Availability Simulation Model of a Complex System:

A Contribution to the RAMI analysis of the ITER LFS CTS System

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***Abstract**: This paper describes a contribution to a RAMI analysis for the ITER Low Field Side Collective Thomson Scattering (LFS CTS) diagnostic system. The focus point is an availability and reliability analyses for the current design of the ITER LFS CTS. Several assumptions were made to overcome the inherent lack of knowledge, typical of early design stages. This study includes Reliability Block Diagrams(RBD) of the system, displaying hierarchical relationships as well as reliability and maintainability information, grounded on existing reliability and maintainability databases and expert's knowledge. Followed by a description of the analytical and computational approaches used to determine the availability and reliability of the system. To obtain the availability of the system two types of Discrete Event Simulations(DES) were implemented – the first one is synchronous it considers every element to be independent from each other while the second one is asynchronous it simulates the interdependencies between components offering a less conservative availability outlook. The implementation of DES allowed the analysis of structurally complex systems and provided a wide range of information regarding the ITER LFS CTS.*

Keywords: Discrete Event Simulation RAMI, Availability, Reliability, Low Field Side Collective Thomson Scattering, ITER.

1. Introduction

The ITER Organisation (IO) is an international endeavour aiming that breaking scientific barriers concerning nuclear fusion.

The ITER Low Side Field collective Thomson Scattering ITER (LFS CTS) is a plasma diagnostics system from ITER. The ITER LFS CTS must undergo a RAMI procedure, which is a technical risk control strategy specifically developed to apply to every equipment in ITER, by accessing the Reliability, Availability, Maintainability and Inspectability. [1]–[3]

The RAMI analysis process is a combination of analytical methods and integrative concepts aiming at driving the system to fulfil the projects targets. The qualities evaluated are the ability of continuous correct operation, reliability; the readiness for correct operation, availability; the ability to undergo repairs and modifications, maintainability; and the ability to undergo visits and controls, inspectability. It has an iterative nature, as it must be updated with every design improvement. During this period, it is still possible to implement corrective design measures that will impact the system's performance positively. This process defined by the ITER Organisation (IO) can be divided into 4 stages [3]:

- Functional Analysis (FA), it comprises a complete breakdown of the system from its main functions to basic functions and components;
- Failure Modes, Effects and Criticality Analysis (FMECA), is the establishment of a list of function failures, cause and effects in accordance to their importance for the availability of the machine; evaluation of the Severity of effects and Occurrence of the failure modes identified;
- Risk mitigation action: actions in terms of design, tests, operation and maintenance that reduce risk;
- RAMI requirements: integration of risk mitigation action accordingly to system's specifications.

The RAMI requirements are the integration of the risk mitigation actions and evaluation of their success and coherence with the requirements. In this case, there are called ITER RAMI process.: [1], [4]

- Meeting targets of availability and reliability for the different systems and subsystems;
- Design changes that are made to improve the current system availability and reliability;
- Tests to be performed on the components or systems;
- Operation procedures and specific training to lower the risks;
- Maintenance requirements: spares, intervals between inspections, preventive maintenance;
- Proposals for standardisation of common parts used in significant number in the project, ensuring inter-changeability of spares in the design of the systems allows for better reliability parameters

The scope of the collaboration of IST is, in part, the maturation of the LFS CTS by providing expertise in the RAMI area. The primary goal of a RAMI analysis is to guarantee that a system meets the project requirements. Evaluating these characteristics requires an understanding of the LFS CTS' global-function, basic-functions and sub-functions, the components involved and their interactions. Furthermore, it calls for the development of a flexible model of the equipment's behaviour, permitting the identification of subsystems and components that profoundly impact the ITER LFS CTS reliability and availability. The tasks, mentioned ahead, have significant input from the Preliminary RAMI analysis:

- Construction of Reliability Block Diagrams (RBD);
- Development of an Analytical Model for the availability and reliability of the ITER LFS CTS;
- Development of a Discrete Event Simulation fitted to the reliability architecture of the ITER LFS CTS system allowing a comprehensive stochastic quantification of the availability of the system; programmed on MathWorks Simulink, the MATLAB extension that allows modelling of continuous processes using block diagrams.

2. Methods

2.1 Reliability Block Diagrams

The Reliability Block Diagrams (RBD) approach uses the functional breakdown as a basis, but concentrates on the reliability-wise relationships linking the function-blocks (components that perform the function). Diagrams describing the multiple levels in a hierarchy consistent with the functional breakdown, together with the input data fed to the lowest level blocks, allow to compute the resulting reliability and availability for the upper levels, down to the main functions of the system or to the whole system itself. For this RAMI iteration the RBD were made with information gathered in previous analyses and by observing the current design of the ITER LFS CTS.[4], [5]

2.2. Analytical Approach

The Reliability $R(t)$, and Failure Function $F(t)$, of a single component can be calculated using equations (1), (2) and (3). The exponential distribution was used given its simplicity and the databases available which gave constant MTBF. Where:

$$R(t) = e^{-\lambda t} \tag{1}$$

$$\lambda = \frac{1}{MTBF} \tag{2}$$

$$F(t) = 1 - R(t) \tag{3}$$

To calculate the reliability and failure function of the entire system every component was considered critical. Thus, equation (4) can be applied to every component. Where:

$$R(t)_{Critical} = \prod R(t)_i \tag{4}$$

The calculate de Availability A, of a single component equation (5) can be used. Where:

$$A = \frac{TTF}{MTBF + TTF} \tag{5}$$

For combinations of components in series it is necessary to apply equation (6) Where:

$$A_{series} = \prod A_i \tag{6}$$

While for m-out-of-n networks equations (7) and (8) should be used. Where:

$$A_{m-out-of-n} = \sum_{j=m}^{n} \binom{n}{j} {A_{TL}}^{n} (1 - A_{TL})^{n-j} \tag{7}$$

$$\binom{n}{j} = \frac{n!}{(n-j)!\,j!} \tag{8}$$

The application of this method provides the average reliability and availability of the system, which is enough to get an idea of how the system behaves. To get more information the literature suggest that discrete event simulations are the ideal way to evaluate complex systems.[5]–[10]

2.3 Discrete Event Simulations

To further an availability analysis a Discrete Event Simulation (DES) is a respectable option. These simulation models are structured in the time domain, where the flow of events can be observed and evaluated. When a discrete event model is built for reliability, availability, maintainability and inspectability analysis, tasks and operations are modelled as discrete, chronologically ordered steps. The data treatment is represented in the Figure 1. The script initialises the simulation and gives the entities that are moved through the workflow attributes (reliability and maintainability parameters). The simulation then generates stochastic events and accordingly to those events enables state changes as time goes by. Data is then stored and analysed. To produce data with statistical meaning, it is necessary to run multiple trials with different outcomes. The number of trials should be chosen accordingly with the confidence interval desired.[11]–[15]

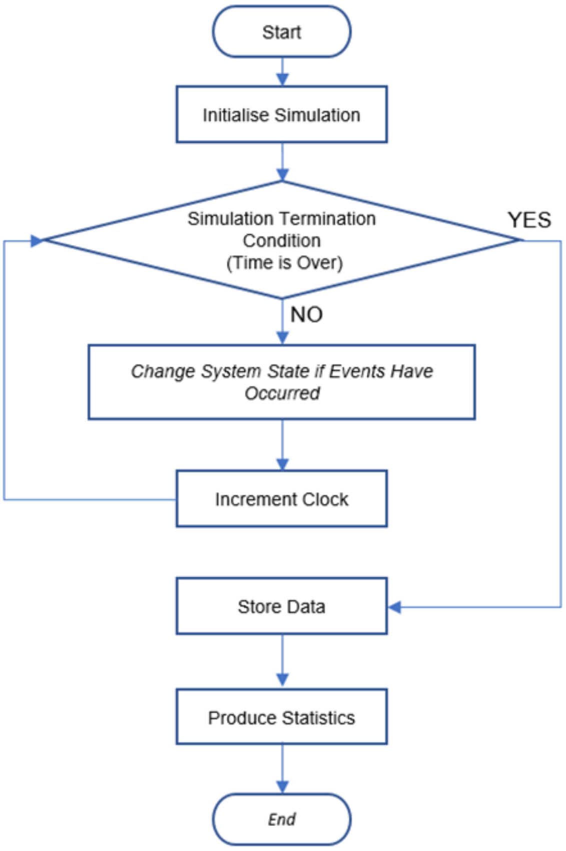

Fig. 1 Flowchart exemplifying one DES trial.

For this analysis two different algorithms and methodologies were developed. They were both programmed using MATLAB Simulink; one is synchronous (there is only one clock for each component) the other one is asynchronous (every component has an internal clock). In spite of the differences, they share basic actions, that are created by activity blocks. Among these blocks are:

- Pseudorandom Time to Failure Generator – using a pseudorandom number generator to get random Reliability probabilities and by reversing equation (1), it was possible to obtain pseudorandom Times to Failure (TTF) for every component;
- Boolean Signal generators for each component, this activity-block differs from one simulation to another;
- Signal processing blocks that combine accordingly to the RBD the different components

The major programming difference between the synchronous and asynchronous simulations are the Boolean Signal generators.
The first approach to a DES considers every component of the simulation independent, which means they work synchronously respecting the same clock. Components engage in failure-maintenance cycles until the trial has ended. Figure 2 shows how the failure-maintenance cycles work, and consequently the synchronous Boolean Signal generator activity-block. At the beginning every component is operational, so its signal is one, a TTF is loaded, when that loaded TTF is reached the component fails instantaneously and maintenance begins immediately, the component is now not-operational and its signal is zero. When maintenance the component becomes operational again, its signal becomes one and at the same time a new random TTF is loaded, so that a new failure will occur.

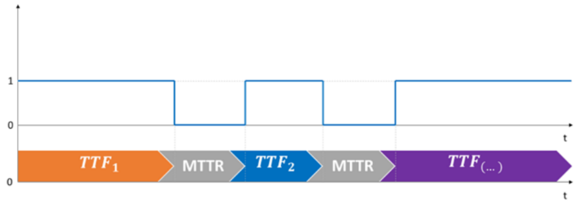

Fig 2. Sequence of Events in the Synchronous Simulation, until the TTF is reached the systems is operational during the MTTR the system is not-operational.

The second approach to a DES considers that there are interdependencies between the components. They work asynchronously, each component has its own internal clock and they engage in a failure-maintenance/delay cycle until the trial is ended. Figure 3 shows the cycle that must be generated by the activity-block of the asynchronous simulation. As before TTF are generated, failures are instantaneous, and repairs start immediately. However, now the system must take into consideration if any critical component has failed, if it has happened the rest of the system is put on hold creating a delay in the internal time. The practical effect is that TTF are postponed. As for the combination of signals from different components it is done accordingly to the RBDs developed.

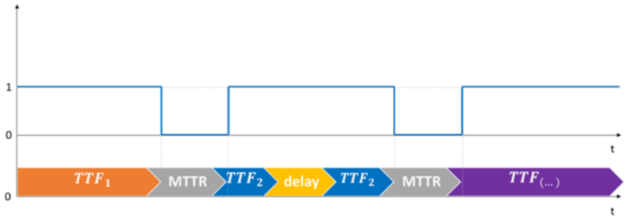

Fig. 3 Sequence of Events in the Asynchronous Simulation with a delay in the Time to Failure TTF_2.

The combination of signals of signals is then retrieved by a MATLAB script and converted into statistical data.

2.4 Critical Components

The first step of the RAMI analysis dealt with the creation of a complete functional breakdown, involving a top-down description of the system and sub-systems, from the main functions to the basic functions performed by the components. Since this work is an iteration of an already existing RAMI procedure [4]. The analysis was based on it and adapted to the changes implemented on the current design of the ITER LFS CTS. The components of this current design are:

- Gyrotron
- MOU Polarizer Unit

- Launcher ex-vessel Transmission Line (TL)
- Diamond Window
- Split-biased WG (electrically biased) – introduced after mitigation actions proposal for the launcher in-vessel TL
- Launcher in-vessel TL (cooled)
- Launcher Mirror M1 (cooled)
- Receiver Mirror M2
- Receiver Mirror M3
- Receiver in-vessel TL
- Fused Silica Window
- Receiver ex-vessel TL
- Receiver electronics
- Data Acquisition System (DAQ)

2.5 Reliability Blocks Diagrams

After having broken down the main functions into lower level functions, the next step addressed is the RBDs, used later on to compute the reliability and the availability of the ITER LFS CTS The RBD approach uses the functional breakdown as a basis, but concentrates on the reliability-wise relationships linking the function-blocks.

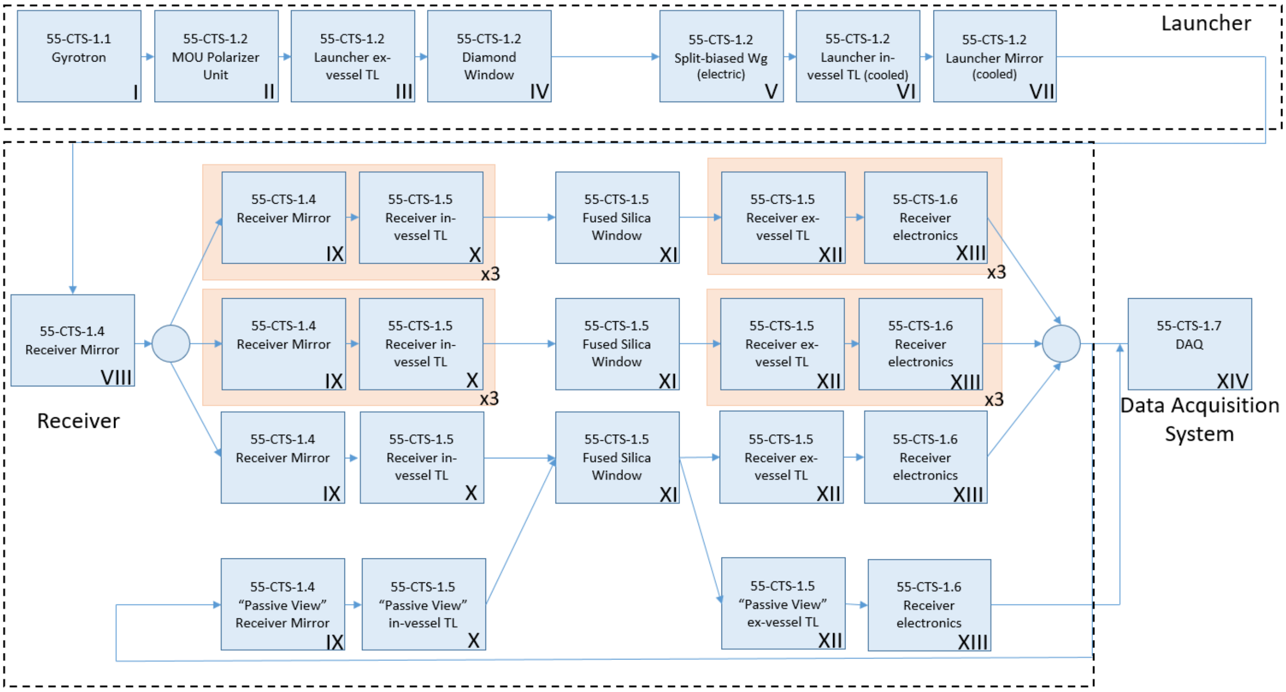

Fig. 4 Overview of the RBD used to evaluate the reliability and availability of the ITER. See Table 1 for Reliability and Maintainability data

The RBDs concentrate the multiple levels in a hierarchy consistent with the previously done analysis (functional breakdown). The low-level blocks are fed input data consisting of reliability and maintainability parameters: time to failure (TTF) and mean time to repair (MTTR). The input information was obtained from databases and the knowledge and experience of RAMI experts

According to the preliminary architecture at System Design Level, three different operation conditions have been considered for the determination of the reliability and availability of the ITER LFS CTS system (Figure 1):

- All sub-systems (launcher, receiver, Data Acquisition System) are in series;
- All components of the launcher and acquisition & control system are in series;
- The receiver sub-system consists of a receiver mirror M2 in series with n=7 identical transmission lines (receiver mirror M3, receiver in-vessel Transmission Line (TL), fused silica window, receiver ex-vessel TL and receiver electronics, each with its components in series. The identical receiver transmissions lines are assumed to be in parallel and the LFS CTS is declared available if at least m-out-of-7 transmission lines are available (the m-out-n case). The passive view is a special transmission line, with the same components as the others but whose operation might be critical depending on the quality of the microwaves received.

One must note that for the transmission lines, there was a key alteration in the design, where once there were seven completely independent transmission lines, now there are six transmission lines sharing two fused silica windows in groups of three as shown in Figure 2.

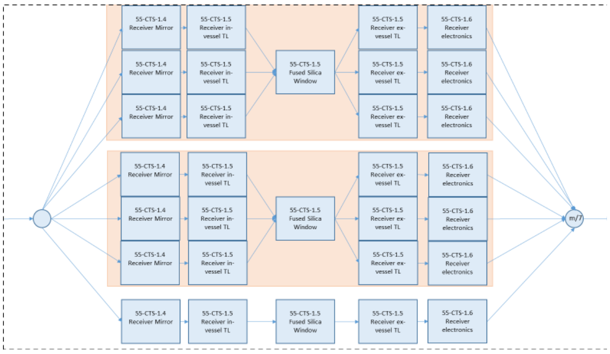

Fig. 5 – Overview of the current transmission line arrangement.

According to the specificities of the ITER LFS CTS, there are components that belong exclusively to the ITER Organisation (IO), but impact its operation, they are termed ex-vessel components (with the IO being responsible for them) and in-vessel components (which are the responsibility of the LFS CTS). To assess the impact of these particularities from the LFS CTS four RBD models were developed:

1. Whole System with Passive View
2. In-vessel components with Passive View
3. Whole System without Passive View
4. In-Vessel components without Passive View

Table 1: Critical Components of ITER LFS CTS. *(Passive View related components)

Critical Components	**Nomenclature**	**TTF (h)**	**MTTR (h)**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Gyrotron	I	35040	2160	1	1	-	-
MOU Polarizer Unit	II	87600	2160	1	1	-	-
Launcher ex-vessel Transmission Line (TL)	III	175200	2160	1	1	-	-
Diamond Window	IV	87600	2160	1	1	-	-
Split-biased WG	V	175200	2160	1	1	1	1
Launcher in-vessel TL (cooled)	VI	87600	2160	1	1	1	1
Launcher Mirror M1 (cooled)	VII	175200	2160	1	1	1	1
Receiver Mirror M2	VIII	175200	2160	1	1	1	1
Receiver Mirror M3	IX	175200	2160	7+1*	7	7+1*	7
Receiver in-vessel TL	X	175200	2160	7+1*	7	7+1*	7
Fused Silica Window	XI	87600	2160	3	3	7+1*	3
Receiver ex-vessel TL	XII	175200	2160	7+1*	7	7+1*	7
Receiver electronics	XIII	332880	24	7+1*	7	7+1*	7
Data Acquisition System (DAQ)	XIV	58516.8	24	1	1	1	1

3. Results and Discussion

3.3. Analytical Approach

3.3.1 Reliability and Availability

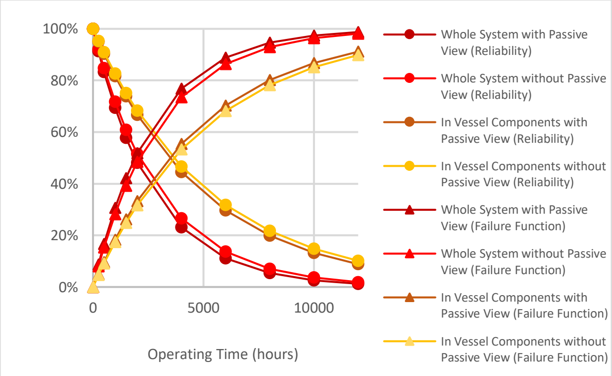

Fig. 4. Reliability and Failure Accumulated Probability for 7-out-of-7 transmission lines working.

The Reliability and Failure Functions were calculated considering 7-out-of-7 transmission lines operational and for the four models developed to analyse the four different models.

Figure 4 presents the results achieved, graphically, for the system reliability and failure probability for the four situations (all components with and without passive view, only in-vessel components with and without passive view). As expected, reliability increases when the ex-vessel components (IO scope) are excluded from the analysis when compared with the reliability of the whole system. For instance, at t = 4000 working hours, a success probability (reliability) of 23% is expected for the whole system (with passive view), and a success probability of 45% is estimated when the ex-vessel components (with passive view) are excluded. Figure 4 also shows that the effect of the passive view can be considered as small in absolute terms in both cases (all and only in-vessel components): the effect is smaller than 3% at t=4000h. However, in relative terms, the effect of the exclusion of the passive view cannot be neglected. At t=4000h its elimination in the case of the whole system means an increase of 6%. The analysis considering all components in series shows that the probability that the ITER LFS CTS system performs a complete run of 16 months without a failure is less than 2%. Excluding the ex-vessel components in the IO scope and considering only the in-vessel ones the reliability for a complete run of 16 months increases to 9% and 10%, with and without the passive view components respectively.

The Availability was calculated according to one of the projects stipulations which was having at least 5-out-of-7 transmission lines working and using equations (5) (6) (7) and (8), for the subsystems and for the project requirements. This boundary allowed for a simplification on the analytical calculations that could have been otherwise strenuous. For the availability the components “Fused Silica Windows” were considered to be in series, since they have become critical to fulfil the operational requirements.

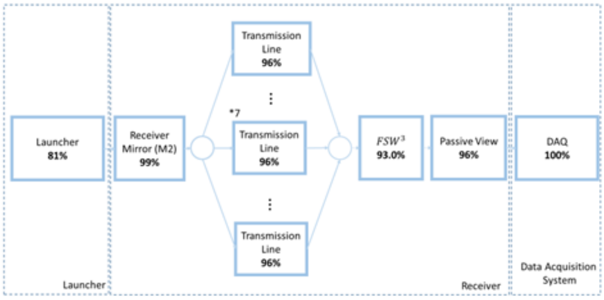

Fig. 5. High level RBD and subsystems availability

By combining the availability of every component accordingly to the reliability-wise relationships presented in Figure 5, it was possible to calculate the availability of the subsystems: Launcher, Receiver and Data Acquisition System, see Figure 5.

The Launcher has an availability of 81%. The Receiver is divided into four components in series, the Receiver Mirror (M2) with and availability of 99%, three Fused Silica Windows (FSW) considered to be in series in this approximation, and thus were represented together in a higher-level block, their combined availability is 93.0%. Then there are seven transmission lines in parallel and another special transmission line in series, the “Passive View”, these transmission lines have the same components, their availability excluding the Fused Silica Windows is 96%. Finally, there is the Data Acquisition system with an availability of 100%.

The transmission lines presented in Figure 5 are a part of an m-out-of-n network, and as an approximation a binomial distribution was used to calculate the availability of the four RBD models, see Table 2.

Table 2. Evolution of ITER LFS CTS system availability with m-out-of-7 receiver transmission lines.

	Whole System		*In-Vessel subsystems*	
m-out-of-n	*With Passive View*	*Without Passive View*	*With Passive View*	*Without Passive View*
7-out-of-7	*55.1%*	*57.2%*	*73.8%*	*75.6%*
6-out-of-7	*69.6%*	*72.2%*	*86.6%*	*88.7%*
5-out-of-7	*71.2%*	*73.9%*	*87.5%*	*89.7%*

As expected, the availability is higher when fewer components are included in series. The most relevant values are the ones related to the projects demands “at least 5-out-of-7 lines working”. For the Whole System with Passive view, the availability is 71.3%, when the passive view is excluded the availability increases by more than 2 points to 73.9%. As for the In-vessel subsystems with Passive View, the availability is 87.5% when the Passive View is excluded the availability increases to 89.7%. From the analytical analysis, the most impacting components seem to be the ex-vessel components. However, the Passive View in relative terms can provide increases on the availability of almost 4%, when excluded from the whole system.

3.4 Synchronous Discrete Event Simulation

Both simulations were run for 200 000 hours (20 years) and with 50 trials each, in order to get statistically relevant results.

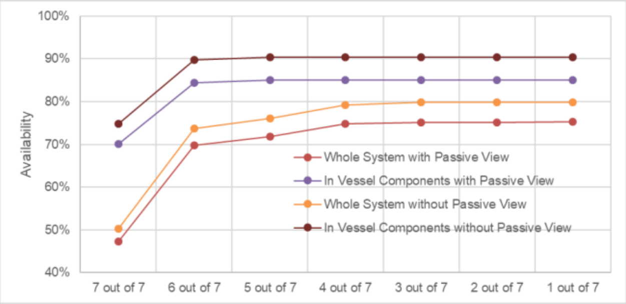

Fig 6 Evolution of the ITER LFS CTS system availability with m-out-of-7 receiver transmission lines, synchronous simulation.

The simulations performed (seen in Figure 6) by the different system models (whole system and in-vessel components, with and without passive view) allow a deeper comprehension of the impact and criticality of certain sub-systems. In the complete simulation including the passive view the availability, as expected is the lowest. It can reach 75%, but it can decrease to 47% as the number of functioning transmission lines increases to 7. Excluding the passive view from the simulation marginally improves the availability, as it now reaches almost 80% with its minimum in 50% when all transmission lines are assumed to be needed.

By excluding the ex-vessel components, the availability gains are superior to those of the passive view. The availability reaches almost 84%. However, for 7-out-of-7 transmission lines, it lowers to 69%. Finally, if the in-vessel sub-systems are simulated without the passive view, again the availability increased marginally to almost 90%, albeit lowering to 75% when 7-out-of-7 transmission lines are required to be functioning.

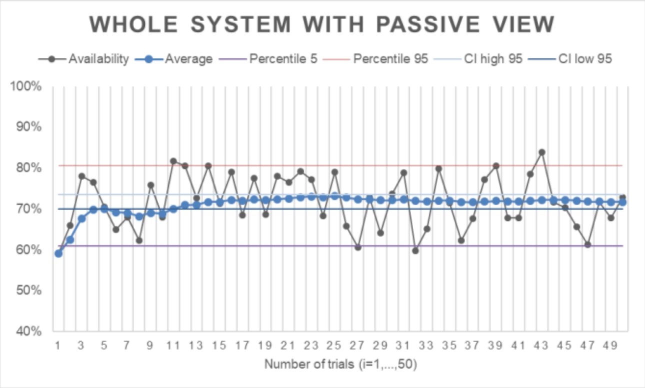

Fig 7. Evolution of the synchronous simulation results and statistical analysis of availability for the whole system with passive view. CI stands for a confidence interval of the mean.

In Figure 7 it is possible to see a synchronous simulation considering at least 5-out-of-7 transmission lines operational. The average availability for the whole system with passive view is 71.7%, and its 95% confidence interval is [69.9%; 73.6%]. Within the 50 runs, the availability ranges from 59.1% to 83.8% (90% of experiments with an availability within the interval [61.0%; 80.5%].

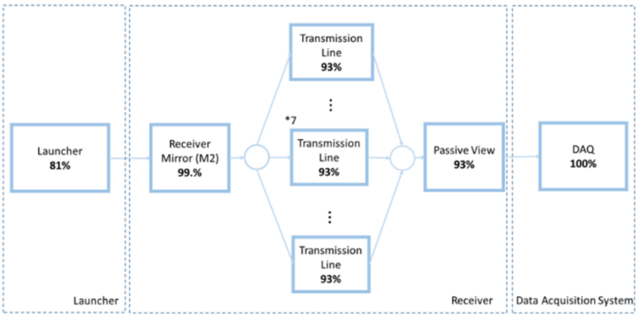

Fig 8. High-level RBD and sub-systems availability synchronous system.

Figure 8 presents a higher-level representation RBD of the ITER LFS CTS system with the availability results for the launcher, receiver mirror M2, transmission lines, passive view and data analysis sub-systems. These sub-systems' availability was estimated by the simulation developed. One can understand that the launcher (ex-vessel components in the IO scope) is the most critical sub-system to the availability of the ITER LFS CTS.

3.5 Asynchronous Discrete Event Simulation

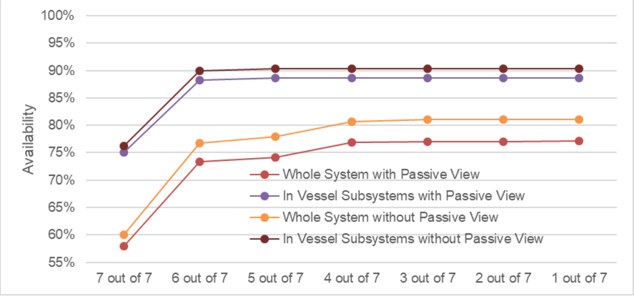

Fig 9. Evolution of the ITER LFS CTS system availability with m-out-of-7 receiver transmission lines for the asynchronous system.

The simulations performed by the different system models (whole system and in-vessel components, with and without passive view) allow a deeper comprehension of the impact and criticality of certain sub-systems. In the whole system including the passive view the availability, as expected is the lowest. As see in Figure 9, it can reach 77%, but it can decrease to 58% as the number of functioning transmission lines increases to 7. Excluding the passive view from the simulation marginally improves the availability, as it now reaches 81% with its minimum in 60% when all transmission lines are assumed to be needed.

By excluding the ex-vessel components, the availability gains are superior to those of the passive view. The availability reaches 87%. However, for 7-out-of-7 transmission lines, it lowers to 75%. Finally, if the in-vessel sub-systems are simulated without the passive view, again the availability increased marginally to 90%, albeit lowering to 76% when 7-out-of-7 transmission lines are required to be functioning.

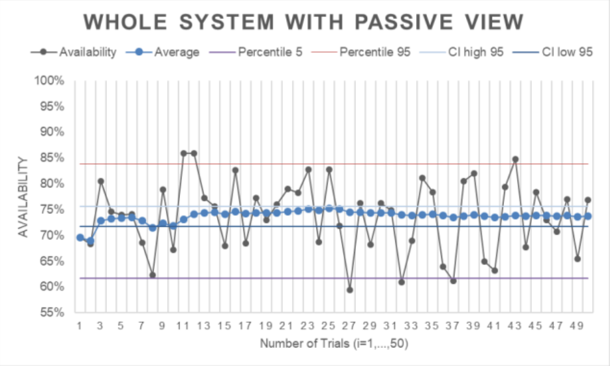

Fig 10 Evolution of the asynchronous simulation results and statistical analysis of availability for the whole system with passive view. CI stands for a confidence interval of the mean.

Figure 10 is an example of the analysis conducted for every RBD model, in this particular case it is the whole system with passive view. The average availability for the whole system with passive view is 74.1%, and its 95% confidence interval is [71.8%; 75.6%]. Within the 50 runs, the availability ranges from 57.2% to 85.9% (90% of experiments with an availability within the interval [61.8%; 84.6%].

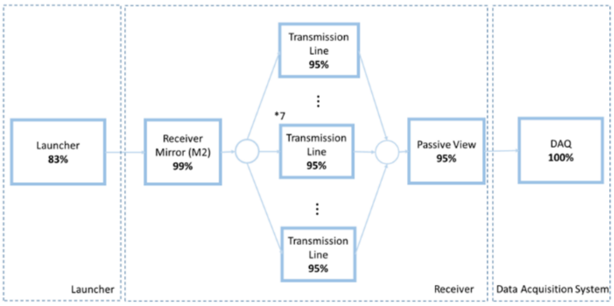

Fig 11 - High-level RBD and sub-systems availability for the asynchronous system, the whole system with passive view was used to get this data.

Figure 11 presents a higher-level representation RBD of the ITER LFS CTS system with the availability results for the launcher (83%), receiver mirror M2 (99%), transmission lines (95%) each, passive view (99%), and data acquisition (100%) subsystems. These subsystems' availability was estimated by the simulation developed. One can understand that the launcher (ex-vessel components in the IO scope) is the most critical sub-system to the availability of the ITER LFS CTS.

4. Conclusions

The stipulated operational conditions created the need to analyse four different cases: the whole system with and without the passive view, and only the in-vessel components also with and without the passive view ones.

With the four models defined, the next step was to make an analytical evaluation of them. It was a quick way to understand the behaviour of the system, its subsystems and estimate some of the impact of the transmission lines.

Then a synchronous Discrete Event Simulation (DES) was developed, allowing a deep understanding of the LFS CTS. The intricacies of the system that weighted on the analytical approach were overcome by the DES. This simulation model used random variables to describe the times to failure of each critical component. However, given that the order magnitude of the MTTR is not sufficiently small when compared to that of the TTF, the results obtained were too conservative, the best solution was to develop an asynchronous DES.

This last simulation allowed for a realistic representation of the LFS CTS, taking into consideration real-life cycles of failure-maintenance-delay. It was achieved by giving each component its own clock and measuring its operational working time. To generate significant results each simulation was run for a time span of 200 000 hours (about 20 years) and was replicated 50 times (50 independent runs). When the simulation model was run for different m-out-of-7 conditions, it was verified a significant degradation on the availability of the system when all the transmission lines have to be working for the system to be considered available. In the complete simulation including the passive view the availability, as expected is the lowest. Excluding the passive view from the simulation marginally improves the availability. By excluding the ex-vessel components, the availability gains are superior to those of the passive view. Finally, if the in-vessel sub-systems are simulated without the passive view, again the availability increased marginally. These sub-systems' availability was estimated by the simulation developed. One can understand that the launcher (ex-vessel components in the IO scope) is the most critical sub-system to the availability of the ITER LFS CTS.

The present RAMI analysis has provided a fundamental understanding of the ITER LFS CTS system availability, however, based on the knowledge gathered some issues were identified warranting further investigation, namely:

- Find and use updated and reliable data values for the reliability and maintainability parameters taking into account the detailed specifications of each critical component.
- Develop a new simulation considering the stochastic behaviour of the time to repair.
- Develop a new simulation model considering the fact that in-vessel maintenance of components that are not critical for ITER operation will have a frequency of about 2 years, i.e. if they fail, it could be 2 years until they are repaired.
- Develop a simulation model for the reliability of the system.

Acknowledgements

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