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To cite this article: T. Pinna *et al* 2025 *Nucl. Fusion* **65** 122005

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# RAMI studies for DONES

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Received 16 October 2024, revised 25 March 2025

Accepted for publication 1 April 2025

Published 24 September 2025



CrossMark

## Abstract

The DONES (Demo Oriented NEutron Source) objective is to irradiate in a simulated fusion irradiation environment a sufficiently large number of specimens with required neutron fluxes for an adequate period of time. To achieve the required results, a target of 70% of operational availability was established for DONES facility design, which means that, the facility is expected to be available for irradiation (i.e. with the beam on at full power) for 255.5 d per year. Such an average operational availability requirement combined with the foreseen scheduled annual maintenance scheme (20 + 3 d) implies an inherent availability requirement of 74.7% (i.e. ~75 %) for the DONES facility. Allocating this target to individual systems within the whole plant, the following system targets for inherent availability were defined: Accelerator Facility 87 %, Lithium Target Facility 94 %, Test Facility 96 %, Conventional Facilities 98% and Central Control System & Common Instrumentation 98 %. Key elements to ensure the availability objective set for a complex and innovative plant such as DONES are to accompany the engineering development of DONES with reliability and availability (RA) analysis, reliability testing of components and systems and the application of 'reliability growth', the structured process of identifying the root causes of reliability problems and predicting and monitoring the increase in system reliability through successive phases. Since RA are closely linked to the maintenance and inspection activities carried out during plant operations, the integrated approach for RA optimization needs to be based on all four issues: Reliability, Availability, Maintainability and Inspectability (RAMI). Accordingly, RAMI analyses cover all stages of DONES progress and specific studies have been performed for the various systems. This paper presents the RAMI studies conducted to date.

Keywords: RAMI, DONES, reliability, availability, FMEA, RBD

(Some figures may appear in colour only in the online journal)

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## 1. Introduction

The design and construction phases of DONES [1], composed for the most part of first-of-a-kind systems, are characterized by numerous uncertainties related to the required technologies. In particular, the coexistence of systems such as the lithium loop, the target system, the test cell and the accelerator that must operate together for very long times presents highly significant technical and technological challenges. These technologies and designs are either not yet sufficiently tested or have very limited operational experience. They have a low technology readiness level. The performance data inherited from previous facilities is currently very limited.

Consequently, the assessments made on DONES systems' reliability initially contain a high level of uncertainty raising questions about the confidence level in the assessment results. These uncertainties in the assessment results need to be made explicit so that the potential risks related to the associated design decisions are properly recognized. This is true for DONES as well as for all fusion facilities under design, construction, or operation.

The reliability of systems under development, such as DONES and fusion plants, is typically not constant, but follows a reliability growth (maturity) curve characterized by initial reliability, a reliability growth rate, and a mature reliability (i.e. final operational reliability) [2, 3]. Initial reliability is highly dependent on the novelty of the design. Typically, the more novelty incorporated into the design, the greater the initial uncertainty and the potential for unexpected systematic failure modes, leading to lower initial reliability.

The reliability of a novel system can be improved as experience and knowledge on system behavior is systematically gained through testing programs or operation cycles. The mature reliability is highly dependent on complexity of the design. A simple design has less opportunity for process-based failures, whereas complexity in design creates manufacturing, assembling and operating uncertainties within the components, their interaction at system level, and the system interaction within its environment.

Therefore, key elements to ensure an adequate reliability response for a complex plant such as DONES are (a) apply the 'reliability growth' process, the structured process of identifying the root causes of reliability problems and of forecasting and monitoring the increase in system reliability through successive phases, (b) conduct reliability tests of components and systems and (c) integrate reliability and availability (RA) analyses throughout the engineering development of the plant to identify weak points and uncertainties as the design progresses.

The objective of DONES is to test materials for use in the construction of future fusion reactors. A large number of specimens, defined Small Specimen Test Technology (SSTT) shall be irradiated in a simulated fusion irradiation environment. The first phase of operations aims to irradiate SSTTs up to 30 dpaNRT, while the second phase will require irradiation and damage levels of up to SSTTs up to 50 dpaNRT [1, 4].

To achieve the required results, the design of the various systems must ensure that the machine remains operational for 70% of the year [1]. This would allow an adequate number of test samples to be irradiated to the desired level of damage in the timescales required to enable the characterization of materials exposed to high-energy neutron radiation.

Since RA are closely linked to maintenance and inspection activities carried out on the plant during the operating phases, the integrated approach for RA optimization needs to be based on all four issues: Reliability, Availability, Maintainability and Inspectability (RAMI).

In fact, availability is influenced by many factors, e.g.: design of systems; manufacturing quality; operational environment; training and skills of people operating and maintaining the plant; maintenance crew policy; spare parts policy; instrumentation and controls available to check processes and detect abnormal operating parameters.

RAMI analyses should be applied throughout all phases of DONES development. During the pre-conceptual and conceptual design phases, the key activity is to understand the rationale of the plant, the related functions, the requirements and the constraints for the different systems. During plant development, the primary RAMI activity is to identify potential failure mechanisms and implement design changes to remove them or mitigate their consequences if they cannot be tolerated. During the realization and installation, the most important RAMI activity is to ensure manufacturing quality to preserve the inherent RAMI qualities of the design. Finally, in operations and support, the key activity for RAMI is to monitor performance in order to facilitate the achievement of RAMI targets and possibly their improvement by optimizing operation and maintenance processes. Achieving the specified RAMI levels for the DONES plant is important for many reasons, but specifically for the effect that RAMI has on safety, mission success and operating costs.

In this paper, the RAMI studies performed so far, as the design of DONES progressed, are summarized.

This paper is part of a special issue of Nuclear Fusion dedicated to DONES. Design information on the DONES plant can be found in the associated papers.

## 2. RAMI requirements issued for DONES conceptual design

During the conceptual design phase of DONES, 70% (average) operational availability target over calendar year was initially set for the whole plant. This means that the facility is expected to be available for irradiation (i.e. beam on at full power) for 255,5 d per year.

The required average operational availability ( $A_0$ ) is determined by the expected annual active time  $T$  (365 d), the scheduled annual downtime for maintenance (DTM) and the annual downtime required for failure repairs (DTF), i.e.

$$A_0 = \frac{\sum U_p \text{ times}}{\text{Total active time}} \rightarrow$$

$$A_0 = (T - \text{DTM} - \text{DTF})/T.$$

**Table 1.** Inherent availability requirements for DONES facilities.

DONES Facilities (and Systems)	Inherent availability $A_i$
Accelerator Facility	87%
Lithium Target Facility	94%
Test Facility	96%
Central Control System & Common Instrumentation (CCS & CI)	98%
Conventional Facilities (excluding CCS & CI)	98%
TOTAL (product)	75%

Where, the degraded operation of the irradiation source with reduced beam intensity is also considered a form of system unavailability (i.e. as system DTF).

Instead, the inherent availability refers to the probability that the system will operate satisfactorily for a given period excluding the scheduled annual downtime. This means considering only DTF (i.e. downtime due to corrective maintenance (CM)) while disregarding downtime for preventive maintenance (PM), logistics, waiting periods, or administrative issues. The average operating availability requirement of 70% combined with the expected scheduled annual maintenance scheme (20 + 3 d) implies an inherent availability requirement of 74,7% (i.e.  $\sim 75\%$ ) for the DONES facility. Together with the 70% operational availability target this implies that:

- the facility is expected to be operational for irradiation 342 d per year (24 h a day, 7 d/ a week);
- the facility should be inoperable for 23 d per year due to scheduled downtime;
- of the scheduled 342 operational days per year, irradiation interruptions at full power due to failures or issues in the systems of the facility can be tolerated for a maximum of 86.5 d annually.

The 74,7% initial inherent availability requirement for irradiation has also been allocated among the systems. As shown in table 1, this allocation implies that, in addition to the scheduled maintenance actions, the Accelerator Facility (AF) would be allowed to be down by failures or problems for a total time of  $\sim 43$  d annually at maximum, while for the lithium facility (LF) and the test facility (TF) the maximum allowed downtime due to the faults would be respectively  $\sim 19$  and  $\sim 12.5$  d annually. The irradiation would be allowed an additional  $\sim 6$  d period of downtime, resulting from faults in conventional structures or in the central control system.

Compliance with these inherent availability requirements, along with the scheduled maintenance downtime activities that interrupt the irradiation phases, will ensure the 70% (average) operational availability target required for the DONES facility. This ensures an adequate duration of irradiation time to produce the desired radiation dose and damage levels on a sufficient volume of test samples.

### 3. Identification of main source of uncertainties for RAMI studies

The first step in RAMI studies was to identify the main sources of uncertainty affecting RAMI analyses for DONES.

A specific uncertainty list has been outlined for different issues. Some examples are provided below.

**Lifetime of the systems to be analyzed.** Currently, DONES is designed to operate for at least 20 years of irradiation experiments with continuous 24/7 operating cycles. Therefore, RAMI assessments are considering 20 years of irradiation activity. Nevertheless, different operational scenarios could arise during the development of the project.

**Decontamination prior to corrective maintenance (CM).** Decontamination procedures in case of a leak of contaminated and/or activated products are not yet defined. They will strongly influence the time required to perform maintenance on components and availability.

**Maintenance policy.** Maintenance plans are conservatively defined based on irradiation cycles. The restoration factor (an index indicating the effectiveness of the repair) for all components should be identified. For the time being, a factor of 10% or 20% has been assumed in the assessments, meaning that maintenance extends component life by 10% or 20% relative to its prior operating life. For replaced components, the restoring factor is 100% (after maintenance the component is new).

For example, a recovery factor of 20% is used for PM on components such as pumps, compressors, valve actuators and probes. Furthermore, the potential impact of improved PM on RAMI parameters is also studied by considering various component aging models combined with different equipment restoration efficiencies ranging from 20%–80% [5].

**Mean Time to Repair (MTTR).** It largely depends on access time to the maintenance area, recovery time and component characteristics such as size, assembly, etc. The analyses should be expanded to cover uncertainties in MTTR.

**Failure Rates.** Since COTS (Commercial-off-the-shelf) components have not yet been chosen and many components are the first of their kind, the failure rates used in the RAMI studies are neither provided by the manufacturer nor obtained through direct operational experience or dedicated tests. Instead, they are estimated from literature on similar applications through an estimation of the most relevant data closest to the analyzed application. As a result, large uncertainties are related to the adopted failure rates or life data distributions. Furthermore, it is not yet known whether a degrading factor should be applied to the component failure rate to account for loading conditions (e.g. component operating outside the design range, thus potentially subject to accelerated aging). On the other hand, it is not yet known whether an enhancement factor should be applied to the component failure rate, as in the case of higher performing technologies [6].

For several analyses performed in the past, as it will be presented below, due to the heterogeneity of data sources, for

a large set of components, multiple failure rate data were available to be taken as a reference in defining component failure rates. Therefore, two failure rates were considered for each event: (1) the most favorable value based on the lowest failure rate among the available reference data set and (2) the most conservative value based on the highest failure rate values of the same data set [7]. The selection of the most promising failure rate, in practice, is based on the high quality of the components and elements that will be used in DONES while the selection of higher failure rates, allows to estimate conservatively the occurrences of single events and the consequential effects on the facility. The two values have been considered in the definition of the component failure models as the 5th and 95th percentile of the failure probability distributions. The Weibull, Lognormal and Exponential distributions have been considered. Specifically, the Weibull and Lognormal distributions are used for the failure models of components subjected to PM, while the exponential distribution is used for the failure models of components subjected only to CM performed after the failure.

An alternative method for integrating the heterogeneous reliability data gathered from multiple sources has been developed using the Monte Carlo-based algorithm. In this approach, once the probability distribution functions are defined for the relevant data records, multiple sampling is performed across all datasets with equal weighting. In this way, the resulting empirical distribution of the component failure rate is constructed taking into account the within-source and between-source uncertainty of the input parameters [8].

**Li loop process boundary.** In the case of small Li leaks, the Li could become solid once released outside the containment potentially causing the leaking section to become plugged. For RAMI some questions should be addressed by specific tests, such as:

- (1) Does any small amount of Li leaking require the shutdown of the facility?
- (2) How much could the Li inventory decrease inside the main Li loop without generating instability in the target?
- (3) How long would it take to recover Li in case of a leak into the test cell or Li loop areas?

Conservatively, in the analyses summarized below, the probability of Li being released from the system often leading to a subsequent system shutdown for maintenance, is estimated on the basis of ‘leaks’ rather than ‘ruptures’. However, once the above uncertainties are resolved or reduced, appropriate failure models can be applied.

**Main Electromagnetic Pump (EMP).** One of the main critical issues for the lithium loop, from the RAMI point of view, was the use of a single EMP in the circuit. To address this issue, the use of two EMPs in parallel was required. For RAMI purposes one of the pumps on stand-by would be sufficient to overcome the trip of the running pump. However, the transient to switch the flow from the running EMP to the stand-by EMP would cause safety issues in the target area. For safety

reasons, the configuration of two EMPs operating in series has been adopted, in this mode the failure of one of the two pumps should leave sufficient time for intervention to put the system into safe mode. However, specific tests should analyze the behavior of the Li target after an EMP failure to verify that the thickness of the target and the conditions of the lithium flow remain in stable conditions to avoid a backplate rupture. This failure could occur due to the strong thermal load generated on the backplate surface if the Li thickness is reduced or its flow changes from laminar to vortical.

**Electromagnetic Flow Meter (EMFM).** The use of Li flow measurement by a single EMFM or a pair of redundant EMFMs has been a subject of discussion for a long time. Again, safety reasons prevailed as the exact control of the Li flow is essential to immediately detect any instabilities in the Li target. Therefore, the configuration with two EMFMs in the Li circuit, placed downstream of the EMPs is currently considered.

However, it has not yet defined what automatic action should be taken when discrepancies arise between the two EMFMs (i.e. it is not yet established whether the beam should be turned off in any case as a precaution or the request for a quick beam shutdown can be left to the target parameter monitoring systems). Conservatively, in the analyses performed from 2018 to 2024 and summarized below, the failure of a single EMFM results in a system shutdown.

**Impurity Control System (ICS).** In the previous ICS design, only the Hydrogen Hot Trap (HHT) was operating in scheduled operation time. The other traps were operational during the maintenance phase and in the commissioning phase. For example, during the annual replacement of a target assembly (TA) or during CM done after some unforeseen events. Instead, in the last design solution, only the Cold Trap and Hydrogen Trap remain for Li purification, and they are operated only during normal Li Loop operations.

**Layout of HTS rooms.** Installing the primary lithium circuit and the secondary and tertiary circuits in separate rooms, in addition to being dictated by safety reasons, could also improve the system’s response in terms of availability. In fact, in this way maintenance on the secondary and tertiary circuits (with the exception of the primary HX) could be performed without emptying the primary Li circuit and without evacuating the inert gas from the Li circuit room. However, procedures for carrying out CM in the secondary and tertiary circuits are not yet defined.

**Fault Tolerant Approach.** Specific fault tolerant operations must be clearly defined. Some examples include:

- How much time do we have to turn off the beam in the event of a loss of flow in the secondary, tertiary or chilled water circuits?
- Does a small oil leak from the secondary circuit or tertiary circuit require an immediate shutdown of the beam for safety reasons or can operations continue until the amount of oil lost becomes significant?

- Can an ICS probe be isolated in the event of a leak to avoid stopping operations, allowing the ICS to continue functioning while curative maintenance is performed during the next scheduled downtime?

The fault-tolerant approach was not considered in the studies conducted from 2018 to 2024.

**Degraded operating mode assumptions.** Degraded mode operation assumes that the main functions/missions of the equipment/systems under consideration can still be performed despite partial failures. Two main categories of degraded mode operation can be envisaged:

- Exploitation of redundant components,
- Fault-tolerant operation: operation continues despite certain failures (e.g. small leaks).

In the absence of assessments demonstrating their feasibility, these assumptions introduce uncertainty and require discussion with designers and necessary, will be subject of dedicated RAMI analyses. For the time being, no degraded operating mode is considered in the definition of RA parameters.

**Sensitivity analysis.** Parametric studies on availability parameters focus on the components that have the greatest negative impact on systems availability, in order to optimize possible redundancies, policy of spare parts, and preventive and CM procedures (All aimed at improving systems reliability, availability and robustness).

#### 4. RAMI evaluation studies for DONES

Dedicated studies on RAMI performance of the different systems are performed since the beginning of the DONES-IFMIF design in order to obtain useful indications for the general design improvement and reduction of safety concerns. In fact, system reliability plays a crucial role in minimizing safety risks by reducing failures in process equipment that handle hazardous fluids and preventing general failures that could expose workers to higher radiation doses during maintenance.

Continuous RAMI studies not only provide inputs for designers highlighting weaknesses in terms of RA, but also inputs for the reduction of the uncertainties described above. The ultimate goal is to achieve a RAMI response from DONES systems that meets the desired availability targets.

##### 4.1. Methodology applied for RAMI analyses

The purpose of the analyses is to evaluate the consequences of functional losses in DONES systems in terms of events that raise RAMI concerns. The loss of system functionality is initially studied by analyzing the possible failure modes of the components and the system equipment dedicated to the execution of the operating and safety functions required. The Failure Mode and Effect Analysis (FMEA) methodology has been applied at this purpose.

The first step of the work is the definition of the plant breakdown structure (PBS) to identify the entire set of components

to be analyzed. Then, in order to have a complete overview of the functions that each single component has to perform, the DONES function breakdown structure is outlined at the process level. In this way, component failures are outlined by possible failures in the execution of the assigned/required functions.

**4.1.1. FMEA table.** The assessments are performed for the normal operation phase of DONES systems. However, for some systems, the maintenance and commissioning phases are also examined. For each elementary component failure, the analysis outlines: (i) possible causes and consequences related to the failure, (ii) detection means used to monitor parameters related to operational functions and to alert in case of failure, (iii) automatic actions performed upon detection, (iv) possible operational actions to be performed to mitigate the consequences of the failure.

From the list of elementary failure events, a set of representative conditions concerning unavailability is defined.

All events that share the same unavailability conditions (UC) within the plant are classified with the same UC label. Therefore, the grouping of failure initiating events into UC is usually performed based on criteria of similarity of the consequences associated with the single event and the plant response in terms of unavailability of individual main equipment and/or subsystems and/or the entire structure.

The failures of each component and the classification of failure events in unavailability conditions have been the input for the RAMI study performed through the use of the Reliability Block Diagram (RBD) analysis. It is aimed at identifying RA parameters considering maintainability and inspectability aspects.

A specific table is used to report the FMEA results.

**4.1.2. Reliability block diagram methodology.** Based on time-varying distributions for equipment success or failure, or other properties such as repair/recovery distributions, RBD analysis explicitly shows how equipment performing its operational functions contributes to the success or failure of the entire system.

RBD analysis uses a graphical representation of how the components of a system are connected in terms of reliability. In particular, each component involved in the operation of the system is represented in the RBD by a single block, which reflects with its parameters the characteristics of reliability, maintenance and operability of the component.

For these studies, ReliaSoft BlockSim<sup>TM</sup> software is used to perform the RBD evaluation. BlockSim RBDs can be configured as analytical diagrams (which use the exact algebraic equation for the model but impose limitations on what can be modeled and what results can be obtained) or as simulation diagrams (which provide more modeling options and results but must be analyzed with discrete event simulation).

In the analytical approach (or algebraic analysis), the system probability density function (PDF) and other metrics of interest are determined analytically based on the failure distribution of each component, using probability theory (e.g.

via mathematical expressions). Analytical diagrams are best suited to perform ‘reliability analysis’ that does not take advantage of any maintenance action to restore failed components or to prevent failures during their operational life.

On the contrary, simulation diagrams can take into account repair and recovery actions, which implies that the age of system components may change based on the repair and maintenance actions performed on them. System availability can be estimated through discrete event simulation. During simulation, random failure times are generated from the failure distribution of each component, and their impact on system reliability over time is identified based on the system reliability configuration. Complex scenarios involving a multitude of probabilistic events, such as CM, PM, inspections, and partial repairs, can be simulated. Finally, by exploiting reliability phase diagrams, RBDs analysis can be extended to account for the system evolution for particular sequential stages of active operations and maintenance phases.

#### 4.2. PBS 3—Site, Buildings and Plant Systems

The following systems are foreseen for the PBS3, the Site, Buildings and Plant Systems:

- 3.6 Heating, Ventilation and Air Conditioning (HVAC) System
- 3.7 Electric Power System (EPS)
- 3.8 Heat Rejection System (HRS)
- 3.9 Service Water System (SWS)
- 3.10 Service Gas System (SGS)
- 3.11 Solid Radioactive Waste Treatment System (S-RWTS)
- 3.12 Liquid Radioactive Waste Treatment System (L-RWTS)
- 3.13 Gas Radioactive Waste Treatment System (G-RWTS)
- 3.14 Fire Protection System (FPS)

For the largest part of them RAMI studies have been performed [9].

**4.2.1. HVAC, HRS, SWS, and SGS studies.** Initial simulations of the RAMI parameters for the four systems have been preceded by FMEA, based on which all identified failure modes were ranked and classified according to their initial frequency and severity. Weibull Reliability Models have been then assigned to the main components of the RBDs. The RBDs simulation have been performed for the whole operational lifetime of the DONES Plant (up to 20 years). RA parameters were evaluated both with and without PM activities on the systems. The results show that the inherent availability of all four systems is much higher than the required 98%, even without PM.

The HVAC system has been analyzed considering its subsystems: Chilled Water Subsystem, Heated Water Subsystem, Nuclear and Industrial Subsystem. The main results are reported in table 2.

The HRS consists of three Cooling Tower Groups (CTG-1, CTG-2, and CTG-3), which provide cooling water to the heat exchangers of the cooling SKIDS or directly to the heat loads. The main results of the analysis are reported in table 3.

The SWS consists of the following subsystems: Portable Water Subsystem, Demineralized Water Subsystem, and Industrial Water Subsystem. The main results of the analysis are reported in table 4.

The SGS consists of the following subsystems: Argon Supply System (ASS), Helium Supply System (HSS), Nitrogen Supply System (NSS) and Compressed Air Support System (CAS). The main results of the analysis are reported in table 5.

The results show a good response of all systems in terms of reliability at 20 years when considering PM.

The simplified analytical approach used at this stage assumed a linear increase in the component failure rates over the system lifetime with its zero value at the initial moment. Such an assumption combined with a relatively high restoration factor of PM (25% for short-period actions and up to 75% for long-period works) resulted in optimistic RAMI parameters (exceeding required targets) that were then updated by further studies.

Another independent study has been performed later with the aim to check the RAMI response considering the last design updates and improved dataset used in RAMI.

Table 6 presents a summary of the RBD simulation results for the analyzed plant systems. Out of the analyzed systems, only the HVAC system does not comply with the inherent availability requirement of 98%.

The ReliaSoft Downtime Criticality Index (RS DTICI) is a metric that indicates the ratio between the system downtime due to component failure and the total system downtime. This metric was used to identify the most critical components for each of the non-compliant systems. For example, according to this index, for the HVAC system, the section of chillers of the main building seems to have the highest contribution for the HVAC system’s non-compliance with the inherent availability requirements. The RS DTICI for the chillers of the main building is of 25.18%. The section comprises 8 chillers, only 1 of which is on standby. By adding further redundancy, it may be possible to improve the system’s availability. In fact, from RBD simulations, it was concluded that by adding a second standby chiller it is possible to improve the HVAC system’s inherent availability to 96.67%, which still does not comply with the requirements for plant systems. Once a second standby chiller is added, the most critical components are the fill and pressurization units and the exhaust fans. If some improving actions are implemented the inherent availability of the system increases up to 97.12%. Such improving actions could be:

- keep spare fill and pressurization units and exhaust fans to reduce their MTTR to 1 week;
- add redundancy to exhaust fans.

**4.2.2. Radioactive Waste Treatment System, Solid (S-RWTS), Liquid (L-RWTS) and Gaseous (G-RWTS).** The inherent availability (AI) and reliability (R) parameters have been estimated for the three subsystems through RBD analyses for:

**Table 2.** Comparison of the RAMI parameters obtained for the HVAC with and without PM.

No.	HVAC Subsystem	Reliability per 1 year without PM	Availability per 1 year without PM	Reliability per 20 years without PM	Availability per 20 years without PM	Reliability per 20 years with PM	Availability per 20 years with PM
1	Chilled Water	99.88%	99.99%	52.34%	99.92%	97.08%	99.99%
2	Heated Water	99.98%	99.99%	88.17%	99.98%	99.33%	99.99%
3	Nuclear	98.73%	99.97%	0.59%	99.45%	74.41%	99.96%
4	Industrial	99.83%	99.99%	54.85%	99.95%	96.51%	99.99%
Total for HVAC		98.43%	99.96%	0.21%	99.31%	69.01%	99.95%

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**Table 3.** Comparison of the RAMI parameters obtained for the HRS with and without PM.

No.	HRS Subsystem	Reliability per 1 year without PM	Availability per 1 year without PM	Reliability per 20 years without PM	Availability per 20 years without PM	Reliability per 20 years with PM	Availability per 20 years with PM
1	CTG-1	99.99%	99.99%	95.01%	99.98%	99.55%	99.99%
2	CTG-2	99.91%	99.99%	82.53%	99.96%	98.42%	99.99%
3	CTG-3	99.99%	99.99%	98.56%	99.99%	99.89%	99.99%
Total for HRS		99.88%	99.99%	77.72%	99.94%	97.76%	99.99%

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**Table 4.** Comparison of the RAMI parameters obtained for the SWS with and without PM.

No.	SWS Subsystem	Reliability per 1 year without PM	Availability per 1 year without PM	Reliability per 20 years without PM	Availability per 20 years without PM	Reliability per 20 years with PM	Availability per 20 years with PM
1	Potable	99.95%	99.99%	98.78%	99.99%	99.92%	99.99%
2	Demineralized	99.38%	99.96%	8.73%	99.60%	86.78%	99.96%
3	Industrial	99.96%	99.99%	99.02%	99.99%	99.94%	99.99%
Total for SWS		99.41%	99.96%	8.71%	99.59%	87.07%	99.96%

**Table 5.** Comparison of the RAMI parameters obtained for the SGS with and without PM.

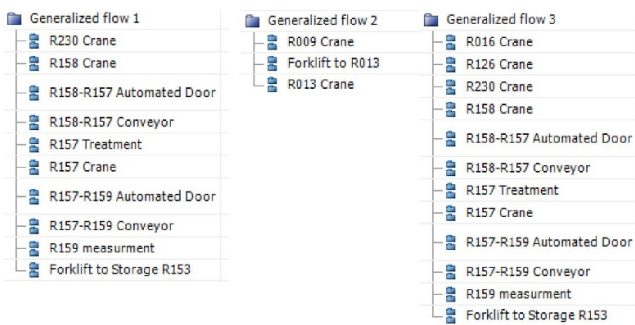
No.	SGS Subsystem	Reliability per 1 year without PM	Availability per 1 year without PM	Reliability per 20 years without PM	Availability per 20 years without PM	Reliability per 20 years with PM	Availability per 20 years with PM
1	Argon (ASS)	99.96%	99.99%	89.21%	99.98%	99.25%	99.99%
2	Helium (HSS)	99.97%	99.99%	91.21%	99.98%	99.27%	99.99%
3	Nitrogen (NSS)	99.98%	99.99%	89.53%	99.98%	99.31%	99.99%
4	Air (CAS)	99.94%	99.99%	88.48%	99.98%	98.36%	99.99%
Total for SGS		99.85%	99.99%	64.69%	99.95%	96.31%	99.99%

**Table 6.** Summary of RBD results for the HVAC, HRS, SWS, and SGS.

System	Subsystem	$A_I(t = 20 \text{ y})$	$A_O(t = 20 \text{ y})$	Compliance with requirements
HVAC	HVAC	95.68%	95.68%	N
HRS	CTG-1	99.83%	93.53%	Y
	CTG-2 + CTG-3	99.39%	93.10%	Y
SWS	Potable water	99.94%	93.64%	Y
	Demineralized water	99.97%	93.67%	Y
	Industrial service water	99.96%	93.66%	Y
	Chemical dosing and sampling	98.93%	92.63%	Y
SGS	ASS	99.93%	93.63%	Y
	HeSS	99.96%	93.65%	Y
	NSS	99.91%	93.60%	Y
	CAS	99.91%	93.61%	Y
	BAS	99.98%	93.69%	Y

**Table 7.** Results of the reliability and availability calculation and simulations for S-RWTS.

No.	S-RWTS Subsystem	$R$ (per cycle)	$A_I$ (per cycle)	$R$ (1 y)	$A_I$ (1 y)	$R$ (20 y)	$A_I$ (20 y)	MDT (20 y)
1	Gen. flow 1	96%	99%	89%	93%	8%	93%	312 h
2	Gen. flow 2	96%	99%	97%	94%	54%	93%	168 h
3	Gen. flow 3	94%	99%	85%	93%	5%	93%	285 h

**Figure 1.** Three groups of the IRW flows.

- One operational cycle (the time between two yearly scheduled PM), where no maintenance activities are included, and
- 1 year and 20 years of plant life, where the corrective and PM activities on the system components are considered.

**S-RWTS**—The purpose of S-RWTS is to manage solid waste from each main system of the DONES plant: Accelerator Systems, Test Systems, Lithium Systems and Building and Plant Systems. The S-RWTS is composed of: (1) Processing Subsystem; (2) Handling Subsystem; (3) Transportation Subsystem; (4) Measurement Subsystem, and (5) Storage Subsystem.

The main equipment of S-RWTS includes: cranes, forklifts, conveyors, lifters, casks, containers, handling devices and tele-manipulators, tools and treatment devices and measurement devices. The Irradiating Waste (IRW) flows were analyzed and it was observed that many of them are using the same paths. Therefore, they were grouped into 3 distinct equipment groups as shown in figure 1.

The three groups of the IRW flows include:

- Generalized flow 1—Equipment required for IRW flow from Test Cell, Target Interface Room, Beam Transport Room, Helium Pump Room, Accelerator Vault, HVAC Filters, R014 (Detritiation System), and R107 (HRS Resins);
- Generalized flow 2—Equipment required for Hydrogen Trap processing;
- Generalized flow 3—Equipment required for processing of main components of Li Loop.

The obtained AI and R parameters for the S-RWTS are summarized in table 7. In the last column, the mean down time (MDT) is reported too.

For all the three ‘flows’ the components that have the most impact on the systems reliability have been identified.

**L-WRTS**—The L-RWTS manages the liquid waste from the main facilities of the DONES plant: Accelerator Systems, Test Systems, Lithium Systems and Building and Plant Systems.

L-RWTS consists of five independent loops for collecting, storage and transfer of five kinds of liquids: waste water with very low activity and low chemical charge (Loop 1); tritiated water from detritiation system (Loop 2); waste water with low chemical charge (Loop 3); waste water with possibly high chemical charge (Loop 4); non-aqueous liquid waste such as oil etc. (Loop 5). Each loop is composed of the following main components: inlet/outlet piping, two tanks to store the liquid waste and two pumps to transfer the liquid waste from the storage tanks to the canister.

The obtained AI and R parameters for the S-RWTS are summarized in table 8.

**Table 8.** Results of the reliability and availability calculation and simulations for L-RWTS.

No.	L-RWTS Subsystem	R (per cycle)	A <sub>I</sub> (per cycle)	R (1 y)	A <sub>I</sub> (1 y)	R (20 y)	A <sub>I</sub> (20 y)	MDT (20 y)
1	Single loop	99.99%	99.96%	99.85%	99.99%	96.94%	99.99%	10 568 h
Total for all L-RWTS loops		99.99%	99.83%	99.38%	99.98%	84.34%	99.97%	10 605 h

**Table 9.** Results of the reliability and availability calculation and simulations for G-RWTS.

No.	S-RWTS Subsystem	R (per cycle)	A <sub>I</sub> (per cycle)	R (1 y)	A <sub>I</sub> (1 y)	R (20 y)	A <sub>I</sub> (20 y)	MDT (20 y)
1	VDS + GDS-V	70.25%	70.23%	47.03%	95.97%	1%	96.99%	17 141 h
2	EDS + GDS-E	89.13%	98.22%	—	—	—	—	—

**Table 10.** Reliability of the gas detritiation system during different operating time.

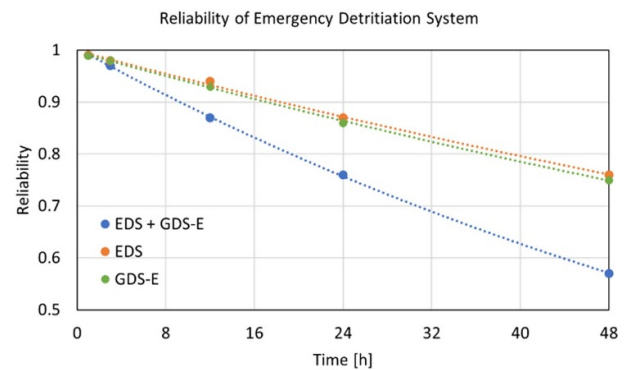
Operation time (h)	Total reliability of EDS and GDS-E	Reliability of EDS	Reliability of GDS-E
1	99%	99%	99%
3	97%	98%	98%
12	87%	94%	93%
24	76%	87%	86%
48	57%	76%	75%

**G-RWTS**—The G-RWTS is designed to perform the following key functions: (1) remove, treat, trap and release Tritium to acceptable levels from the cells and areas where Tritium releases are expected within the Lithium Systems as well as Test Systems and Accelerator System; and (2) remove, treat, trap and release Tritium to acceptable levels from areas where Tritium processes are hosted in case of accidental release. To accomplish these main functions, the system is composed by four subsystems: (1) VDS—Vent Gas Detritiation System; (2) GDS-V—Glove Box Detritiation system of VDS; (3) EDS—Emergency Detritiation System; and (4) GDS-E—Glove Box Detritiation system of EDS. The VDS is designed to process gaseous waste sources coming from the Lithium, Accelerator and Test systems during normal operation. The GDS-V will process vent gases coming from VDS enclosure. The EDS will process gaseous waste in case of accidental release in rooms where the tritium processes occur. The GDS-E will process vent gases coming from EDS enclosure.

The obtained AI and R parameters for the G-RWTS are summarized in table 9.

Subsequently, another study was conducted for the RAMI analysis of the detritiation systems, which are required to operate under accident conditions to prevent the release of tritium into the environment.

The analysis performed for different operation times showed that the required reliability of the Emergency Detritiation System (higher than 97%) can be obtained only for a short period of time (less than 3 h). After 48 h of operation, the reliability would decrease below 60%. The main factor influencing this result is the failure rate of the electric heaters. Therefore, the operation of EDS for longer than a few hours would require significant improvement of the system design towards higher reliability.

**Figure 2.** Reliability trend of the gas detritiation system.

The reliability parameters obtained for different operation times are summarized in table 10. While, the trend of R vs. time is reported in figure 2.

Once the RWTSs reached a higher level of detail, another RAMI study was performed later. Table 11 presents a summary of the RBD simulation results for the systems analyzed bandsaw. Out of the analyzed systems, two of them do not comply with the inherent availability requirement of 98%; the intermediate-level waste (ILW) flow of the S-RWTS, the very low-level waste (VLLW) plus the low level waste (LLW) flow of the S-RWTS. A brief analysis was also performed on these systems to understand which decisions can be taken in order to improve system availability.

The RS DTCI was used again to identify the most critical components for each of the non-compliant systems. For example, through this index, one bandsaw was identified as the most critical component in terms of availability because of its low reliability. System availability may be improved by

**Table 11.** Summary of RBD results for the RWTS.

System	Subsystem	$A_I(t = 20 \text{ y})$	$A_O(t = 20 \text{ y})$	Compliance with requirements
S-RWTS	HFTM	99.25%	92.96%	Y
	ILW	97.08%	90.78%	N
	VLLW + LLW	97.25%	90.96%	N
L-RWTS	Water collection + low activity and chemical charge	99.87%	93.57%	Y
	Tritiated water	99.99%	93.69%	Y
	Low chemical charge	99.99%	93.69%	Y
	High chemical charge	99.99%	93.69%	Y
	Oil collection + non-aqueous liquid waste	99.99%	93.69%	Y
G-RWTS	VDS + GDS-V	98.44%	92.14%	Y
	EDS + GDS-E	98.73%	92.43%	Y

adding a redundant standby bandsaw or by keeping spare components on-site to reduce the MTTR. By adding a redundant bandsaw, the inherent availability of the ILW flow increases to 99.20%, which would comply with the availability requirements for plant systems.

#### 4.3. PBS 4 – Test Systems (TS)

The DONES test system (i.e. test cell and test module) was analyzed at first using an FMEA. Three different unavailability conditions were outlined. These unavailability conditions and the whole set of related failures were useful for discussing design improvements.

Later, the DONES test system ancillaries (TSA) were analyzed using FMEA and RBD methodologies by several studies. Such systems were: the test cell (TC) gas inventory control system (TC-GICS), TC gas purification, Tritium treatment by the TC gas purification system (TC-GPS), TC water cooling system (TC-WCS), Test Systems medium pressure helium cooling system (TS-HCS-MP), Test Systems low pressure helium cooling system (TS-HCS-LP). The loss of functionality of the systems was investigated using FMEA, while the performance of the systems in terms of RA were investigated using RBD. A yearly operating time of 242 d, followed by 23 d of maintenance period was considered.

The last main outcomes of the studies in terms of RA are the following:

- The reliability to operate for one full year without fault of the whole TS and TSA is very low, 1.1%. The most critical system is the HFTM (with a reliability of 12.2%) because the large number of butt welds considered. Then, a deep check had to be done with designers to verify correctness of the assumptions taken (about 500 welds have been counted for the sealing of capsules and HFTM container), see table 12.
- On estimation of 20 years of operations, the yearly operational availability of the TSA is about 80.0% and, the inherent availability is 85.8%; see table 13.
- The yearly operational availability of the whole TS including TSA, TC and HFTM is about 71.2% while, the inherent availability is 76.7%.

- A critical issue exists regarding the availability of both systems. Since the requirement for the inherent availability of the Test Facility is 96%, both at level of the main TS and at level of the incorporated TSA, the system and the subsystem are not compliant with requirements.
- The most critical subsystems of the TS are the HCS cooling circuits and the HFTM.

The last outcome is summarized in table 13, where the evaluated availability values of the Test Systems and ‘Lithium Facility + TS’ are compared with availability targets established in the DONES requirements [1].

In the last three years, more detailed studies have been performed with the aim to extend the previous RAMI analysis of the Test Systems by considering the last design updates and improved dataset used in RAMI.

Particularly, the design updates related to the Maintainable TC Concept (MTCC) has been considered. MTCC is proposed to facilitate the maintenance/replacement of key components and biological shielding (i.e. highly irradiated liner, highly irradiated concrete part) in case of unexpected damage. The concrete walls providing the biological shielding are divided into:

- Permanent part (which is the so-called ‘Bucket’): this is kept as part of the facility building,
- Removable part: highly heated concrete part that requires active cooling and highly activated.

The whole TC liner (with the cooling pipes on the outer surfaces) is fully removable as well.

The MTCC decouples:

- the components that suffer relatively higher failure possibilities than permanent construction structures,
- the components that receive higher nuclear heat, thus requiring active cooling.

These new simulations have been performed for the system required amount of time (20 years mission time). The simulation of TS and TSA result in 97.28% inherent availability, with expected number of failures 258 and failure downtime

**Table 12.** TS&TSA reliability values obtained for one year of operations.

Sub-system	Reliability	Prob. of Failure	Failure Rate (1/h)	Mean Life(h)
GICS	70.4%	29.6%	$4.30 \times 10^{-05}$	14 420
GPS	70.7%	29.3%	$4.30 \times 10^{-05}$	14 410
HCS LP	69.9%	30.1%	$4.50 \times 10^{-05}$	12 635
HCS MP	70.3%	29.7%	$4.40 \times 10^{-05}$	12 708
HCS (Common LP&MP components)	99.9%	0.1%	$7.77 \times 10^{-08}$	69 680
HFTM	12.2%	87.8%	$2.56 \times 10^{-04}$	3901
TC	53.3%	46.7%	$7.70 \times 10^{-05}$	13 035
WCS	70.9%	29.1%	$4.20 \times 10^{-05}$	23 209
<b>TS &amp; TSA</b>	<b>1.1%</b>	<b>98.9%</b>	<b><math>5.94 \times 10^{-04}</math></b>	<b>1829</b>

**Table 13.** TS availability values obtained for twenty years of operations.

System	GICS	GPS	HCS (LP + MP)	HFTM	TC	WCS	Only TSA	TS & TSA
A <sub>O</sub> —Mean Availability (All Events):	90.3%	90.7%	85.9%	89.3%	90.5%	92.3%	<b>80.0%</b>	<b>71.2%</b>
Std Deviation (Mean Availability):	0.0070	0.0040	0.0086	0.0148	0.0090	0.0036	0.0104	0.0149
A <sub>I</sub> —Mean Availability (w/o PM):	96.4%	97.0%	91.8%	89.3%	96.7%	98.6%	<b>85.8%</b>	<b>76.7%</b>
Uptime (hr):	158 174	158 911	150 460	156 409	158 481	161 792	140 077	124 660
Total Downtime (hr):	17 026	16 289	24 740	18 791	16 719	13 408	35 123	50 540
<b>System Failures</b>								
Expected Number of Failures:	35	24	63	40	12	11	116	140
<b>Corrective Maintenance (CM) Actions</b>								
Number of CMs:	35	24	63	40	12	11	116	140
CM Downtime (hr):	6047	5323	14 062	18 791	5714	2393	24 548	40 474
<b>Preventive Maintenance (PM) Actions</b>								
Number of PMs:	20	20	20	0	20	20	20	20
PM Downtime (hr):	10 780	10 966	10 371	0	11 004	11 016	10 160	9772

4770 hrs. Detailed information about the systems availability are presented in table 14.

These new results, if compared with the previous one in table 13, give rise to hope for the possibility of the TS reaching the assigned target in terms of AI.

A parametric study was also performed to provide useful information for design improvement. For instance, the minimum repair time for all components was assumed to be 72 h (3 d). This is not a realistic scenario, but it highlights the importance of determining the time required to replace any component of the systems located in the TC.

In this variant, the inherent reliability of the systems drops to 89.95% with an expected failure downtime of 17 604 h, compared to the previous values of 97.28% and 4770 hrs. respectively.

It is important to note that to achieve the TS AI target of 96%, maintenance times, and therefore maintenance and spare parts policies must be optimized.

#### 4.4. PBS 5—Lithium Systems (LS)

The Lithium systems were analyzed both for the IFMIF and DONES configurations [6]. In the 2016, the LS (i.e. Li

target (LIT) assembly, the main lithium loop or primary loop (PLO), the lithium impurity control system (ICS) and the secondary (SLO) and tertiary (TLO) cooling loops) were analyzed by FMEA. Eleven different unavailability conditions were outlined. Such unavailability conditions and the whole set of related failures were useful to discuss about design improvements.

Later, a functional analysis of the DONES LS was conducted for the following topics:

- The refinement of system functions together a mapping onto detailed PBS.
- The definition of a preliminary behavioral concept integrated with plant Global Operating States and system Common Operating States.
- The definition of a Control Break down structure with initial classification of control functions as Process, Machine Protection or Safety related.

The document had the purpose of providing a base knowledge supporting other activities (e.g. P&ID development, component classification, control system development and RAMI studies).

**Table 14.** TS availability values obtained for twenty years of operations.

System	TC	HFTM	STUMM	TS-GICS	TC-GPC	TC-WCS	TS-HCS-MP	TS-HCS-LP	TSA EPS	Only TSA	TS + TSA
Inherent mean availability (%)	98.31	99.98	99.52	99.99	99.68	99.99	99.87	99.86	99.99	99.41	<b>97.28</b>
Uptime (hr)	172 241	175 174	174 365	175 195	174 634	175 197	174 979	174 957	175 193	174 159	170 430
Total downtime (hr):	2958	26	835	5	565	2.5	220	243	7	1041	4770
MTTR (hr):	35	48	6	21	29	22	24	22	1.3	23	18
Number of CMs:	84	0.55	133	0.25	19	0.1	9	11	5	45	258
Operational mean availability (%)	92.12	93.68	93.25	93.69	93.40	93.70	93.58	93.57	93.69	93.14	<b>91.15</b>

**Table 15.** Li facility reliability values at 1 year obtained at system and sub-system levels.

Sub-system	Reliability	Prob. of Failure	Mean Life(h)
LIT	<b>46.31%</b>	53.69%	10 632
TTC-TVC	91.23%	8.77%	16 503
PLO	80.84%	19.16%	31 423
SLO	96.51%	3.49%	57 313
TLO	96.46%	3.54%	57 189
ICS	<b>56.50%</b>	43.50%	11 725
<b>Lithium Facility System</b>	<b>17.97%</b>	82.03%	4653

**Table 16.** Availability values of Li facility obtained from the 2019 study for twenty years of activity.

System	LIT	TTC-TVC	PLO	SLO	TLO	ICS	Li facility
$A_0$ —Mean Availability (All Events):	89.8%	92.3%	92.5%	93.5%	93.5%	91.2%	<b>85.0%</b>
Std Deviation (Mean Availability):	0.0099	0.0036	0.0049	0.0014	0.0013	0.0065	0.0126
$A_1$ —Mean Availability (w/o PM):	96.1%	98.6%	98.8%	99.8%	99.8%	97.5%	<b>91.2%</b>
Uptime (hr):	157 252	161 719	162 078	163 801	163 796	159 776	148 885
Total Downtime (hr):	17 948	13 481	13 122	11 399	11 404	15 424	26 315
<b>System Failures</b>							
Expected Number of Failures:	16	9	5	3	3	15	46
<b>CM Actions</b>							
Number of CMs:	15	9	5	3	3	15	45
CM Downtime (hr):	6915	2467	2105	363	369	4432	15 382
<b>PM Actions</b>							
Number of PMs:	20	20	20	20	20	20	20
PM Downtime (hr):	11 033	11 014	11 018	11 036	11 036	10 992	10 933

It was defined that the approach adopted should be extended to other systems in future works.

Along the years, FMEA and RBD studies have been carried out hand in hand with the development of the project. Any time, pointing out lack or critical points of the design in terms of process or safety concerns.

Clearly, as the design progressed, more design details were also available, and the component set of the different systems also gradually grew. This has led over time to a greater awareness of the critical issues but also to a reduction in the availability values achieved by the systems to operate for 20 years. In fact, while the first analyzes gave rise to hope that the entire Li system (i.e. LIT, PLO, ICS, SLO, TLO) could reach the 95% inherent availability target, with the latest analyzes it was seen that the AI value achieved by the Li target system is in the order of 91%.

The main results of the ‘reliability analysis’ performed in the 2019 are summarized in table 15. Here, one year of operation (i.e. 8208 h of continuous operation) is considered. In this time, benefit from any maintenance actions to restore failed components or to prevent failures along their operating life are not considered.

In simulation diagrams repair and restoration actions are taken into account. Both CM and PM and situations of partial repairs are simulated. Inspections are not considered in this

study because the premature level of the design information on the matter.

The availability values estimated for the different sub-systems and the whole facility are reported in table 16. By these results it is possible to outline:

- if the maintenance policy that will be defined in the future development of the design will confirm the assumptions taken for the latter study, the Li Facility is not compliant with the requirement of 94% for the AI.
- the most critical subsystems in terms of availability are the Li target and the ICS. Backplate, vacuum pumping systems, heaters, pneumatic valves and cold traps are the components that compromise the most the availability response. Dedicated actions to reduce failure rates and, above all, the time required for CM of components would increase the final availability, but a clear maintenance policy must be established to evaluate the additional time required to put the systems in a safe condition and vent the maintenance area.

In 2022, another RAMI analysis was conducted, focusing on the Li systems, the LIT assembly, the PLO, the ICS, and the SLO and TLO [10]. The aim of this new study was to extend the previous RAMI analysis of the Li facility by considering the latest design updates and improved dataset used in RAMI.

**Table 17.** Last Li facility reliability values at 1 year obtained at system and sub-system levels.

Sub-system	Reliability	Prob. of Failure	Mean Life(h)
LIT	98.6%	0.014	15 872
TTC-TVC	99.1%	0.009	88 412
PLO	94.3%	0.057	26 880
SLO	94.1%	0.059	25 076
TLO	91.9%	0.081	20 322
ICS	93.7%	0.063	18 599
<b>Lithium Facility System</b>	<b>70.3%</b>	<b>0.297</b>	<b>12 077</b>

The following main assumptions have been used in the study:

- Several scenarios are considered but finally the study is based in the worst case in terms of MTTR for the CM (3 or 20 d depending on the subsystem and component).
- Target assembly, filters and traps have been assumed replaced during every long-term maintenance of 20 d.
- Besides the above replacement, during long term maintenance period, PM with partial restoration factor (RF) of the order of 20% and in some cases 85% is performed on active components as pumps, relief valves, valve actuators, heaters, probes. If the component is replaced the RF is 100%.
- Redundancies are considered in the RBDs for sensors not being part of an interlock and for sensors measuring the same parameter within a proximity area.

Main FMEA outcomes have been:

- A set of inputs for the developing of the RBD analysis.
- Criticalities in the design, which need further considerations or design updates.
- First estimation of yearly frequency of unavailability conditions of the different sections of the Li facility.

The main RBD outcomes in terms of RA are the following:

- The reliability of the whole facility to operate without fault for 171 d which is the longest period with no scheduled maintenance is 70,3%. The most critical systems are the TLO and the ICS, respectively, with a reliability to 171 d of 91,9% and 93,7%, see table 17.
- The mean operational availability of the Li facility for 20 years of operations is 79,1% and the inherent availability is 94,5%, see table 18.
- Therefore, if the maintenance policy that will be defined in the future development of the project confirms the hypotheses listed above, the Li facility meets the requirement of 94% inherent availability.
- In terms of availability, the most critical subsystems are the Li target and the ICS. The backplate for the Li target and the cold trap (CT) cooler and getter of the ICS are the components that most compromise the availability response. Actions to reduce failure rates and, above all, to reduce the time required for CM of failed components would increase

final availability, but a clear maintenance policy needs to be established to assess the additional time needed to secure the systems and ventilate the maintenance area.

Then, the last study shows a large improvement of the reliability (70.3% vs 17.97%) at 1 year and inherent availability of the Li facility (94.5% vs 91.2%) due to design improvements, better definition of the Mean Time To Failure (MTTF) reliability data and better definition of maintenance policy.

With the new calculations the Li facility seems to reach the inherent availability target of the 94% (table 1).

In 2022, another RAMI analysis focused on the systems responsible for the supply or inert gas, namely Argon to the Lithium system (PBS 5.1 Lithium Systems Ancillaries: Gas Subsystem). This RAMI analysis includes the identification of the failure modes of the ASS and Lithium system, assessing the risks associated with them and proposing mitigation actions to maximize the availability of Argon supply as well as improve the detectability of component failures. The RBD initial simulations provided a mean inherent availability of 80.49%. By adding spare components, it was possible to improve the availability to 93.45% which still falls short from the 98% availability requirement.

Two components stand out from the rest of the components by the number of spare parts they are expected to use during 20 years of operation. However, these components are not responsible for the low availability of the system.

From the RS DTICI analysis, it can be concluded that the system's downtime can be mostly attributed to the failure of molecular sieves of the Argon purification unit. This is the result of two things:

- The failure rate of molecular sieves was inferred from the failure rates of pressure vessels increased by a factor of 10.
- The architecture of the Argon purification unit is not fully defined. By default, the two units have been considered to operate in series, but they could operate in a parallel/load sharing configuration.

Once the aforementioned issues are solved, either the obtained mean inherent availability of the system reaches the target value of 98% or redundancy will have to be considered for the Argon purification unit. This redundancy may be implemented on the component level or on the entire unit.

**Table 18.** Last Li facility availability values obtained for twenty years of operations.

System	LIT	TTC-TVC	PLO	SLO	TLO	ICS	Li facility
A <sub>0</sub> —Mean Availability (All Events):	—	—	—	—	—	—	79.1%
Std Deviation (Mean Availability):	000 36	0,0039	000 71	000 41	000 48	000 59	0213
A <sub>1</sub> —Mean Availability (w/o PM):	96.9%	99.4%	98.1%	99.1%	98.9%	96.3%	<b>94.5%</b>
Uptime (hr):	169 876	174 190	171 788	173 573	173 186	168 767	138 575
Total Downtime (hr):	5324	1010	3412	1627	2014	6433	36 625
<b>System Failures</b>							
Expected Number of Failures:	11	2	7	9	11	16	46
<b>CM Actions</b>							
Number of CMs:	11	2	7	9	11	16	46
CM Downtime (hr):	5324	1010	3412	1627	2014	6433	9722
<b>PM Actions</b>							
Number of PMs:	—	—	—	—	—	—	34
PM Downtime (hr):	—	—	—	—	—	—	26 902

**Table 19.** Results of the RBDs simulations for Accelerator Systems.

No.	Accelerator Systems	Reliability per 1 year without PM	Availability (A <sub>1</sub> ) per 1 year without PM	Reliability per 20 years without PM	Availability (A <sub>1</sub> ) per 20 years without PM	Reliability per 20 years with PM	Availability (A <sub>1</sub> ) per 20 years with PM
1	INJ	74.88%	98.50%	<0.01%	92.83%	0.17%	98.20%
2	RFQ	78.54%	98.72%	<0.01%	89.58%	0.32%	98.44%
3	MEBT	66.78%	98.05%	<0.01%	94.57%	<0.01%	97.82%
4	SRF	13.91%	91.44%	<0.01%	78.32%	<0.01%	90.32%
5	HEBT	85.41%	99.18%	<0.01%	96.47%	2.59%	99.01%
6	RFP	0.21%	88.02%	<0.01%	85.03%	<0.01%	87.98%
7	ANC	98.68%	99.93%	0.41%	98.83%	71.69%	99.90%
<b>Total for AS</b>		<0.01%	79.05%	<0.01%	58.18%	<0.01%	<b>77.96%</b>

#### 4.5. PBS 6—Accelerator Systems (AS)

The first assessments were carried out in the frame of IFMIF EVEDA [11]. In that study, parameters, methodologies and results were treated. Major problems to face in terms of RAMI and idea of the RAMI performances, even with huge uncertainties, were outlined.

Results showed that availability requirements for the accelerator (AI = 86%) as designed for IFMIF would not be accomplished. Design changes were proposed to improve availability and achieve such requirements. The ones with more impact to the availability were to change the radio frequency (RF) power system to the solid state technology, to have hot spare cryomodules for the SRF Linac and to apply several redundancies in many ancillary systems. Moreover, one important consideration done to achieve such improvement was the capability to continue operation with some failed components in the accelerator. Such failures would degrade the beam, but would allow continuing operation until the scheduled maintenance period.

Later on, new studies have been performed for DONES AS in the years 2020–2024. The PBS of the analyzed AS sub-systems is the following:

- PBS 6.2—Injector System (INJ)
- PBS 6.3—Radio Frequency Quadrupole System (RFQ)
- PBS 6.4—Medium Energy Beam Transport System (MEBT)
- PBS 6.5—Superconducting RF Linac System (SRF)
- PBS 6.6—High Energy Beam Transport System (HEBT)
- PBS 6.7—Radio Frequency Power System (RFP)
- PBS 6.8—Accelerator System Ancillaries (ANC)

The loss of functionality of the systems has been investigated by FMEAs, while the performance of the systems in terms of RA have been investigated by RBDs.

Weibull Reliability Models have been assigned to the main components modeled in the RBDs. A fault tree analysis was performed to obtain the Weibull parameters of the higher-level functional units of the analyzed systems. The RAMI parameters were obtained for 20 years simulations. In the 2020 study, two models were developed for the reference design of each system; one with the two yearly scheduled PMs (20 + 3 d) and another one without PMs. Main results are summarized in table 19. The worse reliability trend is for the SRF and the RFP.

Other analyses have been carried out in recent years to consider the progress of the design and the identification of some maintenance procedures. Here, the great influence of the cooling time after a failure that allows to carry out CM has been highlighted. It is the cooldown period required for radiation decrease to enable hands on maintenance and the duration of startup operations. These logistical delays are longer in the modules of the accelerator closest to the target, where the radiation level is higher. This makes faults in such modules particularly significant in terms of reducing availability. The uncertainty surrounding the cooldown time in the event of faults in the AS modules significantly increases the uncertainty of the RAMI forecasts.

FMEA has been updated again in order to check completeness of potential consequences in terms of RAMI as well as the threat to workers or public safety. New RBDs have been developed for several scenarios, which could give indications for improvement areas:

- Scenario A with redundant low voltage power supplies (LV PS).
- Scenario B with excluded vacuum and cooling water leakages (to quantify their availability impact).
- Scenario C with excluded cooldown period (to quantify the availability impact from cooldown delays).

The three scenarios were all compared with the reference scenario (i.e. single PS LV, possible leak from vacuum and cooling water systems, significant cooldown time before being able to carry out CM) to determine the impact of the individual situations of uncertainty on availability values.

The following main results have been obtained.

**Reference scenario** simulation shows a value of inherent availability of the accelerator of 27.6%. The low value is mainly due to the time necessary for the cooldown time and for restarting the system following a failure. In any case, it should be noted that the cooldown time has been estimated conservatively considering the radiation fields achieved at the end of the life of the plant. However the cooldown time strongly depends on the irradiation duration. At the beginning of the operations, the components will therefore be less activated, therefore the cooldown time will be lower. The equipment responsible for the majority of failures are shutter and scraper components: actuators and linear potentiometer, INJ HV transformer. Current assumption in the model is that shutters and scrapers are used continuously.

**Scenario A**—Redundancy (1 out of 2) added to all LV power supplies of the AS modules. The simulation shows a slight improvement of AI of 0.2%.

**Scenario B**—The inherent availability impact from excluded leakages is an AI improvement of only the 3%. Vacuum and cooling water leakages are modeled in RBDs by leakage failure rate of flange connections. There is a huge number of those connections in AS, but the flange failure rate of  $3.72 \times 10^{-07}$  [1/h] is a relatively small figure. In addition, vacuum connections and cooling water lines are inspected after assembly using multiple methods and pressure tested. In case of small leakage, water or vacuum, there is redundancy in

terms of vacuum pumps or cooling water pumps i.e. those systems are failure tolerant. It is therefore reasonable to exclude vacuum and cooling water leakages from the model used to calculate AS availability for beam operations.

**Scenario C**—To understand the availability impact of cooldown times, the RBD model is simulated without those cooldowns in the repair times to carry out CM. The inherent availability of the accelerator, simulated by excluding cooldown times, reaches the value of 66%, with an improvement in the value of AI almost of the 35%. This improvement therefore suggests to evaluate well, on a case-by-case basis, the cooldown times required for CM and to consider CM carried out with the help of remote handling. These tools, in fact, even if they could request longer actual repair times, could avoid the time required for the cooldown of the activated components. Clearly, a cost-benefit analysis will also be made, as the use of remote handling could accelerate maintenance times, but it may require a strong increase in the construction and management costs.

Therefore, the availability simulation results vary between 28% and 66%. Unfortunately, this shows that the inherent availability of the Accelerator Systems is significantly lower than the target goal (87%) and so further design optimization and availability improvements are needed. Furthermore, the latest evaluations show also a decrease in the AI value previously calculated (table 19) without considering sufficient cooldown time values. But this is due to the fact that for the greater detail achieved by the design, the latest analyses had to take into account a much greater number of components than that considered in previous analyses.

Next studies shall mainly focus on the reduction of the uncertainties in the modeling of RBDs, e.g. reliability models, number of components, functional redundancies, duty cycles, fault tolerance of the components and the system, and safety criteria to carry out maintenance.

Due to the lack of specific reliability data, for some components there is no sufficient confidence in the definition of reliability models. For example, there is no reliability data for boron nitrate disks, so their reliability model is assigned based on engineering judgment, even though they are identified as main concern for the injector reliability. Similarly, the reliability model of the first RFQ module.

Another open issue is the redundancy of sensors on the beamline. The greater the redundancies, the greater the fault tolerance could be. Maintenance of redundant probes can wait until the next scheduled maintenance time to be performed.

#### 4.6. PBS 8 Central Instrumentation and Control Systems (CICS)

In 2023, a RAMI analysis was dedicated to the PBS 8.4 Safety Control System (SCS) and precisely on the PBS 8.4.1 Plant Safety Subsystems (PSS) and PBS 8.4.3 Personal Access Safety Subsystem (PASS).

The SCS must have an inherent availability of at least 98%. Since this RAMI analysis does not cover the entire SCS, but only its PSS and PASS (two subsystems of the four SCS subsystems, which also include the Occupational

Safety Subsystem (OSS) and the Radiation Monitoring for Environment and Safety Subsystem (RAMSES)), an AI response definition for these subsystems is necessary in the next future.

Assuming that the availability of the SCS can be approximated by equation (1), where each subsystem of the four subsystems of the SCS has the same target availability, then, the inherent availability of any subsystem,  $AI_{sub}$  is determined through equation (2). The target availability for each subsystem thus becomes 99.49% and the combined target availability for the PSS and PASS becomes 98.99%

$$AI_{SCS} = AI_{PSS} * AI_{OSS} * AI_{PASS} * AI_{RAMSES} \quad (1)$$

$$AI_{SUB} = \sqrt[4]{AI_{SCS}}. \quad (2)$$

The RAMI analysis included the identification of the failure modes of the SCS components, assessing the risks associated with them and proposing mitigation actions to maximize the availability of the SCS. The initial RBD simulations indicated a mean inherent availability of 88.85%, which is below the target of 98.99%. By adding unlimited spare components, the availability increased to 98.26% which still does not achieve the required availability. This methodology allowed the authors to identify both reliability and architectural issues with the current system designs.

In order to improve the SCS availability the following changes were proposed:

- Redundancy was added to all PSS sensors.
- The MTBF for the PASS door card readers was increased to 1000 000 h.

Through the aforementioned changes, and maintaining unlimited spares, the availability of the PSS and PASS subsystems of the SCS was improved to 99.07%. This availability was maintained after considering limited spares for each component.

To note that the current SCS design is still in its early stages with fundamental documentation missing, namely cabling diagrams, and piping and instrumentation diagrams. As such, the total number of components is not accounted for. Consequently, the current results are overestimated and will need to be revised as the design of the SCS progresses.

## 5. Relevant RAMI parameters for DONES

Nowadays that the design has reached higher level of detail and first RAMI studies for many systems have been carried out, a RAMI-oriented functional model of the DONES plant is required to further investigate systems contribution to main DONES mission functions. In particular such model would enable the assessment of sub-systems mutual impact in case of integrated operation. First aim of the model will be to evaluate the impact of selected parameters on DONES plant availability and to analyze and monitor the availability of the entire plant by the use of such parameters. Some of the RAMI parameters to consider are: MTTF, MTTR, Mean Time for PM, mean

time for logistic, e.g. mean times to prepare the maintenance, to wait after shutdown, to achieve spare parties, to perform re-commissioning (MTC).

Moving from available RAMI analyses at sub-system level, a simplified FMEA table was defined at first in order to aggregate subsystems at PBS level 2 according to maintenance policy and failure models as estimated from analyses results. Then an RBD analysis was performed for the whole DONES plant to estimate resulting RAMI performance at plant level.

Given the current inhomogeneities in the analyses of the various systems and sub-systems analyzed to date and in the level of aggregation of the information used and produced, an important collateral result of this study has been the definition of a format that all RAMI analysts will have to use in the evaluations that will have to be carried out in the future. Homogeneous information must be provided for a clear comparison and a clear use of the results produced for the different systems.

Based on the available RAMI analyses documents from either the EURFOfusion Programme FP8 or the current FP9 EURFOfusion programme an FMEA summary document was created with information aggregated at level 3 of PBS (PBS\_L3) and grouped by failure/repair models. On that basis a DONES RBD model has been defined too.

Unfortunately, the Blocksim files used in FP8 and FP9 to analyses the different DONES systems by different European research teams were not all available. Therefore, most of time-dependent lifetime distribution parameters are missing and only the estimation of an exponential distribution FR (and related MTBF) was possible by means of Reliability performance at 1 yr of operation reported in the different final documents described in the previous section 4. This lack of modeling information prevents enabling PM models in the RBD simulations.

Also, some sub-systems have no previous analyses (hence they are modeled in this study as cannot fail systems) or have only old analyses likely not aligned with current design information such as:

- TS: HFTM(2021), STUMM, TS-GICS(2021), TC-GPS(2021)
- TSA Electric Power Supply System
- AS—RFPS (2021)
- Lithium Systems Ancillaries (Ar supply only available)
- LICS of all systems
- CICS (Safety Control System RAMI not used).

With reference to RBD diagram in figure 3, a simulation was performed according to plant schedule (171 d of operation, 3 d of short maintenance, 171 d of operation, 20 d of annual long maintenance). Simulation shows an Operational Availability at 72% > target of 70%. The Inherent Availability is in the order of 78 %. The model itself is only preliminary for due to the lack of time-dependent FR. To enable a refined DONES plant model it is recommended for future RAMI analysis to report Weibull fitted models for PBS\_L3/L4 sub diagrams aggregated by CM maintenance duration and scheme.

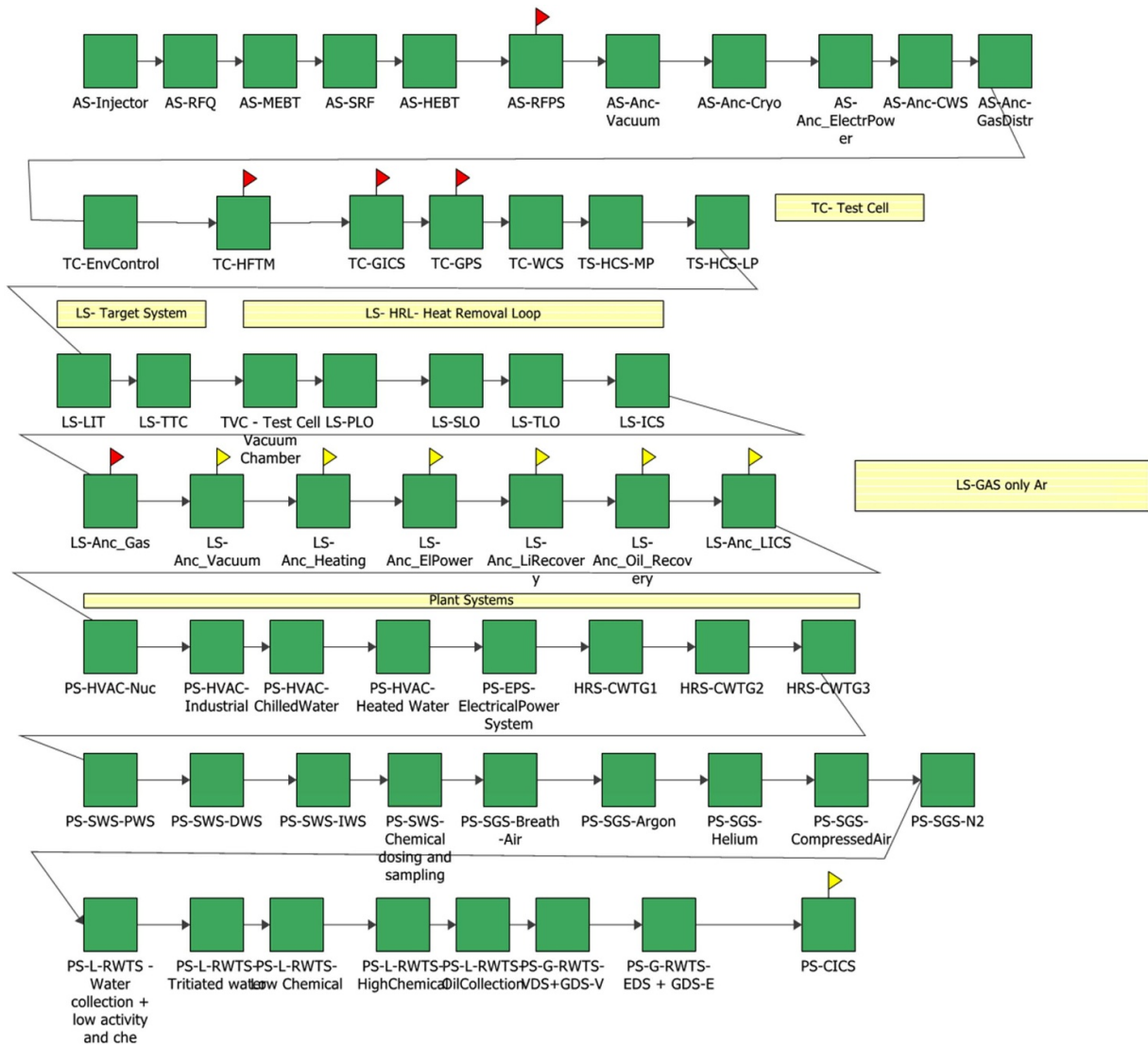


Figure 3. RBD for the DONES plant integrated model.

### 6. LIPAC commissioning collection data

One of the objectives of the RAMI activities for DONES is to collect and analyze operational data from existing facilities. In fact, existing operating experience data are very useful input data in predicting RAMI responses of analyzed systems.

The first step has been the definition of a methodology to collect data from existing and future facilities, of which operational experience can give significant feedback for DONES from the RAMI point of view. In this context the Linear IFMIF Prototype Accelerator (LIPAc) operations are investigated from the RAMI point of view.

The first LIPAC commissioning/operation data relevant for DONES would be:

- Information related to failures or events that lead to stop or malfunction of the installation, i.e. failed component, related failure modes, causes and consequences.
- Information related to repair or replacement process (mainly the total downtime) of main equipment and its

‘sub-components’ (e.g. diagnosis, access, repair or replace, logistic times if any, start-up time, etc.).

- Information on system modifications performed over time.
- Information on modifications of facility operating practices introduced over time.
- Info on scheduled maintenances actions performed over time,
- Periods of operation, i.e. experiments/test runs/other (e.g. operation type, main parameter settings, start time, end time, premature trip).

Particularly during the commissioning phase of the plant, the collection of data are relevant for the collection of data in relation with infant mortality, technology-knowledge associated failures, maintenance procedures and times, conditioning and tuning times, start-up sequence and times, logistic issues and associated times, etc.

In the 2020, the activity of LIPAc data collection was included inside the Broader Approach co-operation between

Japan and Europe, so a plan was defined for the year 2021–2025. The report defines the bases for co-operations in data collection and analyses between analysts and plant operators. Four steps have been identified:

- The first step should be based on the definition of the data set to be collected during the LIPAc operating life. Data on component failures, data on erratic alarms, info on operational delay due to different factors, data on preventive (scheduled) maintenance activities performed on systems and specific components are of interest.
- The second step is to highlight the reference set of plant data. PBS and Bill of Material of the different systems, data on all specific sub-systems and main components and on all specific elements, which will be the subject of time life analysis, the procedure to collect/evaluate the operating time and/or operating cycles of the different systems and different lower level elements during plant operations are the data of interest:
- The third step is to put together the information coming from the operating experience and the reference set of data, performing statistical analysis in terms of frequency of failures, mean time to first failure, mean time to failure, repair time.
- The fourth step, once some statistical data on the past experience is obtained, perform forecast RAMI analysis to operate the machine during its progress. Particularly, to organize as better as possible the scheduled maintenance, spare parties, crew availability. Then RAMI studies for the LIPAc should be performed to forecast the future operations and to check the achieving of RA targets.

To collect the information on operating experiences a proposal for a data collection form has been prepared.

To have an idea about data available from existing accelerators, a literature search has also been performed on representative known accelerator facilities. Limited operational reliability statistics are available (LANSCE and CERN), with most of materials being in the form of target requirement (for equipment suppliers or plant estimated possible achievements).

On the base of the preparatory work a template table has been defined to aggregate information derived from multiple documental sources from component to plant level information.

Design and operational data obtained by means of a collaborative exchange with LIPAc colleagues have then been elaborated on the base of such table template providing preliminary statistics aggregated at PBS L2 level. Also, a categorization of failure events in terms of hardware (HW)/software (SW) and procedural cause was performed. For the HW related failure, a proposal of association with reference literature failure rate (FR) has been also provided.

The actual derivation of failure rate estimates for selected components was not performed due to limited number of events and the unavailability of data to define the component population multiplicity and operating time history. The retrieval of such data enabling the estimation of failure statistics is object of task follow-up activity.

During 2021 analysis concerning operational failure events registered at LIPAc, the Radio Frequency Power Supply (RFPS) system emerged as one of the systems mostly contributing to failure events in previous LIPAc operational failure events analysis. A preliminary RBD analysis of the RFPS system was then performed to support the comparison between expected and actual performance.

The RBD model for RFPS system has been implemented on the base of available LIPAc design documents, considering equipment PBS and failure model. A generic operating schedule based on provided information about LIPAc shifts and annual record of past operation was assumed for calculations.

Such preliminary analysis was mainly based on provided design package documents and performed with the purpose of building an RBD model for the RFPS power to be used as base for information exchange with LIPAc operators. To allow for a comparison with RFPS actual LIPAc performance observed over recent operational history the following further information is required:

- Revised component list (to the level of inventory from maintenance tool) aligned with commissioned systems.
- Implemented LIPAc preventive and CM policy.
- Comparison between the planned historical operational schedule and achieved performance such as actual operating hours, duty cycle for components.

Successively, in the 2023 the RAMI of RFPS system has been revised and refined exploiting up-to-date design documents concerning: Air cooling, Low Voltage PS configuration, RF water cooling system, RF module 100/200 kW: HV/AC distribution. RBD simulation schedule was refined to better match the actual operational schedule of LIPAc up to date.

The annual operating schedule has been created considering a continuous operation for auxiliary systems and conditioning and beam operation phase for remaining systems. Also maintenance models were implemented on the base of maintenance plans provided. It is still to be revised the definition of restoration factor for maintained equipment.

The RAMI performance based on more detailed RBD models resulted in 67.51% of Mean Inherent Availability.

As future work, the obtained performance, especially considering the failure statistics will be compared to actual LIPAc performance.

## 7. Conclusions

RAMI analyses have been part of the development of the DONES project since the early design phases. They have always been a valid aid for designers to have qualitative and quantitative feedback on the effectiveness and correctness of the design solutions, but above all they have always provided indications for their improvement.

The weakest components from the reliability point of view have always been highlighted, as well as the critical maintenance conditions.

It is evident that, given the lack of reliability, availability and maintainability data relating to similar operational experiences and the still poor level of design definition, all the results obtained so far are affected by strong uncertainties.

From the latest RAMI analyses performed, most of the systems seem to be able to reach the desired availability targets. At the moment, the system that appears to have the greatest difficulty in reaching the set target is the accelerator (maximum calculated inherent availability value of 66% versus a target value of 87%). Nevertheless, there is confidence that by solving many of the uncertainties currently related to the accelerator, there will be a significant improvement in reliability/availability performance. This consideration is reinforced by the fact that among all the DONES systems, the accelerator is the most conventional and technologically mature system.

Nowadays the design continues to reach further developments, new RAMI studies are underway to further reduce the uncertainties behind the RAMI parameter evaluations and to reach more and more optimal design solutions.

### Acknowledgment

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 author(s) 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.

Part of this work is a part of the project co-financed by the Polish Ministry of Education and Science under the program entitled International Projects Co-financed.

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