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Risk Management of a Fusion Facility: Radiation Protection and Safety Integrated Approach for the Sorgentina-RF Project

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Abstract: The Sorgentina-RF project will use fusion neutrons to produce ^{99}Mo, a precursor of ^{99m}Tc, by irradiating natural molybdenum. ^{99}Mo is produced by means of the inelastic reaction ^{100}Mo(n, 2n)^{99}Mo on ^{100}Mo, which is an isotope of natural Mo. From a functional point of view, the project consists of two parts: an irradiation neutron source at 14 MeV and a radiochemistry facility dedicated to the extraction of ^{99}Mo from the solid sample irradiated by the neutron source. Given the degree of complexity of such a facility, the risk management strategy is based on an integrated approach that combines the engineering method of safety with that of radiation protection. Therefore, design issues were studied and systems were planned according to both radiation protection and safety criteria already in the preliminary phase, allowing a general strengthening of the safety of the plant. This work discusses the preventive analysis and the related activities to identify the ways in which potential exposures to radiation may occur. In particular, the preliminary safety analysis is presented for the innovative rotating target, developed for the project, and, accordingly, some specific technical solutions are given to refine the initial design of the facility.

Keywords: fusion accelerators; safety analysis; radiation protection

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1. Introduction

The Sorgentina-RF project is devoted to the design and realization of a 250 kW power accelerator-driven 14 MeV neutron source, with an expected nominal neutron emission rate in the range of 5–7 $\times$ 10^{13} s^{-1} over the solid angle. This figure was obtained by rescaling the neutron emission rate achieved at the Frascati Neutron Generator [1], which was in the order of 7 $\times$ 10^{10} s^{-1} with a power of about 300 W, as well as from preliminary Monte Carlo simulations.

Sorgentina-RF is based on an ion source providing about 830 mA of a mixed beam of deuterons and tritons (50:50) impinging onto a Ti-coated metallic rotating target where (mainly) deuterium-tritium (D-T, hereafter) fusion reactions occur [2].

The main focus of the facility is the production of ^{99}Mo as a precursor of ^{99m}Tc, a radiotracer used in single-photon emission computed tomography (SPECT) [3].

The project aimed at investigating and developing a methodology for ^{99}Mo production alternative to the irradiation of ^{235}U samples at research fission reactors, as recommended by different international organizations [4,5].

The design and realization of such an irradiation plant need a comprehensive and thorough approach to address important issues related to safety and radiation protection.

The Sorgentina-RF project is composed of several subsystems: the irradiation facility within the bioshield (ion source and rotating target), the tritium system (for tritium supply and recovery), the radiochemistry facility, the waste repositories, the cooling system, and the ancillary units (control room, power supply system, etc.). Most of these systems are not standard but are specifically designed within the research project.

The risk management team decided to exploit design analysis methodologies typically used in the licensing of nuclear facilities, even though they are not strictly required for this kind of system, which is not classified as a nuclear plant. Consequently, an integrated approach was developed by combining the engineering method of nuclear safety with that of radiation protection, i.e., a radiation protection and safety integrated approach, implemented by a multi-disciplinary team of experts.

The primary goal of the safety analysis is demonstrating the plant compliance with the regulatory dose limits in terms of worker and population exposure to ionizing radiation, hence giving support in the design phase to minimize exposure and radioactive materials' release.

The probabilistic safety assessment is the main instrument to provide important safety insights, identifying accident sequences that can follow from potential initiating events [6,7]. In this context, to identify potential failures or hazards and their impact on the safety of the plant and then address preventive measures, the FMEA (failure mode and effects analysis) method was exploited, which is extensively used in a vast variety of applications, from nuclear power plants to the use of radiation in medical procedures [8,9].

In the design phase, while systematically identifying system functions to point out a credible combination of failures possibly resulting in people's exposure risks, conservative assumptions are made at all steps regarding accident sequence and consequences to show the response of the plant and its safety systems to postulated events.

In the integrated approach developed for the Sorgentina-RF project, the role of radiation protection is to provide confidence on the initial assumptions, which the safety analysis is based on, and to assess the severity of the radiological consequences of the accident initiators on workers and population, so that the postulated initiating events can possibly be classified as relevant by selecting the most representative ones in terms of radiological impact.

The present article shows the preliminary methods and steps developed for the integrated approach applied to a non-nuclear facility such as Sorgentina-RF. Given the state of progress of the project, the aim was to highlight elementary failure events to be grouped into representative events able to jeopardize the system safety, in a graded process that always uses an integrated point of view.

The methodology presented here is more and more important for complex systems made up of interconnected subsystems, aiming for a better implementation of the ALARA principles, and to align the facility design with the fundamental safety objectives as established by IAEA [10].

2. Materials and Methods

2.1. Radiation Protection Analysis

In the development of a nuclear fusion facility, radiation protection has a key role as part of the safety culture, which, according to IAEA, is "that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance" [11].

With this aim, a preventive analysis of the Sorgentina-RF facility and the related activities was carried out in order to identify ways in which potential exposure to ionizing radiation could occur.

In particular, Sorgentina-RF will operate with deuterium and tritium ions. Deuterons and tritons will be implanted in a few-microns-thick titanium layer where D-D and D-T nuclear fusion reactions will produce secondary radiation fields according to the following reactions:

$$D + T \rightarrow \alpha\ (3.5\ \text{MeV}) + n\ (14.1\ \text{MeV}), \quad (1)$$

$$D + D \rightarrow \begin{cases} T(1.01\ \text{MeV}) + p\ (3.03\ \text{MeV}) \\ {}^{3}_{2}\text{He}(0.82\ \text{MeV}) + n\ (2.45\ \text{MeV}) \\ \alpha + \gamma\ (Q = 23.85\ \text{MeV}) \end{cases} \quad (2)$$

$$T + T \rightarrow \alpha + 2n\ (Q = 11.33\ \text{MeV}) \quad (3)$$

While stray radiation will be shielded, tritium has high solubility and diffusivity. Therefore, the radiation protection activities will be focused mainly on tritium hazards during operation and in case of accident, along with neutron-activation products hazards (occupational radiation doses, radioactive-waste problems, and possible release during accidents).

Tritium may be present in different chemical forms due to intermolecular exchange with other hydrogen isotopes (i.e., H and D) and oxidation reactions [12]: gaseous form (mainly HT and minor amounts of DT, T_2), oxide form (mainly HTO and minor amounts of DTO and T_2O vapor or liquid), bound to exchangeable or non-exchangeable sites (i.e., bonding with carbon) in an organic molecule-forming organically bound tritium (OBT). This chemical form includes OBT in a gaseous form (e.g., tritiated methane, CH_3T).

By far the most common of these forms is HTO, which is formed from elemental tritium (HT) whenever it is exposed to oxygen or water vapor. Tritium, either as HT gas or as HTO liquid or vapor, is highly mobile even under normal operating conditions and, in the case of an accident, it would be one of the more likely radionuclides to escape. Tritium produced inside the facility is poured off in the environment (air, water, or soil) by the ventilation system and then spreads rapidly. Past research indicated that 10 GBq of tritium emitted to the environment from a 10 m high ventilation stack in forms of molecular tritium (T_2 or HT) and tritiated water (HTO) produces a negligible dose contribution to the population, i.e., below 1 mSv/y [13].

Moreover, tritium tends to diffuse relatively rapidly through most materials migrating through the crystal lattice; its diffusion can be measured at relatively low temperature. Therefore, future studies are needed to assess the adsorption of tritium onto the structural materials constituting the Sorgentina-RF facility and the extent to which tritium contamination may contribute to occupational exposure.

The other sources of ionizing radiation present in the facility are mainly direct radiation and prompt and delayed gamma radiation due to material activation, in detail:

- The primary neutronic field resulting from fusion reactions;
- The gamma radiation generated from neutrons' interaction with the machine components and the shielding;
- The gamma radiation emitted by activated products in the machine components and in the shielding;
- Activated dust generated in the machine components;
- Activated corrosion products (ACPs) generated in the cooling loops after the activation of the pipes' inner surface and of the corrosion products in the cooling fluid that reach high neutron flux regions of the circuit;
- Activated cooling water;
- Activated air (mainly ^{41}Ar);
- Wastes containing gamma emitters.

As mentioned, primary neutrons represent the other major radiation protection issue because, in addition to the neutronic field itself, they are likely to produce the activation of the materials surrounding the facility, including air.

Neutron-activation products are generated when fusion neutrons (at 14.1 MeV from D-T reactions and at 2.45 MeV from about 50% of the D-D reactions) strike the main constituents of the plant, including the coolant, material impurities, building atmosphere, dust, and objects present in the facility. The array of activation products is very large, taking into consideration the diversity of materials present in the plant as well as the multistep reactions in which activation products (or their decay) are themselves hit by further neutrons. For this reason, as further discussed below, in order to minimize activation hazards, the choice of structural materials and other components is essential in the design phase.

As a matter of fact, neutrons produced via D-D and D-T reactions are likely to activate the so-called ACPs formed in the water-cooling systems. Corrosion products are formed by the water physical action and by the chemical reaction between metal and water coolant. The build-up of ACPs in specific components of the cooling system (e.g., filters) may represent a relevant radiological issue for workers and operators inspecting or maintaining the cooling equipment. Among the APCs, the γ-emitting radionuclides (^{58}Co, ^{60}Co, ^{65}Zn, ^{56}Mn, and ^{59}Fe) are the most relevant in creating the radiation field around the cooling components, thereby posing specific radiation protection issues for the workers [14]. On the other hand, the longer-lived species (^{55}Fe, ^{63}Ni, and ^{60}Co) may represent a concern for the radioactive waste handling and disposal.

Ultimately, primary neutrons can activate the air inside the bunker hosting the ion source. The primary activation product of interest in terms of airborne release and occupational exposure is ^{41}Ar, a short-lived (half-life 1.83 h) beta/gamma emitting radionuclide, produced via the $^{40}\mathrm{Ar}(\mathrm{n},\gamma)^{41}\mathrm{Ar}$ reaction, involving also the Ar ions present in the vacuum chamber for the titanium facility of Sorgentina-RF. Other radionuclides can be generated by air activation but their contribution is generally small due to the low cross section of the process, low abundance of target nuclide, high threshold energy, and short half-life of the radionuclide produced or exceedingly long half-life, so that the activity during the irradiation session is negligible. Even though it is a short-lived radionuclide, ^{41}Ar is readily released from the ventilation system and most of it has not decayed by the time it moves offsite with normal wind speeds.

All these source terms can constitute a risk of both external exposure and internal contamination for workers and the population. The design of the installation requires specific features and equipment to limit radiation risks and prevent the contamination of the staff, working environment, and equipment and dispersion of radioactive substances outside the facility, thus also ensuring the protection of the population.

Therefore, in the design phase of Sorgentina-RF an accurate qualitative and quantitative characterization of these source terms was conducted and various technical and organizational requirements were addressed, relating to each source term, including [15]:

- Optimal spatial arrangement and organization of the premises;
- Appropriate ventilation system;
- Installation of special equipment;
- Adequate solutions for the management and storage of solid and liquid waste and airborne and liquid effluent;
- Working procedures aimed to the safe management of activities involving the risks of exposure to ionizing radiation;
- Monitoring programs and systems.

2.2. Safety Analysis

The safety assessment developed for Sorgentina-RF exploits the complementary techniques of probabilistic safety analysis (PSA) and deterministic safety analysis (DSA) [16].

The first step is the probabilistic safety analysis (PSA), which identifies the most representative accident initiators, known as postulated initiating events (PIEs), and classifies them according to the likelihood and severity of consequences.

A PIE is a representative failure event of some system or component capable of initiating an accident sequence possibly resulting in the reduction/loss in plant capability to manage hazards to people or the environment (e.g., release of radioactive material), depending on the successful operation of the various mitigating systems of the plant. Examples of an initiating event related to nuclear facilities are a loss of coolant accident (LOCA), loss of vacuum accident (LOVA), loss of offsite power (LOSP), and fire.

Then, the DSA addresses the facility behavior under the specific predetermined operational states and accident conditions, screening the PIEs identified in the previous step and investigating the effectiveness of the safety provisions in the event of the accidents they are intended to control or mitigate.

A failure mode and effect analysis (FMEA) [17] methodology is exploited to define possible accident initiators, starting from a thorough functional analysis of the system. The FMEA tables include:

- Component identification;
- Process functions for each component;
- Safety functions for each component;
- Component failure modes;
- Possible causes associated to a specific failure mode;
- Possible consequences in terms of machine damage, radioactive inventory mobilization through the different containment barriers, and dose to workers and population;
- Means of detection;
- Automatic actions on detection;
- Automatic means to prevent the causes or mitigate the consequences of failure;
- Identification of the representative PIEs for a single elementary failure.

The DSA is performed on a reduced set of PIEs identified as the most representative of the similar ones, in order to investigate the consequences and verify compliance with the regulation limits in terms of worker and population exposure to ionizing radiation. To this aim, source terms and plant hazards were characterized by a multi-disciplinary team of experts applying the integrated approach to trace the amount and isotopic composition of the material postulated to be released from Sorgentina-RF.

In the preliminary analysis described in this paper, only tritium as a radioactive source term was considered as, during normal operations, it is released in the vacuum chamber hosting the rotating target and it is recovered by the tritium system through penetrations in the bioshield. Confinement and containment performances of the vacuum system, the ion source, the tritium system, and the bioshield will be addressed.

A future activity of occupational safety will involve the estimation of the collective dose for workers employed in Sorgentina-RF operation.

2.3. The Integrated Approach

The safety analysis of the Sorgentina-RF fusion facility applies the approach of complex systems, typically used for evaluating the risks at nuclear power plants, starting from the study of process functions. This methodology is aimed at identifying potential critical issues of the plant and to introduce new components that derive from safety needs but may not be considered in the design phase.

If an integrated approach is followed in the preliminary phase, it is possible to anticipate accident initiating events and finalize the design not only in terms of system objectives but also for safety and radiation protection purposes.

Under this approach, radiation protection tools can improve the accuracy of the initial risk assumptions, so that the safety analysis can proceed also on the basis of the information gathered by radiation protection. On the other hand, radiation protection experts can make assessments based on the outcomes of the safety analysis: in this way it is possible to reduce the potential exposures of workers and the population already in the design phase, avoiding modifications to the civil works already completed and/or introducing additional shielding. This is a highly effective approach also in reducing costs, according to the ALARA principle of optimization.

Moreover, the integrated approach can be exploited in the occupational radiation exposure (ORE) evaluations, based on a quantitative assessment of the ORE for workers involved in preventive scheduled maintenance operations, resulting in preventive maintenance operations that can be optimized by adopting the ALARA principle. In order to have rigorous ORE estimations, operations entailing human intervention, work efforts (i.e., the product of the number of persons involved in a task and the exposure time necessary to perform the task), maintenance frequency for each component, and dose rate maps around each component have to be identified. To this aim, an iterative process of design and analysis is necessary, demonstrating that the ALARA requirements are satisfied, which utilizes the results of the safety analysis and the tools of radiation protection to characterize the different radiation source terms and map the environmental dose rates.

Finally, safety analysis can support radiation protection activities, relating the management of radwaste as, for example, when there is the need of designing delay or treatment tanks for radioactive liquid effluents, even if this probably is not the case for the Sorgentina-RF project.

3. Results

3.1. Radiation Protection Activities

The risk management of the Sorgentina-RF project has involved the radiation protection activities from the planning stage, identifying the vulnerability of the workflow, and addressing technical and organizational requirements for each source term according to the principles of optimization and the application of dose limits, with particular attention on tritium hazards.

3.1.1. Site Arrangement and Organization of Premises

The choice of the building that will host the facility in the ENEA research center of Brasimone was made also according to radiation protection criteria. The building has adequate size to contain a biological shield, a radiochemistry facility, and the necessary ancillary structures and is far away from other buildings. Moreover, it is already equipped with a small, shielded bunker suitable for the storage of solid radioactive waste (such as exhausted targets). The radiochemistry facility is next to this bunker so as to obtain the shortest possible transport route for the irradiated materials that have to be processed for the production of medical radioisotopes.

A stack will be built with a height ensuring sufficient dilution of the airborne effluents into the atmosphere before reaching the ground.

3.1.2. Ventilation System

An adequate number of air changes per hour and pressure gradients will be determined for the bunker that will host the ion source, for the room with the tritium system, and for the hot cells of the radiochemistry facility, depending on the usage, dust contamination, estimated air activation, and tritium concentration in air. The technical characteristics of the ventilation system are designed according to international guidelines [15].

The ventilation systems of the bunker, the radiochemistry facility, the room for the tritium system, and relative piping as well as the vacuum system are connected directly to the stack of the facility. The tritium system is placed within a glovebox, with an independent closed-loop ventilation system.

3.1.3. Special Equipment

A biological shield will be placed around the ion source to reduce the ambient dose equivalent rate on the external surface of the shield to the design constraint of 10 μSv/h.

Preliminary design studies were performed using the MCNP (Monte Carlo N-Particles) code for radiation transport [18], coupled with the Joint Evaluated Fission and Fusion (JEFF [19]) and Fusion Evaluated Nuclear Data Library (FENDL-3.1d [20]) nuclear data.

The simulations aimed at identifying a proper layout for the bioshield structure were carried out using an isotropic monoenergetic 14 MeV neutron source with an intensity of 7×10^{13} s^{-1}. This definition does not take into account the angular and energetic distribution that the real source will have. For the sake of simplicity, a simple 10 cm diameter disk-like source emitting 14 MeV neutrons over the solid angle was considered, thus resulting in a conservative approach.

The analysis considered the contribution to the ambient dose due to both the neutrons emitted from the target and the secondary photons generated by means of (n,γ) reactions in the shielding material itself. A 3 m thick shield was designed, with a layered structure made of 2 m of ordinary concrete followed by 1 m of barite concrete devoted, respectively, to neutron and gamma moderation [21]. The access to the vault was guaranteed by means of a dog-leg corridor closed by a sliding door: the layout for the access path was designed in order to protect the entrance from the direct and scattered neutrons emitted by the source. A system for tritium confinement will be added to the shielding.

The irradiated materials will be processed for the production of medical radioisotopes within hot cells able to physically isolate the critical area, equipped with automated transfer systems based on high containment technologies. The shielding thickness of the hot cells and the transfer systems (from the bunker of the ion source to the radiochemistry facility) will be calculated or chosen based on the type, energy, and activity of the radioactive material being handled and on the activities carried out.

Whenever possible, all structural materials of the components of the machine will be reduced-activation materials for fusion, such as reduced-activation steels and non-ferrous low-activation alloys, in order to reduce the exposure of personnel and the production of radioactive waste.

3.1.4. Radioactive Waste

Machines that use nuclear fusion reactions do not present critical points regarding the production of radioactive waste or residues [22]. Solids are activated because of high-energy neutrons; so, as already said, the component materials for the plant will be selected in order to limit the activation and the decay time. Predicting the transport of ACPs in the cooling circuit may also provide benefits in terms of waste management, as they can agglomerate in clusters even in the farthest regions of the circuit.

However, some radioactive waste is expected to be produced, in different physical forms.

Regarding solid waste, a dedicated, shielded bunker is available for exhausted targets and solid waste produced in the radiochemistry facility, with an automated material transport system. A volume-reduction strategy for radioactive waste, based on appropriate material characterization, will be considered for identifying both those materials that can be safely released to a conventional landfill and materials that have to be disposed and managed as proper radioactive waste.

Liquid effluent potentially produced will be managed according to national regulations and international guidelines [23,24].

Additionally, the radiological impact on the workers and the population of the discharge of airborne effluent during operation will be assessed, which, in general, is not relevant [25,26]. Static and dynamic containments will be provided to the heat exchanger of the cooling system and to the pipes connecting the bunker of the ion source to the tritium system, all connected to the stack of the facility, which will be equipped with a tritium trapping system.

An operational decommissioning plan of the facility will be prepared according to the national legislation and international guidelines. The biological shielding will be constructed employing prefabricated modules in order to allow easier dismantling, confinement, and treatment of activated parts.

3.1.5. Working Procedures

In the planning of the operations, a prior assessment of individual doses and risks of workers was done. According to this assessment, dose constraints are defined for radiation classified and non-classified workers and members of the public as an operational tool for optimization. Wherever work activities may potentially imply significant doses to the workers, such as maintenance operations, detailed and optimized work plans will be provided.

Doses received by workers due to ACPs and activated products in the machine components, in the cooling water, and in the shielding will be evaluated considering the components subject to operator intervention for normal activity, inspection, and maintenance and assessing the dose rates around these components. These assessments will be made by a multi-disciplinary team of experts according to a radiation protection and safety integrated approach, so as to define an adequate choice of materials and specific working procedures.

According to the optimization of radiation protection, in the radiochemistry facility, most of the planned activities are performed by automated equipment, including the transport of the irradiated materials form the bunker of the ion source to the hot cells.

3.1.6. Monitoring Programs and Systems

A monitoring program will be established for each pathway of exposure, specifying the media to be sampled, the location and frequency of the sampling and measurements, radionuclides to be quantified, and the monitoring systems to be used [27].

The monitoring systems implementing the monitoring program for a fusion facility [28] are composed of portable instruments, passive dosimeters, and active measuring stations to detect and record the appropriate dosimetric quantities both for neutrons and photons in order to measure radiation dose rates within and outside the plant as well as to monitor potential radioactive releases in the workplace and in the environment. In particular, tritium diffusion or leakage will be evaluated and monitored through sampling techniques.

The exposure of individual workers will be assessed by means of personal passive dosimeters for photons and neutrons and personal active dosimeters for real-time monitoring.

3.1.7. Licensing

The request of licensing to the regulatory body has to be accompanied by a detailed technical report related to the radiological protection of workers and the population, ensuring that the risks have been adequately assessed and that appropriate control measures are in place.

The license application file must include, at least, a description of the installation and the activities carried out; the suitability of the chosen site, buildings, and structures; radiation protection structures and organization, such as the classification of areas and personnel; shielding calculation; dose rate assessment; accident analysis and relevant consequences; radioactive waste assessment and management; dose constraints for the process of optimization; assessment of the radiological impact of the release of radioactive effluent into the environment during operation.

This licensing documentation provides the basis for the safety of the facility throughout its lifetime and needs to be updated periodically to account for, among other things, modifications made to the facility and operating experience feedback.

The main technical issues are related to the level of protection guaranteed to workers and to the public during normal and accident situations.

To this aim, an individual surveillance program of workers is defined for routine, task-related, and special monitoring and an appropriate set of emergency procedures is outlined that define actions to be taken and roles and responsibilities during emergency.

The critical aspect about population safety is related to the release of radioactive waste into the environment. A thorough analysis of scenarios involving potential exposures has to be conducted applying a radiation protection and safety integrated approach, also estimating the vulnerability of the activities carried out in the facility for extreme weather events [29]. Potential releases will be monitored in order to take any precautions and provide, where necessary, an early-warning; the radioactive contamination of the air will be checked immediately before its expulsion into the atmosphere, after filtration. ACPs and tritium in the cooling circuits can be an important source term and are considered in accidental scenarios such as LOCAs.

As already mentioned, an environmental monitoring program will be defined considering each potential pathway of exposure for ensuring that there are no negative effects from plant operations. As an integral part of programs for source monitoring, environmental monitoring, and individual monitoring, a quality assurance program will be provided.

3.2. Integrated Analysis of the Target System

For the sake of clarity, the preliminary layout of the Sorgentina-RF plant is reported in Figure 1, showing the irradiation facility within the bioshield (ion source and rotating target), the tritium room (hosting the system for tritium supply and recovery), the radiochemistry facility, the stack, the connecting pipes, and the solid waste repository.

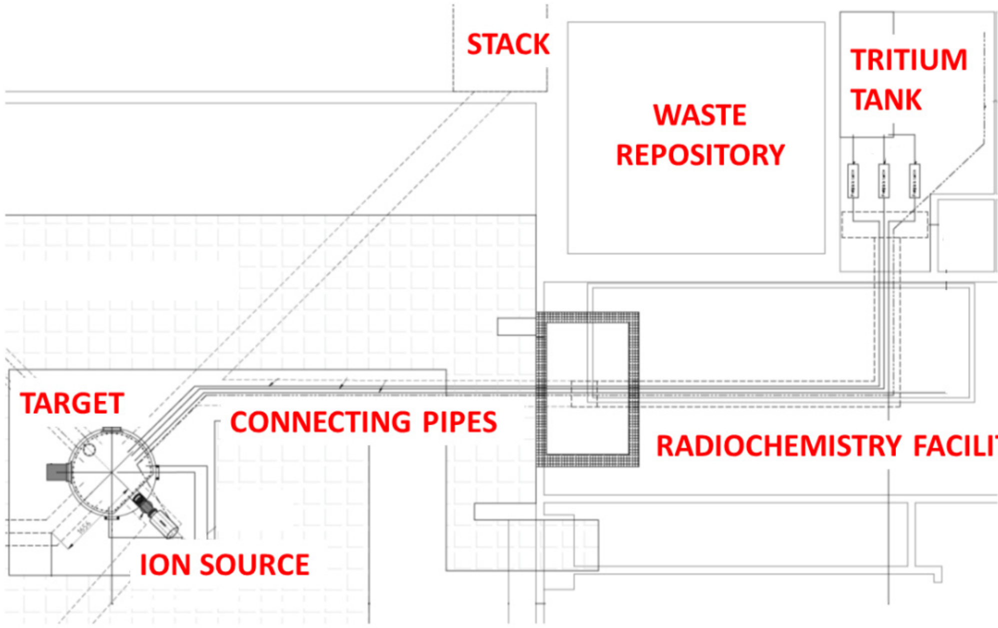


Figure 1. Preliminary layout of the Sorgentina-RF plant: the irradiation facility (with the ion source and the rotating target) and the tritium room (which hosts the tritium tank) are highlighted, with the pipes connecting the two.

FMEA Application

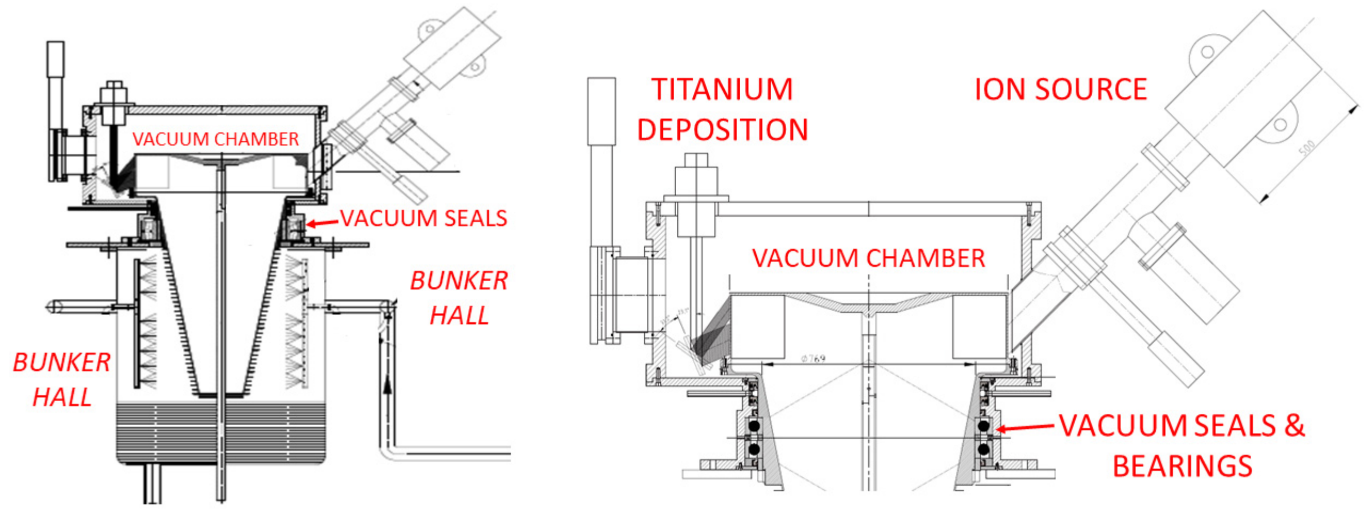
The approach presented in the previous sections was applied for a preliminary safety analysis of the most innovative part of the Sorgentina-RF project, i.e., the rotating target on which the deuterium/tritium ions impinge.

A functional breakdown structure (FBS) and a plant breakdown structure (PBS) were conducted, and a group of process functions and safety functions were associated to each component of the target in the FMEA, then identifying failure modes, failure causes, consequences of the failures, detection modes, and automatic actions upon detection.

By means of the FMEA (Table 1), among the most relevant PIEs from a radiological point of view, the LOVA PIE related to the failure of the ferrofluidic seals in the vacuum chamber (VC) was identified as one of the reference PIEs. Such seals are composed by the active seal and the ball bearings for the centering (Figure 2). Due to the rotation, the bearings are subject to high tangential forces, which can compromise their performance. Clearly, the process function of the bearings is "to allow target rotation", but a rupture of the bearings would also impair the functioning of the seals to provide vacuum leak tightness during the rotation of the target to prevent the diffusion of air into the VC.

Table 1. FMEA of the seals for the vacuum inside the VC.

PBS Element (Component)	Process Function	Safety Function	Failure Mode	Failure Cause	Consequence	Detection	Automatic Actions upon Detection
VC Seals	Provide vacuum leak tightness	Confine within the target	Leak	Ball bearings rupture; thermo-mechanical stress in structures; possible component damage; vibrations, fatigue; impact with heavy load	Ingress of air in VC; loss of vacuum; release of tritiated gas into the surroundings of the VC after pressure equalization	Pressure monitor; temperature monitor; tritium monitor in the bunker	Closing of the stack and expulsion of air through the tritium trap; beam stop



(**a**) (**b**)

Figure 2. Preliminary design of the rotating target for the Sorgentina-RF project (**a**), and blowout of the ferrofluidic seals (**b**).

4. Discussion

4.1. Description of the Most Representative Incidental Sequence

During operation, the ferrofluidic seals provide for the vacuum of about 10^{-1}–10^{-3} Pa inside the VC within which rotates the target (Figure 2). The rupture of the bearings or a leak from the active seals (due to other failure reasons, see Table 1) can cause the diffusion of air in the VC, which is consequently pressurized.

When the oxygen in the external air comes in contact with the D_2/T_2 flux, there is a high risk of explosion if the concentration of hydrogen is more than 4% and there is a hot spot [30]. This event can cause a further breach in the containment and, therefore, an even greater inlet of air from the outside.

From the VC, the air at atmospheric pressure can move up the ion source (irradiating the target) to the plasma chamber (Figure 2) and then through the pipes connecting the ion source to the tritium system (for tritium supply and recovery) (Figure 1). The loss of vacuum in the ion source causes the immediate quench of the beam and the operation block.

However, if neither an operator nor an automatic system stops the D_2/T_2 flux coming from the supply tank during operation, the tritium inventory contained in the tank at 10^4 Pa (in the room for the tritium system, see Figure 1) would continue to come out at the usual rate of about 60 μg/s [24].

Then, if the external air at atmospheric pressure reaches the tank and pressurizes it, the tritium inventory would be expelled through the pipes and the leaking component up to the bunker and then outside the building through the stack (Figure 1).

4.2. Design Actions and Safety Provisions

The DSA has to estimate the worst consequences that a possible leak of the ferrofluidic seals and the resulting loss of vacuum in the VC can cause, both from the dynamic loads due to air–Q_2 reactions and from a radiological point of view. Accordingly, a series of automatic systems of detection and consequent action shall be defined and required.

Possible solutions could be the presence of automatic systems of detection, preferably redundant, which isolate the D_2/T_2 lines when a predefined threshold is exceeded, and the choice of some design and organizational actions, such as:

- Pressure sensors in the VC and in the ion source;
- Temperature sensors on the bearings;
- A system to control the vibrations (i.e., rigid displacements) of the bearings;
- A system of torque control (i.e., mechanical control) on the motor for the rotation because, if the motor current increases, it means that the bearings are failing;
- A current sensor in the ion source that detects if the beam stops;
- Tritium sensors in the bunker so that, when the concentration exceeds the threshold, the air expulsion system is automatically diverted to an oxidation bed, which captures the tritium: this way there is more permeation than expulsion of tritium to the environment, with a highly reduced dose to the workers and the public;
- A second containment barrier around the seals of the VC, with less high vacuum;
- A program of periodic preventive maintenance on the seals of the VC and the bearings.

Another project solution could be the presence of a check valve between the tritium tank and the ion source inside the connecting pipes: this kind of device would allow the exit of tritium from the supply tank along the pressure gradient during operation but not the reverse air flow from the pipes to the tank. Moreover, as the tritium tank is at a pressure of 10^4 Pa, in the case of an accident, the air coming from the outside would stop at the check valve and, being at atmospheric pressure, it would act as blockage, automatically stopping the tritium flow from the supply tank to the ion source. Thus, the check valve could provide an automatic stop to the discharge of tritium in the presented scenario of maximum credible accident, preventing an accidental release to the surrounding environment without operator intervention even in the case of a failure of all the automatic systems of detection.

5. Conclusions

The probabilistic and deterministic safety analyses are powerful tools in the safety assessment of nuclear plants. In the present work, this kind of safety assessment was applied to the fusion facility Sorgentina-RF for ^{99}Mo production, developing an integrated approach that combines the safety and radiation protection methodologies to improve the safety of workers and the population.

In the first step, the probability safety analysis was used to identify the initiating events of an accident; in the second step, the deterministic safety analysis will involve the evaluation of the criticalities of the identified failure modes, with the aid of the radiation protection methods.

As the Sorgentina-RF project is still in the planning stage, this integrated approach is used to support the engineering works, identifying the risks of failure of the single subsystems of the facility and proposing possible actions already in the preliminary design, thus avoiding expensive revisions in the subsequent phases of the project.

The integrated analysis of the rotating target is reported, as this is the most innovative component of the facility, developed ad hoc for the Sorgentina-RF project, and thus requires an in-depth study. The outcomes of this work have a significant impact on the optimization of the initial facility design by elaborating specific technical and organizational solutions.

The safety analysis of the whole facility is ongoing and will be the subject of future articles.

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