Fusion Engineering and Design 193 (2023) 113792

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

RAMI analysis of DONES Lithium systems updated to the last design modifications

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ARTICLE INFO

Keywords:
IFMIF
Fusion
RAMI
Reliability
Availability
Cooling
Lithium

ABSTRACT

IFMIF-DONES project is aimed at building a neutron source facility for fusion materials development and qualification. This facility will provide a database of materials exposed to similar irradiation conditions as in DEMO. Neutrons are obtained by means of a deuteron beam impacting onto a liquid lithium film target provided by the Lithium System (LS). An important aspect of the project design activities is to assess the system reliability at all phases of the facility life-cycle to support a reliability growth during the ongoing design phase and to monitor the compliance with the stated availability goals. Following RAMI methodology, first a Failure Mode Effect Analysis (FMEA) is done in order to point out all the relevant unavailability conditions in the Lithium Systems (e.g. main loop and related heat removal systems, impurity control system, target system, etc.). Then, RBDs (Reliability Block Diagram) are derived from FMEA by implementing a reliability-wise representation of system component behavior and simulate the system performance under due operating conditions. Finally, a Phase Diagram (PD) is defined to have into account all the different states of the LS (e.g. normal opeation, corective maintenance (CM) and preventive maintenance (PM)) during two years of operation, a cycle that is repeating for 20 years of operation. The current design detail level and functioning logic is taken into account also considering the foreseen Local Instrumentation & Control System. The compliance with the availability target of 94% attributed to the Lithium System during its operation time is verified.

1. Introduction

The International Fusion Material Irradiation Facility Demo Oriented Neutron Source (IFMIF-DONES) is a key project to understand the degradation of materials and components under the irradiation conditions present in the future fusion power plants during its operational life [1,2]. This knowledge achieved in terms of a proved and reliable set of data for materials qualification is essential to support both the design and the safety licensing of next generation power facilities. In order to accomplish with all the timeline constraints of the fusion roadmaps, a high neutron flux with a fusion-like energy spectrum shall be provided by means of a dedicated high availability facility. The technology established to produce this neutron flux is based on a deuteron accelerator-driven source.

The IFMIF-DONES will be such dedicated facility using a 40 MeV deuteron linear accelerator [3]. This accelerator is designed to deliver a 125 mA beam current, which impinges onto a liquid-lithium jet based target. The Li(d,n) nuclear stripping reaction resulting from the beam/target interaction eventually provides an intense neutron flux of about 10^{18} n/m^{2}s, with the required fusion-like energy spectrum to irradiate the candidate materials [4,5].

RAMI (Reliability, Availability, Maintainability and Inspectability) performance is currently recognized among the main challenges for the economic viability of nuclear fusion power plants [6,7,11]. Due to the demanding schedule of the Fusion Roadmap, the operation schedule of IFMIF-DONES is also very challenging in terms of the required Reliability and Availability of the machine during the whole life of the facility. Consequently, proper performances are indispensable for the fulfillment of the availability target impossed by the project. For this reason, not only a good and efficient design is important, but also the

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https://doi.org/10.1016/j.fusengdes.2023.113792
Received 31 October 2022; Received in revised form 14 April 2023; Accepted 1 May 2023

Maintainability and Inspectability of each system are critical. A complete and well-settled plan is needed for inspection during the scheduled maintenance (PM) as well as for CM to be executed when a failure takes place. The radioprotection constraints, in terms of access to personel to those areas subjected to components activation, make maintenance tasks more difficult [8,9]. This is due to both the radioative cool-down waiting time required for a safe access and the short times of intervention imposed by ALARA principles. This constraint is particularly relevant in the LS, in which there will be flowing liquid lithum (at 100 l/s) carring some radionuclides produced in the target.

The main objective of this study is to:

- Assess current design RAMI performance, and in particular to verify whether the mean inherent availability requirement of 94% is accomplished
- Highlight main contributors to system unavailability in terms of equipment and failure modes to promote system reliability growth.
- Provide insight on possible RAMI performance improvements driven by maintenance policy.

In the context of a program of reliability growth for the DONES plant [3,10,11], a RAMI assessment for the Lithium Systems was presented in 2015 [10] and a new one is presented here. It is aimed at evaluating design criticalities in terms of RAMI perspective, taking into account recent design developments, new components and locations and also new CM and PM policy applied in the new PD created and applied for this assessment.

2. Materials and methods

2.1. Analysed system

IFMIF-DONES plant is composed by five main Groups of Systems: Accelerator Systems [11], Lithium Systems (LS) [12], Test Systems (TS) [13], Site, Buildings and Plant Systems (B&PS) [14] and Central Instrumentation and Control Systems (CICS) [15]. This study is focused on the LS part.

The LS represents the biggest sized system and one of the main parts of the IFMIF-DONES facility. Its main functions are: (i) Provide the liquid lithium target (in which inpinges the beam generating the neutron flux for the irradiation of the test modules) and (ii) Evacuate the heat power deposited in the liquid metal by the beam. To accomplish these points, the target is required to provide a high speed cross flow of liquid metal to evacuate the thermal power deposited and to maintain a constant shape and thicknes to interact properly with the beam.

Within the LS four systems can be identified: Target System (TSY) [16], Heat Removal Loops (HRL), Impurity Control System (ICS) and Lithium System Ancillaries (LSA). Present study scope is limited to three LS sub-systems: TSY, HRL and ICS. Fig. 1 shows a schematic view of DONES LS architecture.

The TSY is the system in charge of creating and maintain, during operational time, the liquid metal screen as target for the deuteron beam to collide. It is composed by four subsystems (Fig. 2): Target Assembly (TAA), Support for the Target Assembly (TAAS), Quench Tank (QTA) and Local Instrumentation and Control Subsystem (LICS).

The TAA is the core of the TSY since it is the part that shapes and gives the proper speed to the liquid lithium in order to set the target. Besides this, it creates the vacuum environment in which the interaction between the lithium and the deuterons occurs.

The functions of the TAAS are to support the TAA, to accommodate the QTA just bellow the TAA and also to allocate the centering and positioning system for the TAA.

The mission of the QTA is to give back the lithium the proper conditions to be injected into the main Li loop pipe, thus it turns the characteristics of the lithium coming from the outlet of the TAA with temperature gradients and high speed, to low speed and temperature uniformity within the QTA vessel.

The HRL is the system designed to provide the Li flow to the TSY under the propper conditions so it can be used for generating the Li jet target. The main functions of the HRL are summarized as follow: Provide

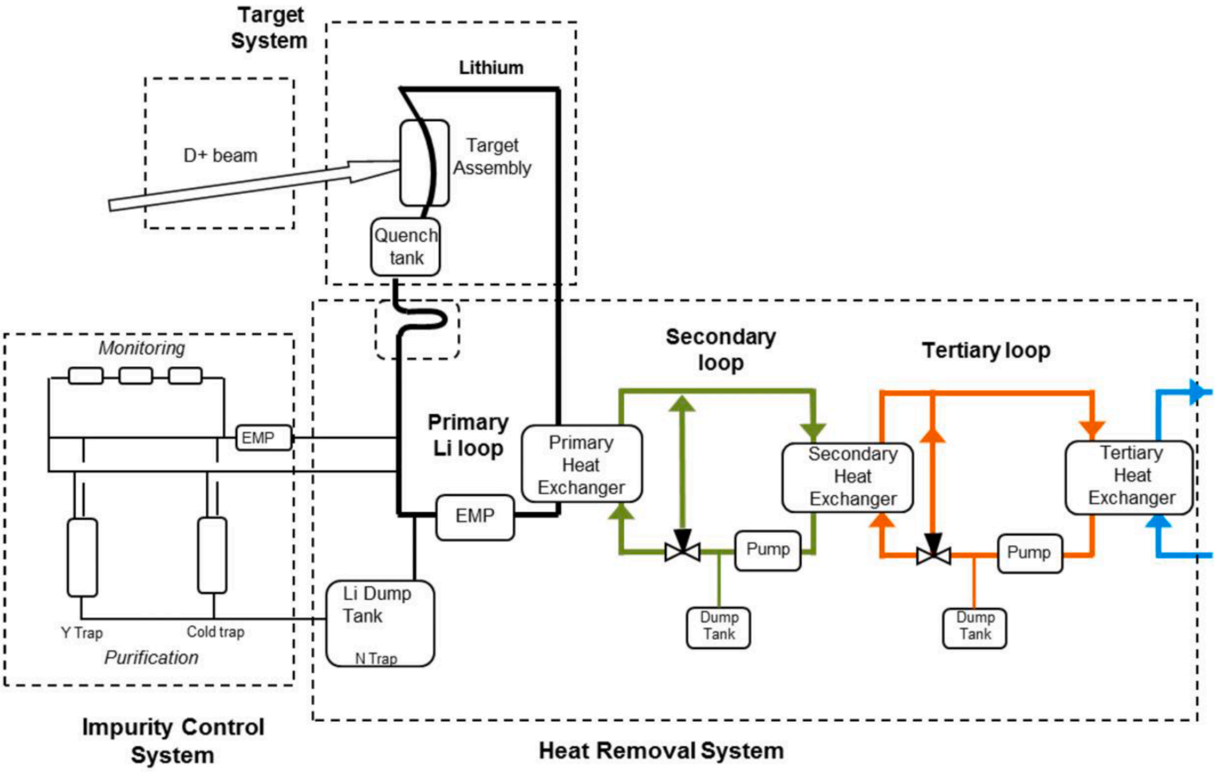

Fig. 1. Lithium Systems schematic view extracted from the plan design description document of IFMIF-DONES.

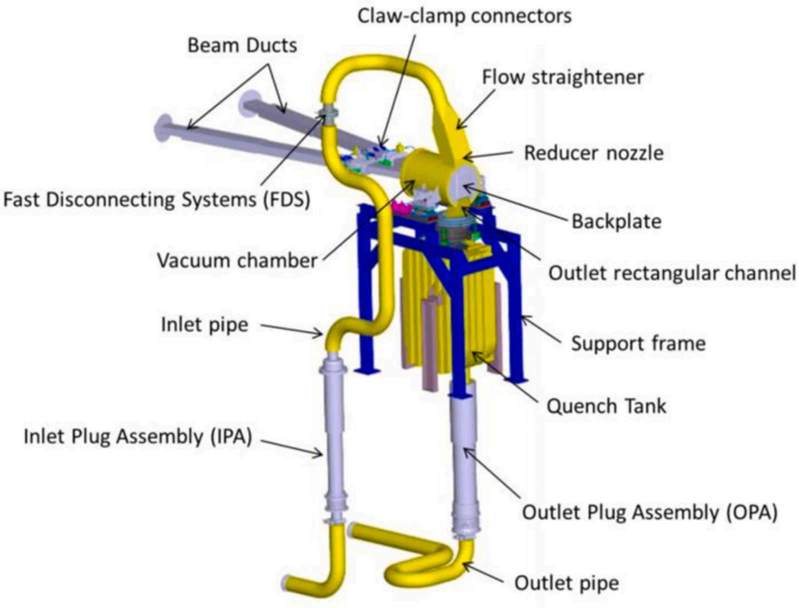

Fig. 2. Target System.

a constant mass flow of 50 kg/s of Li to the TSY, guarantee a constant temperature of Li at the nozzle exit in which the Li jet is generated and remove the 5 MW of thermal power deposited in the Li jet by the beam.

In turn, the HRL consists of the following subsystems: Primary Loop (PLO), Secondary Loop (SLO) and Tertiary Loop (TLO). The PLO operates with liquid lithium in the range of 250–300° containing activated impurities, hence many of their interventions shall be done by means of Remote Handling. In addition, the rooms housing the PLO will be inertized by Ar atmosphere in order to avoid lithium-air reaction risk. To minimize the risk of liquid lithium – water reactions in case of leakage, two intermediate cooling loops operating with oil have been foreseen: the SLO and TLO (Fig. 3). These loops provide the heat sink function for the PLO by means of three heat exchangers in cascade. There is air atmosphere and no radiations in the rooms where these cooling loops are located, so they are accessible for hands-on maintenance and inspection.

Last LS system considered in scope is the ICS whose main functions are: Control the sources of radioactivity, control the sources of the corrosion and erosion on structural components, assure the physical properties of liquid lithium and process the generated impurities. It is formed by two loops: the monitoring loop in which the samples are analysed and the purification loop, where the remove of the impurities takes place.

Several design progresses have been introduced by DONES project with respect to previous assessments [10] concerning system layout, additional physical components (including I&C) and maintenance policy, whose impact in terms of RAMI performance have been addressed in this paper.

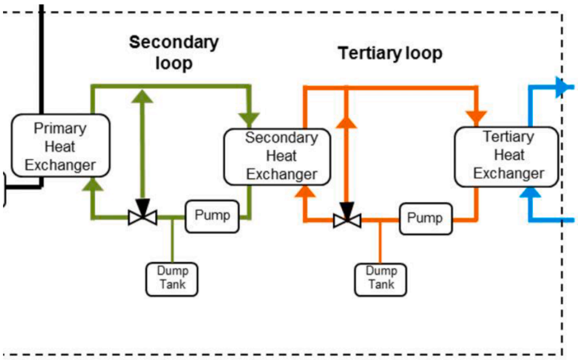

Fig. 3. Schematic flow diagram of the HRL showing SLO and TLO.

Also a new phase diagram was built to have into account the CM and the PM depending on the events and the timeline. This diagram is described later.

2.2. Failure mode and effects analysis

A Failure Mode and Effects Analysis (FMEA) [17] was performed as a first step. All the components belonging to the TSY, HRL and ICS were considered (e.g., probes, valves, pipes, etc.). For each one of those components and for each one of the failure modes (FMs) associated to, the following information fields were taken into account and

Table 1
Causes and consequences analysis example for a pipe with a FM of rupture extracted from FMEA.

Item	FM	Causes	Consequences
Inlet Fixed Pipe (TSY)	Rupture	Erosion/corrosion Material defects Earthquake Thermo-mechanical stress Incorrect assembling /installation; Vibrations	Lithium release in TTC; Li-air reaction (fire/explosion) if air is present within TTC because failure in the inert gas supplying system and/or in the vacuum system; TTC contamination; Loss of Li flow in target section or Li flow perturbation due to the disturbance generated by the Li leaking; Back plate rupture, if the no flow or flow perturbation in the Li stream induces the direct discharging of beam energy on its surface (possible); Local Li boiling or vaporization in target chamber; Loss of vacuum in beam duct; Deposition of beam energy on TVC and duct walls due to the beam interaction with the vaporised material; TVC and duct walls damage; Ingress of air in TVC and Li-air reaction in target section

Table 2
Unavailability conditions identified by FMEA.

UC	Description
U_LIL	Unavailability of the main lithium loop
U_LIT	Unavailability of the lithium target
U_TVC	Unavailability of the target vacuum chamber
U_TTC	Unavailability of the target test cell structure
U_HTS2	Unavailability of the secondary cooling loop
U_HTS3	Unavailability of the tertiary cooling loop
U_ICS	Unavailability of the impurity control system
U_IMP	Unavailability of the impurity monitoring system
N/U	Not Unavailability concern / enough redundancy

systematically populated: process function, operation mode, causes, consequences, detection, actuation on detection, mitigations, actions, unavailability condition (UC) and FR.

The unavailability of each sub-system (e.g. ICS, PLO, TLO, etc.) was assessed as emerging from the respective components failure occurrence and reliability-wise configuration. The overall impact of such sub-systems unavailability was then assessed by focusing on the LS capability to provide the liquid lithium target within nominal domain. In particular, any failure mode of any component that would bring the liquid lithium target outside its operation limits was considered as leading to an UC of the system. This is not only valid for the PLO but also

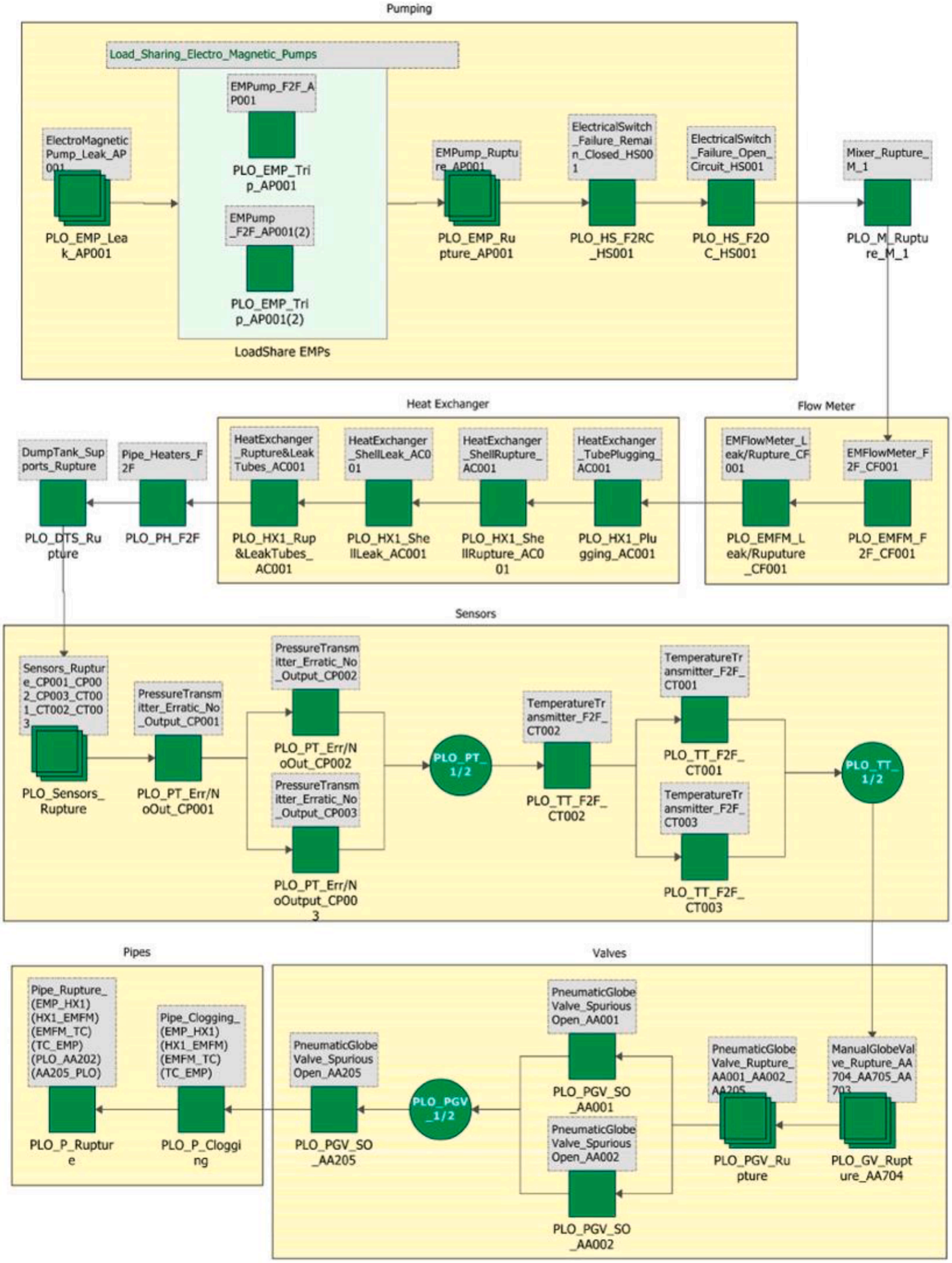

Fig. 4. Reliability Block Diagram for U_LIL unavailability condition.

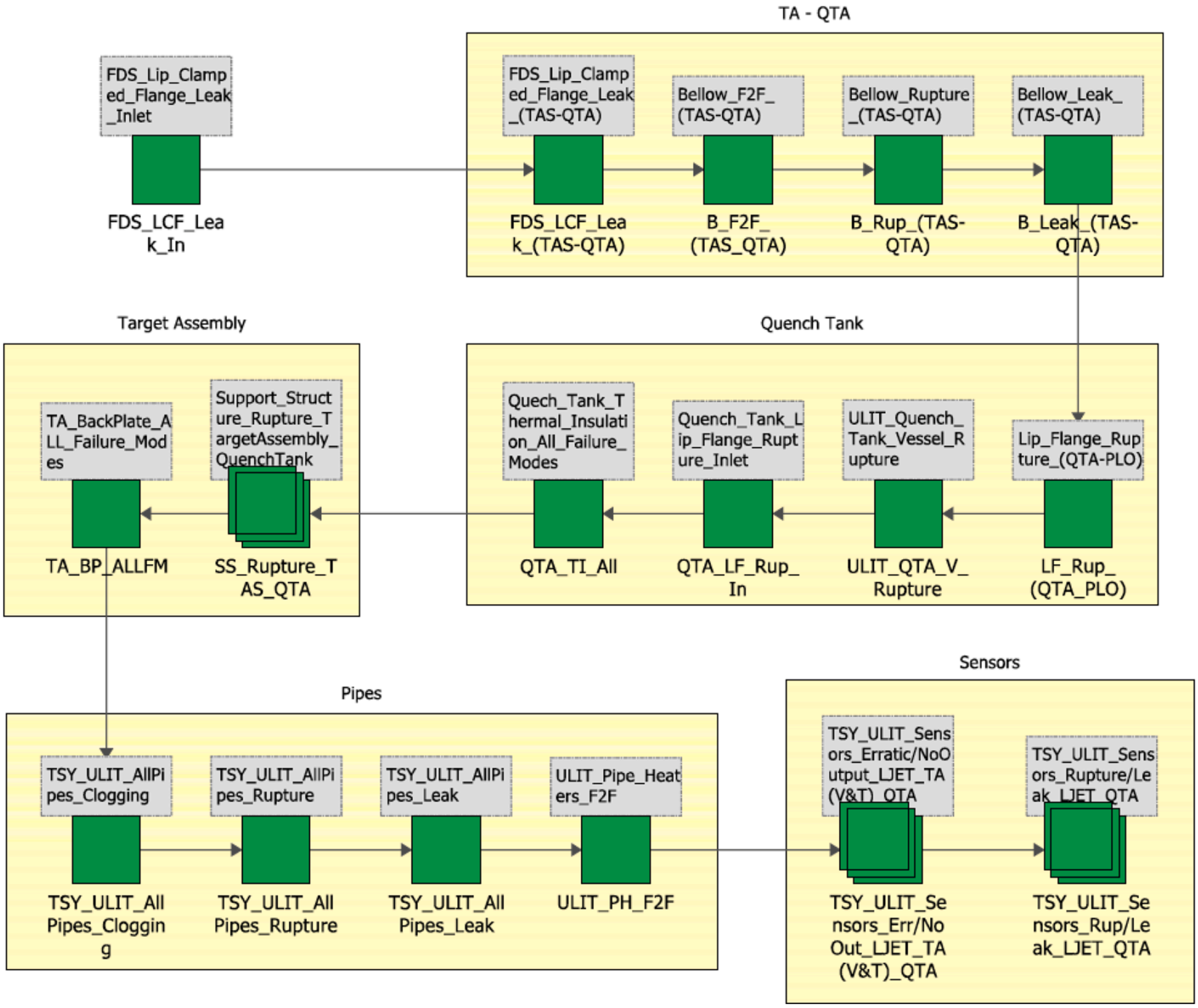

Fig. 5. Reliability Block Diagram for U_LIT unavailability condition.

for the oil cooling loops and the TSY. Regarding ICS, the UCs generated in that system are also considered despite the little percentage of Lithium that is extracted from PLO to purify, due to the uncertainty on the time necessary for affecting the proper functioning of the HRL and the TSY.

All FM were considered for each component. They can lead or not to an UC depending on the severity of the consequences. The FMs related to flow, heat sink, leak tightness, loss of vacuum, or control and operation of the system were selected for the study. In the table below it is shown an example extracted from the FMEA. An extract example of FMEA is provided in Table 1.

In addition, it shall be remarked that every defined UC also leads to a beam shutdown interlock in the AS, since a beam impact on a degraded Li jet would endanger the back plate of the target. Having this into consideration, the UCs were defined and derived as an eventual outcome of every considered system component in the FMEA. They are reported in Table 2.

2.3. Reliability block diagrams

Once the UCs are defined, the failure events related to the different components resulting into each UCs were translated into Reliability Block Diagram (RBD) representation. In particular, RBD diagrams were implemented by reliability-wise configuration, connecting all components that lead to the same UC (Table 2). Within the RBD, every FM for each component was represented by a different block including FR and Mean-Time-to-Repair (MTTR) data.

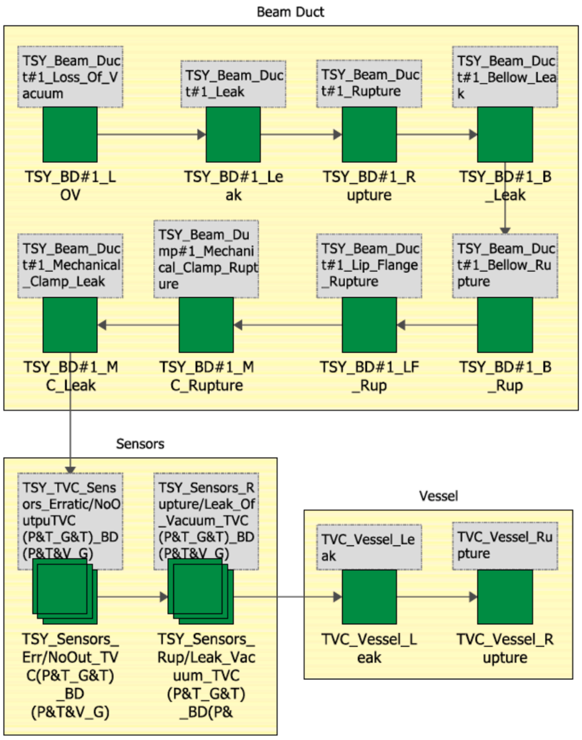

Fig. 6. Reliability Block Diagram for U_TVC unavailability condition.

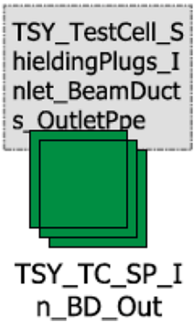

Fig. 7. Reliability Block Diagram for U_TTC unavailability condition.

Reliasoft Corporation's Blockslim software 2022 version [18] was used in present analysis.

Figs. 4-10 report the RBD diagrams implemented to study the unavailability conditions separately. Fig. 11 shows the general RBD with seven folders, each one of them containing all the respective unavailability conditions.

The following assumptions were made:

i Failure rates (FR) assumed were taken from ENEA Fusion Components Failure Rates Data Base [19,20-22]. See Table 4 on pages 5 to 9. Note that the approach adopted in present study relied on the selection of a specific literature failure rate judged representative for the actual DONES LS component. Other approaches [10] rely either on the indication of a min-max range for the FR data or on the merging of multiple literature data to obtain a new FR estimate [22]. Note that failure models exploited in the analysis are expressed either in terms of λ parameter of exponential life distribution for the selected component or (μ,σ) parameters of lognormal life distribution for the selected component. Exponential 1-parameters distribution have been defined mostly for passive component (e.g. pipework) while lognormal models have been defined for active components (e.g. I&C, valves actuators). Note that 1-parameter exponential failure models do not benefit from preventive maintenance operation since presenting a constant failure model not varying with time/aging of the component.

ii According to available P&ID information, each system has different sensors for checking all the parameters related to the operation, like pressure, temperature or flow (Fig. 12). The more

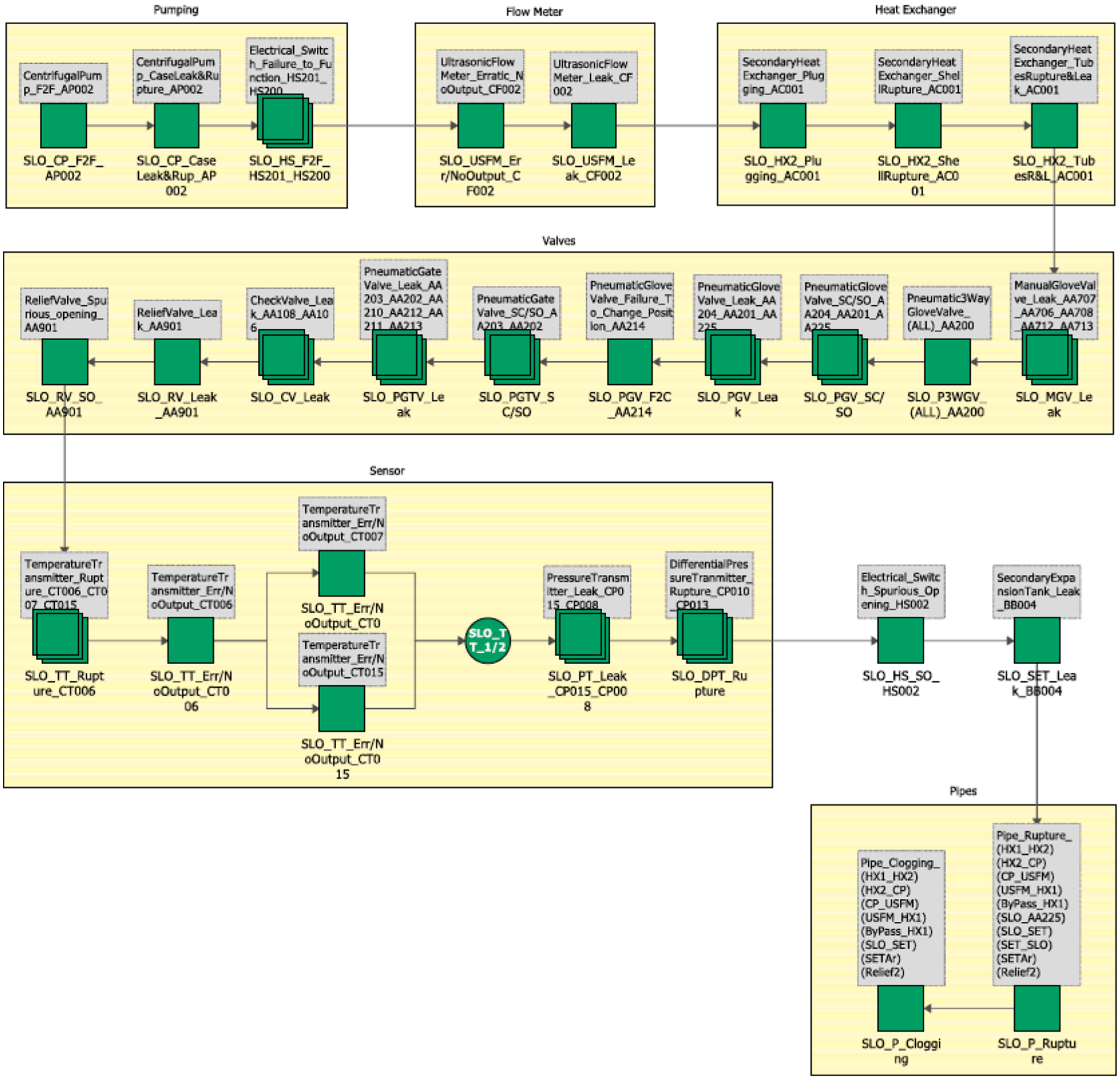

Fig. 8. Reliability Block Diagram for U_HTS2 unavailability condition.

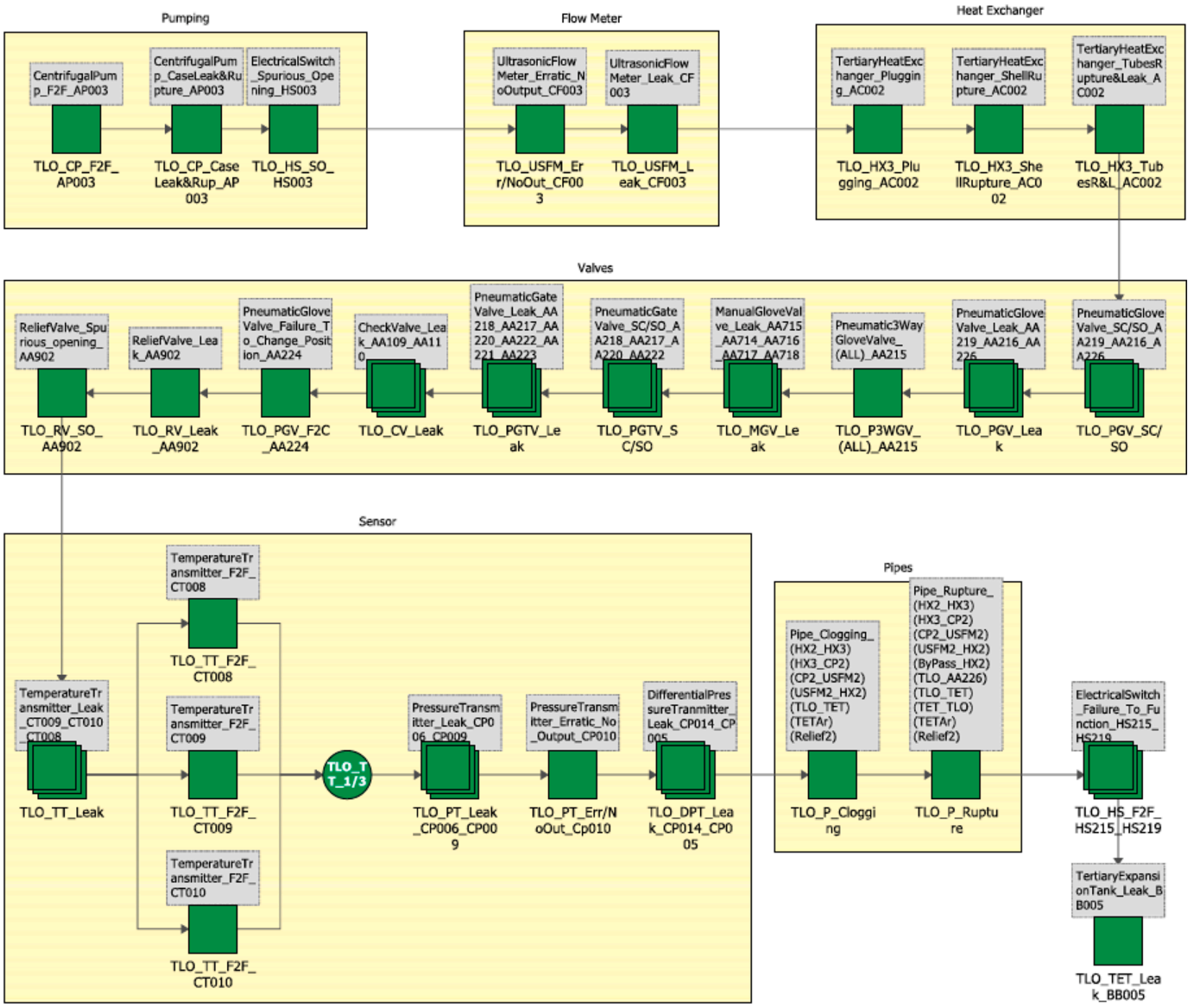

Fig. 9. Reliability Block Diagram for U_HTS3 unavailability condition.

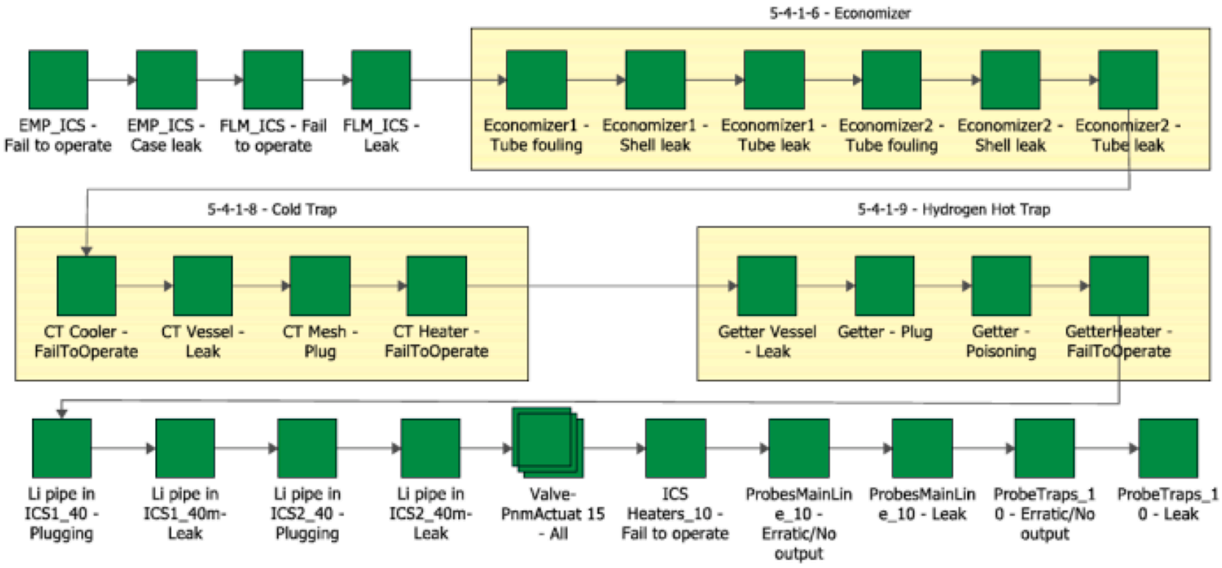

Fig. 10. Reliability Block Diagram for U_ICS and U_IMP unavailability conditions.

sensors for the same parameter within a system, the more redundancy for that parameter exists. That redundancy must be taken into account for the arrangement of RBDs. Some of those probes can also be part of an interlock for controlling important components like pumps or valves.

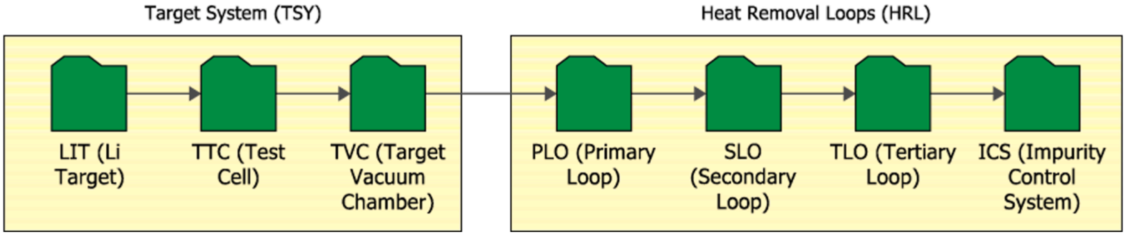

Fig. 11. Reliability block Diagram for LS system overall unavailability.

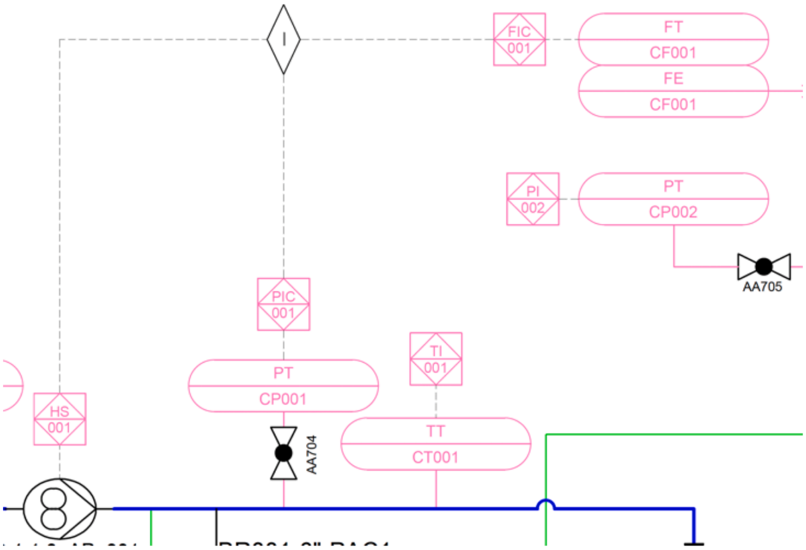

Fig. 12. Detail extracted from P&ID documentation from the LS.

iii Sensors exploited for interlock logic (e.g. sensors related to feedback control of electromagnetic pump as shown in Fig. 12) were considered as directly leading to UC and system stop in case of failure thus, if a sensor is part of an interlock and it is the unique sensor of that class working for such interlock, then there is no redundancy for it

iv Sensors measuring the same parameter, not being part of an interlock and located within the same subsystem, were considered as having redundancy. In these cases, the sensors were integrated within the RBDs with an "1 out of n" configuration.

v Due to room access policy and to account for current uncertainty in repair time, several scenarios were considered, but the study is based in the worst case in terms of MTTR for the CM. In this scenario, CM time for SLO, TLO and ICS are either 3 days or 20 days depending on the component (Table 3). Those number of days were extracted from the annual scheduled calendar of operations of IFMIF-DONES (Fig. 13), and were considered as the maximum stopping time.

vi The PM was considered only for active components (valves, sensors, pumps…) and for failures not related with leak tightness.

vii A restoration factor (RF) was defined for each active component after PM (e.g. 20%, 85% or 100%). If a replacement of the component was scheduled, then a RF of 100% was applied.

Table 3
CM time considered for each system.

System	CM [days]
TSY	20
PLO	20
SLO	3/20
TLO	3/20
ICS	3/20

2.4. *Operating schedule and considered mission time*

Fig. 13 shows the timeline for a full year of scheduled normal operation in IFMIF-DONES (365 days). It includes two periods of 171 days of normal operation and another two of scheduled maintenance: first one for short preventive maintenance (SM) (3 days) and last one for long preventive maintenance (LM) (20 days).

These periods of time (3, 20 and 171) were considered for the calculation process through the PD. It was assumed that the replacements of the components could not be carried out in one year, so a

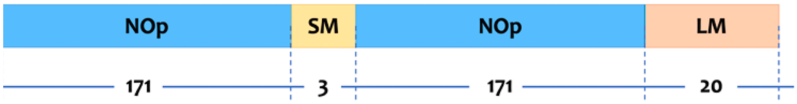

Fig. 13. Timeline for a full year in IFMIF-DONES.

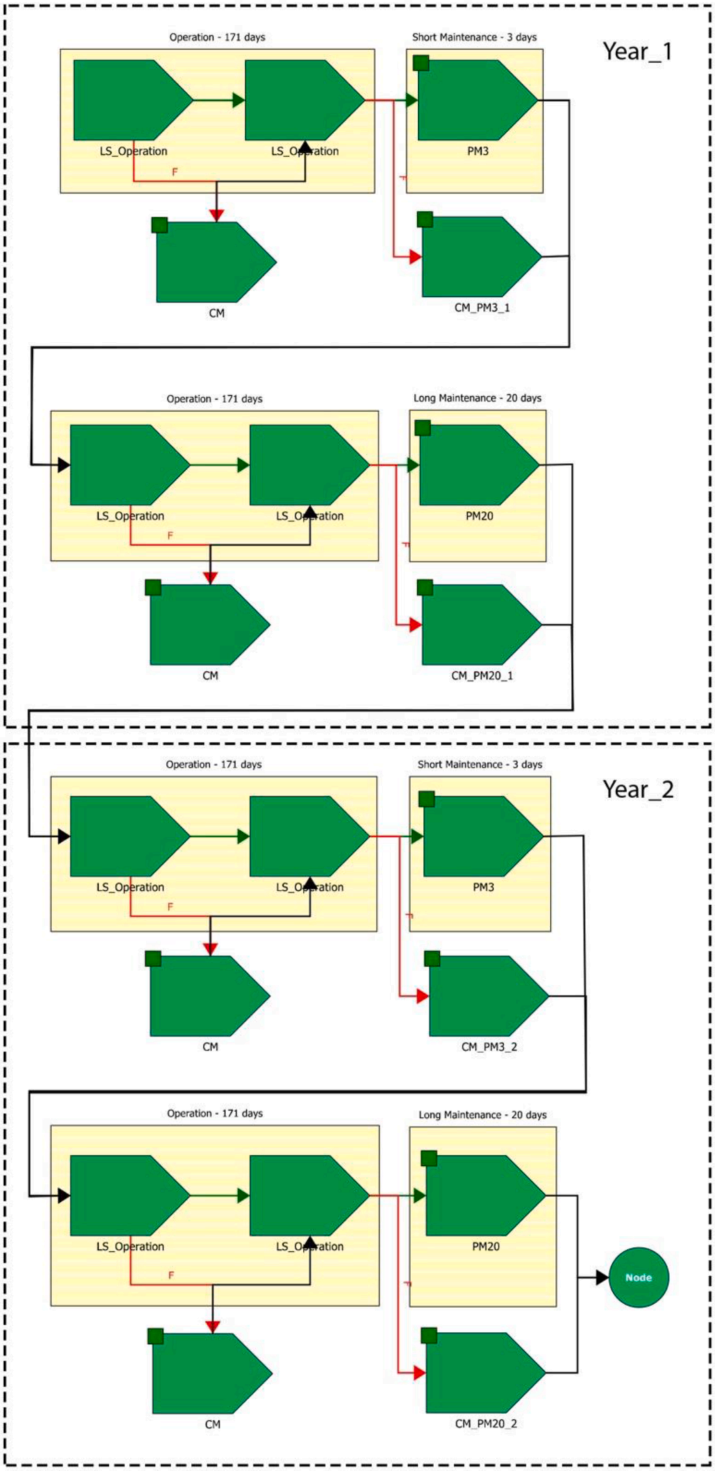

Fig. 14. Phase diagram for a cycle of two years of operation.

cycle of two years (1 + 1) for the PD was defined for restoration and maintenance as shown in Fig. 14.

The 171 days of normal operation period was divided into two: 70% and 30%, which means two periods of 120 and 51 days respectively. This is necessary for the model to be able to launch the CM phase only if the failure occurs within the first 120 days of operation since the last stop. If the failure happens within the 51 days period, which are closer to the next scheduled maintenance, then the CM and the PM are activated at the same time (phase CM_PM3/20). In this way, the PM phase is slightly ahead of schedule in order to take advantage of the CM stop.

Once the PD layout was finished, it was configurated by assigning the LS RBD to the normal operation phases, the CM template to the CM phases and each PM template to its correspondent phase in the PD.

A two-year cycle representing the mentioned maintenance approach was therefore implemented by means of phase diagram (presented in Fig. 14) and exploited to run availability simulations of the LS considering a mission time of 20 years of operation.

Regarding the reliability of the system, it was considered an

Table 4
List of the considered failure rates and maintenance policy.

Syst	RBD	Component	FM	Distrib.	MTTF [y]	Lam	Mu	Sig	CM [d]	PM	PM Phase
TSY	LIT	Inlet Pipe from HRL fixed	Clogging	Lognormal	38,051.75	–	18.65	1.40	20	–	–
TSY	LIT	Inlet Pipe from HRL fixed	Rupture	Lognormal	76,103.50	–	20.31	0.14	20	–	–
TSY	LIT	Inlet Pipe from HRL fixed	Leak	Lognormal	1014.71	–	15.98	0.19	20	–	–
TSY	LIT	Inlet Pipe from HRL removable	Clogging	Lognormal	11,415.53	–	17.44	1.40	20	–	–
TSY	LIT	Inlet Pipe from HRL removable	Rupture	Lognormal	22,831.05	–	19.10	0.14	20	–	–
TSY	LIT	Inlet Pipe from HRL removable	Leak	Lognormal	304.41	–	14.78	0.19	20	–	–
TSY	LIT	IPA_Inlet Plug Assembly	Clogging	Lognormal	22,831.05	–	18.13	1.40	20	–	–
TSY	LIT	IPA_Inlet Plug Assembly	Rupture	Lognormal	45,662.10	–	19.80	0.14	20	–	–
TSY	LIT	IPA_Inlet Plug Assembly	Leak	Lognormal	608.83	–	15.47	0.19	20	–	–
TSY	LIT	Flow straightener	Clogging	Lognormal	122,221.90	–	19.81	1.40	20	–	–
TSY	LIT	Flow straightener	Rupture	Lognormal	244,443.79	–	21.47	0.14	20	–	–
TSY	LIT	Flow straightener	Leak	Lognormal	3259.25	–	17.15	0.19	20	–	–
TSY	LIT	Reducer Nozzle	Clogging	Lognormal	570,776.26	–	22.02	0.79	20	–	–
TSY	LIT	Reducer Nozzle	Rupture	Lognormal	1,141,552.51	–	22.02	1.42	20	–	–
TSY	LIT	Reducer Nozzle	Leak	Lognormal	15,220.70	–	16.57	2.07	20	–	–
TSY	LIT	Channel BP-QTA	Clogging	Lognormal	380,517.50	–	21.62	0.79	20	–	–
TSY	LIT	Channel BP-QTA	Rupture	Lognormal	761,035.01	–	21.61	1.42	20	–	–
TSY	LIT	Channel BP-QTA	Leak	Lognormal	10,147.13	–	16.17	2.07	20	–	–
TSY	LIT	Channel QTA fixed	Clogging	Lognormal	76,103.50	–	20.01	0.79	20	–	–
TSY	LIT	Connection DJ2QTA	Clogging	Lognormal	285,388.13	–	21.33	0.79	20	–	–
TSY	LIT	Connection DJ2QTA	Rupture	Lognormal	570,776.26	–	21.32	1.42	20	–	–
TSY	LIT	Connection DJ2QTA	Leak	Lognormal	7610.35	–	15.88	2.07	20	–	–
TSY	LIT	Connection QTA-PLO	Clogging	Lognormal	285,388.13	–	21.33	0.79	20	–	–
TSY	LIT	Connection QTA-PLO	Rupture	Lognormal	570,776.26	–	21.32	1.42	20	–	–
TSY	LIT	Connection QTA-PLO	Leak	Lognormal	7610.35	–	15.88	2.07	20	–	–
TSY	LIT	Pipe QTA-PLO	Clogging	Lognormal	16,307.89	–	18.47	0.79	20	–	–
TSY	LIT	Pipe QTA-PLO	Rupture	Lognormal	32,615.79	–	18.46	1.42	20	–	–
TSY	LIT	Pipe QTA-PLO	Leak	Lognormal	434.88	–	13.02	2.07	20	–	–
TSY	LIT	OPA_Outlet Plug Assembly	Clogging	Lognormal	22,831.05	–	18.80	0.79	20	–	–
TSY	LIT	OPA_Outlet Plug Assembly	Rupture	Lognormal	45,662.10	–	18.80	1.42	20	–	–
TSY	LIT	OPA_Outlet Plug Assembly	Leak	Lognormal	608.83	–	13.35	2.07	20	–	–
TSY	LIT	All pipes and conductions	Clogging	Lognormal	3383.98	–	16.23	1.40	20	–	–
TSY	LIT	All pipes and conductions	Rupture	Lognormal	7082.91	–	17.93	0,14	20	–	–
TSY	LIT	All pipes and conductions	Leak	Lognormal	94.44	–	13.61	0.19	20	–	–
TSY	LIT	inlet FDS Lip Clamped Flange	Leak	Exponential	195.81	1.72E+06	–	–	20	–	–
TSY	LIT	(TAS-QTA) FDS Lip Clamped Flange	Leak	Exponential	195.81	1.72E+06	–	–	20	–	–
TSY	LIT	(TAS-QTA) FDS Bellow	F2F(compensate angular moves)	Exponential	106.69	9.35E+05	–	–	20	PM20_85%	PM20_2
TSY	LIT	(TAS-QTA) FDS Bellow	Leak	Exponential	3805.18	3.33E+07	–	–	20	PM20_85%	PM20_2
TSY	LIT	(TAS-QTA) FDS Bellow	Rupture	Exponential	38,051.75	3.33E+08	–	–	20	PM20_85%	PM20_2
TSY	LIT	LIT Pipe Heaters	Failure to operate	Lognormal	114.16	–	12.84	1.40	20	PM20_100%	PM20_1
TSY	LIT	Backplate	All failure modes	Lognormal	1.87	–	9.68	0.21	20	PM20_100%	PM20_1_2
TSY	LIT	TAS Support structure	Rupture	Lognormal	11,415.53	–	17.44	1.40	20	–	–
TSY	LIT	QTA Support structure	Rupture	Lognormal	11,415.53	–	17.44	1.40	20	–	–
TSY	LIT	QTA Vessel	Rupture	Lognormal	951.29	–	14.62	1.62	20	–	–
TSY	LIT	QTA Lip Flange	Rupture	Exponential	19,025.88	1.67E+08	–	–	20	–	–
TSY	LIT	QTA Thermal Insulation	All failure modes	Lognormal	11,415.53	–	17.44	1.40	20	–	–
TSY	LIT	(QTA-PLO) Lip Flange	Rupture	Exponential	19,025.88	1.67E+08	–	–	20	–	–
TSY	LIT	Sensors (LJET - TA - QTA)	Erratic/NoOutput	Lognormal	57,077.63	–	19.05	1.40	20	PM20_85%	PM20_1
TSY	LIT	Sensors (LJET - QTA)	Rupture/Leak	Lognormal	95.13	–	12.65	1.40	20	PM20_85%	PM20_1
TSY	TVC	TVC Vessel	Leak	Lognormal	198.88	–	14.00	0.86	20	–	–
TSY	TVC	TVC Vessel	Rupture	Lognormal	951.29	–	15.86	0.39	20	–	–
TSY	TVC	Beam Duct	Loss of Vacuum	Exponential	4566.21	4.00E+07	–	–	20	PM20_85%	PM20_2
TSY	TVC	Beam Duct #1	Rupture	Lognormal	57,077.63	–	20.02	0.14	20	–	–
TSY	TVC	Beam Duct #1	Leak	Lognormal	761.04	–	15.69	0.19	20	–	–
TSY	TVC	BD FDS Bellow	Leak	Exponential	3805.18	3.33E+07	–	–	20	PM20_85%	PM20_2
TSY	TVC	BD FDS Bellow	Rupture	Exponential	38,051.75	3.33E+08	–	–	20	PM20_85%	PM20_2
TSY	TVC	BD FDS Lip Flange	Rupture	Exponential	19,025.88	1.67E+08	–	–	20	–	–
TSY	TVC	BD FDS mechanical clamp	Leak	Exponential	272.45	2.39E+06	–	–	20	PM20_85%	PM20_2
TSY	TVC	BD FDS mechanical clamp	Rupture	Exponential	2724.47	2.39E+07	–	–	20	PM20_85%	PM20_2
TSY	TVC	Sensors (TVC - BD)	Loss of Vacuum	Lognormal	1141.55	–	15.14	1.40	20	PM20_85%	PM20_1
TSY	TVC	Sensors (TVC - BD)	Erratic/NoOutput	Lognormal	57,077.63	–	19.05	1.40	20	PM20_85%	PM20_1
TSY	TTC	Inlet Shielding Plugs	Seal/Leak	Lognormal	243.92	–	13.60	1.40	20	PM20_100%	PM20_1
TSY	TTC	Outlet Shielding Plugs	Seal/Leak	Lognormal	243.92	–	13.60	1.40	20	PM20_100%	PM20_1
TSY	TTC	Beam Ducts Shielding Plugs	Seal/Leak	Lognormal	243.92	–	13.60	1.40	20	PM20_100%	PM20_1
HRL	PLO	Pump	Failure to operate	Lognormal	114.16	–	12.84	1.40	20	PM20_85%	PM20_1
HRL	PLO	Pump	Rupture	Lognormal	5435.96	–	15.54	2.07	20	–	–
HRL	PLO	Pump	Leakage	Lognormal	543.60	–	13.24	2.07	20	–	–
HRL	PLO	PLO Switch	All failure modes	Lognormal	1164.85	–	15.16	1.40	20	PM20_85%	PM20_1

(*continued on next page*)

Table 4 (*continued*)

Syst	RBD	Component	FM	Distrib.	MTTF [y]	Lam	Mu	Sig	CM [d]	PM	PM Phase
HRL	PLO	Mixer	Leakage	Lognormal	11,415.53	–	17.44	1.40	20	–	–
HRL	PLO	Flow meter	Leak/rupture	Lognormal	95.13	–	12.65	1.40	20	–	–
HRL	PLO	PLO Flow meter	Failure to operate	Lognormal	26.55	–	11.84	1.01	20	PM20_85%	PM20_1
HRL	PLO	Heat Exchanger 1	Tube plugging	Lognormal	3805.18	–	16.34	1.40	20	PM20_20%	PM20_2
HRL	PLO	Heat Exchanger 1	Rupture in the shell	Lognormal	2283.11	–	15.83	1.40	20	–	–
HRL	PLO	Heat Exchanger 1	Leak in the shell	Lognormal	300.41	–	12.65	2.07	20	–	–
HRL	PLO	Heat Exchanger 1	Rupture/Leak in the tubes	Lognormal	28.54	–	11.45	1.40	20	–	–
HRL	PLO	PLO Pipe Heaters	Failure to operate	Lognormal	132.74	–	12.99	1.40	20	PM20_100%	PM20_1
HRL	PLO	Valve	Rupture	Lognormal	1141.55	–	15.14	1.40	20	–	–
HRL	PLO	PLO Sensors rup	Rupture	Gamma (U-L)	187.14	1.64E+06	–	–	20	PM20_85%	PM20_1
HRL	PLO	PLO Sensors Err/NoOut	Erratic/NoOutput	Exponential	142.69	1.25E+06	–	–	20	PM20_85%	PM20_1
HRL	PLO	PLO Sensors F2F	Failure to operate	Lognormal	163.08	–	13.95	0.67	20	PM20_85%	PM20_1
HRL	PLO	Pipe	Clogging	Lognormal	796.95	–	14.78	1.40	20	–	–
HRL	PLO	Pipe	Rupture	Lognormal	1593.90	–	16.44	0.14	20	–	–
HRL	PLO	PLO PGV Valve SC/SO	Spurious closing/ opening	Lognormal	951.29	–	15.53	0.90	20	PM20_85%	PM20_2
HRL	PLO	Valve	Rupture	Lognormal	4291.55	–	16.46	1.40	20	–	–
HRL	PLO	Dump tank Vessel	Rupture	Lognormal	951.29	–	14.96	1.40			
HRL	PLO	Dump tank Vessel	Leak	Lognormal	95.13	–	12.65	1.40			
HRL	PLO	Dump Tank Support structure	Rupture	Lognormal	11,415.53	–	17.44	1.40	20	–	–
HRL	SLO	SLO Pump	Failure to operate	Lognormal	18.41	–	11.97	0.22	3	PM3_85%	PM3_1
HRL	SLO	Pump	Case Leak/Rupture	Lognormal	114,155.25	–	19.74	1.40	20	–	–
HRL	SLO	Flow meter	Leak/rupture	Gamma (U-L)	308.53	2.70E+06	–	–	3	–	–
HRL	SLO	SLO Flow meter	Erratic/NoOutput	Exponential	118.91	1.04E+06	–	–	3	PM3_85%	PM3_1
HRL	SLO	Valve	Leakage	Lognormal	543.60	–	13.24	2.07	3	–	–
HRL	SLO	Heat Exchanger 2	Tube plugging	Lognormal	3805.18	–	16.34	1.40	20	PM20_20%	PM20_2
HRL	SLO	Heat Exchanger 2	Rupture in the shell	Lognormal	2283.11	–	15.83	1.40	20	–	–
HRL	SLO	Heat Exchanger 2	Rupture/Leak in the tubes	Lognormal	1141.55	–	15.14	1.40	20	–	–
HRL	SLO	Sensor	Rupture	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	SLO	SLO PG Valve SC/SO	Spurious closing/ opening	Lognormal	951.29	–	15.53	0.90	3	PM3_85%	PM3_2
HRL	SLO	Valve	Valve External leak	Lognormal	4291.55	–	16.46	1.40	3	–	–
HRL	SLO	SLO PG Valve F2CP	Failure to change position	Lognormal	76.10	–	13.40	0.17	3	PM3_85%	PM3_2
HRL	SLO	SLO Switch F2F	All failure modes	Lognormal	1164.85	–	15.16	1.40	3	PM3_100%	PM3_1
HRL	SLO	SLO Switch SO	All failure modes	Lognormal	1164.85	–	15.08	1.46	3	PM3_100%	PM3_1
HRL	SLO	SLO 3 W Valve	All failure modes	Lognormal	18.68	–	11.43	1.08	3	PM3_85%	PM3_1
HRL	SLO	Sensor	Rupture	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	SLO	SLO Sensors Err/NoOut	Erratic/NoOutput	Exponential	1563.77	1.37E+07	–	–	3	PM3_85%	PM3_2
HRL	SLO	SLO PGT Valve SC/SO	Spurious closing/ opening	Lognormal	951.29	–	15.53	0.90	3	PM3_85%	PM3_2
HRL	SLO	Valve	Valve External leak	Lognormal	4291.55	–	16.46	1.40	3	–	–
HRL	SLO	Valve	Valve External leak	Lognormal	1141.55	–	15.14	1.40	3	–	–
HRL	SLO	Sensor	Leakage	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	SLO	Pipe	Clogging	Lognormal	274.58	–	13.71	1.40	20	–	–
HRL	SLO	Pipe	Rupture	Exponential	21,966.66	1.92E+08	–	–	20	–	–
HRL	SLO	SET Vessel	Leak	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	SLO	SLO Relief Valve	Valve External leak	Lognormal	1934.83	–	15.67	1.40	3	–	–
HRL	SLO	SLO Relief Valve	Spurious opening	Lognormal	19.99	–	11.85	0.67	3	PM3_85%	PM3_2
HRL	TLO	TLO Pump	Failure to operate	Lognormal	18.41	–	11.97	0.22	3	PM3_85%	PM3_1
HRL	TLO	Pump	Case Leak/Rupture	Lognormal	114,155.25	–	19.74	1.40	20	–	–
HRL	TLO	TLO Switch SO	All failure modes	Lognormal	1164.85	–	15.25	1.34	3	PM3_100%	PM3_1
HRL	TLO	TLO Switch F2F	All failure modes	Lognormal	1164.85	–	15.16	1.40	3	PM3_100%	PM3_1
HRL	TLO	TLO Flow meter	Erratic/NoOutput	Exponential	118.91	1.04E+06	–	–	3	PM3_85%	PM3_1
HRL	TLO	Flow meter	Leak/rupture	Gamma (U-L)	308.53	2.70E+06	–	–	3	–	–
HRL	TLO	Valve	Leakage	Lognormal	543.60	–	13.24	2.07	3	–	–
HRL	TLO	Heat Exchanger 3	Tube plugging	Lognormal	3805.18	–	16.34	1.40	20	PM20_20%	PM20_2
HRL	TLO	Heat Exchanger 3	Rupture in the shell	Lognormal	2283.11	–	15.83	1.40	20	–	–
HRL	TLO	Heat Exchanger 3	Rupture/Leak in the tubes	Lognormal	1141.55	–	15.14	1.40	20	–	–
HRL	TLO	TET Vessel	Leak	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	TLO	Sensor	Leakage	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	TLO	TLO PG Valve SC/SO	Spurious closing/ opening	Lognormal	951.29	–	15.53	0.90	3	PM3_85%	PM3_2
HRL	TLO	Valve	Valve External leak	Lognormal	4291.55	–	16.46	1.40	3	–	–
HRL	TLO	TLO PG Valve F2CP	Failure to change position	Lognormal	76.10	–	13.40	0.17	3	PM3_85%	PM3_2
HRL	TLO	TLO 3 W Valve	All failure modes	Lognormal	18.68	–	11.43	1.08	3	PM3_85%	PM3_1
HRL	TLO	Sensor	Leakage	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	TLO	TLO Sensors F2F	Failure to operate	Lognormal	163.08	–	13.95	0.67	3	PM3_85%	PM3_2

(*continued on next page*)

Table 4 (*continued*)

Syst	RBD	Component	FM	Distrib.	MTTF [y]	Lam	Mu	Sig	CM [d]	PM	PM Phase
HRL	TLO	TLO PGT Valve SC/SO	Spurious closing/ opening	Lognormal	951.29	–	15.53	0.90	3	PM3_85%	PM3_2
HRL	TLO	Valve	Valve External leak	Lognormal	4291.55	–	16.46	1.40	3	–	–
HRL	TLO	Valve	Valve External leak	Lognormal	1141.55	–	15.14	1.40	3	–	–
HRL	TLO	Pipe	Clogging	Lognormal	366.54	–	14.00	1.40	20	–	–
HRL	TLO	Pipe	Rupture	Exponential	29,323.21	2.57E+08	–	–	20	–	–
HRL	TLO	Sensor	Leakage	Lognormal	95.13	–	12.65	1.40	3	–	–
HRL	TLO	TLO Sensors Err/NoOut	Erratic/NoOutput	Gamma (U-L)	142.69	1.25E+06	–	–	3	PM3_85%	PM3_2
HRL	TLO	Valve	Valve External leak	Exponential	1934.83	1.69E+07	–	–	3	–	–
HRL	TLO	TLO Relief Valve SO	Spurious opening	Lognormal	19.99	–	11.85	0.67	3	PM3_85%	PM3_2
HRL	ICS	EMP_ICS - Fail to operate	Fail to operate	Lognormal	38.05	–	12.36	0.84	20	PM20_20%	PM20_1
HRL	ICS	EMP_ICS - Case leak	Case Leak	Lognormal	1934.83	–	16.44	0.65	20	PM20_20%	PM20_1
HRL	ICS	FLM_ICS - Fail to operate	Fail to operate	Lognormal	15.22	–	11.43	0.86	20	PM20_20%	PM20_1
HRL	ICS	FLM_ICS - Leak	Leak	Lognormal	2853.88	–	16.02	1.43	20	PM20_20%	PM20_1
HRL	ICS	ICS Heaters_10 - Fail to operate	Fail to operate	Exponential	16.79	1.47E+05	–	–	20	–	–
HRL	ICS	Economizer1 - Tube fouling	Tube fouling	Lognormal	15.53	–	11.81	0.17	20	PM20_20%	PM20_1
HRL	ICS	Economizer1 - Shell leak	Shell leak	Lognormal	124.08	–	13.70	0.63	20	PM20_20%	PM20_1
HRL	ICS	Economizer1 - Tube leak	Tube Leak	Lognormal	350.17	–	14.31	1.12	20	PM20_20%	PM20_1
HRL	ICS	CT Vessel - Leak	Leak	Lognormal	4756.47	–	17.30	0.70	20	–	–
HRL	ICS	Li pipe in ICS1_40 - Plugging	Plugging	Exponential	1756.23	1.54E+07	–	–	20	–	–
HRL	ICS	Li pipe in ICS1_40 m - Leak	Leak	Exponential	116.48	1.02E+06	–	–	20	–	–
HRL	ICS	Probes in MainLine_10 - Erratic/No output	Erratic/NoOutput	Exponential	46,784.94	4.10E+08	–	–	3	PM3_20%	PM3_2
HRL	ICS	Probes in MainLine_10 - Leak	Leak	Exponential	40.47	3.54E+05	–	–	20	–	–
HRL	ICS	Valve-PnmActuat_15 - All modes	All failure modes	Exponential	2.73	2.39E+04	–	–	20	PM20_20%	PM20_1
HRL	ICS	Li pipe in ICS2_40 - Plugging	Plugging	Exponential	1756.23	1.54E+07	–	–	20	–	–
HRL	ICS	Li pipe in ICS2_40 m - Leak	Leak	Exponential	116.48	1.02E+06	–	–	20	–	–
HRL	ICS	Economizer2 - Tube fouling	Tube fouling	Lognormal	15.53	–	11.81	0.17	20	PM20_20%	PM20_1
HRL	ICS	Economizer2 - Shell leak	Shell leak	Lognormal	124.08	–	13.70	0.63	20	PM20_20%	PM20_2
HRL	ICS	Economizer2 - Tube leak	Tube Leak	Lognormal	350.17	–	14.31	1.12	20	PM20_20%	PM20_2
HRL	ICS	CT Cooler - Fail To Operate	Fail to operate	Lognormal	3.04	–	10.10	0.42	20	PM20_20%	PM20_1
HRL	ICS	CT Mesh - Plug	Plugging	Lognormal	163.08	–	13.90	0.73	20	PM20_100%	PM20_2
HRL	ICS	CT Heater - Fail To Operate	Fail to operate	Exponential	168.29	1.47E+06	–	–	20	PM20_20%	PM20_2
HRL	ICS	Getter Vessel - Leak	Leak	Exponential	5897.96	5.17E+07	–	–	20	PM20_100%	PM20_2
HRL	ICS	Getter - Plug	Plugging	Lognormal	163.08	–	13.90	0.73	20	PM20_100%	PM20_2
HRL	ICS	Getter-Heater - Fail To Operate	Fail to operate	Exponential	168.29	1.47E+06	–	–	20	PM20_20%	PM20_2
HRL	ICS	Getter - Poisoning	Poisoning	Lognormal	3.76	–	10.40	0.04	20	PM20_100%	PM20_2
HRL	ICS	ProbeTraps_10 - Erratic/No output	Erratic/NoOutput	Exponential	46,784.94	4.10E+08	–	–	3	PM3_20%	PM3_2
HRL	ICS	ProbeTraps_10 - Leak	Leak	Exponential	40.47	3.54E+05	–	–	20	–	–

Table 5
Reliability results for 171 days of operation.

Results for Reliability	
Mission End Time	4104 h → 171 days of operation
Individual RBDs outputs	
RBD	Reliability [%]
LIT	98.6
TTC-TVC	99.1
LIL	94.3
HTS2	94.1
HTS3	91.9
ICS	93.7
System Output	
LS	**70.3**

operation time of 171 days, which is the longest time without scheduled stops within the normal operation of the plant.

3. Results

Calculations for Reliability were made for 171 days (expected period of operation with no stops between two consecutive scheduled maintenance periods) and for each one of the RBDs individually. Results are reported in table 5.

Mean Inherent Availability simulations were performed according to IFMIF-DONES operational schedule (Fig. 14). Results are reported in table 6.

Regarding the calculations for reliability at 171 days a value of 70.3% was obtained for the LS (LIT + TTC-TVC + LIL + HTS2 + HTS3 + ICS) for the operation time considered. The most critical systems in terms of reliability are the TLO and the ICS with a result of 91.9% for the first one and 93.7% for the second. These results are consequent with the larger number of components with similar FRs that integrate these systems than others in the assessment. It must be highlighted that if a failure occurs in the ICS, there is some uncertainty on the timing affecting the main systems of the LS even appearing as the second worst result in terms of reliability.

Depending on combined effect of assumed FR data and possible redundancy, some of the components emerge as main contributors to system unavailability. In particular, among the components most affecting the criticality index, we highlight the TLO heat exchanger (shell rupture 6.87%) and the probe traps (leak 5,67%) from the ICS.

Concerning the availability results (Table 6), the LS output for the inherent availability (without PM) is 94.5% for 20 years of operation, complying with the 94% target established for the LS in DONES.

The most critical systems in this case are the LIT and the ICS with values for availability of 96.9% and 96.3% respectively. The

Table 6
Availability results for 20 years of operation.

Results for Availability				
Mission End Time	20 years			
Individual RBDs outputs				
RBD	Mean *Av.* w/o PM [%]	Uptime [h]	Downtime [h]	
LIT	96.9	169,876	5324	
TTC-TVC	99.4	174,190	1010	
LIL	98.1	171,788	3412	
HTS2	99.1	173,573	1627	
HTS3	98.9	173,186	2014	
ICS	96.3	168,767	6433	
System Output				
RBD	Mean *Av.* All Events [%]	Mean *Av.* w/o PM [%]	Uptime [h]	Downtime [h]
LS	79.1	**94.5**	138,575	36,625
Summary Metrics				
RBD	MTTFF [h]	MTBF [h]	Expected Number of failures	
LIT	15,872	15,301	11.45	
TTC-TVC	88,412	83,151	2.11	
LIL	26,880	23,510	7.45	
HTS2	25,076	18,626	9.41	
HTS3	20,322	16,455	10.65	
ICS	18,599	10,966	15.98	
LS	8393	3790	46.23	

Table 7
Results 20 years criticality ranking.

	Block Name	RS FCI [%]
1	CT Cooler - FailToOperate	8.76
2	Getter - Poisoning	5.89
3	TLO_HX3_TubesR&L	4.37
4	TLO_HX3_ShellRupture	4.37
5	PLO_HX1_Rup&LeakTubes	4.31
Sys	Mean Availability (All Events)	79.1
Sys	Uptime [h]	138,575
Sys	Downtime [h]	36,625

components leading the criticality ranking in terms of availability are CT Cooler and Getter, both from the ICS (failure to operate 8,76% and poisoning 5,89% respectively) and the Heat Exchanger from the TLO (tubes rupture and leak and shell rupture both with 4,37%).

Regarding the LIT, one of the most critical components is the backplate, on which the free surface jet of liquid lithium flows at a speed of about 15 m/s. It is the first component that is braked through by the neutrons flux, hence its FR is restrictive (lognormal with 0.2088 as first parameter and 9.6845 as second parameter). That is why the new maintenance policy stablishes that this component is going to be replaced once per year during the long-scheduled maintenance. The bellows or expansion joints included in the TSY have been considered also with a replace time of 1 year for the maintenance policy.

Table 8
Results 20 years increasing CT Cooler PM to once a year.

	Block Name	RS FCI [%]
1	CT Cooler - FailToOperate	8.68
2	Getter - Poisoning	5.95
3	TLO_HX3_TubesR&L	4.44
5	TLO_HX3_ShellRupture	4.27
4	PLO_HX1_Rup&LeakTubes	4.38
Sys	Mean Availability (All Events)	80.6
Sys	Uptime [h]	141,146
Sys	Downtime [h]	34,054

In relation to HRL system, the accuracy of the model has been increased due to the new detail of the sensors and valves included in the P&ID documentation and in this assessment. Type, number and location of sensors and valves as well as interlocks already defined, were considered for creating the failure mode and effect analysis and building the model. Besides the new layout with two electromagnetic pumps in series configuration for the PLO, was considered.

At this point a sensibility analysis can be done to emphasize the possibilities of this assessment in order to improve the maintenance policy for example. As said above, the principal contributors to the results criticality in terms of availability considering the FRs and maintenance policy showed in table 6 and for 20 years of operations are listed below together with the general results of availability:

Note that, as mentioned in Section 2.3, all the blocks appearing in table 7, have time-varying FRs, hence possibly benefiting from PM operation. On the other hand, the blocks 3,4 and 5 have leak-tightness based FMs for which no time-varying FRs have been adopted and no PM applied on them. Because of this, the sensitivity analysis is focused on the first two components: CT Cooler and Getter, both from ICS.

The scheduled PM for those components is applied each two years, with restoration factors of 20% for the Cooler and 100% for the Getter. By increasing the frequency of the PM to once a year, it is possible to see how it affects to the criticality ranking and the results. Three cases are presented below:

i The frequency of the PM for the CT Cooler is increased by 1 year (Table 8):
ii The frequency of the PM for the getter is increased by 1 year (Table 9):
iii The increase on the frequency for the PM is applied on both components (Table 10):

To better observe the sensitivity on the final results, the increase or decrease on the main variables respect the original results is presented in Fig. 15:

As shown above, the variability on the results increasing the frequency on the PM on the Cooler from the ICS does not reach the 2%. On the other hand, the results coming from the other two cases (Gett and Both) are very similar and practically are twice better than those from the first case, which means that changes done on the Cooler are not significant in comparison with those done on the Getter.

Therefore, if an improvement on the availability result is decided, it is better to do an effort in the consumption of human and economic resources to increase the PM applied on the Getter (1/year) than in the Cooler despite the first position in the criticality index belongs to the Cooler.

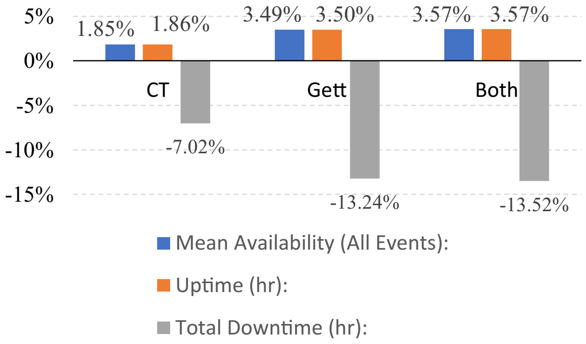

Fig. 15. Sensitivity analysis on the availability results with respect to baseline case when changing the frequency on the PM for CT Cooler and/or Getter….

Table 9

Results 20 years increasing Getter PM to once a year.

	Block Name	RS FCI [%]
1	CT Cooler - FailToOperate	9.43
–	~~Getter Poisoning~~	–
2	TLO_HX3_TubesR&L	4.76
4	TLO_HX3_ShellRupture	4.61
3	PLO_HX1_Rup&LeakTubes	4.66
Sys	Mean Availability (All Events)	81.9
Sys	Uptime [h]	143,422
Sys	Downtime [h]	31,778

Table 10

Results 20 years increasing Getter PM to once a year.

	Block Name	RS FCI [%]
1	CT Cooler - FailToOperate	9.18
–	~~Getter Poisoning~~	–
2	TLO_HX3_TubesR&L	4.68
3	TLO_HX3_ShellRupture	4.67
5	PLO_HX1_Rup&LeakTubes	4.54
Sys	Mean Availability (All Events)	81.9
Sys	Uptime [h]	143,526
Sys	Downtime [h]	31,674

4. Conclusions

The LS of DONES with its current layout and the maintenance policy applied, has an availability of 94.5% during 20 years of operation. The required availability target for the LS of 0.94 for DONES project is verified.

Note that the assumptions made in the maintenance policy concerning the duration of the MTTR have a repercussion on the results.

A sensibility analysis changing the PM on the most critical components is presented aimed at demonstrating that this type of assessment is necessary in decision making.

Future work will focus on assessing separately the ICS from the rest of the LS based on the assumption that a failure in that system may be not as critical as it happens in others. Besides it will be checked the global target achievement for IFMIF-DONES plant including all the group of systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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). In addition, it has been financed by the Junta de Andalucía through the projects "TAN19_UGR_IFMIF-DONES" and “SE2021 UGR IFMIF-DONES” co-financed by the European Regional Development Fund ERDF “A way to make Europe”/“Andalusia moves with Europe”. 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.

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