 \cdot 10^{-6} \cdot \exp[-54300/(R \cdot T)]$	T=100-600 °C	[14]
Sievert's constant (mol/m <sup>3</sup> /Pa <sup>0.5</sup> )	$\Phi/D$ (derived)	T=100-600 °C	[14]
Permeability (mol/m/s/Pa <sup>0.5</sup> )	$1.06 \cdot 10^{-6} \cdot \exp[-64000/(R \cdot T)]$	T=100-600 °C	[14]

Table 7. AISI 304L transport parameters.

AISI 304L	Correlation	Temperature range	Ref.
Diffusivity (m <sup>2</sup> /s)	$4.7 \cdot 10^{-7} \cdot \exp[-53900/(R \cdot T)]$	T=112-440°C	[14]
Sievert's constant (mol/m <sup>3</sup> /Pa <sup>0.5</sup> )	$\Phi/D$ (derived)	T=112-440°C	[14]
Permeability (mol/m/s/Pa <sup>0.5</sup> )	$8.4 \cdot 10^{-8} \cdot \exp[-59800/(R \cdot T)]$	T=112-440°C	[14]

Due to the lack of data for correlations related to the tritium, all the previous relations are referred to the hydrogen. Therefore, also the results shown are for the hydrogen permeability. Nevertheless, the results are expected to be the same even for the tritium. Actually, the correlations for AISI 304L are evaluated for deuterium and not for hydrogen. For the calculations, they are properly adjusted using physical considerations relating the permeation of hydrogen and deuterium [15], [16].

$$D_H = \sqrt{2} \cdot D_D \quad (10)$$

$$k_{s,H} = 2^{1/4} \cdot k_{s,D} \quad (11)$$

As indicated in Table 4 to Table 7, the temperature range of validation for each material is different. Moreover, the foreseen operational temperature range in the tritium tubes is from ambient temperature at 20°C, at which normal operations are carried out, to 120 °C for the bake-out process. The correlations are

outside this interval, therefore the results and the comparison between materials is only given by an extrapolation of these quantities.

The diffusivity and permeability of hydrogen for each steel are reported in Figure 19 and Figure 20, where the dotted lines indicate the two quantities outside their temperature range (from correlations in literature), while the vertical dashed lines show the Tritium Facility operative window.

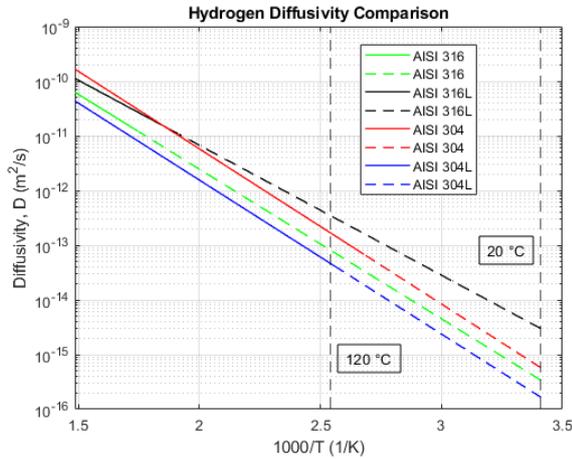


Figure 19. Diffusivity comparison for the different stainless steels considered.

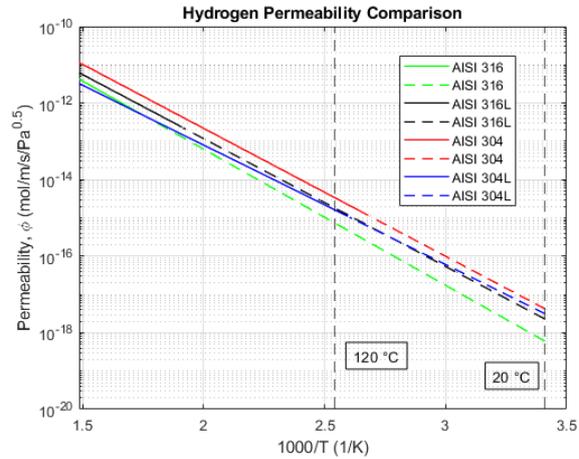


Figure 20. Permeability comparison for the different stainless steels considered.

Knowing the transport parameters for every material, it is possible to determine the permeation parameter for each stainless steel. For the determination of the regime, it is supposed that  $W \geq 400$  means diffusion limited regime,  $W \leq 0.07$  means surface limited regime, and in between the two there is the mixed regime (either SDR or DDR). The division in the different regimes follows the legend reported in Table 8 whereas the results of the calculations are reported in Table 9.

Table 8. Colour map for different permeation regimes.

Colour	Acronym	Meaning	Note
	SLR	Surface-limited regime	$W \leq 0.07$
	SDR	Surface-dominating regime	$0.07 < W \leq 1$
	DDR	Diffusion-dominating regime	$1 < W < 400$
	DLR	Diffusion-limited regime	$W \geq 400$

Table 9. Permeation parameters for the tritium tubes.

	20 °C		120 °C		300 °C		400 °C	
	1/4 in.	1/2 in.						
AISI 316	0.0992	0.196	3.21	6.36	79.0	156	223	442
AISI 316L	0.00483	0.00956	0.43	0.851	26.8	53.0	102	203
AISI 304	0.242	0.479	3.43	6.79	39.4	77.9	86.9	172
AISI 304L	2.18	4.31	21.7	42.9	179	355	356	704

### 3.2.2 Comparison between piping materials

The first important quantity evaluated is the total permeation flux, which is the sum of the fluxes from the two types of tubes, for each stainless steel. The permeation flux is given in (mol/m²/s) and they are grouped and compared in a single graph. The continuous lines indicate results obtained from correlations

within a verified temperature range; the dotted lines of flux are outside the range of the transport parameters, and therefore the results are obtained by the extension of the correlations, and circles are the limits between the results in the verified range and in the interpolated one. Finally, vertical lines are the range of operation in SRF. In Figure 21 the curves are valid for a temperature range different from the one predicted for Sorgentina, and as previously said the results in that range are an extrapolation. Actually, the only two steels which are in part inside this range are AISI 304 and AISI 304L. Approximations aside, confronting the flux and the molar rate for each stainless steel, it is clear that the materials that guarantee lower emissions are AISI 316 and AISI 316L. But this is not enough to say that they are the better choice for sure, since there are other aspects to take into account (like conductance and price).

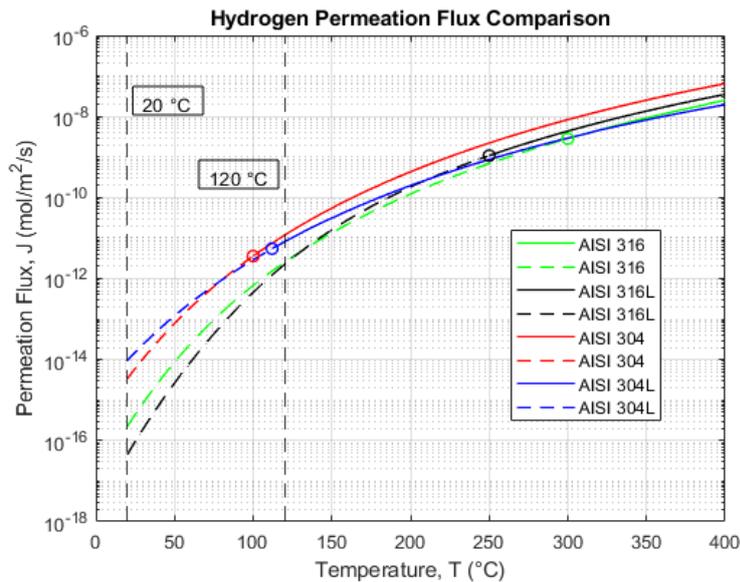


Figure 21. Comparison of total permeation fluxes between the SS.

Another important quantity to evaluate is the activity of the tritium, evaluated outside the tubes. A comparison of the activity in  $\mu\text{Ci}/\text{year}$  of hydrogen for each steel is plotted in Figure 22. The curves are taken at  $20^\circ\text{C}$  since it is the expected operation temperature of the system. Regarding the molar rate needed for the activity, the tube lengths selected are from 20 m to 50 m with a step of 1 m between each measure.

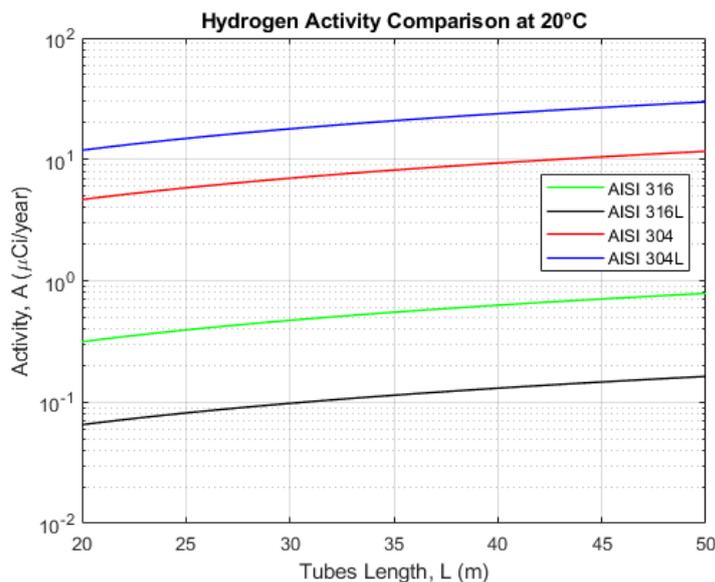


Figure 22. Activity of every stainless steel evaluated at  $20^\circ\text{C}$  assuming steady-state permeation.

For a better visualization of the results, a comparison between the materials for these two quantities is reported in Table 10 and Table 11 at different and specific temperatures. In particular, the chosen temperatures are 20 °C because it is the operating one, 120 °C because is the bake-out temperature, 300 °C is the minimum temperature in common among the correlations and finally 400 °C is a reference temperature for usual permeation applications.

Table 10. Flux comparison in (mol/m<sup>2</sup>/s).

Material	20 (°C)	120 (°C)	300 (°C)	400 (°C)
AISI 316	2.22e-16	2.52e-12	2.83e-09	2.51e-08
AISI 316L	4.51e-17	2.23e-12	4.35e-09	3.52e-08
AISI 304	3.37e-15	1.18e-11	8.34e-09	6.46e-08
AISI 304L	9.45e-15	8.11e-12	2.92e-09	1.95e-08

Table 11. Activity comparison in (μCi/year) at 20 °C.

Material	20 (m)	30 (m)	40 (m)	50 (m)
AISI 316	0.314	0.472	0.629	0.786
AISI 316L	0.0651	0.0976	0.130	0.163
AISI 304	4.66	6.99	9.32	11.7
AISI 304L	11.9	17.8	23.8	29.7

The regulation limit to analyse the results is given by the DOE [3], and in particular is 740 Bq/l. It is a limit on the concentration of the radioactive gas expressed by its activity, and after a measurement units' conversion its value is 20 μCi/year. The tubes that contain tritium are designed to be encapsulated within another external pipe, which separates them from the external conduct that connect the tritium facility with the ionization chamber, providing an additional protection barrier. The calculation is carried out for AISI 316 and the precedent results are considered only for 20 m length of the piping, which guarantees the minimum volume and in turn the most strict comparison. The temperature range is restricted to the foreseen one, from 20 °C to 120 °C, and the internal diameter of the protection tube varies from the sum of the external diameter of the tritium tubes (1/2 in. + 1/4 in.) to seven times the quantity. Finally, the volume considered for the regulation is the one between the external pipe and the tritium tube.

As shown in Figure 23, the dotted black line indicates the limit suggested by DOE of 740 Bq/l. For high temperatures, the limit is never respected even for large diameters, but increasing the latter the maximum temperature for safety rises. It is important to notice that for the lowest diameter, the limit is exceeded at less than 60 °C, which is half the bake-out temperature. In the plot, the values of the tritium concentration are limited at 1000 Bq/l, which means that the concentrations in that area are actually higher. The reason is that with the full range of values the values of the concentration below and in part also above the regulation limit were indistinguishable. Reducing the maximum value to a concentration slightly above the limit, those differences are better appreciated.

The results are affected by major assumptions to guarantee the conservation of the results: the values of concentration are the one reached after the tritium has permeated through AISI 316 for an entire day without ventilation of the volume to reduce its concentration. Moreover, the volume considered is significantly lower than the real one since it is only inside the protective tube, while in reality the gas permeates through it toward the external conduct. With this second permeation the concentration inside the conduct is lower and the volume is larger. Finally, this external conduct is not designed to allow the presence

of people, therefore no workers will be present and the tritium has to permeate toward another room to be in contact with employees.

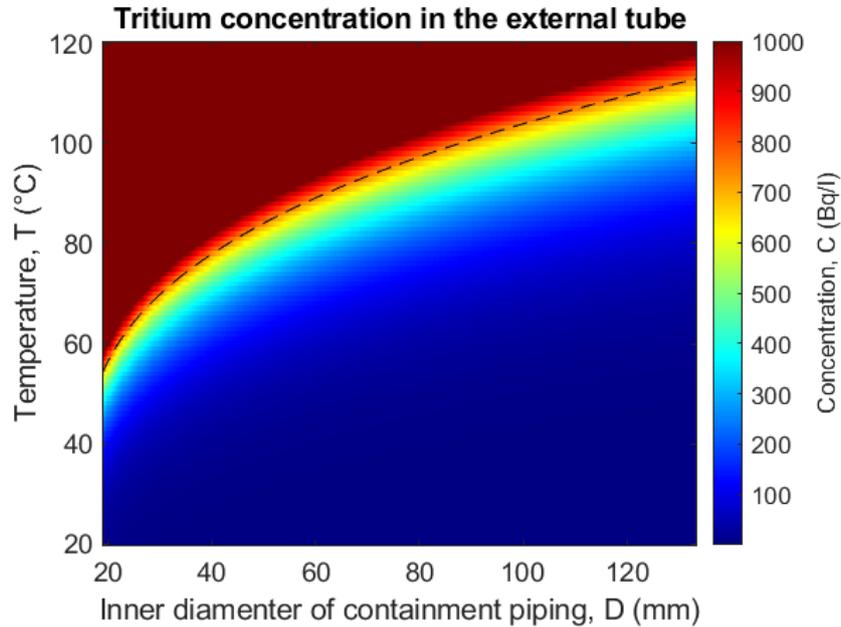


Figure 23. Tritium limit concentration in the external containment pipe.

It is important to notice that these values of concentration are given by a permeated flux in stationary condition. The transient needed to reach this condition is neglected, but in reality, the flux increase for a certain period of time before reaching its maximum value in equilibrium condition.

A preliminary estimation of the time needed to reach the stationary condition for the permeated flux is given by the DOE [3].

$$t = \frac{0.045 L}{D} \quad (12)$$

where  $t$  (s) is the time,  $L$  (m) is the thickness of the surface and  $D$  ( $m^2/s$ ) is the diffusivity of the gas to that material. Considering AISI 316 for both the tubes at the maximum temperature of 120 °C, the time in which the flux reaches its stationarity is about 85 years ( $2.68 \cdot 10^9$  s) for the 1/2 in. tube and 43 years ( $1.35 \cdot 10^9$  s) for the 1/4 in. tube.

These results are an over-estimation because the previous formula is valid only in Diffusion-Limited Regime, but they are sufficient to state that the concentration reported in figure is higher than what it is to be expected during the functioning of the system.

Proper analyses to study the transient of the phenomena and to properly evaluate the activity after one year of function are foreseen for the future and will be carried out with COMSOL software.

### 3.3 Pressurized Storage Tanks

For the correct management of deuterium and tritium inside the Tritium Processing System, three different pressurized storage tanks are necessary to accumulate the two gases; according to the PFD in Figure 5 they are all placed inside the tritium control system (200) and are indicated as V1, V2 and V3.

The first one interfaces the vacuum system (100) and receives the gas stream previously filtered in order to eliminate solid particles like TiD and TiT. Therefore, the gas accumulated in V1 is a mixture of deuterium and tritium combined with heavier elements like argon or oxygen. On the other hand, V2 and V3 are placed

downstream the permeator, meaning that they only store pure D-T mixture (with small quantity of impurities foreseen by design and tolerated).

The storage tanks have to be preferably realized in 304L or 316L stainless steel. They are designed to have the same high maximum pressure guaranteeing compact sizes of the vessels, but the volume of V1 is planned to be twice as large as the other two (see Table 12 for the details).

Table 12. Main constraints for the storage tank design.

	Maximum Pressure (Pa)	Volume (l)
V1	10000	10
V2	10000	5
V3	10000	5

All the three pressurized storage tanks interact with the rest of the Tritium Processing System receiving and releasing the gas, the pressure inside them is constantly monitored and when necessary the composition of the mixture inside must be verified. Therefore, the tanks are equipped with three penetrations for the gas flow and the spilling and one to accommodate the pressure transducer. Moreover, the two tanks V2 and V3 are connected with the external sources of deuterium and tritium, each requiring other two penetrations for the input of the gas.

The piping connected to the tanks is 1/4 inches diameter Swagelok tubes [9], meaning that the penetrations must have the same measures of the pipes, or in alternative suitable fitting devices are needed. Penetrations or other connections to the tanks can be welded or all-metal mechanical joints can be employed to join components in tritium systems. Typically, copper, silver-plated nickel, or silver-plated stainless steel have been used as gaskets. Commercial high and ultrahigh vacuum fittings are normally compatible with tritium.

As of now, the supplier selected to provide all the three tanks is the Steel Head Composites company [17].

### 3.4 Pd/Ag Permeators

In Sorgentina-RF Tritium Facility, the separation of Q<sub>2</sub> species from the other impurities is carried out through Pd-Ag permeators, with the aim to purify, and then reuse, the Q<sub>2</sub> mixture in the ion beam.

Metal membranes and, especially, Pd-based membranes have been extensively studied and applied in tritium recovery technologies ([18], [19]). In fact, dense and defect-free Pd membranes exhibit an infinite selectivity to the hydrogen isotopes which allows high detritiation factors with operating temperatures in the range of 300 – 450 °C. In pure palladium, the uploaded hydrogen can coexists in two hydrogen phases ( $\alpha$  and  $\beta$ ) having different lattice parameters. Consequently, in pure Pd, the  $\alpha \leftrightarrow \beta$  phase transition involves important lattice strains with macroscopic embrittlement. The alloying of palladium with other metals reduces the coexistence zone of the two hydride phases, thus reduces the embrittlement. For such reason, commercial palladium alloys have a silver content in the range of 20-25 wt.% and the permeators designed for Sorgentina-RF have their membrane made in a palladium and silver alloy.

When the surface reactions (adsorption/desorption and dissociation/recombination) are fast, the kinetics of hydrogen diffusion through the membrane is the controlling step and the hydrogen permeation flux across the membrane can be described by the formula [20]:

$$J_p = \frac{\Phi}{t_s} (\sqrt{p_h} - \sqrt{p_l}) \quad (13)$$

where  $\Phi$  [ $\text{mol s}^{-1} \text{m}^{-1} \text{Pa}^{-0.5}$ ] is the permeability coefficient,  $t_s$  [m] is the membrane thickness,  $p_h$  [Pa] is the hydrogen partial pressure at the high pressure side,  $p_l$  [Pa] is the hydrogen pressure at the low pressure side and  $J_p$  is the permeated hydrogen flux [ $\text{mol m}^{-2} \text{s}^{-1}$ ]. In addition, it is important to recall that the permeation is an energy activated phenomena for which an Arrhenius' kind dependence from the temperature can be written:

$$\Phi = \Phi_0 \cdot \exp(-E_a/RT) \quad (14)$$

where  $\Phi_0$  is the permeability pre-exponential factor [ $\text{mol m}^{-1} \text{s}^{-1} \text{Pa}^{-0.5}$ ],  $E_a$  is the permeation activation energy and  $R$  is the gas constant [ $\text{J mol}^{-1} \text{K}^{-1}$ ].

### 3.4.1 Permeators design for SRF

In Sorgentina-RF Tritium Facility, the separation of  $\text{Q}_2$  species from the other impurities is carried out through Pd-Ag permeators, with the aim to purify, and then reuse, the  $\text{Q}_2$  mixture in the ion beam. They are the fundamental main devices of the Pd/Ag permeator system (300). These two identical components operate in parallel, one in operation and the other in standby mode; this configuration allows continuous operation even in the event of failure or maintenance of one module.

In practice, the gas flow, containing 99% D-T and about 1% impurities, enters the permeator through the open valve (FV-1101) and reaches the lumen (inner) side of the Pd-Ag tube through a dedicated stainless steel tube.

According to the specified operating conditions, the inlet gas flow has a total pressure of 200 Pa. To avoid a large temperature gradient between the operating temperature of the membrane (400 °C) and the incoming gas stream, the latter must be preheated accordingly. Once in the membrane lumen, the  $\text{Q}_2$  species can permeate through the membrane wall and reach the shell side of the module.  $\text{Q}_2$  permeation occurs thanks to the  $\text{Q}_2$  partial pressure difference between the two sides of the membrane; the shell of the module is continuously maintained at 10 Pa by a special pumping unit. The impurities (i.e. all non- $\text{Q}_2$  species) do not permeate across the membrane and form the so-called "retentate stream". This retentate stream collects in the membrane lumen and along the line to a special valve. This valve must be opened only when the pressure inside the membrane lumen rises and exceeds the operating value of 200 Pa. When this condition occurs, the retentate stream is collected in a dedicated tank and can be further processed or freely discharged depending on its activity. The Process Flow Diagram representing the permeator system is shown in Figure 24.

The main components of each permeator are listed below [20].

- External cylindrical shell made of a 304L steel tube which the indicative dimensions are a wall thickness of 1.5 mm, the external diameter of 25 mm and its length of 300 mm.
- Pd-Ag (23 wt.% silver) membrane placed inside the shell. One of the membrane extremities is fixed to a flange of the cylindrical shell while the other one is not fixed and thus able to move. In fact, when the Pd-Ag membrane starts to adsorb hydrogen, an elongation can occur especially if the membrane temperature is below 200 °C. So, to avoid the generation of superficial stress over the membrane surface, and thus the risk of rupture, one end of the membrane has to be free to move.
- A heater surrounding the cylindrical shell. It can be a tape or a jacket with an external power supply which should allow to heat the membrane up to 450 °C.

The instrumentations and controls of the permeator unit consist essentially of pressure transducers, thermocouples and automatic On-Off valves. All these components are available on the market but, for this particular application, they have to be tritium compatible.

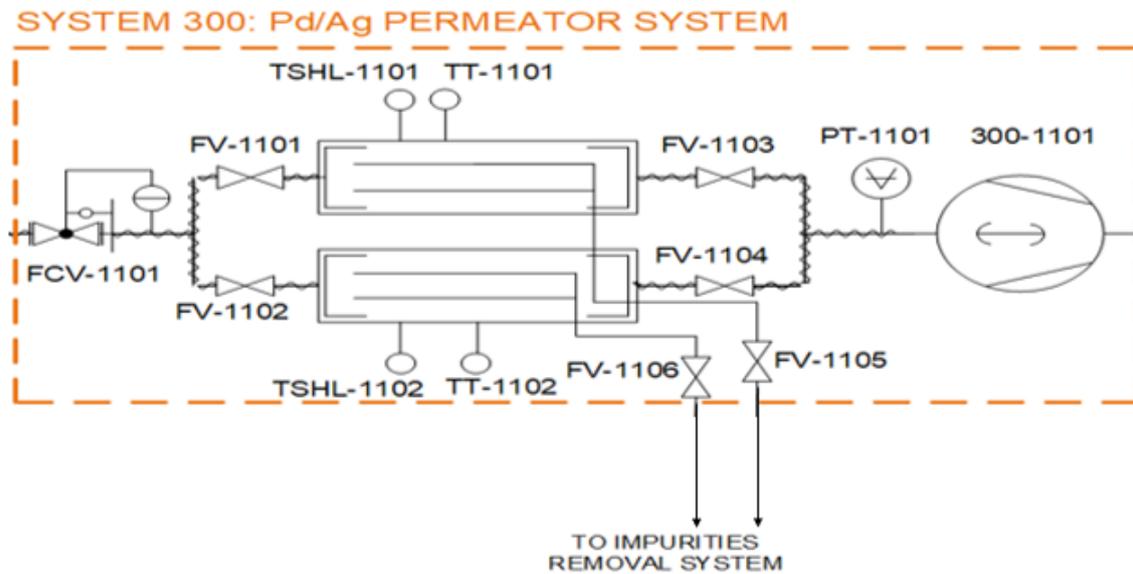


Figure 24. Process flow diagram of the permeator unit.

Table 13 lists the input data of the permeator:

Table 13. Parameters characterizing the Pd-Ag membrane.

Parameter	Value	Unit	Note(s)
$\Phi_0$	$3 \cdot 10^{-8}$	$\text{mol m}^{-1} \text{s}^{-1} \text{Pa}^{-0.5}$	Permeability pre-exponential factor [20]
$E_a$	3600	$\text{J mol}^{-1}$	Activation energy [20]
$Q_2$ flow rate	$1 \cdot 10^{-5}$	$\text{mol s}^{-1}$	-
Impurity content	10	ppm	-
$P_{Q_2, \text{lumen}}$	200	Pa	-
$P_{Q_2, \text{shell}}$	10	Pa	-
$T_{op}$	400	$^{\circ}\text{C}$	-

### 3.5 Uranium getter for the tritium system

Uranium is currently the most useful material for general-purpose tritium storage beds. Uranium beds are used successfully to pump, store and purify tritium gas. Uranium tritide not only has a high tritium capacity but also a low dissociation pressure at room temperature. Such tritides provide an attractive alternative to compressing and storing tritium in pressured containers. At room temperature, tritium in the presence of uranium powder forms uranium tritide. The tritium partial pressure in the bed is very low, thus at room temperature the bed acts as a vacuum pump that absorbs all the hydrogen isotopes.

The impurity gases that may be present, such as  $^3\text{He}$ ,  $\text{N}_2$ ,  $\text{O}_2$ , or  $\text{Ar}$ , either remain in the overpressure gas in the bed or react with uranium to form stable compounds. Inert gases, such as  $\text{Ar}$ , will remain in the overpressure gas, and can be removed by pumping off with a vacuum pump after the pressure has stabilized; however,  $^3\text{He}$  cannot be pumped off without first heating the bed.  $\text{N}_2$  and  $\text{O}_2$  will react chemically with the uranium to form stable uranium compounds in the bed, and, therefore, cannot be pumped off at all. As the

temperature of the bed is increased, the tritium partial pressure increases as a function of temperature and it can be transferred into and out of manifolds, containers, etc., by heating the bed and then cooling it to room temperature. In particular,  $UT_3$  is dissociated by heating and tritium liberated from the solid phase. On cooling, the uranium metal quickly reabsorbs the tritium gas. This reversible liberation and re-uptake of tritium from uranium beds can be performed many times under appropriate conditions without loss of efficiency. In Figure 25 the dissociation pressure of hydrogen compounds formed with uranium is shown [3].

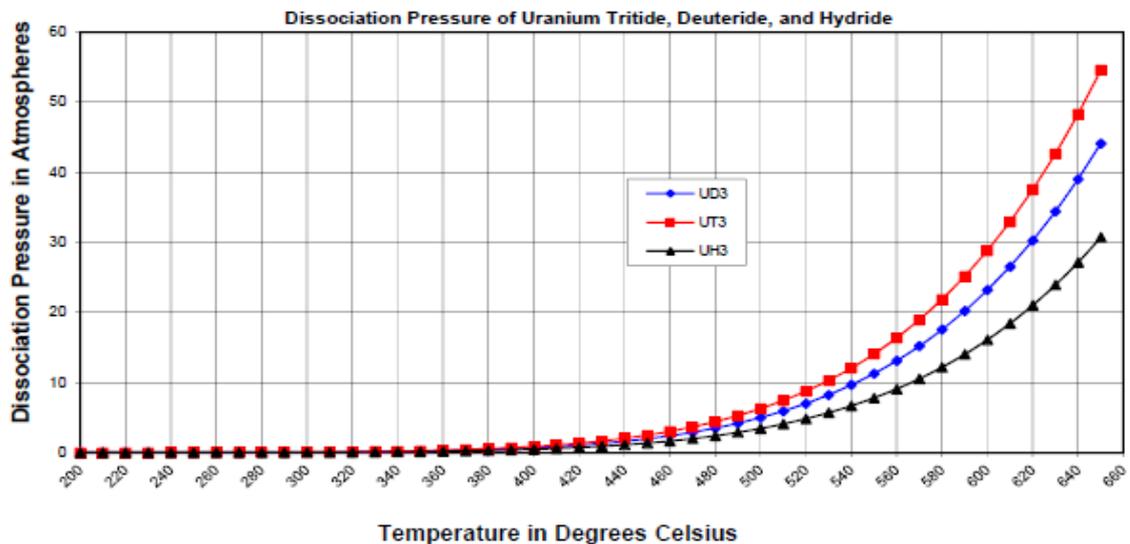


Figure 25. Dissociation pressure of uranium hydride, deuteride, and tritide evaluated by [3].

Each time the tritium is cycled into the system manifolds, it picks up impurity gases. These impurities collect in the bed overpressure gas and may be pumped off to remove them after each heating/cooling cycle. Active impurity gases, such as oxygen and nitrogen, are irreversibly removed by reaction with the uranium.

The main advantages of using a uranium getter are that large quantities of tritium can be stored in the smallest volume and that high-purity tritium gas can be generated "in situ" for any experiment. Moreover, the surplus tritium can easily be recovered at room temperature from the vacuum system and be reabsorbed back onto the tritium getter for later reuse. The decay product He-3 which has accumulated during storage can simply be pumped off.

There are some disadvantages to using uranium tritide beds. First, uranium powder is pyrophoric. Then, the generation of significant tritium pressure requires a high temperature that results in permeation of tritium through the vessel wall. The last downside is that the capacity of the getter is also permanently reduced by exposure to active impurity gases.

The heat transfer analysis of a uranium getter containing up to 5 g of hydrogen was already carried out by the work of [21]. There, a simplified heat transfer analysis of a getter bed for storing small quantities of hydrogen in the form of uranium hydride is carried out; in particular, this model predicts the time-temperature characteristics of the bed during hydriding reaction phase. Looking at the results, the pressure profile inside the getter during hydriding is discontinuous. Therefore, a check on the results is carried out using the same equations and parameters: the results are different from the ones presented by [21], which are reported in Figure 26. In particular the temperature range obtained (Figure 27) is lower and the pressure (Figure 28) has a continuous behaviour.

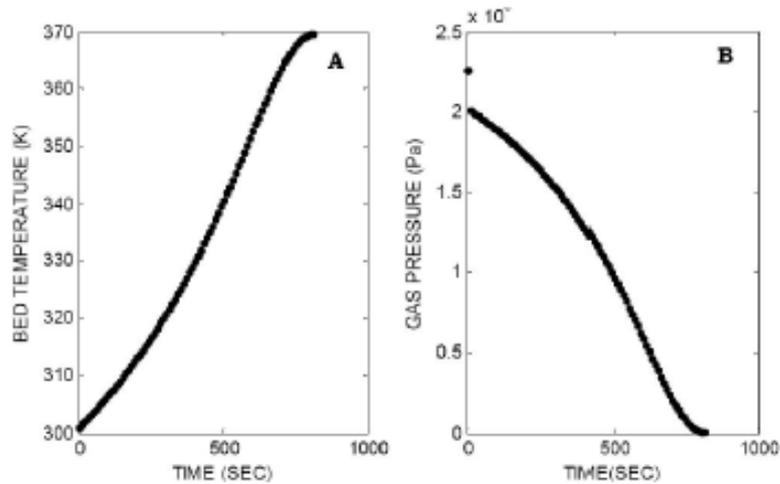


Figure 26. Temperature and pressure during hydriding evaluated by [21].

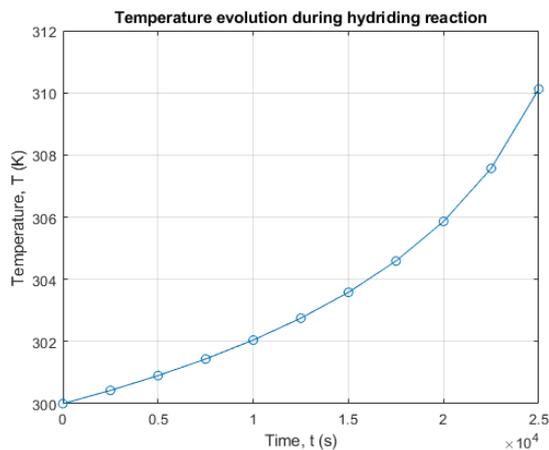


Figure 27. New calculation for temperature during hydriding.

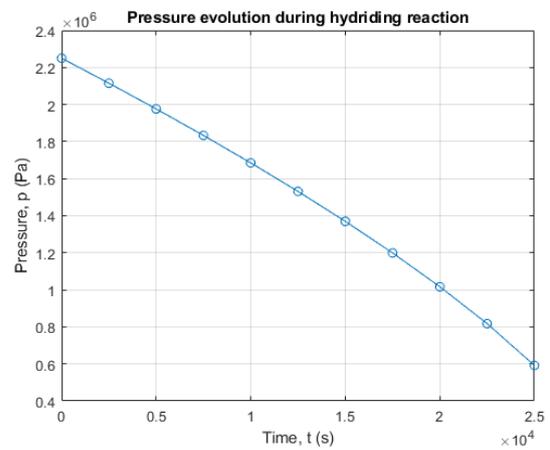


Figure 28. New calculation for pressure during hydriding.

Nevertheless, some companies already produce functioning tritium getters made of uranium bed. The ones chosen by this Thesis are from the RC-Tritec [22]. The company adopts for all structural materials stainless steel series 316, due to its particularly high resistance to hydrogen embrittlement and its great diffusion properties for tritium. They propose two different designs for the uranium bed: the “One-valve uranium beds” are used for storing and generating fresh, high-purity tritium “in situ” and for reabsorbing surplus tritium from an experiment, while “Flow-through uranium beds” are used to accelerate complete recovery of surplus tritium, especially if it contains larger amounts of He-3 or other noble gas impurities. In Figure 29 and Figure 30 the two designs are reported.

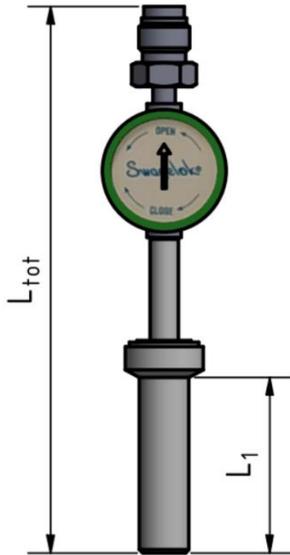


Figure 29. "One-valve uranium beds" design. Courtesy of RC-Tritec.



Figure 30. "Flow-through uranium beds" design. Courtesy of RC-Tritec.



In the rendering shown in Figure 29 of the "One-valve uranium beds", the length  $L_1$  where the getter is placed goes from 50 to 80 mm, while  $L_{tot}$  goes from 160 to 200 mm. Both the designs adopt the tubes from Swagelok [9].

### 3.6 Glovebox Design

The whole Tritium Processing System, dealing with radioactive hydrogen, needs proper barriers to minimize the risk for contamination of workers and environment. As already described, tritium tends to permeate through the barriers containing it, like through the piping walls, therefore it is necessary to further encapsulate all the components directly facing this gas. For this purpose, Sorgentina-RF foresees two different glovebox that will contain the whole TPS within them: the smaller one is dedicated solely to the tritium getter storage system (index 400 from Figure 5), which includes the uranium getter and its instrumentation, while the larger one comprises both the tritium control system (200) and the permeator system (300).

Each glovebox must be designed to comply with the legislation. In particular, the aforementioned regulation is the one provided by the American Department of Energy (DOE), which considers gloveboxes properly working if their leakage is  $10^{-3} - 10^{-4} \text{ cm}^3(\text{He})/\text{s}$  [3]. In this case, the temperature range is chosen smaller to the one analysed for the tubes, more specifically it goes from 20 °C to 120 °C. Moreover, it is important to evaluate different dimensions of the glovebox, and thus a range for the total surface area is taken from 1 m<sup>2</sup> to 8 m<sup>2</sup>. An example of glovebox operating with tritium is displayed in Figure 31.



Figure 31. Glovebox at CEA (courtesy of CEA).

### 3.6.1 Choice of the materials

Among the many producers of glovebox, the main materials that compose a glovebox are stainless steels (usually manufacturers produce them in AISI 304) or plastic materials (see Figure 31 above, mainly built with plastic materials). The choice for the possible plastic materials is determined by the availability of proper correlations for the tritium permeation present in literature. Moreover, like for the piping, the correlations are related to the hydrogen and the behaviour of the gas is supposed similar to the tritium, leading to the same kind of results. Therefore, the materials selected for the glovebox are AISI 304, PVC e Polyethylene.

Tritium is expected to permeated better through plastic materials, therefore AISI 304 should be the better choice. PVC and HDPE are analysed because, considering the same thickness among the materials, the bremsstrahlung radiation emitted from stainless steels is higher than from plastics, which in turn are safer from this perspective. Glovebox producers offer different possible materials for their gloveboxes, but among the plastic materials there are data about hydrogen permeation only for PVC and polyethylene. Regarding the steels, many of them do not specify which stainless steel they adopt and the ones who do that, they all use AISI 304. This is the reason for the choice of the three aforementioned materials.

The permeability for these three materials is shown in Table 14:

Table 14. Transport parameters of the considered materials for the glovebox.

Material	Permeability	Temperature range	Ref.
AISI 304	$1.06 \cdot 10^{-6} \cdot \exp[-64000/(R \cdot T)]$ (mol/m/s/Pa <sup>0.5</sup> )	100 – 600 °C	[14]
PVC	$0.65 \cdot 10^{-3} \cdot \exp[-34500/(R \cdot T)]$ (mol/m/s/Pa)	25 – 80 °C	[23]
HDPE	$0.05 \cdot 10^{-3} \cdot \exp[-27000/(R \cdot T)]$ (mol/m/s/Pa)	-38 – 27 °C	[23]

The permeability of AISI 304 has slightly different units from the two other materials, in particular the former is proportional to the square root of the pressure, the other ones are proportional to the pressure. The reason is that the solubility in stainless steels follows the Sieverts' law, whereas for polymers it obeys to Henry's law.

A way to compare the parameters for the materials is to plot them independently from the pressure. To have a comparison between plastic and metallic materials, the solubility is considered since for permeability different laws govern the process (Sieverts' law for metals, Henry's law for plastics). This calculation was performed at the pressure of the tritium foreseen inside the glovebox, which is 10000 Pa. For this purpose, the solubility of the three possible choices is plotted in a comparison chart (Figure 32).

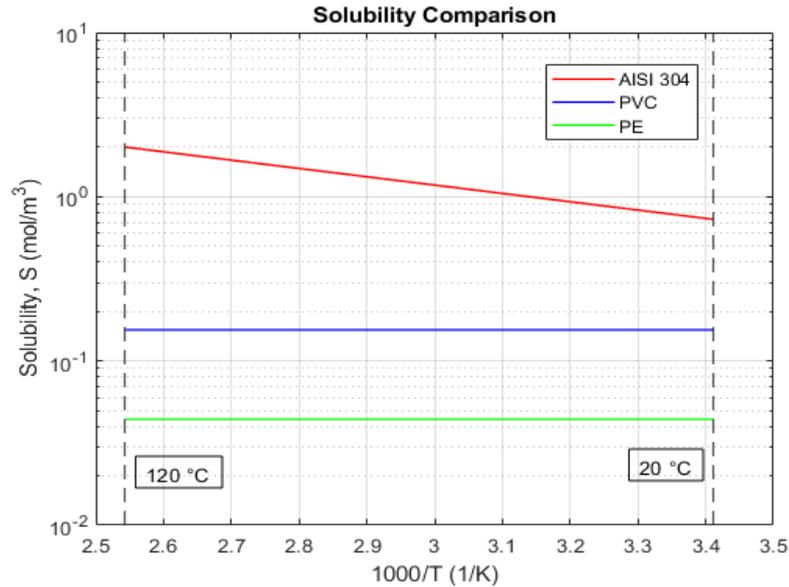


Figure 32. Comparison of solubility between the materials.

### 3.6.2 Analyses on the glovebox wall thickness

The main parameter of a glovebox to evaluate is the thickness of its walls required in order to safely contain the tritium and avoiding its permeation in quantities above the safety threshold. The following obtained results are a consequence of considering the glovebox made of a single material for each case. This assumption leads to some approximations. In reality, the glovebox usually has a transparent panel made of a particular material. In accordance with the American Glovebox Society standard AGS-001 [24], the screen should be made of PVB (polyvinyl butyral).

A common procedure for each material selected for the glovebox has been applied: first, the DOE limit of  $10^{-4}$  cm<sup>3</sup>/s has been chosen and it has been divided by the molar volume of an ideal gas (22.4 l/mol) in order to obtain the molar rate limit (mol/s). Different values of external surface have been considered to evaluate the permeation flux limit (mol/m<sup>2</sup>/s). Finally, the worst possible conditions are assumed, which means the permeated flux is the maximum possible, and therefore the Diffusion-Limited Regime model is adopted [6]. For AISI 304 the equation considered is:

$$t_{lim} = \frac{\Phi}{flux_{lim}} \cdot \sqrt{p} \quad (15)$$

While for PVC e HDPE it is influenced again by Henry's Law, and it is [23]:

$$t_{lim} = \frac{\Phi}{flux_{lim}} \cdot p \quad (16)$$

Figure 33 shows that AISI 304 is the best choice for each operating temperature, even though the difference with the plastic materials reduces at higher temperatures. In fact, inside this temperature range the minimum thickness for the AISI 304 is several orders lower than the one calculated for the plastic materials.

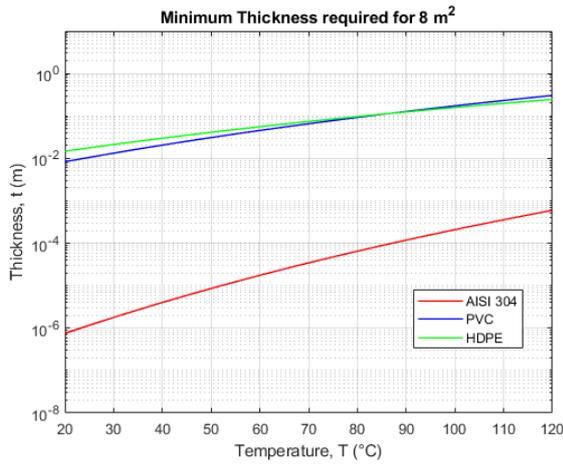


Figure 33. Thickness over temperature for a total permeation surface of 8 m<sup>2</sup>.

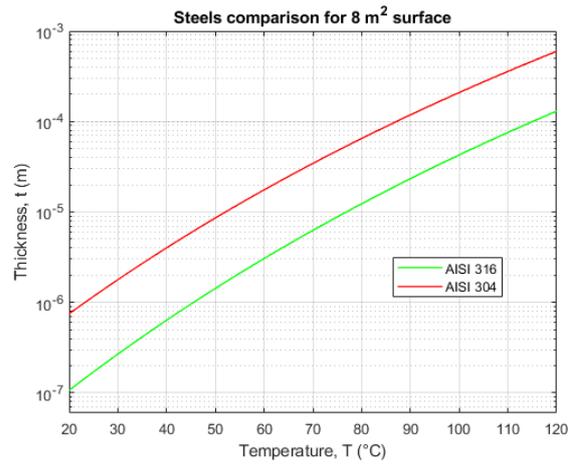


Figure 34. Comparison AISI 316/AISI 304 for a permeation surface of 8 m<sup>2</sup>.

Moreover, the curves are plotted in Figure 33 and in Figure 34 for the maximum surface area, but it is recommended to have the permeation surface as low as possible in order to reduce the molar rate, therefore this assures conservation of the results.

Recalling the results from the analysis of the tubes, the best choice for them is not AISI 304, but 316 or 316L. In this range of temperature, the permeability of AISI 316 is much lower to the 304, so it is recommended to use the former as a material for the glovebox, since the latter is sub-optimal. Looking at the chart with the permeability in Figure 20, another valid possibility is 304L. Again, inside the same temperature range, where the thickness for AISI 304 is at most around  $6 \cdot 10^{-4}$  m, for the AISI 316 it is lower and, specifically, around  $1.2 \cdot 10^{-4}$  m (Figure 34). The difference between the two stainless steels and the plastic materials is even more evident if the results are compared (Table 15) for different surface areas at the minimum temperature considered, which is 20 °C and yet expected to be higher than the one foreseen during operation: in fact, Figure 35 shows the average temperatures at Lake Brasimone, data from [25].

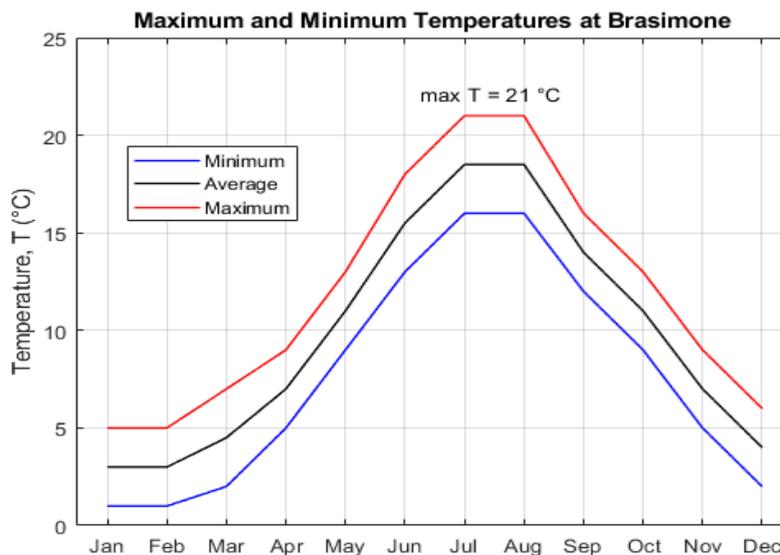


Figure 35. Minimum, maximum and average temperatures at Brasimone during the whole year (2022).

In Table 15 the materials previously considered are compared at 20 °C for different permeation areas. The difference in minimum thickness required between stainless steels and plastic materials is evident, but at this temperature even the biggest thickness among the four materials is in the order of a centimetre.

Table 15. Thickness comparison at a temperature of 20 °C.

Surface	AISI 304	AISI 316	PVC	HDPE
1 m <sup>2</sup>	9.38·10 <sup>-8</sup> m	1.34·10 <sup>-8</sup> m	1.04·10 <sup>-3</sup> m	1.84·10 <sup>-3</sup> m
2 m <sup>2</sup>	1.88·10 <sup>-7</sup> m	2.67·10 <sup>-8</sup> m	2.07·10 <sup>-3</sup> m	3.67·10 <sup>-3</sup> m
3 m <sup>2</sup>	2.81·10 <sup>-7</sup> m	4.01·10 <sup>-8</sup> m	3.11·10 <sup>-3</sup> m	5.51·10 <sup>-3</sup> m
4 m <sup>2</sup>	3.75·10 <sup>-7</sup> m	5.34·10 <sup>-8</sup> m	4.15·10 <sup>-3</sup> m	7.34·10 <sup>-3</sup> m
5 m <sup>2</sup>	4.69·10 <sup>-7</sup> m	6.68·10 <sup>-8</sup> m	5.19·10 <sup>-3</sup> m	9.18·10 <sup>-3</sup> m
6 m <sup>2</sup>	5.63·10 <sup>-7</sup> m	8.01·10 <sup>-8</sup> m	6.22·10 <sup>-3</sup> m	1.10·10 <sup>-2</sup> m
7 m <sup>2</sup>	6.56·10 <sup>-7</sup> m	9.35·10 <sup>-8</sup> m	7.26·10 <sup>-3</sup> m	1.28·10 <sup>-2</sup> m
8 m <sup>2</sup>	7.50·10 <sup>-7</sup> m	1.07·10 <sup>-7</sup> m	8.30·10 <sup>-3</sup> m	1.47·10 <sup>-2</sup> m

Considering a Surface-limited Regime in every case is a conservative approximation because for each temperature the actual regime could be different. A method that considers this fact is used for comparison with the conservative results. Since the thickness required is unknown, the permeation regime cannot be evaluated. Therefore, the only way to implement this method is with an iterative process. The same DOE limit of 10<sup>-4</sup> cm<sup>3</sup>/s has been considered and it has been divided by the molar volume of an ideal gas (22.4 L/mol) in order to obtain the molar rate limit (mol/s). Again, the same values of external surface have been selected to evaluate the permeation flux limit (mol/m<sup>2</sup>/s). The physical model adopted is the one described by [6]. For each surface, the thickness chosen as the initial value is one tenth than the respective one calculated in DLR. Knowing this quantity and the transport parameters of the materials it is possible to evaluate the permeation parameter, and in turn the permeation regime, and eventually the permeation flux and the molar rate for each surface and each temperature. If the molar rate is higher than the limits, the guessed value of the thickness is increased and the process is repeated until a suitable value is found. The results are shown in Figure 36.

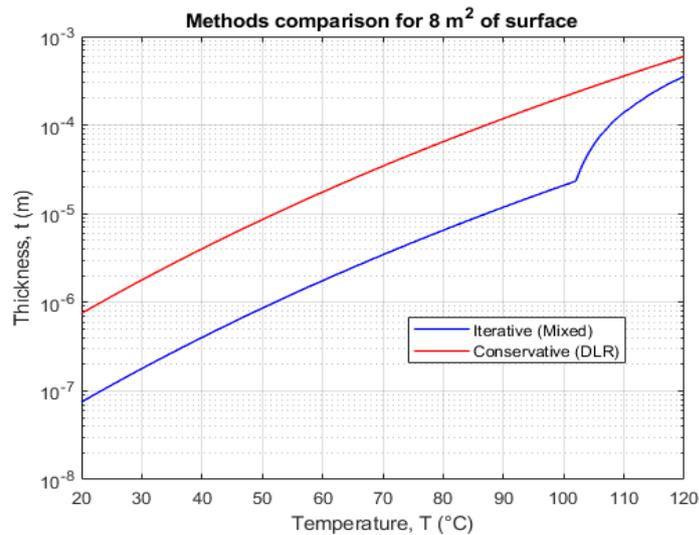


Figure 36. Comparison between results obtained in mixed permeation regime and in Diffusion-Limited regime.

While for lower temperatures the legislation limits of DOE are respected even for smaller thicknesses, increasing the temperature the difference between the two methods wears thin, and if the temperature

would increase further, they are expected to converge and the solutions become the same. The reason is because over a certain temperature, the regime becomes effectively diffusion limited and so the result is equal to the conservative method.

Finally, as said the DOE limit considered for the dimensioning is  $10^{-4} \text{ cm}^3(\text{He})/\text{s}$ . If the lower limit of  $10^{-3} \text{ cm}^3(\text{He})/\text{s}$  is considered acceptable, the results would be different and the thickness required way lower. In Figure 37, a comparison between the two limits is shown for AISI 304.

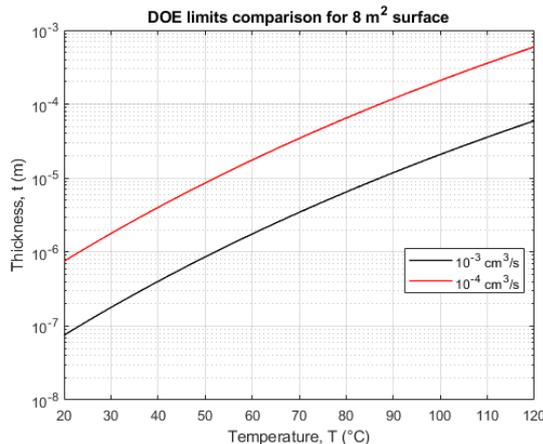


Figure 37. Comparison between the far ends of the regulation limit proposed by DOE.

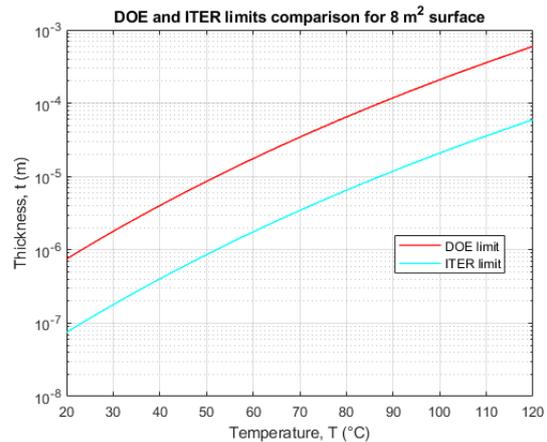


Figure 38. Comparison the limits suggested by both DOE and ITER.

As shown in the Figure 37, within the whole temperature range, the minimum thickness required for the conservative limit is around one order of magnitude less than for the loosened limit. Finally, a second limit proposed by a document, released by ITER about tritium systems and their handling [4], is considered to make a confrontation with the limit adopted until now. In particular, the limit proposed by the ITER Tritium Handbook for gloveboxes is a maximum leak rate of  $10^{-5} \text{ Pa m}^3/\text{s}$  of air equivalent. Dividing this value by the pressure of the tritium inside the glovebox and considering the molar volume, it is possible to derive the maximum molar rate and, with the same conservative process used before, find the required minimum thickness. In Figure 38, the comparison between the limits proposed by DOE and ITER is shown. The limit proposed by DOE is more conservative than the one suggested by ITER, at least for the tritium pressure reached for this application. Actually, the limit given by ITER is similar to the DOE lower limit introduced before of  $10^{-3} \text{ cm}^3/\text{s}$ .

### 3.6.3 Glovebox features and specifications

The evaluation of the wall thickness in a glovebox is a key point for the safety of the system, but it is not a sufficient requirement to validate the design of the glovebox: a proper one must adhere to the international guidelines, respecting the features dictated by normative codes and implementing the required additional components.

The two main normatives applied for the design of both gloveboxes are ISO 10648 [26] and ISO 11933 [26], in particular the section considered are:

- ISO 10648-1:1997
- ISO 10648-2:1994
- ISO 11933-1:1997
- ISO 11933-2:1997
- ISO 11933-3:1998

- ISO 11933-4:2001
- ISO 11933-5:2001

ISO 10648-1:1997 is about the general definition of containment enclosures and their design principles. It deals with only three types of enclosures: glovebox, tongue box and larger enclosures with remote manipulators. This normative indicates the materials suitable for the glovebox construction, in particular it suggests plastic materials (good chemical resistance, light weight, transparent and generally low cost), glass materials (only special types of toughened, laminated and stabilized glass shall be used as structural material in containment enclosures) and metallic materials (good thermo-mechanical properties, easy to decontaminate and good radiation resistance). For each material, the normative suggests the best and worst chemical agents to be contained inside a specific type of glovebox and describes their correct use and possible dimensioning.

ISO 10648-2:1994 focuses again on containment enclosures in general, but it aims to produce a classification according to the leak-tightness and describing the associated checking methods. The classification is based on the calculation of the “hourly leak rate”, which is defined as the ratio between the hourly leakage of the containment enclosure under normal working conditions and the volume of the said containment enclosure. Depending on its value, the glovebox is classified in one of the four leak-tightness ranks, where Rank 1 indicates best performance among them. After the classification, the normative introduces three possible checking methods, which are oxygen method, pressure change method and constant pressure method, and describes each of them, differentiating between the working principle, the procedure and the validity range.

Every section of ISO 11933 is related to different components necessary for the containment enclosures. ISO 11933-1:1997 describes glove/bag ports, bungs for glove/bag ports, enclosure rings and interchangeable units.

ISO 11933-2:1997 instead focuses on gloves, welded bags, gaiters for remote-handling tongs and for manipulators.

ISO 11933-3:1998 describes the components necessary to access the inside of the enclosure for maintenance and any other necessary reason. It defines the transfer systems such as plain doors, airlock chambers, double door transfer systems, leak-tight connections for waste drums.

ISO 11933-4:2001 define the components necessary to keep the atmosphere inside the enclosure the safest possible: it introduces ventilation and gas cleaning systems such as filters, traps, safety and regulation valves, control and protection devices.

ISO 11933-5:2001 deals with the connections of the containment enclosures with the external systems, defining the penetrations for electrical and fluid circuits and the necessary countermeasures such that they do not act as weak points for the leakage of dangerous substances towards the outside.

All the standards discussed above are applied on the design of the two gloveboxes for the Tritium Permeation System in the Sorgentina-RF plant. It is important to remember that in this particular case the substances handled inside the two containment enclosures are deuterium and tritium: they are extremely volatile gases and the latter is radioactive, which in turn demand strict measures in the design. Therefore, the two gloveboxes necessarily present additional features and specific components:

- Enclosure shells shall be made of uncoated stainless steel.

- Enclosure windows shall comprise of a double pane of tempered safety glass of 12.7 mm total thickness with a layer PVB (poly-vinyl-butryal) sandwiched between, in accordance with American Glovebox Society standard [24].
- The glovebox must be ranked at least “Class 2” for leak-tightness in accord with ISO 10648-2.
- Ventilation and gas-cleaning systems such as filters, traps, safety and regulation valves, control and protection devices designed in accord with ISO11933-4.
- Adoption of HEPA filters and a system to control the atmosphere in order to guarantee 1% of O<sub>2</sub>.
- Glove ports shall be fitted with accepted removable covers.
- Enclosures shall operate at least 250 Pa below ambient room pressure.
- The enclosure shall be fitted with features (gloves/airlock etc.) to allow the maintenance operations and guarantee access to all the components.
- After the RAMI analysis, the number and position of openings to operate within the glove boxes (glove ports, air locks, viewing windows) to access components which require maintenance or replacement operations should be assessed. Based on the RAMI analysis, proposals for improvements in the final design shall be developed.

The two gloveboxes will both comply with the described standards and will present the additional features, but the TPS components that will be contained by the two enclosures are completely different, which in turn will implicate a different sizing of the two.

The *Main Glovebox*, which is the one that encapsulates both the tritium control system (200) and the permeator system (300), contains the majority of the components. In particular they are:

- Two permeators (each has 25 mm OD and 300 mm length).
- 3 tanks (one sized 10 l and two 5 l, producer is Steel Head Composites [17]).
- Deuterium tank (external source of deuterium).
- 6 pressure transducers (from Pfeiffer CMR 361 with 55 mm OD and 136 mm height [27]).
- Pumping station (from Pfeiffer ACP 15 Root pump with L x W x H 514 x 190 x 270 mm).
- Many On-Off and control valves with pneumatic actuators (selected SS-4BK-1C from Swagelok [9]) and a pressure reducing valve with its transducer.
- 4 temperature transducers (negligible dimensions).

The reasons behind the choice of the pump are that the pressure to generate is not extreme and root pumps work without oils, which makes them compatible with tritium. Pfeiffer Vacuum [27] pumps are also compatible with Swagelok piping, which constitutes the tubes inside the TPS. Moreover, among the possible ACP Series root pumps, the ACP 15 is selected for the limited dimensions and price.

For the design of the airlock that permits to place all the components inside the glovebox, and eventually accessing them when needed, the largest component’s dimensions are the reference. In this case the root pump is the largest one, thus, supposing a circular section, the airlock internal diameter has to be at least 270 mm, imagining to insert the pump along its length.

Finally, the number of penetrations suggested are: 2 related to V1 (inlet mass flow and spilling), 1 connected to the waste management system, 1 for the tritium coming from the external source, 1 for the exiting D-T flow, 2 for V2 and V3 spilling, 1 for electricity cable (alimentering pump, transducers and the ventilation with filters).

The *TGSS Glovebox*, which is solely dedicated to the containment of the tritium getter storage system (400), is smaller and handle much less components:

- Tritium getter with 20 mm OD and 200 mm height (from RC-Tritec [22]).

- A pressure reducing valve (reading Swagelok catalogue [9]) with its transducer (again from Pfeiffer Vacuum CMR 361 with 55 mm OD and 136 mm height [27]).
- 2 temperature transducers (negligible dimensions).

The design of the airlock is again related to the largest component, which in this case is the pressure transducer, since the height of the getter can be negligible if the component is inserted along that dimension.

In this case only two penetrations are needed, 1 for the outlet of the tritium and 1 for electricity cable (alimentering transducers and ventilation with filters).

Finally, different manufacturers are explored in order to find a suitable producer to purchase the two needed gloveboxes from. The option suggested is Jacomex company [28]: they have a long experience and provide solutions for many important nuclear institutions. Their “nuclear containment enclosures” are usually built in stainless steel (either 304L or 316L) and are equipped with systems mentioned in the required additional features a glovebox needs to handle tritium, like HEPA filters and safety valves. Even more important, they assure a Class-1 for the tightness according to the ISO 10648-2 [26]. Different sizing of the glovebox dimensions is proposed, which also influence the number of glove ports, including the possibility to request a custom-made dimensioning: if possible, it is suggested to select two standard gloveboxes in order to lower the expenses on this front. Figure 39 shows an example of glovebox produced by Jacomex.



Figure 39. Example of glovebox produced by the Jacomex company belonging to the G(safe) series. Courtesy of Jacomex.

### 3.7 Other components and instruments

It is presented a brief general overview of the heating elements belonging to the TPS of Sorgentina-RF, especially the ones applied along the whole length of the tubes and used for the bake-out process of the piping. Moreover, an overall methodology to design tritium-facing instrumentations is proposed, suggesting periodic recalibration and warning about the issue manifesting in the recalibration itself, caused by the tritium permeated inside these components.

### 3.7.1 Heating elements

Heaters are designed redundant such that if one of them fails, the others can perform their function if it is determined to be necessary by the proper safety analysis. One or more latching over-temperature trip circuits protect the heaters. Once the failure is detected, it is necessary to be able to recover the system without breaching the tritium confinement.

### 3.7.2 Instruments and control

Design of instrumentations, which may encounter tritium, must consider the effect of tritium contamination on their operation. It is suggested to implement particular system designs which allow to perform decontamination on the instruments. To facilitate this process, the surface exposed to the tritium must be minimized. A particular consideration is also given to system design that allows in-service periodic recalibration for components like pressure transducer, mass spectrometer and the ionization chamber.

An important issue related to the recalibration of the instruments is the so-called memory effect. The tritium memory effect is caused by tritium adsorption and tritium absorption in the upper bulk area of materials exposed to the tritiated process gas, and it creates a history-dependent background signal in activity monitoring systems for tritiated gases. This effect can reduce the accuracy of the measurements. For pressure transducers and mass spectrometers this effect is eliminated by the degassing of the systems, which eliminates the tritium simply by heating them up.

Concerning the ionization chamber, the memory effect is mainly due to the adsorption of tritium onto the electrodes of the ionization chamber. It is particularly important for ionization chambers since they are generally used to monitor the tritium level in a gas stream because of their reliability, flexibility and wide range of measurement. To reduce this effect, several solutions are proposed. The first one suggests that swamping with water vapor can diminish the memory effect to background level after about 30 minutes. Tritiated water in surface water on the electrode material reacts with water vapor in the gas stream, and this chemical reaction reduces the level of tritium absorbed [29].

The Institute of Nuclear Physics and Chemistry (INCP) has carried out experiments with tritium in form of both HTO and HT to examine the impact of memory effect. Their results show that a gold-plated treatment of the internal part of the chamber could effectively reduce the influence of memory effect caused by tritium absorption to background level in 1 minute after 1 h of tritium exposure with dry air swamping [30].

Another technology which can be adopted for the monitoring of tritiated gas species is the Beta-induced X-ray spectrometry (BIXS) [31]. This method is based on the measurement of bremsstrahlung radiation and characteristic X-rays generated by interactions of beta particles with the surfaces inside the measurement chamber. Even in this case, the accuracy is limited by the memory effect due to the absorption of tritium onto the surfaces. Recent studies [32] showed that the lowest tritium-induced background level, and in turn the lowest memory effect can be achieved implementing gold-coated cells or uncoated stainless steel 316LN. Other materials, such as multi-layer systems with a gold coating or ceramics, have been found to yield sufficient memory reduction.

## 4 Modelling of the tritium facility

The tritium and deuterium management inside the TPS is modelled using the Simscape software [33]. The Simscape software enables to model physical systems in the Simulink environment (Matlab based tool) employing the Physical Network approach: the modelling is made using a set of blocks that represent real physical components. Differently from the standard Simulink modeling approach, Simscape is particularly suited for systems that consist of real physical components, and each system is represented with functional elements that interact with each other by exchanging energy through their ports.

Simscape helps to develop control systems and test system-level performance, therefore it is a software suitable for representing the Tritium Processing System of Sorgentina-RF. The model presented in this Master Thesis is the first one produced and it is just a preliminary one because it only represents the filling and successive emptying of a tank in the system, coupled with the external sources of deuterium and tritium. Nevertheless, it is a fundamental step because it describes the logic behind the fuelling of the ion accelerator and it serves as the starting point for the realization of the model simulating the whole TPS.

### 4.1 Description of the Simscape model

The model reported in Figure 40 depicts a simplified version of the gas circuit connected to one of the two tanks (either V2 or V3 in Figure 5) filled with a pure D-T mixture placed within the Tritium Processing System. In particular, the boundaries of the system are represented by the permeator, where tritium and deuterium are separated from various impurities, and the system linked to the accelerator, which provides the fuel for the fusion reactions.

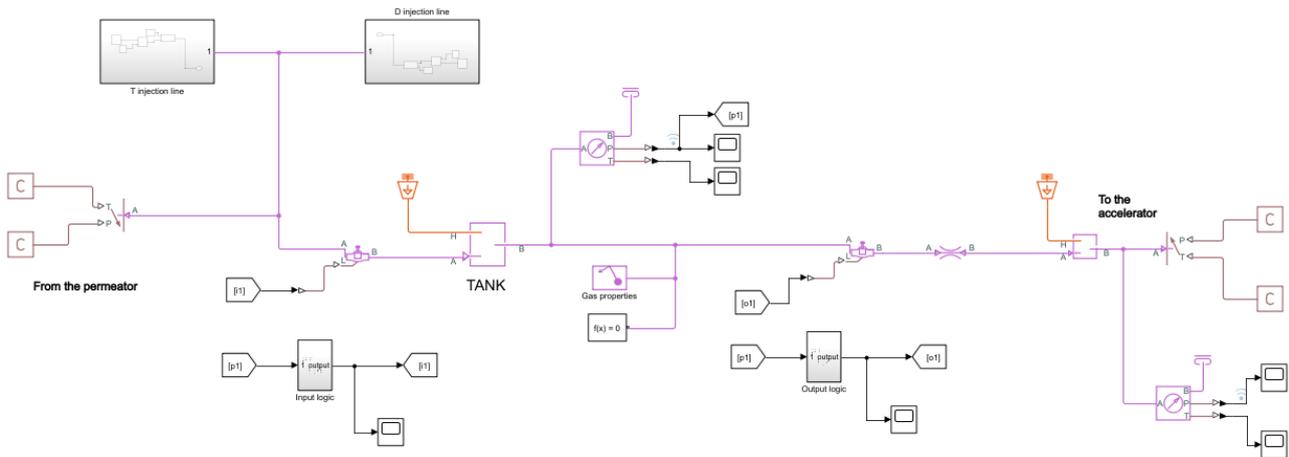


Figure 40. Simplified Simscape model of the TPS.

The permeator in this model acts as the source of the system and it is represented by a “reservoir” block maintained at constant pressure and temperature, while the gas sink for the system is the accelerator represented by “constant volume chamber” and “reservoir” blocks, again at a constant pressure and temperature.

The external source of tritium and deuterium, which are respectively the TGSS and a simple cylinder in the PFD of Figure 5, are implemented in this model with the two subsystems placed at top-left of Figure 40. The two subsystems, called “T injection line” and “D injection line”, contain the same components but with the characteristic parameters of tritium and deuterium to differentiate between the two radioisotopes. They are simply modelled with three different blocks, a “controlled mass flow rate source”, a “constant volume chamber” and a “reservoir”, and the tritium line is shown in Figure 41 below.

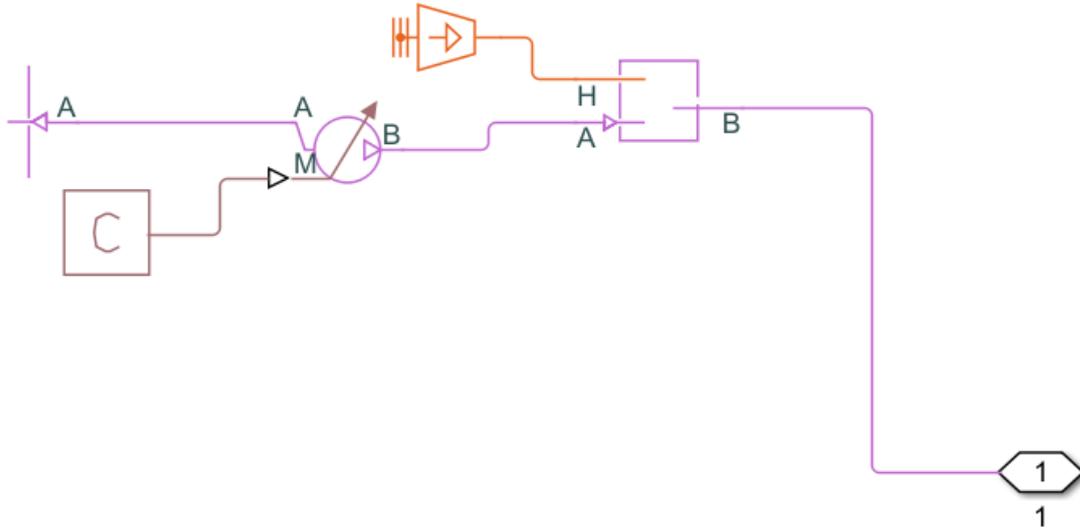


Figure 41. Tritium injection line model.

As already said, Sorgentina-RF needs deuterium and tritium as fuel, therefore this model incorporates a gas with the characteristics of the D-T mixture. They are specified by the block “gas properties” and are evaluated at a temperature of 20 °C, maintained constant in the whole model, and calculated as a weighted average on the molar mass between the properties of the two gases. The temperature is chosen equal to the one foreseen for the SRF normal operation.

Table 16 lists the properties of deuterium and tritium adopted in the model:

Table 16. Gas parameters at 20 °C for deuterium and tritium adopted in the model.

	<i>Deuterium</i>	<i>Tritium</i>
Specific gas constant, R (kJ/(K*kg))	2.7566	4.1289
Specific enthalpy, h (kJ/kg)	$3.8604 \cdot 10^3$	$3.8604 \cdot 10^3$
Specific heat, $c_p$ (kJ/(K*kg))	14.2799	14.2799
Dynamic viscosity, $\mu$ (Pa*s)	$8.8000 \cdot 10^{-6}$	$8.8000 \cdot 10^{-6}$
Thermal conductivity, W (W/(m*K))	0.1820	0.1820

The properties of the two gases are basically the same, with the exception of the gas constant, which depends on the molar mass and is in turn different between the two isotopes.

## 4.2 Preliminary results

This model is just a preliminary one because it only represents the filling and successive emptying of a tank in the system (either V2 or V3), coupled with the external sources of deuterium and tritium. While the temperature in the system is constant and taken at the operative value foreseen for SRF of 20 °C, the pressure values for the source (permeator) and the sink (accelerator) are chosen arbitrarily only for the sake of the simulation, and are respectively 100 Pa and 1 Pa.

The model has been developed considering the following simplifications:

- Negligible D-T consumption and losses in the system;
- Piping volume non considered;
- Pd/Ag permeator not modeled;

The first is particularly reasonable for the short transient considered. The second and third simplification are more impactful, but still permit to obtain a preliminary dimensioning of the tank. All the above assumptions will be relaxed in future models.

The gas flow coming from the vacuum chamber enters the TPS and is filtered by the permeator. The pure mixture of D-T fills the tanks V2 and V3 with a 50-50 stoichiometric ratio, coming both from the permeator and the external sources. In this model, the gas flow entering the tank is controlled by a “gate valve” block, which either opens or closes depending on the pressure measured inside the tank; the logic that regulates the state of the valve is contained in the subsystem “Input logic”, which input parameter is the tank pressure “p1” and the output parameter is a Boolean value of 0 (which closes the valve) or 1 (completely opening the valve). The subsystem for this valve is shown in Figure 42:

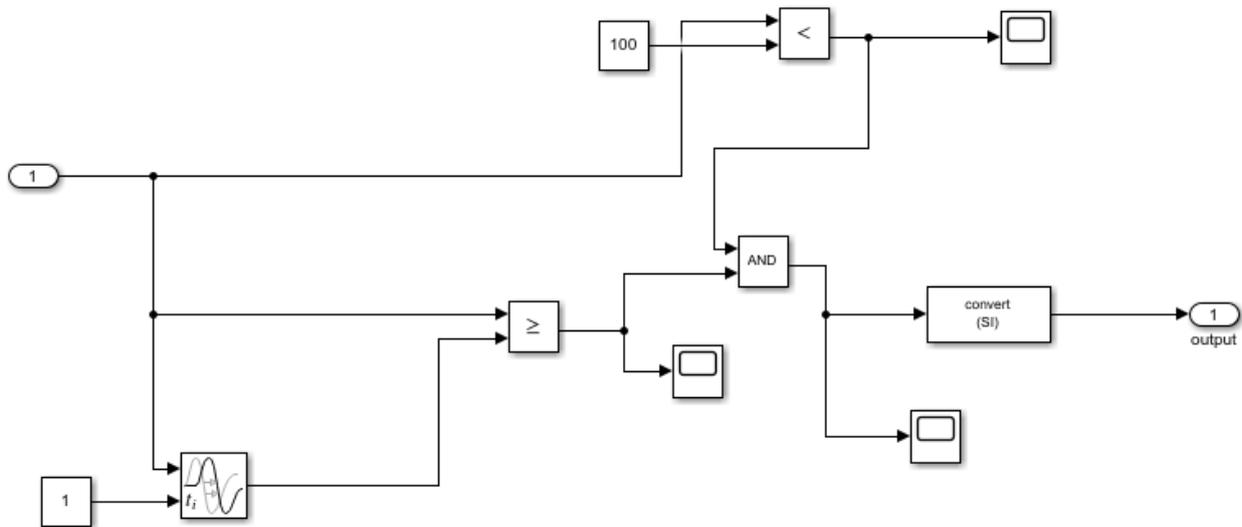


Figure 42. Logic regulating the valve related to the tank filling.

The logic here represented considers the value of the pressure inside the tank at a certain time step and compares it with the same pressure 1 s before (calculated by the “transport delay” block on the bottom left) and the pressure defined by the boundary condition of 100 Pa, which in turn becomes the maximum pressure inside the tank. In particular, if the pressure value is greater or equal to the pressure in the second before and at the same time below the maximum pressure, the system condition is in the phase of tank filling because the pressure is rising. Therefore, the valve that control the inlet of the gas stream inside the tank must be open, and in fact the result of the loop in this case is 1. Important is the “equal” sign in the logic, which assures that when the tank is empty for two consecutive time steps, the valve opens and the gas starts pouring in the tank. On the other hand, when the pressure is lower than the one at the previous time step it means that the system is in a phase of tank emptying (or fuelling phase of the accelerator), thus the result of the loop logic is 0, which in turn closes the valve.

In Sorgentina-RF, once one of the two tanks is filled with deuterium and tritium, it starts to refuel the accelerator and therefore emptying itself. In this preliminary model, the gas flow leaving the tank is controlled by another “gate valve” block, which either opens or closes depending on the pressure measured inside the tank, coupled with a “local restriction” block, which assures the decrease of the pressure in the tank; similarly to the case before, the logic that regulates the state of the valve is contained in the subsystem “Output logic”, which input parameter is again the tank pressure “p1” and the output parameter is a Boolean value of 0 or 1 (completely closing or opening the valve). The subsystem for this valve is shown in Figure 43:

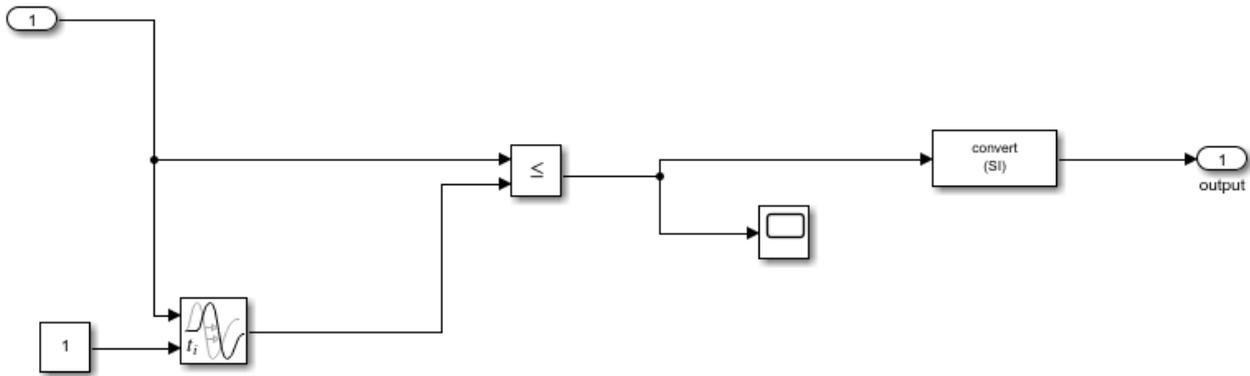


Figure 43. Logic regulating the valve related to the tank discharging.

The logic adopted for the control of the valve is very similar to the previous one. Once more, the value of the pressure inside the tank at a certain time step is compared with the same pressure 1 s before (calculated by the “transport delay” block on the bottom left), but not with the maximum pressure because it is irrelevant in this case. In particular, if the pressure value is lower or equal to the pressure in the second before, the system condition is in the phase of tank emptying because the pressure is decreasing. Therefore, the valve that control the outlet of the gas stream toward the accelerator must be open, and in fact the result of the loop in this case is 1. On the other hand, when the pressure is lower than the one at the previous time step it means that the system is in a phase of tank filling, thus the result of the loop logic is 0, which in turn closes the valve.

The behaviour of the gas pressure inside the tank is shown in Figure 44: the pressure rises until it reaches the maximum pressure of 100 Pa and after that it decreases to the sink pressure of 1 Pa as defined before. This process is repeated for the entire duration of the simulation and it is valid for both the tanks V2 and V3, with the sole difference that the filling and the emptying of one of the two tanks is delayed in time with respect to the other. This measure is essential to guarantee the continuity of the whole Sorgentina-RF plant because it assures that while one tank is filled with the right stoichiometric ratio, the other fuels the accelerator until it is empty; therefore, the two tanks alternate their process of filling and discharging, assuring a continuous flow of gas to the ionization chamber. The x-axis represents the time, in seconds, in which the model is simulated, while the y-axis corresponds to the gas pressure, in Pa, inside the tank.

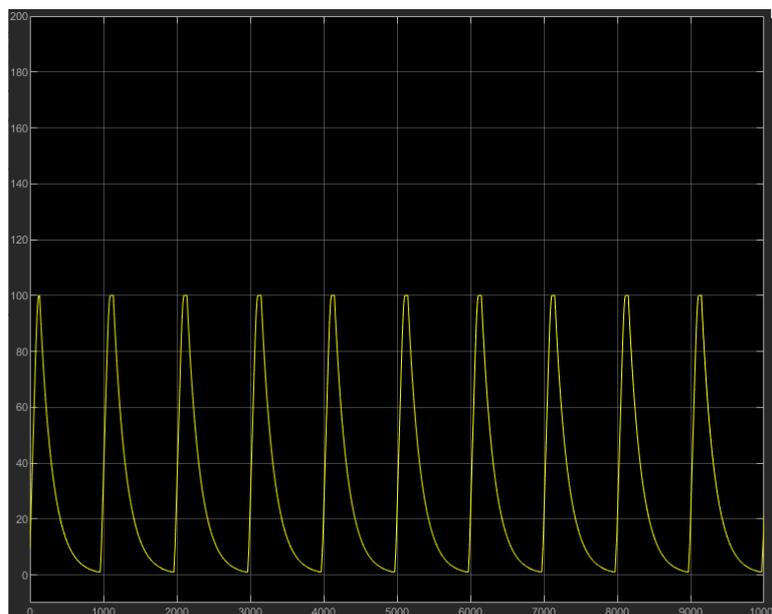


Figure 44. Pressure behaviour of the gas inside the tank.

## Conclusions

The SORGENTINA-RF facility (SRF) is a project developed by ENEA Brasimone and their partners that aims to develop and optimize the  $^{99}\text{Mo}$  production routes that are alternative and complementary to those presently adopted, exploiting an innovative technique based on fusion reactions between deuterium and tritium. Different research groups, each assigned to a specific Task, complement each other's works in order to design the whole plant. This work is related to the Task 5 objective, which is the design of the Tritium Processing System (TPS) and the management of the fuel, a 50-50 mixture of deuterium and tritium (D-T).

The first part of the Master Thesis examines the Sorgentina facility and its management of the tritium. Several systems are introduced and different processes are described, each of them ultimately aiming to protect workers and environment from radioactive release. A Process Flow Diagram (PFD) of the system is presented: it divides the TPS in three subsystems and highlights all the necessary components and instrumentation. The safety systems related to the TPS are introduced, proposing a classification for the Confinement and Containment System and describing auxiliary safety systems, like the ventilation one. The processes carried out in the TPS are analysed and dissected into their fundamental actions by the Functional Analysis (FA), and eventually the Interfaces connected to the Tritium Facility are described.

The second part of the Thesis is dedicated to the design of the main components present inside the Tritium Permeation System; the tritium piping and the gloveboxes containing the systems are analysed in detail: a study on the most suitable materials and their dimensioning is conducted in order to guarantee the respect of international safety guidelines. The results described are an overestimation since some approximations are introduced. A smaller description on the other components' design (tanks, permeators, getter and auxiliary systems) is presented, introducing a preliminary dimensioning and some operating parameters. For most components a possible provider is suggested.

The last part of the Master Thesis is dedicated to the preliminary model developed for the description of the Tritium Processing System by means of the Simscape software. This model is just a preliminary one because it only represents the filling and successive emptying of a tank in the system, coupled with the external sources of deuterium and tritium. The components adopted for the model are described and the logic regulating them is explained. Finally, the results of this simplified model are presented.

Sorgentina-RF is supposed to be built in about three years; in the short term some analyses are needed: it is fundamental to evaluate the conductance of the tubes, which leads to the design of the vacuum lines. The permeated flux through piping and glovebox is supposed stationary but a transient analysis of the phenomena is foreseen for the future works. Moreover, the bremsstrahlung radiation produced by metals is higher than plastics and therefore, for reasons of radiation protection, it is necessary a future analysis of this phenomenon, possibly influencing the material choice.

Not all the tritium is separated in the permeators: the Tritium Removal System aims to extract the tritium from the gas mixture sent to the chimney in order to recycle it, and the main parts of this system must be designed. The design on the other components has to be finalised and a 3D CAD representation of their spatial arrangement inside the gloveboxes must be produced before ordering them from the chosen supplier. The PFD must be updated at every step in order to accommodate possible modifications of the design, before finally upgrading it into the P&ID.

Finally, the future development of the Simscape model is directed toward the implementation of the two tanks in a comprehensive manner, as well as the addition of the components of the TPS placed before the permeators, while maintaining the logic and showing their alternate functioning.

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