Radiation safety at the PRIMA facility: a review of shielding solutions and personnel dose assessment

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Abstract

The Neutral Beam Test Facility (NBTF), also called PRIMA (acronym for Padova Research on ITER Megavolt Accelerator) consists of two separate development test beds currently under construction in Padua (Italy): the ion source test facility, named SPIDER (Source for Production of Ion of Deuterium Extracted from Rf plasma) and the megavolt test facility, called MITICA (acronym for Megavolt ITER Injector & Concept Advancement). Both injectors accelerate negative deuterium and hydrogen ions with a maximum energy of 1 MeV for MITICA and 100 keV for SPIDER, and a maximum beam current of 40 A for both the experiments. Accelerated ions are stopped on a.CuCrZr alloy calorimeter where an intense neutron field is generated following to D-D and D-T reactions.

In the present paper, a systematic review of the radiation safety analysis for both injectors is presented. The shielding design is described, including special shielding solutions planned with the aim of allowing personnel access for inspection and maintenance of the injector. In addition, the major results regarding the activation level of the corrosion products (ACPs) generated inside the cooling loops are reported, as a function of the neutron yield, time campaign and pulse duration. Furthermore, personnel classification, tritium inventory and dispersion are also presented and discussed in the paper.

Our analysis indicates that the radiation safety system for the PRIMA facility is appropriate in maintaining the individual doses for workers and population well below the Italian (and internationally stated) regulatory limits.

Tritium diffusion from the facility is not an issue from the radiation protection point of view. Even considering the most conservative scenario, the dose rate per year to the reference group (population) is about three orders of magnitude lower than the dose limit.

Furthermore, our results indicate that for SPIDER, even considering the maximum workload, the contribution of ACPs to external exposure is negligible. On the other hand, due to the higher neutron yield, ACPs produced on MITICA cooling loops may significantly contribute to external exposure of workers.

Radiation shielding and radiation protection criteria were assessed in order to meet the Italian regulatory limit for non radiation workers (1 mSv/yr). Our analysis and project evaluations confirm that this limit is never exceeded during operating phases of the injectors.

Key Words: ITER, accelerator, neutral beam, radiation safety

INTRODUCTION

ITER (International Thermonuclear Experimental Reactor) starts as a joint international research and development project with the aim of demonstrating the scientific and technical feasibility of fusion power. ITER is currently under construction in France. It is a tokamak, in which strong magnetic fields confine a torus-shaped fusion plasma. The device´s main scope is to demonstrate prolonged fusion power production in a deuterium-tritium plasma.
In order to initiate a sustained fusion reaction, ITER employs many methods to heat the plasma, including RF heating, electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH), Neutral Beam Injectors (NBI). In particular, the NBI system delivers a high-energy beam of neutral atoms (typically a hydrogen isotope such as deuterium) into the core of the tokamak plasma. These energetic atoms transfer their energy to the plasma, raising the overall temperature.
The experimental neutral beam test facility named PRIMA (Padova Research Injector Megavolt Accelerated) currently under construction at the Consorzio RFX (Padua, Italy), will be the testing station for the ITER NBI systems. PRIMA consists of two injectors which will test the source section, i.e. the main component of the final system, and the whole arrangement of the ITER neutral beam injector station. The PRIMA test stands are named respectively SPIDER (Source for Production of Ion of Deuterium Extracted from RF Plasma - ion source only) and MITICA (Megavolt ITER Injector Concept Advanced - the whole system). Both injectors accelerate negative deuterium ions with a maximum energy of 1 MeV for MITICA and 100 keV for SPIDER, and a maximum beam current of 40 A for both the experiments. In MITICA accelerated ions are stopped on a CuCrZr alloy calorimeter and in SPIDER on a beam-dump (either copper or graphite made). Radiation protection design both for MITICA and SPIDER has been completed and the facilities are now ready for the licensing phase. According to the Italian regulation both injectors are classified as particle accelerators.

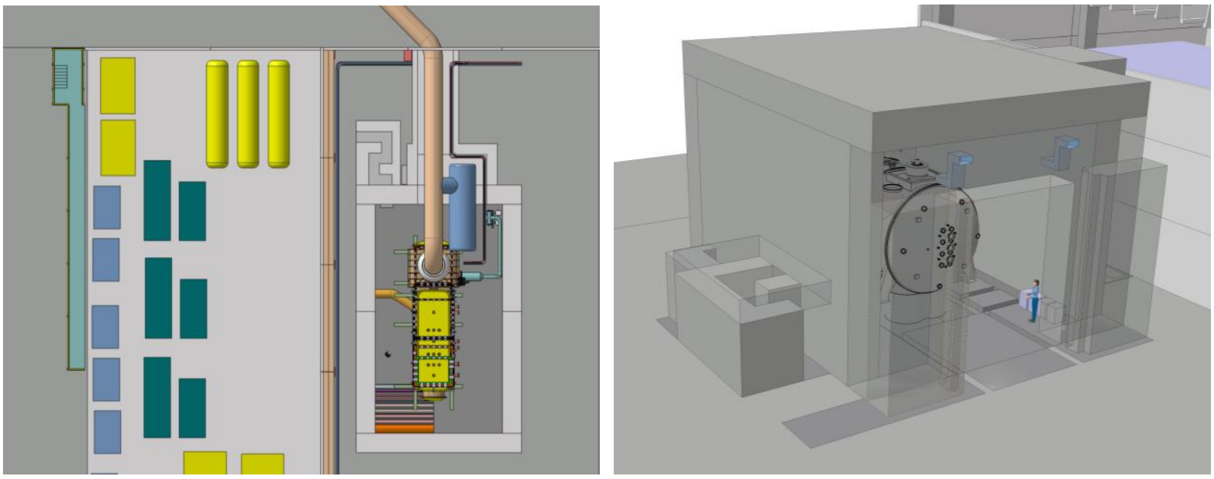


Figure 1. Left) MITICA facility. The shielding walls are clearly visible along with the entrance maze. Right) SPIDER facility, where entrance maze is also shown.

The Italian Regulatory Authority Board (IRAB) is responsible for licensing and regulating the operation of particle accelerators in Italy. All particle accelerators applications must undergo a safety and environmental review by the IRAB; thus, before the injectors can operate, approval must be obtained from such Board following a detailed licensing process. The radiological safety report for both injectors has been prepared under the responsibility of one of the authors of this work, namely a Qualified Radiation Protection Expert according to the Italian law.
The present manuscript contains the main design information and criteria for the radiological safety of both accelerators. A review of shielding solutions and personnel dose assessment is presented.

SOURCE SPECIFICATION

Both injectors will produce intense neutron fields following D-D and D-T reactions which are likely to occur on the CuCrZr calorimeter panels for MITICA and on the beam-dump for SPIDER.

PRIMA injectors are supposed to work in two different operating conditions: interim campaign and final test. In order to perform a conservative neutron flux assessment, extreme operational scenarios were defined for both phases:

- 20 s pulses of 40 A each, for a total duration time of 100 days with 100 pulses per day for the interim campaign (average daily current 0.93 A)
- 3600 s pulses of 40 A each, for a total duration time of 14 days with 6 pulses per day for the final test (average daily current 10 A).

Average daily currents $\bar{I}_{day}$ were calculated as follows:

$$\bar{I}_{\mathrm{day}} = \text{current per pulse(A)} \times \frac{\frac{\text{pulses}}{\text{day}} \times \text{pulse duration (s)}}{86400 \frac{\text{s}}{\text{day}}}$$

Conservatively, three interim campaigns and one final test per year were considered with an average yearly current of:

$$\bar{\mathrm{I}}_{\mathrm{year}} = \frac{3 \cdot 100 \cdot \mathrm{days} \cdot 0.93\,\mathrm{A} + 14 \cdot \mathrm{days} \cdot 10\mathrm{A}}{365 \cdot \mathrm{days}} = 1.144\,\mathrm{A}$$

The related neutron yield for D-D and D-T reaction on copper are reported in table 1.

Neutron Yield	
MITICA	SPIDER
$\text{D-D}_{1\mathrm{MeV}} \rightarrow 3.78 \cdot 10^{12} \frac{\mathrm{n}}{\mathrm{sec} \times \mathrm{A}}$	$\text{D-D}_{100\mathrm{keV}} \rightarrow 3 \cdot 10^{10} \frac{\mathrm{n}}{\mathrm{sec} \times \mathrm{A}}$
$\text{D-T}_{1\mathrm{MeV}} \rightarrow 5.20 \cdot 10^{7} \frac{\mathrm{n}}{\mathrm{sec} \times \mathrm{A}}$	$\text{D-T}_{100\mathrm{keV}} \rightarrow 3 \cdot 10^{5} \frac{\mathrm{n}}{\mathrm{sec} \times \mathrm{A}}$

Table 1. Neutron Yield for D-D and D-T reactions at 1 MeV and 100 keV.

The main contribution comes from neutrons produced via D-D reactions. Neutron spectra around the injectors were evaluated by Monte Carlo simulations. In past years both the experiments were modeled with MCNP (version 4c) and total neutron production was calculated as well as the activation of the main components [1-4]

Given the severe radiological scenario, the design of PRIMA injectors required a detailed and accurate analysis of the radiation protection and safety issues. The following main items are discussed below:

- Shielding evaluations required to reduce the dose rate outside the facilities at the desired level (namely, below 0.25 μSv/h, see further).
- Evaluation of tritium that is likely to be produced inside the facilities
- Evaluation of the activated corrosion products (ACPs) inside the cooling loops of the facilities.

SHIELDING EVALUATIONS

The general layout for the main buildings of the facility has been defined during year 2008 through MCNP simulations (figure 2). The main dimensions of the MITICA and SPIDER halls have been fixed. The working procedures and the needing for the staff shifts have been indicated by the research managing. According to these arrangements, the main shielding walls have been defined in materials and dimensions taking into account the parametric assessments outlined in a specific report [1]. The shielding assessment was performed for the two main halls, for the different operation phases, considering the neutron radiation produced during D-D operations for some D beam energy scenarios. Neutron attenuation for standard and borated concrete was considered to determine the walls dimensions. In table 2 and in table 3 annual dose limits and constraints that have been used for the design are recalled. In table 3 the constraints proposed for the design of the NBTF facility were simply stated multiplying the limits by a safety factor of 0,5. The hourly constraints are obtained by considering 2000 hours of working time during each year. Reference material for the shielding is the standard concrete. The borate concrete has been considered too expensive and regarded as a possible solution only in case space needing would be the main issue. A dose rate constrain of 0.25 μSv/h beyond the concrete shield was considered in order to meet the legal requirements for permitting free access even to non exposed workers into those areas.

Project Guidelines	
Project guideline for annual individual worker doses	5 mSv/a
Project guideline for individual dose per shift	0.5 mSv/shift
Collective annual worker dose target averaged over life time of plant	0.5 pers-Sv
Interim ALARA Guidelines	
ALARA threshold for dose rates	100 μSv/h
ALARA threshold for collective worker dose to operate and maintain a system for a year.	30 pers-mSv
ALARA threshold for collective worker dose for a task performed less often than annually.	30 pers-mSv

Note, an ‘ALARA threshold’ is a level that triggers a formal ALARA assessment during the ITER design phase. This does not imply that ALARA reviews will not be performed when the design is below the thresholds.

Table 2. Dose constraints according to the NBTF radiation protection program

Categories	Individual Effective Dose Limits (mSv/ year)	Annual Constraints (mSv/ year)	Hourly Constraints (μSv/ h)
POPULATION	1	0,5	0,25
CAT. B Radiation Workers	6	3	1,5
CAT. A Radiation Workers	20	10	5

Table 3. Limits and constraints for population and radiation workers

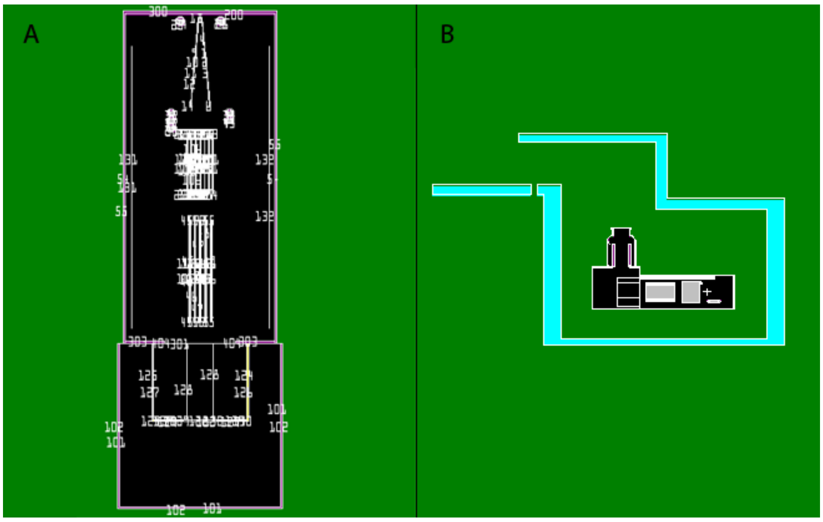
In table 4 the attenuation coefficient and the thickness calculated for the walls of the MITICA shields are recalled for the specific dose constraint in the adjacent areas, considering a 5 m reference distance from the MITICA vessel.

	Attenuation coefficients	Standard concrete thickness (cm)
BL VESSEL	1,09E+06	174
BS VESSEL	1,71E+05	151
NB front end	1,22E+06	176
NB rear end	4,12E+04	133

Table 4. Minimum wall thickness for the MITICA bunker

A thickness of 176 cm of ordinary concrete is then required for the areas around the BL vessel and the front end of MITICA; minor thicknesses are acceptable for the portion of the bunker walls in the areas

of the BS vessel and of the rear end. Therefore the following minimum thicknesses of ordinary concrete are recommended for the MITICA bunker walls:
•180 cm from the floor and for an eight of 3 m from the MITICA symmetry axis in the front end and BL vessel areas,
•155 cm from the floor and for an eight of 3 m from the MITICA symmetry axis in the BS vessel area,
•135 cm from the floor and for an eight of 3 m from the MITICA symmetry axis in the rear end area,
•the upper part of the MITICA wall, over 3 m from the MITICA symmetry axis, could have a thickness reduced by 30% of the lower one



Figre 2. A) The MCNP geometry of MITICA, where the main elements inside the injectors are shown. B) Design of the MITICA shielding walls with MCNP 4c.

The evaluation for the shielding of the ceiling has been done in a previous analysis using the approach suggested by NCRP [5] and considering that the main neutron diffusion is due to the atmosphere above the bunker roof. According to this assessment the needed attenuation required to allow free access to non radiation workers is: $5,0 \cdot 10^2/0,25 = 2,0 \cdot 10^3$, and the related minimum roof thickness is 95 cm of standard concrete. This thickness could be reduced by a 20% factor in the area of the ceiling corresponding to the BS vessel.
Considering that the simulation was performed with a simplified geometry and that not all the detailed structure of the MITICA surrounding was implemented into the model a more conservative approach was adopted in the final design. A 180 cm wall all around the facility was planned and a reduced thickness, of the order of 1 m, was established for the lateral walls in the dome area around the power supply line only. Due to special requirements for the connection of some auxiliary systems (HV and other components) in the upper rear part of the bunker, the wall thickness was reduced accounting for the needed room, meeting meanwhile the recommendation for the minimum shielding thickness reported above.
The SPIDER facility will be devoted to the testing phase of the source section only. The source will operate at a maximum voltage of 100 kV. This testing phase will take place in another area of the same building; thus an independent shielding is required. Even in this case a 0.25 µSv/h dose rate constraint was considered and the consequent shielding thickness for the SPIDER bunker were calculated. Results are shown in Table 5.
For the SPIDER bunker the following minimum thicknesses of ordinary concrete are therefore recommended:
•120 cm from the floor and for an eight of 3 m from the SPIDER symmetry axis in the front end and BL vessel areas,
•95 cm from the floor and for an eight of 3 m from the SPIDER symmetry axis in the BS vessel area,
•80 cm from the floor and for an eight of 3 m from the SPIDER symmetry axis in the rear end area,
•the upper part of the SPIDER wall, over 3 m from the SPIDER symmetry axis, could have a thickness reduced by 30% of the lower one

	Concrete wall thickness required to have an hourly constraints of 0.25 μSv/ h
BL VESSEL	116
BS VESSEL	93
NB front end	118
NB rear end	76

Table 5. Minimum wall thickness for SPIDER facility (100 keV energy)

For the ceiling a 90 cm ordinary concrete is needed as well. This thickness could be reduced by a 20% factor in the area of the ceiling corresponding to the BS vessel.
Also in this case the final design was defined according to more conservative considerations and some wall thickness was adjusted where needed.

PRODUCTION AND DIFFUSION OF TRITIUM INTO THE ENVIRONMENT

The study of the atmospheric transport of the radioactive tritium plays a central role in site specific radiation safety analysis. In the present paragraph, the analysis of the diffusion into the environment of the tritium produced inside MITICA and the assessment of thecommitted dose following tritium intake are presented. Tritium production was assumed to be negligible inside SPIDER [6].
In order to perform the evaluations, the main results obtained by Borgognoni et Al. regarding tritium production inside the facility [7] have been used as input data. Mathematical models for the study of radioactive releases into the environment are widely used today as the main technique in risk assessment and environmental impact. In the current study three different codes were used and the related results are compared: Resrad 6, Genii-Lin 1.486 and Hot Spot 2.06.
Tritium produced inside the facility (specifically in the injector bulk) is poured off in the environment by the ventilation system. Once released into the environment (air, water, or soil), tritium spreads rapidly. Tritium is emitted from the ventilation stack of the NBI facility (about 10 meters high) to the environment in forms of molecular tritium (T_2 or HT) and tritiated water (HTO). Since HTO is taken up by organisms and environmental media far more readily than molecular tritium, for conservative reasons, it will be assumed that all the tritium released from NBI facility is in the HTO form of. Our aim was to compare the different results obtained with the three computer codes. Two different scenarios have been considered:
1) Inhalation dose due to the passage of the radioactive plume in case of acute release of 10 GBq of tritium from the stack. This scenario was assessed comparing the output obtained running Hot Spot and Genii-Lin codes. The effective dose due to the passage of the radioactive plume was calculated at different distances from the source. Within this scenario, the dose contribution due to cloud submersion was also considered.
2) Total dose due to the introduction of tritium in the food chain. This scenario was calculated in very conservative conditions summing the dose due to all the pathways in which the nuclide can be incorporated. In this case Genii-Lin results were compared to Resrad output. For this purpose, tritium concentration in soil was derived from the ground deposition data obtained with Hot-spot.
Both for Genii-Lin and Hot Spot the dose rates received during the plume passage are reported in terms of total effective dose equivalent (TEDE), which include the cloud submersion effective dose equivalent (EDE) and the inhalation committed effective dose equivalent (CEDE).

Hotspot/Genii-Lin Parameters	
Total Tritium Release	0,01 TBq
Airborne Fraction/ Respirable Fraction	1 (both)
Physical Stack Height	10 m
Stack Diameter	0.5 m
Stack Effluent Temp.	23.0 deg C
Air Temperature	15.0 deg C
Effective Release Height	17 m
Wind Speed (h=10 m)	2.0 m/s
Stability Class	D (Neutral)
Receptor Height	1.5 m
Breathing Rate	$3.33\ 10^{-4}\ m^3/sec$

Resrad and Genii-Lin Parameters	
Tritium Concentration in Soil (conservative option)	26 mBq/g
Thickness of contaminated Area	0.5 m
Density of contaminated zone	$1.5\ g/cm^3$
Breathing Rate	$3.33\ 10^{-4}\ m^3/sec$
Indoor time fraction	0.5
Outdoor time fraction	0.25
Meat and Fish Consumption	80 kg/yr
Fruit, grain, vegetable consumption	160 kg/yr
Milk consumption	50 liters/yr
Drinking Water Intake	510 liters/yr
Exposure duration	30 yrs

Table 6. Values of the parameters implemented both in Hot-Spot and in Genii-Lin codes for scenario 1

CEDE represents the 50-year committed effective dose equivalent (expressed in Sv) received by an individual due to plume passage or to remaining at the specified location throughout the entire radioactive material release. This value is the sum of the 50-year committed dose equivalents to various tissues in the body, each multiplied by the appropriate weighting factor. EDE represents the external exposure due to plume passage. The time period over which the dose evaluation is performed is represented by the whole plume passage duration.

In Genii-Lin the doses that results from one year of external and internal exposure plus the extended internal dose that results from the one-year intake (ingestion plus inhalation) were calculated. A 50 year dose-commitment period was used (i.e., the one-year intake period plus 49 years). Dose evaluations with Resrad were performed considering the "resident farmer" scenario, which includes all environmental pathways for on-site or near-site exposure and is expected to result in the highest predicted lifetime. Even in this case a 50 year dose-commitment period was considered. For the purpose of estimating risk from tritium emissions two different areas have been considered and therefore two population reference groups. The first zone is the area surrounding the facility, where only workers are likely to be present. This area is assumed to have a circular shape with a radius equal to 50 m. The second zone is everything lies outside the first one, and thus the area surrounding the facility with a radius > 50 m. In this case the reference group is the population living in the area.

The purpose of the assessment is to determine how tritium doses might be distributed among the occupational and non-occupational populations in the areas surrounding NBTF facility.

With reference to the first scenario, a good agreement between Hot-Spot and Genii-Lin output was found. With Hot-Spot, the maximum tritium dose is approximately 0.23 µSv, located about 40 meters away from the source. This might be considered as the maximum dose received by workers, which are supposed to move onto the area surrounding the facility. In both codes a wind speed of 2 m/s was selected since typical of that area (table 2).

Genii-Lin is only able to perform calculations over distances greater than 100 meter form the source. At 100 m, a maximum dose of 0.15 µSv was found. At such distance, an excellent agreement with Hot-Spot was found ($d_{Hot\text{-}Spot} \approx 0.16$ µSv at 100 m). The dose at 100 m can be conservatively assumed as the dose to the population. At a distance of 1 km from the source, the doses drop down to 15 nSv and 0.5 nSv, respectively for Hot-Spot code and Genii-Lin.

The second scenario takes into account total dose due to the introduction of tritium in the food chain (all the pathways summed). Results obtained by Resrad and Genii-Lin codes were compared in this case. For this purpose an area surrounding the facility over a radius bigger than 50 meters was considered. People potentially at risk within the considered zone are inhabitants of the areas and sites at least 50 meters far away from the facility.

Table 6. Values of some parameters implemented in Resrad and Genii-Lin codes for scenario 2

Scenario	Exposure way	Distance from the source	Reference Group	Dose
1	Inhalation + Submersion (HOT-SPOT)	40 m	Workers	0.23 μSv/yr
		100 m	Population	0.16 μSv/yr
		1000 m	Population	15 nSv/yr
1	Inhalation + Submersion (GENII-LIN)	< 100 m	Workers	N.A.
		100 m	Population	0.15 μSv/yr
		1000 m	Population	0.5 nSv/yr
2	Total dose (RESRAD)	Constant for d > 50 m	Population	1.65 μSv/yr
2		50 m	Population	0.55 μSv/yr
	Total dose (GENII-LIN)	1000 m	Population	1.1 nSv/yr

Table 7. Calculated annual doses following tritium intake, according to different codes and scenarios.

In order to carry out this analysis, in Resrad the worst-case scenario ("resident farmer") was used. This scenario is not realistic but it is plausible; it can generally be assumed to be the most restrictive and, therefore, may be used to demonstrate that all plausible scenarios will not exceed dose limit. In the resident farmer scenario, a family is assumed to move onto the site after the release without radiological restrictions, build a home, and raise crops and livestock for family consumption. Members of the family can incur a radiation dose by direct radiation from radionuclides in the soil, inhalation of resuspended dust, ingestion of food from crops grown in the contaminated soil, ingestion of milk from livestock raised in the contaminated area, ingestion of meat from livestock raised in the contaminated area, ingestion of fish from a nearby pond contaminated by water percolating through the contaminated zone, ingestion of water from a well or pond contaminated by water percolating through the contaminated zone, and ingestion of contaminated soil.

A key parameter while performing Resrad simulation is the soil concentration radioactivity. In the present study, the tritium soil concentration was derived from Hotspot output. Hotspot yielded a maximum tritium concentration in soil of 20 kBq/m^2 about 50 m away from the source (where the resident farmer scenario was considered in order to assess dose levels to the population). In order to obtain the tritium ground concentration (in Bq/g) a number of assumptions have to be made. The

thickness of contaminated area was considered to be 0.5 m, and the density of contaminated zone was assumed to be 1.5 g/cm^3. With these data, a maximum tritium concentration in soil of 0.026 Bq/g was found and implemented in Resrad. It is worth remembering that this represents a quite conservative option, since this ground activity value was considered to be constant all over the contaminated area (for distances from the source greater than 50 m).
Genii-Lin was also used to calculate the total dose at different distance from the emission point due to the introduction of tritium in the food pathways. Two reference points were considered, 50 m and 1000 m. The total activity of released tritium is still assumed to be 10 GBq.
Even taking into account the most conservative situation, the total dose obtained with Resrad code turns out to be negligible (1.65 µSv/year); though this value is about one order of magnitude bigger than the inhalation dose, it is still about three order of magnitude lower than the dose limit of 1 mSv/year for the population. Dose values calculated with Genii-Lin at 50 and 1000 m are respectively 0.55 µSv/year and 1.1 nSv/year. It can be observed that Genii-Lin provides dose rates significantly lower than Resrad. This is because Genii-Lin algorithm takes into account the effective drop of nuclide ground concentration with the distance, while Resrad assumes a constant ground concentration all over the soil. Resrad calculation leads therefore to less conservative but more realistic dose values.

ACTIVATED CORROSION PRODUCTS IN THE PRIMA FACILITY COOLING LOOPS

The assessment of activated corrosion products produced (ACPs) in the prima facility cooling loops is described in detail in [8]. The whole PRIMA cooling plant is composed of three plant units (PU): a plant unit shared between the two experiments, and two plant units specifically devoted to each one of the two injectors. Both MITICA and SPIDER plant units include the following equipment: primary heat transfer system, local control system, pressurization system and electrical plant. The shared unit comprises: secondary and tertiary heat transfer systems, chemical control systems, drying system, pressure test system, fluid supply system, electrical plant and a local control system. In order to reduce the installed power of the heat rejection devices (air coolers and cooling towers), two underground water basins were designed at the PRIMA site: a water basin with capacity of about 315 m^3 and a second one with capacity of about 545 m^3, both to be interfaced with the shared unit.
Neutron fields produced on the calorimeter panels via D-D and D-T reactions are likely to activate materials and components around the injectors. The production of corrosion products formed in the cooling loops by the water physical action and by the chemical reaction between metal and water coolant may represent a relevant radiological issue once the products are activated. In fact, ACPs are likely to be dissolved into the coolant and transported around the cooling loop; workers and operators inspecting or maintaining cooling circuit equipment may thus be exposed to radiation dose due to ACPs which build up inside the cooling system components. ACPs may be present in such a concentration high enough to restrict personnel accessibility, even after the accelerator shut down.
Doses received by workers and operators during maintenance and inspection activities were calculated in [8] and the main results are reported in table 8. Within 24 h the major contribution to radiation exposure is represented by ^{56}Mn (half life = 2.58 h) for both plants. Given the high thermal and epithermal cross sections (13.3 and 1.13 barns, respectively) this radioisotope is produced in great abundance (about ≈ 700 GBq after 6 hr irradiation for MITICA and 1 GBq for SPIDER). After 24 h from shutdown, radiation dose drops down more than a factor 100, since ^{56}Mn contribution becomes negligible; after 24 h, long lived radionuclides such as ^{55}Fe and ^{60}Co provide the highest dose levels with a total activity of 450 MBq and 130 MBq for MITICA and of 2 MBq and 100 kBq for SPIDER, respectively. Although the dose rate of such nuclides is of no radiological concern if maintenance and inspection activities are carried out after 24 h from shutdown, they might represent a relevant issue for radioactive waste handling and disposal.

Critical Item	Total Dose (µSv/yr)			
	MITICA		SPIDER	
	t = 6 hr	t = 24 hr	t = 6 hr	t = 24 hr

Main Pump	11300	83.9	59.1	0.6
Heat Exchanger	7400	51.8	38.1	0.3
Large Valve	4500	35.4	23.4	0.2
TOTAL	**23.2E3**	**171.1**	**120.6**	**1.1**

Table 8. Total dose from maintainance operations of MITICA and SPIDER cooling loops.

CONCLUSIONS

According to the present analysis, personnel and population radiation exposure at PRIMA injectors is well below regulatory dose limits for all the scenarios considered. For both facilities shielding walls have been studied and designed in order to reduce the dose rate beyond the concrete shield below 0.25 μSv/h, providing a total dose of 0.5 mSv/yr. The results obtained after a release of 10 GBq of tritium from a 10m high stack, show that the dose limit of 1mSv/year stated by Italian law for the population is not exceeded around the facility and away from it. More specifically, even considering the most conservative scenario the dose contribution per year to the reference group of the population is negligible, being about three order of magnitude lower than the dose limit. Therefore tritium releases in the environment do not represent a concern from the radiological protection point of view. Furthermore, our studies concerning the production of ACPs indicate that for SPIDER, even considering the maximum workload, the contribution of ACPs to external exposure is negligible. On the other hand, ACPs produced in the MITICA cooling loops may significantly contribute to the external exposure of workers if maintenance and inspection activities are performed before 24 hr after the shutdown. With water being used as a coolant, in a number of operative conditions, it may be necessary to remove some of the impurities by a continuous purification process to prevent a build-up of long-lived induced activity in the system. In such case, personnel turnover is recommended. Even considering the worst scenario, dose contributions from ACPs during maintenance activities on SPIDER are negligible.

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