Analytical and Simulation Models for RAMI Analysis of a Complex System

A Contribution to the ITER PPR System

João Pedro Bachega Cruz

bachega@poli.ufrj.br

Instituto Superior Técnico, Universidade de Lisboa, Portugal

November 2018

This paper document describes a contribution to the updated RAMI Analysis for the Plasma Position Reflectometry (PPR), one of the main diagnostic system for ITER Operation. The procedure behind the analysis was started by reinterpretation of Functional Analysis, having as output a list of critical components for the system's objectives (one measurement and one main function) and whole ITER action. So, was developed new Failure Modes, Effects and Criticality Analysis and Reliability Block Diagrams, both adapted to the last design of the PPR System, with relevant new assumptions made. Using the Reliability and Maintainability databases guided by a theoretical background, an analytical approach was developed to evaluate the Reliability and Availability of the measurement and function, besides the possible impact to ITER machine operation. The structural complexity of the system demanded the development of a Synchronous Discrete Event Simulation, using the Monte Carlo Method as base. The Availability Simulation approach provided a wide range of information regarding the PPR System, among the confidence interval for Availability. All procedure was done having as objective guide the ITER PPR System to a better operation, reflecting in mitigation actions regarding the System and its components, once the System is under the Availability requirements established for ITER Organization.

Keywords: *RAMI; PPR System; ITER; Availability; Reliability; Discrete Event Simulation.*

1. Study Background

1.1. Introduction

The International Thermonuclear Experimental Reactor (ITER) Operation intend to be the first device to maintain fusion for long periods of time, with the largest Tokamak in the world achieving a 500MW controlled plasma. For the Fusion Experimental Reactor (FER) is planning 20 years of lifetime, divided in plasma operation periods of 16 months and further major shutdown of 8 months. [1]

The Plasma Position Reflectometry (PPR) System, one of ITER's main diagnostic systems used for diagnostics, provides information for plasma operation and for establishing performance characteristics, collecting information about the Plasma through a specific measure, the Electron Density Profile Measurement, accomplishing to the Plasma Position, essential function of the system.

Working as a part of ITER, PPR system must be accompanied by an iterative RAMI Analysis. This technical risk control strategy was stablished for IO, being a new interpretation of Maintenance and Safety study presented in literature, with the objective to be an apparatus for continuous commitment in guide the system to meets the project requirements in terms of the Reliability, Availability, Maintainability and Inspectability. Based on analytical methods and integrative concepts, RAMI Analysis aims to ensure that in a certain time, the system in study is Reliable (continuity of correct operation until the time instant), Available (readiness for correct operation), Maintainable (ability to undergo repairs and modifications) and Inspectable (ability to undergo visits and controls), guiding the project to frame in specified requirements.

The procedure defined is focused on the Functional Analysis of the PPR at system and sub-system level, on the Reliability of the components involved in the execution of each function, being divided into 5 stages: System Functional Analysis (FA); Reliability Block Diagrams (RBD); Failure Modes, Effects and Criticality Analysis (FMECA); Risk mitigation actions; RAMI requirements. One complete iteration of RAMI Analysis was already done by ITER Organization (IO) and it document is the major input for this new study. [2,3]

The first step is a Functional Analysis (FA), part that comprises a Functional Breakdown with the creation of a top-down description of the system and it sub-systems levels, from the main to the basic functions performed. The objective of the FA consists in identify all basic functions that the system must perform to meet the requirements and objectives of the whole system, having as output a list of the critical components associated with these functions. [4]

The second step consists in a schematic representation of the system using the Reliability Logic through an RBD, having as objective determine if each connection is operating or failed, given the information whether each block is in operating or failed state, being the system considered operational if a path of "closed switches" is found from the input to the output of the diagram. The output gave for this stage consist in RBD for each sub-system inside the PPR architecture, making possible plot structure representations creating a logic hierarchy for the system. With these representations added by the Reliability (MTBF) and Maintainability (MDT) parameters, it is feasible to achieve expected Reliability and Availability measures of different levels.

The third step is the Failure Modes, Effects and Criticality Analysis (FMECA), based on FA and RBD, intending to identify all failure modes (FM) for the components that accomplish each basic function, identify the causes and effects on the overall functions of each FM and make the qualitative assessment of the frequency of Occurrence of causes and Severity of effects, scales that form the Criticality, creating a criterion of prioritization of risks, to guide the design evolution.

The fourth stage consists in risk mitigation actions to reduce the risk level associated to the FM identified in FMECA with warning alarms of Criticality and/or Severity. These actions are distinguished by the way they reduce the Criticality Level, either by reducing the Severity, introducing more protection actions, or reducing the Occurrence, introducing more prevention actions, and also by the development phase of the project in which they are related to (design, test, operation or maintenance).

With the actions taken possible new Reliability Block Diagrams can be done (if structure was modified) and the changes result in Reliability and Availability reevaluation for the components and consequently for all following hierarchy.

The final step is the RAMI Requirements evaluation, comparing the final results of RAMI with established requirements, being these targets possibly complex and composed by different terms to be achieved by the System, like Availability, Reliability, Maintainability, Inspectability, Test and Validation of RAMI Performance, Spares and Standardization. But for the thesis study just concerns about Availability are considered, being the requirements minimize the Impact of PPR System's maintenance/replacement on ITER Operation and achieve 98.58±0.20% of Availability for ITER machine. [2]

1.2. Objectives

The RAMI Analysis for ITER PPR System intend to guide the system to meets the requirements, increasing the chances of great operation, what is possible to be achieved by the accomplish of basic stages of RAMI Analysis. So according to the functions and components defined in the reinterpretation of the IO System Functional Analysis, this document wants to produce new FMECA and RBD models, changed from last iterations of RAMI, to accommodate modifications on the reliability-wise relationships between components, introduction of new components and elimination of removed components, in accordance with the design evolution of the ITER PPR system.

Based on the architecture of the current RBD models the Reliability and Availability of the system must be calculated/estimated involving different studies:

- Evaluation of the Impact of the PPR system on the ITER Operation;
- Evaluation of Availability and Reliability of the ITER PPR Electron Density Profile Measurements;
- Evaluation of Availability and Reliability of the ITER PPR Plasma Position Function.

The calculation/estimation can be subdivided by approaches, being:

- Analytical approach made by analytical equations for Reliability and Availability of connections between components;
- Discrete Event Simulation approach made by a Synchronous Model, using the Monte Carlo Simulation as base.

2. RAMI Approaches and Models

2.1. Reliability Block Diagrams

The RBD approach uses the Functional Breakdown output (list of components for the Sub-Systems) as a basis but concentrates on the new assumptions for reliability-wise relationships linking the function-blocks (components that perform each basic 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 (components), allow to compute the resulting Reliability and Availability for the upper levels (Sub-Systems/Gaps), up to the main Measurement and Function of the PPR System or to the Impact for whole ITER Operation. These input data consist in the Reliability parameter, Mean Time Between Failures (MTBF), and maintenance parameter, Mean Down Time (MDT), both were obtained for this study from ITER Reliability databases. [4]

2.2. Analytical Approach

With organized hierarchy structure of System's Objectives, Sub-Systems and components, made by different RBD, the analytical approach intends now to calculate the Reliability and Availability parameters for each hierarchical level, starting in the lower level (component) until reach the main objectives (upper level).

Applying Equations (1), (2), (3) and (4) it is possible to calculate the Reliability or Failure functions for one isolated component and the maintenance parameter Mean Down Time (MDT), aware that the exponential distribution was used once a Useful Life approach is considered, i.e. the hazard rate is constant and the failures occur randomly or unpredictably, being described as stochastic processes. The available ITER databases give constant MTBF and repair rates μ_i for components, what agree with this supposition. [4,5,6,7,8]

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

$$R(\Delta t, \lambda_i) = e^{-\lambda_i . \Delta t} \tag{2}$$

$$MTBF = \frac{1}{\lambda_i} \tag{3}$$

$$MDT = \frac{1}{\mu_i} \tag{4}$$

Calculate the Instantaneous Availability for one component is possible using Equation (5), what is a characteristic of a "Two-State Markovian" model, a system that can just have two possible states, available ("up" condition) or unavailable ("down" condition), passing from available to unavailable by a failure rate λ_i and from unavailable to available by a repair rate μ_i. [4]

$$\mathrm{A}(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\mu+\lambda)t} \tag{5}$$

After calculate Reliability and Availability for separated components, the Equations (6), (7), (8), (9), (10) and (11) enable the calculations for series, active parallel and "*m* out *n*" parallel connections of components. [4,5,6,7,8]

$$R_S(t) = \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} e^{-\lambda_i t} \tag{6}$$

$$A_s(t) = \prod_{i=1}^{n} A_i(t) \tag{7}$$

$$R_P(t) = 1 - \prod_{i=1}^{n} \big(1 - R_i(t)\big) = 1 - \prod_{i=1}^{n} (1 - e^{-\lambda_i t}) \tag{8}$$

$$A_p(t) = 1 - \prod_{i=1}^{n} (1 - A_i(t)) \tag{9}$$

$$R_{moutn}(t) = \sum_{i=m}^{n} \frac{n!}{i!\,(n-i)!} \big(R(t)\big)^i (1 - R(t))^{n-i} \tag{10}$$

$$A_{moutn}(t) = \sum_{i=m}^{n} \frac{n!}{i!\,(n-i)!} (A(t))^{i} (1 - A(t))^{n-i} \tag{11}$$

Equations (1) until (11) applied on RBD outputted from RAMI Analysis provide analytical calculations for the System's Main Objectives, Sub-Systems and components. But for complement and increase the safety guarantee, the literature suggests the Discrete Event Simulation (DES) as a tool for achieve a confidence interval for Availability Simulation. [5]

2.3. Discrete Event Simulation

Develop an Availability Analysis through a Discrete Event Simulation procedure is a good option found in literature. The simulation is different effort to accomplish trustful results for the Availability, making a parallel deeper study based on the stochastic nature of the problem under analysis (modelling component's life). Two different DES were develop using the same Synchronous methodology, one for Impact to ITER Operation and one for Electron Density Profile Measurement/Plasma Position Function Analyses. [5,9,10]

PPR System's Main Objectives, Sub-Systems and components operations are modeled as working in a series of discrete time events, being ordered steps, separated by a computational sample time, with the total simulation time chose before the simulation starts (made for 116800h and 11680h). So, the simulation generates stochastic events (possible components failure) and accordingly to those events possible state changes can happen with the simulation time passing. A final Availability measure was outputted from each iteration. That data was then stored in Excel file to be analyzed. To produce data with statistical meaning, it is necessary to run multiple trials.

Both DES were programmed using MATLAB Simulink. The basic actions of the DES were common (between units) and created by blocks, being: Pseudorandom Time to Failure (TTF) Generator (Using a pre-programmed block from Simulink that generate pseudorandom numbers for Reliability and using the Inverse Transform Method in Equation (2), with failure rate being a weight coefficient factor, the TTF was generated); Boolean Signal generators for each component (Gives the state of component for all the simulation time); Connection between components blocks (Logical gates: AND for series, OR for active parallel and Relational Operators for "m out n" parallel) pre-programmated from Simulink are used in the Boolean Signal of each component to make a hierarchical connection between the blocks.

In the Synchronous Model Simulation, System's internal clock synchronize all the states changes happen in the system operation, considering each component of the simulation independent, which means they work synchronously governed by one global clock. Figure 1 shows how cycles of work are succeeded (operation/failure), and consequently the synchronous Boolean Signal generation. Every component starts operational, so its first signal is 1, a new TTF is loaded, when that loaded TTF is reached the component fails instantaneously and the MDT is loaded and begins immediately, so the component stays not-operational and its signal stays 0 until the maintenance finish and the component becomes operational again. Then, its signal returns to 1 and immediately a new random TTF is loaded and the process continues. This procedure is done iteratively until que simulation clock reaches the simulation time chose in the start. Every entire run of simulation time (11680h or 116800h) is one iteration. [11]

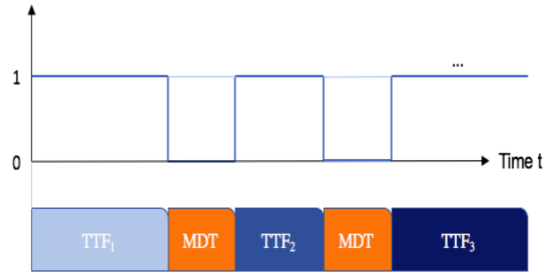

Figure 1: Sequence of Events in the Synchronous Simulation, until the TTF is reached the systems is operational and during the MDT the system is not-operational, giving a Boolean Signal of "life".

3. RAMI Results

3.1. Functional Analysis

Based on the last Functional Analysis (FA) document, which delimit all sub-divisions and objectives in PPR project, and in new schematics presented for Sub-System, a new interpretation of functions and components association was done, giving as final output a new list of critical components, that can be divided in 3 parts (In-Port-Plug/In-Vessel, Ex-Vessel and Back-End) inside each Sub-System, what can be understand by following resumed hierarchy (components divided in locations compose Sub-Systems named Gap(s) that collect measurements to accomplish the a main function, concerned about impact to the ITER machine operation): [12, 13]

1) The System Requirement generate an analysis to be done, that is the Impact to ITER Operation Analysis (must be minimized and achieve [98.58%±0.20%] of Availability for ITER machine).
2) System's Objectives: Electron Density Profile Measurement and Plasma Position Function.

The measurements are carried out at four toroidal/poloidal locations, known as Gap 3, Gap 4, Gap 5 (containing a redundancy in parallel, Gap5(A) and Gap5(B)) and Gap 6. It makes the PPR System device a collection of channels installed in different locations of the ITER Building, each one with the objective of collect from Plasma one measurement. Providing measurements of plasma edge density as a function of the distance from the wall at four defined locations known as Gaps, the PPR System can provide the main action, the Plasma Position Function.

A) Sub-Systems that form the PPR System:

As explained, the Sub-Systems are the reflectometry channels Gap 3, Gap 4, Gap 5(A), Gap 5(B) and Gap 6.

B) List of critical components (that compose each Gap, in different quantities and combinations):
    - Antenna to route microwaves;
    - Antenna supports/holders to withstand loads;
    - In-port-plug waveguide to route microwaves;
    - In-port-plug waveguide supports to withstand loads;
    - In-vessel waveguide to route microwaves;
    - In-vessel waveguide supports to withstand loads;
    - Feedthrough;
    - First Confinement Barrier SIC-1;

- Vessel/Port movement/expansion compensation arrangements;
- IEWT to transmit microwaves;
- Ex-vessel waveguide to route microwave signals;
- Ex-vessel transmission lines (TL) support to withstand load (Interspace);
- Ex-vessel transmission lines (TL) support to withstand loads (Port-Cell and Gallery);
- Mitre bend in interspace to route microwaves;
- Mitre bend outside interspace to route microwaves;
- Radial movement compensation units;
- Secondary Barrier (A) SIC-2;
- Secondary Barrier (B) SIC-2;
- Notch Filter;
- Slow Shutter;
- Spurious operation of Fast Shutter;
- Combiner/De-Combiner (CDC) to combine/de-combine microwave signals;
- Protection Filters;
- Detection System (Stray Sensor);
- Pin switches of the fast shutter;
- DC breaks;
- Radio Frequency (RF) source to generate microwaves;
- Receiver or and associated electronics to detect;
- Data Acquisition (DAQ) system;
- Back-end supports/holders;
- Local Controller;
- Control Software.

Noticing that, there is not yet information that allows to characterize the reliability behavior of some considered critical components. That way, this component was considered as “Transparent Units”, that means, with no considered failure rate associated, what needs to be review for upcoming RAMI iterations. For the secondary barriers, a separated simulation analysis was done giving values to be used in this RAMI Analysis. [14]

3.2. Failure Modes, Effects and Criticality Analysis (FMECA)

Applying the scales for Severity and Occurrence (qualitative judgment), and classification of prioritization of risk through the Criticality scale (formed for Severity and Occurrence combinations), is possible to make a Criticality Matrix and present components that may need mitigation actions or individual study. [2]

Therefore, the components in the sequence are considered as components with possible Impact to ITER Operation:

- Antenna supports/holders to withstand loads;
- In-Vessel waveguide to route mm wave;
- First Confinement Barrier SIC-1;
- IEWT to transmit;
- Secondary Barriers (A) and (B) SIC-2;
- CDC to combine/decombine mm-wavesignal.

Once the RAMI Requirement presented was clear about the importance that the PPR System do not present damage for the ITER machine operation, having a parameter in Availability to be achieved, these components can compose the Impact to ITER Analysis, studying if the combined impact caused by PPR System meets the requirements.

3.3. RBD

3.3.1. RBDs for the Reflectometry Channels (Sub-Systems, Gaps)

After having broken down the main functions of the system into lower level functions (addressed to components), the next stage consists is structuration in form of RBD, composed by components in the list of critical components, that can be used later to compute the Reliability and the Availability of the PPR System.

Starting by the representation of Sub-Systems (Gaps) in RBD form, Figures 2 until 5 represent each Gap, being each one composed by two reflectometry lines used for diagnostics purposes. The signal is issued from Gap final region (Back-End) of each Sub-System and travels all the structure through one emission line, until reaching the Plasma, and then comes back through another receiving line.

According to the system design it was assumed that all components inside each Gap structure are in series. Most blocks in the RBDs include more than one elementary component. In case one block consists of similar components, their number is presented below each block, and the set has a series Reliability connection too. [12]

However, in the Back-End sub-division, Reliability blocks (Stray Radiation Protection System, Back-End, and Local Control System) present a more complex architecture in terms of lower level components and Reliability relations among them, being represented at Figures 6 until 8.

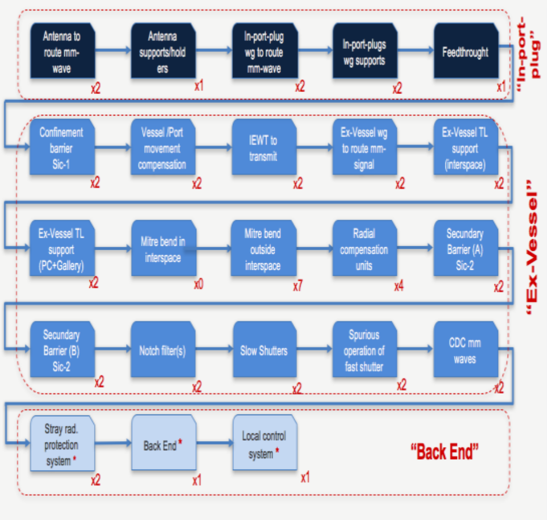

Figure 2: RBD of reflectometry channel Gap 3.

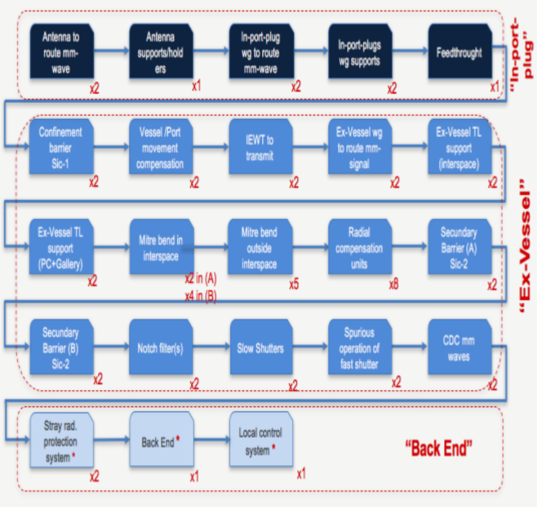

Figure 3: Generic representation for RBD of reflectometry channel Gap 5(A) and Gap5(B).

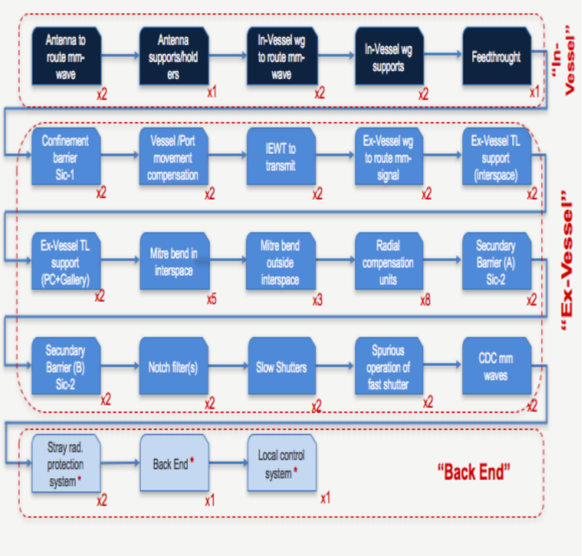

Figure 4: RBD of reflectometry channel Gap 4.

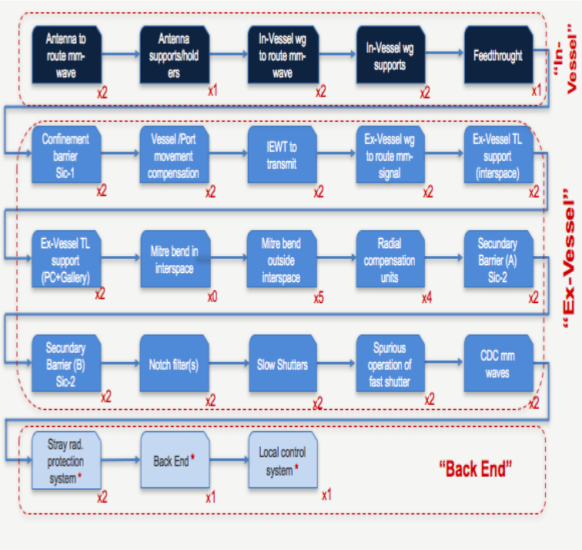

Figure 5: RBD of reflectometry channel Gap 6.

It should be noted that even if the RBD of the Stray Radiation Protection System represents its components in a parallel arrangement, if fact the requirement that the four parallel lines of 5 components in series must be operational ("4 out of 4" active parallel connection) for Stray Radiation Protection System to be considered available, results and logics converge in a classical series connection between all components (see Figure 6).

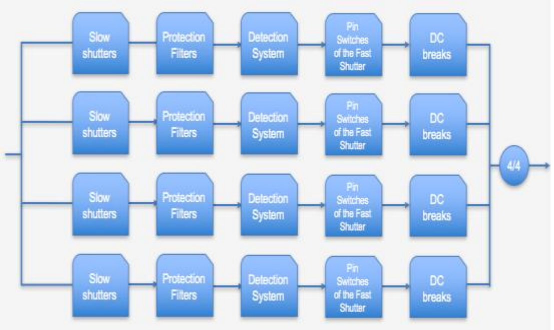

Figure 6: RBD of Stray Radiation Protection System.

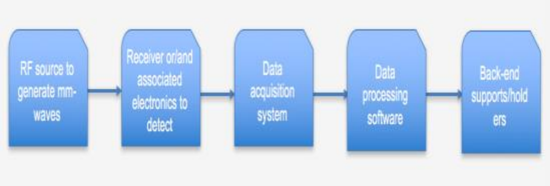

Figure 7: RBD of Back-End.

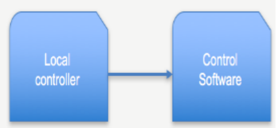

Figure 8: RBD of Local Control System to Control and Monitor.

3.3.2. RBDs for the Electron Density Profile Measurement and Plasma Position Functions (Main PPR System's Objectives)

Considering the objective of the ITER PPR System to provide Electron Density Profile Measurements and based on these measurements allow performing the Plasma Position Function, the higher level RBD for these measurements and position function are presented in Figures 9 and 10.

In fact, each Gap can provide an Electron Density Profile Measurement arising from one distinct location in the plasma, meaning that to have '*m* measurements out of the 4' possible ones, only *m* Gaps must be operational: the RBD presented below at Figure 9 considers a "*m* out 4" Parallel condition for the measurement case.

However, to ensure that the Plasma Position Function is available to guarantee the position of Plasma inside the Tokamak machine, all the 4 measurements must be provided. This means that Gap 3, Gap 4, Gap 5 and Gap 6 must present their measurements, and in the corresponding RBD this function is represented by a series of Gaps with a redundant active parallel for Gap 5, at Figure 10.

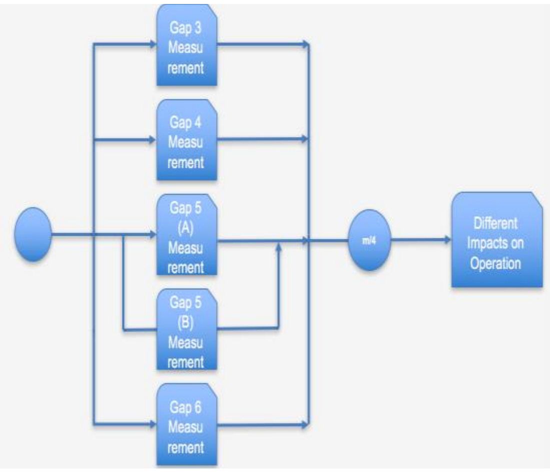

Figure 9: RBD of Electron Density Profile Measurement.

Figure 10: RBD of Plasma Position Function.

3.3.3. RBDs for the Impact on ITER Operation

Since the impact on ITER operation of a failure or any maintenance and/or replacement of the PPR System equipment is intended to be minimized, the components whose failure can result in a potential break of all ITER operation were identified in FMECA. Figure 11 presents the RBD designed to estimate the potential Impact to ITER Operation. All the identified components were considered in a series connection, reflecting that a failure of any of them determines a stoppage on ITER operation, such as previous sections, the number of components for each block it is designed below the block, where all the components are in series connection. Notice that the Secondary Barrier components was placed together in the RBD, once they are similar and have the same Input Data, presented next.

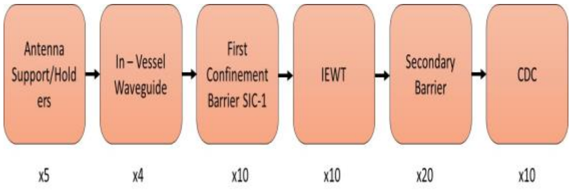

Figure 11: RBD of Impact on the ITER operation.

3.4. Reliability and Availability Measures

3.4.1. Analytical Results

With the main assumption of each reflectometry channel and component of the PPR system were considered as fully independent, the analytical calculations were done by the approaches considered, being the Analysis presented by: Table 1 and Figure 12 for Electron Density Profile Measurement; Table 2 for Plasma Position Function; Table 3 for Impact to ITER Operation.

	Reliability			Availability	
	R (264h)	**R (11680h)**	**R (116800h)**	**A (11680h)**	**A (116800h)**
"1 out 4" condition	99.93%	0.00%	0.00%	100.00%	100.00%
"2 out 4" condition	98.12%	0.00%	0.00%	99.94%	99.94%
"3 out 4" condition	84.01%	0.00%	0.00%	98.09%	98.02%
"4 out 4" condition	42.67%	0.00%	0.00%	77.51%	77.13%

Table 1: Results for ITER PPR System Electron Density Profile Measurement.

The results show a relevant dependency of Reliability and Availability with the number of reflectometry channels that must be available for the measurement operation. However, the damage in the results is only significant when 3 or 4 out of 4 Gaps should be operational for the measurement operation (see Figure 12).

It should also be noted that the Reliability becomes zero for a time line of 16 months (and consequently for 20 years). Nevertheless, the effect of time evolution in the Availability of measurement operation is almost worthless, as the MDT of components are significantly lower when compared with their MTBF.

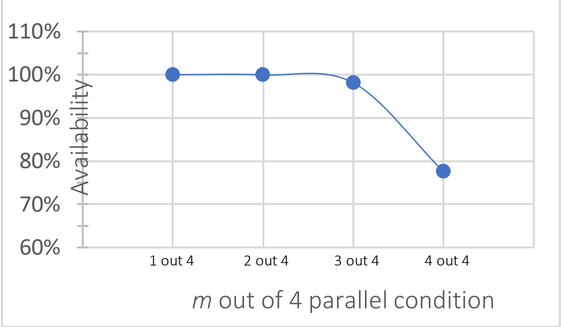

Figure 12: "m out 4" parallel analysis for Availability of the Electron Density Profile Measurement in a mission period (16 months).

Reliability			Availability	
R (11 days, 264h)	**R (16 months; 11680h)**	**R (20 years; 116800h)**	**A (16 months; 11680h)**	**A (20 years; 116800h)**
42.67%	0.00%	0.00%	77.51%	77.13%

Table 2: Results for ITER PPR System Plasma Position Function.

It should be noted that the results achieved for Plasma Position Function are equal to the ones obtained in the "4 out 4" reflectometry channels in the Electron Density Profile Measurement, as expected, once a "4 out 4" active parallel connection has a convergence to values of a series connection.

This notable results of Reliability and Availability in the PPR Plasma Position Function are a consequence of unexpected high values of the failure rate of Pin switches of the fast shutter components. Their failure rate is 1.14E-04 failures per hour. Besides it the single component with a failure rate in the 10^{-4} order of magnitude (all the other have significantly lower failure rates), it is worth remembering that each Gap have 8 Pin switches of the fast shutter in a series connection, inside the Stray Radiation Protection System, leading to a high damage in the function Reliability.

The effect of Pin switches of the fast shutter components in the Reliability and Availability of the PPR System brings the opportunity for a separated analysis of this component presented at Table 4, looking for solutions to increase their performance. The Preventive Maintenance is actually a practice based on Literature, where for the Maintenance phase of the project is programmed inspections and replacements to resolve problems of possible failures. It is used together with applications of redundant components in design phase for concern about the occurrence of a failure (Prevention Actions).

Reliability			**Availability**	
R (11 days, 264h)	**R (16 months; 11680h)**	**R (20 years; 116800h)**	**A (16 months; 11680h)**	**A (20 years; 116800h)**
99.80%	91.39%	40.63%	97.16%	96.79%

Table 3: Results for Analysis of Impact to whole ITER operation.

As expected the results of Reliability decrease when time evolves: the reliability within a timeline of 11 days is high, but in the mission time of 16 months it significantly reduces and for life time of the ITER operation the reliability is only 40.63%. It means that the probability of achieving a life of 20 years without any failure in the PPR System affecting the ITER operation is only 40.63%. The Availability results reflect this and are not accordance with the requirement for Availability presented in which is mention that the Availability shall be compatible with the overall 98.58±0.20%, and impact on ITER operation should be minimized.

The Reliability and Availability of elementary Pin switches of the fast shutter was calculated for decreased failure rates, according with the individual judgments of the design experts that only can explain a so high failure rate based on extremely severe operating conditions which is not the case on the PPR System, for this mechanical actuation component (see Table 4).

Failure Rate λ [1/h]	**Reliability**			**Availability**	
	R (11 days, 264h)	**R (16 months; 11680h)**	**R (20 years; 116800h)**	**A (16 months; 11680h)**	**A (20 years; 116800h)**
1.14E-04	97.04%	26.41%	0.00%	99.73%	99.73%
1.14E-05	97.70%	87.53%	26.41%	99.97%	99.97%
1.14E-06	99.97%	98.68%	87.53%	100.00%	100.00%

Table 4: Reliability and Availability for an elementary Pin switches of the fast shutter for decreasing failure rates.

Also, the Reliability and Availability were calculated at Table 5 for the Stray Radiation Protection System, considering decreasing values of failure rate of the Pin switches of the fast shutter.

Failure Rate λ [1/h] of Pin switches of the fast shutter	**Reliability**			**Availability**	
	R (264h)	**R (11680h)**	**R (116800h)**	**A (11680h)**	**A (116800h)**
1.14E-04	88.51%	0.45%	0.00%	98.89%	98.89%
1.14E-05	98.64%	54.49%	0.23%	99.87%	99.87%
1.14E-06	99.71%	88.01%	27.88%	99.97%	99.97%

Table 5: Reliability and Availability for the Stray Radiation Protection System for decreasing failure rates of Pin switches of the fast shutter.

For the same decreased failure rates of the Pin switches of the fast shutter, and assuming its preventive replacement every 6, 3 or 1 month(s), Table 6 presents the lower Reliability achieved for an elementary Pin switches of the fast shutter over the 16 months of the mission or the 20 years of the ITER operation life time (or in any period higher than the replacement interval).

Failure Rate λ [1/h] of Pin switches of the fast shutter	**Minimum Reliability**		
	6 months	**3 months**	**1 month**
1.14E-04	60.69%	77.91%	92.01%
1.14E-05	95.13%	97.53%	99.17%
1.14E-06	99.50%	99.71%	99.92%

Table 6: Reliability of an elementary Pin switches of the fast shutter for decreasing failure rates and different preventive replacements.

Table 7 (found in Annexes) presents the integrated effect of a higher value of the Pin switches of the fast shutter failure rate together with its preventive replacement on the Reliability and Availability of the Electron Density Profile Measurement and Plasma Position Function of the PPR System.

The Reliability values for the PPR System have significantly increased if preventive replacement of Pin switches of the fast shutter is implemented and a smaller failure rate is considered. The Reliability of the Electron Density Profile Measurement (in "1 out 4" Situation) increases from 0.00% (in a case with the actual failure rate for the component and no preventive maintenance) to more than 80% for the 16 months of a mission (example with lower failure rate and with preventive maintenance), and the Reliability of the Plasma Position Function increases from

0.00% to near 2% in the same time line. However, due to the effect of the remaining components for the life time of ITER operation, Reliability although larger is still almost 0%.

It should be noted that the replacement policy of the Pin switches of the fast shutter has no influence on the Availability. In fact, components failure rates are modeled as constants, in the called Useful Life approach and the components instantaneous availability is given for Equation (5), so by a deeply look it is plausible to understand that the Availability is negligible affected because the order of magnitude of the repair rate is already far higher them the failure rate.

3.4.2. Discrete Event Simulation Results

Figure 13 shows the stop criterion based on stabilization of Average Availability where the blue points represent each iteration Availability result, and the orange points the Average of Availability calculated at the iteration. Doing the DES for more trials until reach a number of iterations that stabilize the average (25 iterations for both) and enable to develop a good confidence interval. The Impact to ITER Operation Analysis, with less components (49), ran for 116800h of simulation time, corresponding to all ITER operation, while for the Plasma Position Function (Figure 14), with 346 components, just was possible to run 16 months' operation.

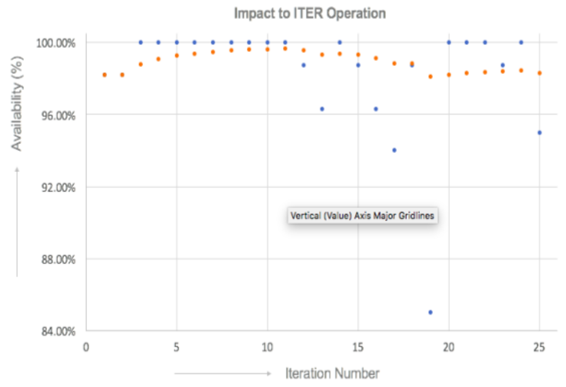

Figure 13: Results stabilization for Availability outputted from DES made for the Impact to ITER Operation Analysis, run 116800h.

Figure 14: Results stabilization for Availability outputted from DES made for the Plasma Position Function, run 11680h.

Using the 25 values for Availability collected from Synchronous DES made for Impact to ITER Operation and Effect to Electron Density Profile Measurement/Plasma Position Function Analysis and doing the Average, Standard Deviation and 95% Confidence Interval of the measures, Table 8, 9 and 10 present the results for the three analysis, respectively.

Availability Confidence Interval for DES		
Availability (Simulation sample time: 116800h)	**Standard Deviation (Simulation sample time: 116800h)**	**Confidence Interval of 95% (Simulation sample time: 11680h)**
98.33%	3.20%	[98.33% ± 6.27%]

Table 7: Availability Results for DES made for Impact to ITER Operation.

The Availability Average result are not in accordance by a slim margin with the requirement for Availability, therefore like in the Analytical Model, the Impact on ITER Operation should be minimized, even in this simulation, where 14 of 25 simulations for Impact to ITER Operation Analysis does not present any failure, achieving 100% of Availability. Looking for the standard deviation and the consequent confidence interval, the system may or not stay in accordance with the requirements, but even for more trials of simulation, the average value do not tend to converge for the requirement. (An amplified version of the graph illustrated in Figure 13 is placed on Annexes, Figure 15, being easier to see the results under the ITER requirements).

Should be noticed that the DES Average Result achieved of 98.33% with the following Standard Deviation of ±3.20% stays close for the Analytical Results of 96.79% achieved using Instantaneous Availability Equation (5), "for the same operation time" of 116800h. The statistical resulting for a Synchronous simulation tends to the Analytical Availability, because both gives the possibility of overlap failures, computed in an erroneous way for the System Availability. But the Synchronous Simulation is enough for the PPR System case, once the small MDT in comparison with the MTBF complicates the probabilities of overlapping, refuting an Asynchronous Simulation.

Availability for DES			
	Availability (Simulation sample time: 11680h)	**Standard Deviation (Simulation sample time: 11680h)**	**Confidence Interval of 95% (Simulation sample time: 11680h)**
"1 out 4"	100.00%	0.00%	[100.00% ± 0.00%]
"2 out 4"	99.96%	0.06%	[99.96% ± 0.12%]
"3 out 4"	97.72%	4.21%	[97.72% ± 8.25%]
"4 out 4"	75.77%	12.34%	[75.77% ± 24.19%]

Table 8: Availability Results for DES made for Effect to Electron Density Profile Measurements Analysis.

The values of Average Results from DES stay again close to the Analytical Results achieved using Instantaneous Availability Equation (5), for the same "time" of 11680h.

Availability Confidence Interval for DES		
Availability (Simulation sample time: 116800h)	**Standard Deviation (Simulation sample time: 116800h)**	**Confidence Interval of 95% (Simulation sample time: 11680h)**
75.77%	12.34%	[75.77% ± 24.19%]

Table 9: Availability Results for DES made for Effect to Plasma Position Analysis.

Again, the result of Average Availability for DES stay close to the Analytical one, 77.51%, but for this function, equally for the “4 out 4” case for the Effect in Electron Density Profile Measurement, the standard deviation and confidence interval stay too big, due to a simulation with variable results, guiding the possible necessity to more trials.

4. Conclusions

The Reliability Analysis of the PPR System was made considering the potential impact on ITER Operation, the effect on Electron Density Profile Measurement and the effect on the Plasma Position Function, with regards based on ITER operation proposition that the ITER machine Availability is the major focus of the project, so the whole operation interests must stand out in front of other lower Systems.

An availability of 97.16% for 16 months of mission time and of 96.79% for the ITER operation life cycle was achieved for the ITER machine due to critical failures on the PPR System, calculated by an Analytical Approach. These values are not in accordance with the diagnostic Availability requirements (that is stablished as 98.58±0.20%). This means that mitigation actions are needed specially driven for the components on the PPR System that directly can affect the ITER Operation. It should be noted that achieved Availability for ITER operation is the result of the Reliability of the different elementary components involved, which is quite high, along with the number of similar elementary components, which accounts for 59 components. With the same components, a Synchronous Simulation was modeled for the Impact to ITER Analysis guiding for 25 iterations of simulation, achieving for the ITER Operation life cycle one Average Availability of 98.33% with 3.20% of standard deviation, guiding for a confidence interval of [98.33%±6.27%]. The simulation confirms the possible necessity for mitigation actions to reduce the impact of PPR System on ITER Operation, being even possible that the system achieves the requirement due to the confidence interval. At this stage seems like design actions should be driven not only to increase the Reliability of the components but essentially to the reduction of the number of components involved in the impact of ITER Operation.

In the case of Electron Density Profile Measurement, due to the very high level of redundancy (five redundant reflectometers, Gap 3, Gap 4, Gap 5(A), Gap 5(B) and Gap 6, are considered as able to provide this measurement), the Availability results are very similar to the ones calculated for the case of the analysis of the expected impact of PPR system on ITER availability (99.94% of Analytical Availability and 99.96% for simulation Average Availability to take until 2 measurements for all ITER operation life cycle, showing that the damage in the results is only significant when 3 or 4 out of 4 Gaps have to be operational for the measurement operation.), and therefore they are in line with the general requirement for diagnostics, what is confirmed for the Synchronous Simulation results.

In the case of the Plasma Position Function, the Analytical Availability figures are around 77%. This is mainly due to the fact that all gaps are needed to provide a useful input to the ITER plasma position and control, and therefore every failure of a single component would lead to the failure of the measurement. Besides that, the In-Vessel Waveguides are only repairable during the LTM period, so the failure of a waveguide would significantly reduce the usefulness of the measurement for the ITER life time, what was not considered at this RAMI Analysis, once a MDT of 5840 hours was used to check this scenario, once the designers are concerned about this components with no maintenance during the operations of 16 months. The simulation leads for closer results (with Average Availability around 75%) and proves the worry about the Plasma Position Function.

Hence, in the case that this measurement is essential for the operation of ITER (which is not the case assumed in the present report), then design measures should be implemented in order to increase substantially the level of Reliability and Availability up to the general objective for this kind of measurement in ITER. Probably the implementation of redundancy (within PPR system or other reflectometers), and other design improvements would be needed. More trials on the simulation are another good choice to achieve a better (small) confidence interval for this Function.

A sensitivity analysis was performed on the influence of Pin switches of the fast shutter on the Reliability and Availability results of the Stray Radiation Protection System and on Electron Density Profile Measurement and Plasma Position Function, as it is a component with the higher failure rate and a high number of them are involved in a series connection. Also, the potential effect of its preventive replacement was analyzed. Results show that a significant increase in the Reliability is obtained. Although the high number of different components involved and their Reliability characteristics highly constraint the sensitivity of the PPR System to the Pin switches of the fast shutter. Event with these components with a null failure rate, the Reliability of the Plasma Position Function is 2.16% for the 16 months of mission time, and for the Electron Density Profile function is 87.17% for the same time frame (1 out of 4 measurements condition), showing that the Pin Switches of the fast shutter is not the unique problematic component affecting Reliability. Another time the Synchronous Simulation confirms the Analytical Results, showing a lot of failures in this specific component during a 16-month operation for one iteration of simulation.

Further iterations of the analysis are needed not only to accommodate the design evolution, but also to increase the accuracy and representativeness of the components input data and specially to include the missed Reliability and Maintainability data of some of the components.

Acknowledgments

This work was funded partially under the F4E 375 SG02 – 1018P.04333 project and would not have been possible without the instruction of my supervisors and the contribution of Instituto de Plasma e Fusão Nuclear (IPFN) and Instituto Superior Técnico (IST).

References

[1] ITER ORGANIZATION. Project.Inafewlines. [In line]. ITER. [2018] Available in WWW:<https://iter.org/proj/inafewlines.

[2] ITER Official Document: F4E_D_3DTWRE, v1.2/F4E-FPA-375-SG03: D08 - RAMI Analysis and Mitigation Plan for the Selected ISA.

[3] ITER Official Document: F4E_D_25PH75v4.2. Technical PA Requirement Annex for ITER PBS5.55.F3 (PPR).

[4] Infante V. and Henriques E., FRAMEWORK PARTNERSHIP AGREEMENT FOR DIAGNOSTIC DEVELOPMENT AND DESIGN: LFS COLLECTIVE THOMSON SCATTERING (CTS) Specific Grant 03 - System Level Design RAMI analysis of the best placed option and mitigation plan for unacceptable risks (D08), Lisbon, 2016.

[5] Zio, E.; The Monte Carlo Simulation Method for System Reliability 7 and Risk Analysis, Springer Series in Reliability

Engineering; DOI: 10.1007/978-1-4471-4588-2_2; Ó Springer-Verlag London; 2013.

[6] Zio, E.; An introduction to the basics of reliability and risk analysis. Singapore; World Scientific Publishing Company; 2007

[7] B.S. Dhillon; Engineering Maintenance: A modern approach; 2002.

[8] Ben-Daya, Mohamed; O. Duffuaa, Salih; Raouf, Abdul; Knezevic, Jezdimir; Ait-Kadi, Daoud; Handbook of Maintenance Management and Engineering; Springer; 2009.

[9] MATSUOKA, T.; Overview of system reliability analyses for PSA; International Journal of Nuclear Safety and Simulation; 2012.

[10] D. K. Chaturvedi; *Modeling and Simulation of System Using Matlab and Simulink*; 2010.

[11] Fragoso, Inês; Availability Simulation Model of a Complex System, A Contribution to the RAMI Analysis of the ITER LFS CTS System; Lisbon IST; 2017.

[12] ITER Official Document: F4E-FPA-375 (DG): SG03 Framework Partnership Agreement for Diagnostic and Design: ITER Plasma Position Reflectometry Specific Grant 05 – R&D for In-Port-Plug Components (PPR Gaps 3&5).

[13] ITER Official Document: F4E-FPA-375-SG03: Updated Functional Analysis at Sub-System Level (D7).

[14] ITER Official Document: UP01 PPR Penetration Window [D14] - Annex 3/F4E – Integration Design of Diagnostics into ITER Port – SC02/ID-19628-DEL-14-02-A3-UP01_PPR_Penetration_Window.docx.

Annexes

Pin switches of the fast shutter Component			**Electron Density Profile Measurement "1 out 4" Situation**		**Plasma Position Function**	
Failure Rate λ [1/h]		**Preventive Replacement**	**Reliability**		**Reliability**	
			16 months	**20 years**	**16 months**	**20 years**
Current Value	1.14E-04	6 months	3.06%	0.00%	0.00%	0.00%
		3 months	20.85%	0.00%	0.00%	0.00%
10^{-1} the λ	1.14E-05	6 months	72.19%	0.01%	0.47%	0.00%
		3 months	80.08%	0.01%	1.01%	0.00%
10^{-2} the λ	1.14E-06	6 months	85.84%	0.01%	1.86%	0.00%
		3 months	86.51%	0.01%	2.01%	0.00%
Failure Rate λ [1/h]		**Preventive Replacement**	**Availability**		**Availability**	
			16 months	**20 years**	**16 months**	**20 years**
Current Value	1.14E-04	6 months	100.00%	100.00%	77.51%	77.13%
		3 months	100.00%	100.00%	77.51%	77.13%
10^{-1} the λ	1.14E-05	6 months	100.00%	100.00%	82.43%	82.02%
		3 months	100.00%	100.00%	82.43%	82.02%
10^{-2} the λ	1.14E-06	6 months	100.00%	100.00%	82.93%	82.53%
		3 months	100.00%	100.00%	82.93%	82.53%

Table 7: Effect of "Pin switches of the fast shutter" failure rate and Preventive Maintenance on the PPR System reliability and availability.

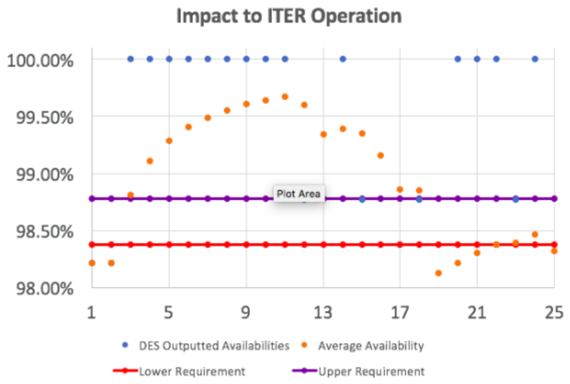

Figure 15: Amplified version of graph presented in Figure 13, presenting the Availability Results for Impact to ITER Operation under the Requirements (red line).