Nuclear Science and Technology Symposium - SYP2022
Helsinki, Finland, 1-2 November 2022

Design-Phase Probabilistic Risk Assessment for the International Fusion Materials Irradiation Facility

Tero Tyrväinen, Atte Helminen, Essi Immonen
VTT Technical Research Centre of Finland Ltd
P.O. Box 1000, FI-02044 Espoo, Finland
Tero.Tyrvainen@vtt.fi, Atte.Helminen@vtt.fi, Essi.Immonen@vtt.fi

ABSTRACT

This paper briefly presents Probabilistic Risk Assessment (PRA) developed for the International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Energy Source (IFMIF-DONES) at the design-phase of the facility. The IFMIF-DONES facility is used to test the suitability of certain materials for fusion power plant (DEMO plant) conditions. The neutron flux for the irradiation of the materials is produced by directing a deuteron beam through a lithium target. In this process, radioactive tritium and activation products are also produced, and there is a risk for a radioactive release to environment. Based on the safety analyses performed in the design-phase of the facility, the main risks of the facility are that either the deuteron beam damages the structures behind the lithium target or lithium reacts with oxygen. The accident scenarios with potential for significant radioactive releases have been modelled by eight event trees in the PRA model. Failures of safety functions, such as beam shutdown, inerting functions and isolation functions, have been modelled using fault trees. Preliminary quantification of the PRA model has been performed based on component reliability data collected from fusion applications as well as nuclear power plant domain.

1 INTRODUCTION

The International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Energy Source (IFMIF-DONES) [1, 2] is used for testing the suitability of certain materials for fusion power plant (DEMO plant) conditions. It produces the high neutron flux required for the irradiation of materials by directing a deuteron beam through liquid lithium flowing constantly through a target system. In 2022, the construction phase of the facility is about to start, but the design of several safety important systems is still not finished. The IFMIF-DONES is developed in the Work Package Early Neutron Source (WPENS) funded by EUROfusion.

The IFMIF-DONES produces significant amounts of radioactive materials, such as tritium, beryllium-7 and activated corrosion products. Therefore, the radiation safety of the facility needs to be ensured. The licensing of facility will mainly be based on deterministic safety assessment, but also Probabilistic Risk Assessment (PRA) has been developed during the design-phase to support risk-informed decision making. This paper presents the current state of the PRA briefly.

2 IFMIF-DONES FACILITY

The IFMIF-DONES facility [1, 2] consists of accelerator systems, lithium systems, test systems, and site, buildings and plant systems. Figure 1 illustrates the plant configuration.

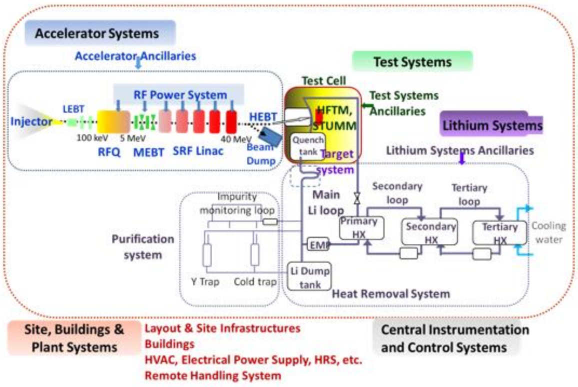

Figure 1: IFMIF-DONES plant configuration [2].

The accelerator systems produce the deuteron beam that is gradually accelerated starting from an electron cyclotron resonance ion source at 100 keV. The low-energy deuteron beam is injected through a radiofrequency quadrupole (RFQ) system, and through a medium-energy beam transport (MEBT) to a superconducting radiofrequency (RF) Linac. Finally, the beam has been accelerated to 40 MeV and is guided to the target system.

The lithium systems consist of a target system, a heat removal system, and an impurity control system. The main purpose of the lithium systems is to circulate liquid lithium at high velocity inside a loop, in order to host the D-Li reaction in the target system. The deuteron beam crosses the lithium stream in a target assembly, producing a neutron flux.

The lithium loop needs to also be constantly cooled during beam operation. The heat is transferred by a heat exchanger to the secondary oil loop and from there to the tertiary oil loop. From the tertiary oil loop, the heat is transferred to the water loops of the heat rejection system, which uses cooling towers as the ultimate heat sink.

The test systems host the irradiation of the test samples with the neutrons. The systems include a High Flux Test Module (HFTM), which contains the samples to be irradiated. The lithium target and the HFTM are contained in a test cell with a steel liner. Support systems fill the test cell with helium, control the pressure and purify the helium atmosphere during operation. The test systems need to also be continuously cooled during beam operation.

Several plant systems are also important for safety. Argon supply system performs inerting function for rooms where lithium could leak in order to prevent lithium fire. Heating, Ventilation and Air Conditioning (HVAC) system is responsible of isolating rooms with radioactive leaks during an accident. Gas radioactive waste treatment system cleans tritiated gases from certain systems during normal plant operation and from certain rooms during accident conditions. The heat rejection system acts as the heat sink for all systems that require cooling.

Beam shutdown is a central safety function at the facility. Its design is not yet complete, but the safety control system is responsible of the function, and the shutdown is likely performed by opening circuit breakers to cut off the power from the beam.

3 ACCIDENT SCENARIOS

There are several different accident scenarios that can potentially lead to significant radioactive releases to environment.

If the lithium flow is lost and the beam is not promptly shut down, the beam can break the back-plate of the target system, the HFTM and the back-wall of the test cell. This could cause a release of large amounts of activation products from the back-plate and HFTM.

If lithium gets in contact with oxygen, a reaction and consequent release of tritium are possible. This could occur in several different ways. Lithium could leak from the piping system. However, in that case, oxygen could get in contact with lithium only if the inerting of the corresponding room has failed or fails before the solidification of lithium. Air or water could also leak to the accelerator and enter the target system from there.

If the cooling of the HFTM was lost and the beam was not shut down in 15 minutes, large amounts of activation products could be released from the HFTM to the test cell. If also the test cell leaked, a release to environment could be possible.

4 PROBABILISTIC RISK ASSESSMENT

4.1 Challenges

The development of the PRA for the IFMIF-DONES facility has involved several challenges compared to the PRA of a nuclear reactor. The facility is the first of its kind and includes new systems and components that cannot be found from any other plant. The PRA has been developed during the design phase meaning that design details of some important systems have been missing and accident scenarios have not been well defined. The uncertainties related to PRA modelling have therefore been considered large, and the PRA model has gone through significant changes during the years.

In 2022, as the construction phase of the facility is about to start, the design of most of the systems is quite established. Mainly the control systems have not been completely designed yet. Accident scenarios are also relatively well known. However, the number of deterministic analyses performed has been limited, and significant uncertainties are still related to the accident sequence modelling in several scenarios from the point of view of PRA, particularly concerning the consequences.

4.2 Approach

The PRA has been developed following the traditional approach. Event trees have been used to model accident progression from initiating events (IE) to consequences. Fault trees have been used to model possible failures of safety functions.

Figure 2 illustrates the PRA development process. The qualitative steps required for PRA model are IE analysis, accident sequence analysis and system analysis. Descriptions of reference accident scenarios developed for deterministic analyses have provided inputs to the IE analysis and accident sequence analysis required for event tree modelling. Failure mode and effects analyses (FMEA) developed for safety systems have provided inputs to the IE analysis and the system analysis required for fault tree modelling.

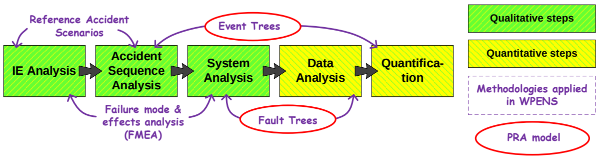

Figure 2: PRA development process.

To perform the quantification of the PRA model, data analysis is required. The reliability parameters of components have been collected from fusion applications as well as from nuclear power plant domain. The quantification of the accident sequences is finally performed based on the failure probabilities of component and the minimal cut sets (minimal combination of events that causes the analysed consequence) are solved based on the fault trees.

It should be noted that the PRA development process is iterative. The model has gone through many iterations during the development years.

4.3 Event trees

The current version of the PRA model includes eight event trees, which are listed in Table 1. Typically, one event tree covers a large set of initiating events. The aim has been to combine events with similar plant response to the same event tree. For example, loss of lithium flow at target can be caused by failure of the primary pump, clogging of the lithium loop, spurious lithium drainage or loss of vacuum. Lithium leak from the loop also causes loss of lithium flow. Such lithium leaks can actually initiate two accident sequences that are modelled separately: lithium leak to the lithium loop cell or test cell and loss of lithium flow at target.

Table 1 Event trees of the PRA model

Event tree	Worst consequence
Large lithium leak to the lithium loop cell	Large release
Small lithium leak to the lithium loop area	Medium release
Lithium leak to the test cell	Medium release
Loss of lithium flow at target	Large release
Loss of cooling of lithium	Large release
Loss of HFTM cooling	Large release
Air ingress in beam duct	Large release?
Water in beam duct	Large release?

Accident sequences in the event trees have been divided into release categories “large release” (over 100 TBq), “medium release” (1-100 TBq) and “small release” (less than 1 TBq). This categorization has been seen convenient for modelling so far, but it could well be changed later when more source term estimates become available. The worst release category for each event tree is also presented in Table 1. For the last two event trees, the release categorization is preliminary as the potential source terms have not been estimated yet at all (therefore the question marks). There is uncertainty related to other event trees as well, because mainly the worst possible source terms have been estimated.

4.4 Large lithium leak

The event tree for large lithium leak to the lithium loop cell is presented here as an example, because it is one of the simpler trees. The event tree is shown in Figure 3. Four fault trees are linked to the event tree: the fault tree covering initiating events, the fault tree for the failure of argon inerting, and fault trees for the failures of room isolation and HVAC duct isolation.

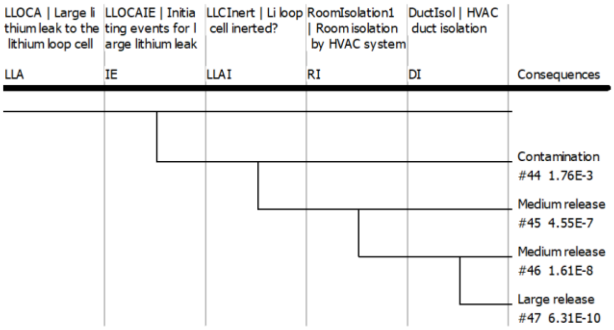

Figure 3: Event tree for large lithium leak.

The main safety function in this scenario is the inerting of the lithium loop cell by argon. The inerting is assumed to prevent lithium fire and any significant consequences. However, if the inerting fails, a lithium fire with a large release outside the lithium loop cell is conservatively assumed with certainty. After that the room where radionuclides leak or the HVAC duct can still be isolated by the HVAC system to limit the releases to environment. If all safety functions fail, a large release is assumed as the maximum tritium content in lithium is slightly above the large release limit. If the isolation is successful, a medium release is conservatively assumed, because there is uncertainty on the effectiveness of the isolations.

As seen in Figure 3, the large release frequency in this scenario is small, and the medium release frequency is also quite moderate despite of the conservative assumptions. The main reasons for that are that a large leak is quite unlikely in the first place, and the inerting function is very reliable.

4.5 Preliminary results

Quantitative results are not presented in this paper, because they are preliminary and highly uncertain. The preliminary results are discussed qualitatively instead.

In the current results, the most important scenario is that the lithium flow at the target is lost and the beam shutdown fails. If the beam breaks through the test cell, a large release to environment is assumed. This is assumed to occur within a minute, though the time window is based on a conservative assessment which does not take into account beam divergence and quenching in gas atmosphere. Very high reliability of the beam shutdown function is therefore required as the loss of lithium flow is a relatively likely event.

Loss of cooling of lithium has similar consequences as the loss of lithium flow, even though the time windows are longer, and the magnitude of the risk is also similar.

Significantly smaller risks are related to the scenarios where lithium reacts with oxygen based on the current results. Air ingress in the beam duct is the most significant scenario of those, but its modelling is only tentative and very conservative. Loss of HFTM cooling also has small significance.

4.6 Uncertainties

The current PRA model involves large uncertainties. Conservative assumptions have been applied in many cases to tackle the uncertainties. The main uncertainties have been collected to the PRA documentation and should be addressed in future analyses.

Currently, the most interesting uncertainty is related to the damage caused by the beam. If the assumption that the beam breaks through the test cell within a minute can be shown incorrect, the large release frequency is reduced significantly.

Important uncertainties are also caused by the lack of source term estimates, knowledge of lithium fires and knowledge on the effectiveness of the isolation functions. In addition, there are uncertainties related to the data and failures of the safety functions.

5 CONCLUSIONS

This paper has briefly presented design-phase PRA developed for the IFMIF-DONES facility. The accident scenarios with potential for significant radioactive releases have been modelled by eight event trees in the PRA model. Failures of safety functions, such as beam shutdown, inerting functions and isolation functions, have been modelled using fault trees. Preliminary quantification of the PRA model has been performed based on component reliability data collected from fusion applications as well as nuclear power plant domain.

Based on the preliminary results, the most important accident scenario of the facility is that the lithium flow at the target is lost, and the beam shutdown fails. Other significant risk scenarios include scenarios where lithium gets in contact with oxygen and loss of HFTM cooling. However, the model still involves large uncertainties, e.g. related to the damage caused by the beam, source terms and beam shutdown design. The development of the model will be continued, and the list of identified uncertainties forms a good basis for model improvements.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

REFERENCES

[1] A. Ibarra, F. Martin-Fuertes, D. Regidor, F. Arbeiter, U. Fischer, S. Gordeev, F. Schwab, D. Bernardi, G. Micciche, F.S. Nitti, A. Aiello, W. Krolas, R. Heidinger, M. Cappelli, A. Munoz, T. Pinna, N. Bazin, N. Chauvin, S. Chel, G. Devanz, “The European Approach to the Fusion-Like Neutron Source: The IFMIF-DONES Project”, Nuclear Fusion, Vol. 59(6), pp. 1-21, 2019

[2] F. Martin-Fuertes, M.E. Garcia, P. Fernandez, A. Cortes, G. D’Ovidio, E. Fernandez, T. Pinna, M.T. Porfiri, U. Fischer, F. Ogando, F. Mota, Y. Qiu, A. Helminen, S. Potempski, E. Gallego, A. Ibarra, “Integration of Safety in IFMIF-DONES design”, Safety, Vol. 5(4), p. 74, 2019