Fusion Engineering and Design xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Availability simulation software adaptation to the IFMIF accelerator facility RAMI analyses

Enric Bargalló [a,*], Pere Joan Sureda [a], Jose Manuel Arroyo [b], Javier Abal [a], Alfredo De Blas [a], Javier Dies [a], Carlos Tapia [a], Joaquín Mollá [b], Ángel Ibarra [b]

[a] Fusion Energy Engineering Laboratory (FEEL), Technical University of Catalonia (UPC) Barcelona-Tech, Barcelona, Spain
[b] Laboratorio Nacional de Fusión por Confinamiento Magnético – CIEMAT, Madrid, Spain

HIGHLIGHTS

- The reason why IFMIF RAMI analyses needs a simulation is explained.
- Changes, modifications and software validations done to AvailSim are described.
- First IFMIF RAMI results obtained with AvailSim 2.0 are shown.
- Implications of AvailSim 2.0 in IFMIF RAMI analyses are evaluated.

ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form 22 October 2013
Accepted 5 December 2013
Available online xxx

Keywords:
IFMIF
RAMI
Availability
Reliability
Accelerator
AvailSim

ABSTRACT

Several problems were found when using generic reliability tools to perform RAMI (Reliability Availability Maintainability Inspectability) studies for the IFMIF (International Fusion Materials Irradiation Facility) accelerator. A dedicated simulation tool was necessary to model properly the complexity of the accelerator facility.

AvailSim, the availability simulation software used for the International Linear Collider (ILC) became an excellent option to fulfill RAMI analyses needs. Nevertheless, this software needed to be adapted and modified to simulate the IFMIF accelerator facility in a useful way for the RAMI analyses in the current design phase. Furthermore, some improvements and new features have been added to the software. This software has become a great tool to simulate the peculiarities of the IFMIF accelerator facility allowing obtaining a realistic availability simulation. Degraded operation simulation and maintenance strategies are the main relevant features.

In this paper, the necessity of this software, main modifications to improve it and its adaptation to IFMIF RAMI analysis are described. Moreover, first results obtained with AvailSim 2.0 and a comparison with previous results is shown.

1. Introduction

The planned International Fusion Materials Irradiation Facility (IFMIF) has the mission to test and qualify materials for future fusion reactors. An adequate high energy neutron irradiation is provided by colliding accelerated deuteron ions on a lithium target, where the deuteron–lithium stripping reaction occurs. The generated neutrons are used to irradiate material specimens placed in the test modules inside the IFMIF test cell.

IFMIF high availability is a fundamental requirement for the international fusion roadmap. Obtaining the fusion materials database to find suitable materials for DEMO (DEMOnstration Power Plant) design on anticipated timeline is essential. RAMI (Reliability Availability Maintainability Inspectability) analyses are being performed from the early stages of the design to accomplish such requisites [1–4].

IFMIF RAMI analyses have evolved and became more complex as design and operation information aroused. Probabilistic calculations, comparisons with other facilities and simulations are done to cover the analyses on all fronts [3]. Customized software to perform global availability calculation for IFMIF accelerator facility was necessary. The software used, the modifications done to it and its implication in the IFMIF RAMI analyses are shown in next chapters.

2. Why a simulation?

Previous RAMI analyses were based upon fault tree calculations performed with Riskspectrum software. Some tricks and partial

* Corresponding author. Tel.: +34 660067655.
E-mail address: enric.bargallo-font@upc.edu (E. Bargalló).

0920-3796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fusengdes.2013.12.004

solutions permitted to obtain models that represented adequately the availability performance of the accelerator systems individually. However, a calculation for the whole accelerator facility was not feasible.

When failure acceptance, beam degradation operation and maintenance policies had to be added, a simulation of the whole performance of the accelerator became necessary.

A simulation tool allows modeling the accelerator characteristics in a way that would be impossible with any calculation. Moreover, customized simulation software allows taking into consideration relevant parameters and complexities that reflect the behavior of the whole accelerator in a better way than commercial software packages do. The drawback is that a simulation is more time-consuming in computing terms than a calculation.

3. AvailSim 1.0

The availability simulation software called AvailSim 1.0, developed for the International Linear Collider (ILC) [5] was an excellent option to fulfill RAMI analysis needs.

AvailSim 1.0 is a Matlab® Monte Carlo program that simulates the availability and beam characteristics of an accelerator. It simulates the continuous failure of components during the operation and the effect those events have on the accelerator performance. It allows flexible configuration of things like maintenance management, manpower requirements and operational parameters among others.

Some features of this software are: several ways problems can degrade performance, different kinds of maintenance (vault access required or not, hot swappable or not), turn-on recovery time (depending on failure, location and time expended), manpower control, and maintenance procedures customization (component priorities, kludges, wait until next scheduled maintenance period, etc.) [5].

However, AvailSim 1.0 needed to be modified in order to be useful for the IFMIF RAMI studies. AvailSim 2.0 is the modified version of the software that includes the changes to adapt it to IFMIF and some useful improvements. These changes are explained in Section 5.

4. How does AvailSim 2.0 works?

In a general manner, AvailSim 2.0 works in a similar way to its predecessor. However, there are several changes that make it considerably different than the previous version.

AvailSim 2.0 simulates the development of two elements linked between them: events and functions. Events represent the failure modes of the physical components of the accelerator and other actions like scheduled maintenance periods or periodic tests. Functions represent the accelerator operation parameters and the state of their systems. Moreover, buildings, facilities, rooms and locations and their characteristics like access time, maximum number of people allowed or radiation cool down times are included in the input data.

The software generates a timeline in which future events are placed. These events are generated following the probability distributions specified in the input data files. When simulation begins, the software takes the first event in the timeline and depending on its nature and its implications; it decides what has to be done. For example, if it is a failure with no consequences on the accelerator operation thanks to a redundancy, the operation continues. However, if the failure reduces a critical function below its minimum, the software will stop the operation and will plan the corresponding maintenance. In this case the software will define which components will be repaired, how many people are required and the time that will be needed.

After performing the maintenance, the software analyzes if the parameters and functions are in an acceptable state to continue operation. If they are, it starts operation again until the next event in the timeline.

The simulation continues until the simulation time defined is ended. Then, the software summarizes and records all parameters and results. After that, it will start again the simulation for the specified number of iterations. Finally, the software calculates the results for all iterations.

5. AvailSim 2.0 new features

In this section, the changes and improvements implemented in order to perform an adequate simulation for IFMIF are described.

5.1. Data and inputs

Failure modes: Components can fail in more than one way. In the new version, every failure can have different consequences on the system and different repair times. There is more than one possible event for each component.

Quantity: Unlike AvailSim 1.0, this version treats every component individually, considering specific consequences for each failure mode of each component.

Group of events: Every component belongs to a bigger system that is directly affected by it. The aim of the system indicator is to prevent an already failed component or system from further affecting the accelerator.

Input files: These files are text files in comma delimited format. The structure has been adapted to the IFMIF databases and design information.

5.2. Functions and parameters

Failures are not easily accepted for the IFMIF accelerator. Nearly every failure forces a degradation of beam parameters in order to continue operation [3]. Failure consequences require a complex tool to be properly modeled. This is the reason why functions have been modified to make them much more flexible in order to simulate the machine's peculiarities. Complex degraded operation and redundancies can be modeled. With these functions it is possible to make models similar to fault trees.

There are three kinds of functions: standard, special and critical. Standard functions are used for any redundant or any nonessential parameter. Special functions are used to gather different functions values or to have different minimum limits. Finally, critical functions are the top functions, the ones that determine the operation and state of the facility.

Every function has a design value and a minimum value, if a function value is decreased below its minimum, it will degrade another function or it will halt the machine operation if it is a critical function. Functions can be affected by other functions or by components' failure modes. Functions and failure modes can affect more than one function and in different ways. They can decrease its value, multiply it by a factor or set its value to a specified number.

Relationships between parameters can be included in function limits in order to stop the machine when different situations are reached. For IFMIF, it is assumed that operation with less intensity than the nominal can be accepted. However, beam intensity is directly related to the damage produced in the samples and therefore to beam availability. Consequently, if the beam intensity is too low, it may be preferable to repair the failed components than to continue in a degraded operation mode. The decision will depend on the amount of intensity degradation, the downtime to repair the

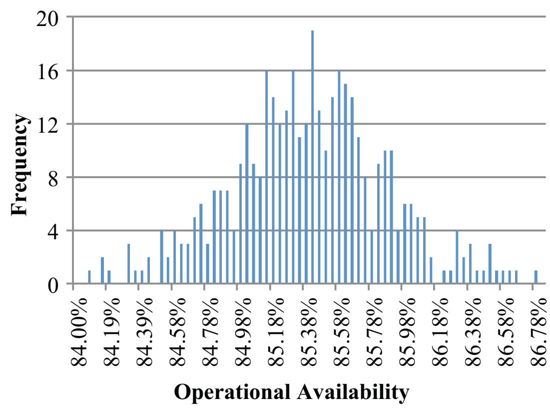

Fig. 1. Histogram for IFMIF accelerator facility operational availability results.

component and the remaining time to the next scheduled maintenance period. This is explained in the parameter evolution example of Section 7.3.

5.3. Simulation iterations

A loop in which the software runs any number of iterations of a simulation has been implemented. The results are statistically treated to obtain mean values, errors, standard deviation and confidence intervals among others.

As an example, Fig. 1 shows a histogram of the availability obtained in 400 iterations of a 30 years simulation.

5.4. Outputs

A great deal of detail about a simulation run can be output if desired. The history files record all actions and events occurring during the simulation (like in the previous AvailSim version). However, the structure has been adapted to allow database queries in order to be able to extract information easily.

Components and their failure modes can be evaluated in terms of the size of their contribution to unavailability. Individual and combined information about number of failures and mean downtime can be obtained. Moreover, other information like maintenance while the accelerator was down due to another failure or the times that the scheduled or unscheduled maintenance periods were increased to perform repairs due to a particular component have been included in the results.

Furthermore, data about the evolution of each facility during the 30 year simulation have been included to see time dependencies of the parameters.

5.5. Other changes and improvements

Like in the previous version, it is possible to introduce a parameter that defines how much the scheduled maintenance periods can be increased to perform nonessential maintenance actions. Moreover, in the new version, if a failure occurs before a scheduled maintenance period, the scheduled maintenance actions can be done during this non-scheduled downtime (e.g. preventive maintenance). These specifications can be defined in the input files.

In the new version, it is not considered that all failures are repaired during the long scheduled maintenance period. Therefore, it is possible to start a new run with a failure in a non-essential component. This usually occurs when a scheduled maintenance has to be increased too much and there is no important degradation in beam parameters.

Table 1
Generic AvailSim 2.0 results.

Parameter	Value
Accelerator operating	210,331 h
Accelerator down	35,908 h
Scheduled maintenance	16,560 h
Operational availability	80.03%
Hardware availability	85.42%
Vault access	17,508 h
Maintenance extended	352 h
Downtime for scheduled maintenance	940 h
Number of beam stops	2521 times
Times the vault has been accessed	164 times

6. Software validation

Due to the unique nature of AvailSim 2.0, it is not possible to easily compare it with other software. However, tests, verifications and comparisons were done.

6.1. Basic simulation tests

Basic tests were done by performing simple availability analyzes using AvailSim 2.0 and RiskSpectrum (which is a validated software) and comparing the results. In these tests, the basic core of the simulation is checked after being altered with the new features.

The results showed that mean values for both programs had a difference of less than 0.002%. Moreover, more specific results such as lists of principal contributors are essentially the same for both cases.

6.2. Enhanced features verification

As there is no software with which to compare these features, an exhaustive check of the AvailSim 2.0 history file was done. This file contains every action done by the software during the simulations. All features were analyzed in numerous and specific situations.

6.3. Comparison with former IFMIF analyses

Previous IFMIF accelerator models done with RiskSpectrum were simulated with AvailSim 2.0. These models did not include the enhanced features but were useful to assure that the whole facility could be equally simulated with AvailSim. Results were very similar to the ones obtained with RiskSpectrum.

7. AvailSim 2.0 results

Results obtained with AvailSim 2.0 are numerous and detailed. A sample of results obtained for the IFMIF Accelerator facility is shown in this chapter. The results were obtained in 80 iterations of 30 year simulations. The model evaluated is an IFMIF accelerator facility interim design.

7.1. Global results

Mean values of global parameters of the simulation are shown in Table 1. This information is relevant to understanding the global behavior of the accelerator. Furthermore, it is useful to forecast the importance of easy access to the rooms or the number of people required and other things.

7.2. Results by system

Availability results can be obtained for each system, subsystem or group of components. The comparison between the results

Please cite this article in press as: E. Bargalló, et al., Availability simulation software adaptation to the IFMIF accelerator facility RAMI analyses, Fusion Eng. Des. (2014), http://dx.doi.org/10.1016/j.fusengdes.2013.12.004

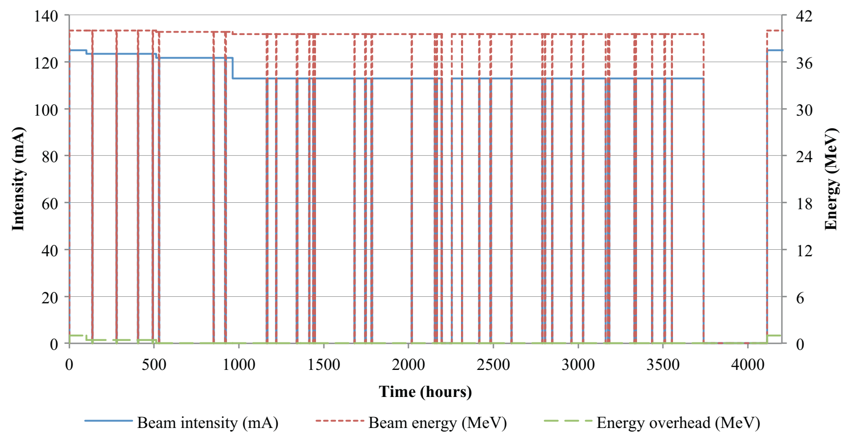

Fig. 2. Example of beam intensity and energy parameters evolution.

Table 2
Availability results for IFMIF accelerator systems.

System	RiskSpectrum results	AvailSim 2.0 results
Injector	97.03%	97.85%
Diagnostics	99.58%	99.67%
HEBT	99.13%	99.16%
MEBT	98.62%	98.90%
RF system	94.64%	95.28%
RFQ	99.10%	99.26%
SRF Linac	93.15%	94.42%
TOTAL	82.52%	85.42%

obtained with the calculation done with RiskSpectrum and the simulation done with AvailSim 2.0 is shown in Table 2. The difference between the results is mainly due to the differences of degraded operation limits. AvailSim limits are defined for the whole accelerator while for RiskSpectrum they are defined for each system individually. Moreover, synergies between systems are better represented in AvailSim 2.0 results.

7.3. Beam parameters evolution

Every function has a record about its value during the simulation. It is interesting to see the evolution of beam parameters. As an example, the beam intensity, energy and energy overhead parameters are graphically presented in Fig. 2. In it, several failures force decreases of beam parameters in order to allow continued operation.

7.3.1. Examples of parameter degradation

As an example, when a SRF Linac cavity fails, it can be completely detuned. Therefore, it will be transparent to the beam, as if no component were there. The consequences are a lack of acceleration and of defocusing effect. The beam focusing can be easily compensated with the solenoids nearby. However, as the periodicity of the structure is broken, the beam halo will increase and a decrease of the beam intensity should be planned. The energy of the beam will decrease depending on the energy that the cavity was supplying.

7.3.2. Beam parameter limits and mean values

The nominal beam energy is 40 MeV. It is assumed that the minimum energy acceptable for the users is 38 MeV. Furthermore, each cavity has some electric field margin. It is conservatively assumed that the total energy overhead that the accelerator is able to supply is about 1 MeV. In Fig. 2, energy reduction caused by first failures is compensated with the energy overhead. Further reductions decrease beam energy below 40 MeV.

Table 3
Beam parameters results.

Name	Mean value	Design value	Min value
Energy	39.35 MeV	40 MeV	38 MeV
Intensity	115.31 mA	125 mA	65 mA
Energy overhead	0.53 MeV	1 MeV	0 MeV

When intensity is reduced, the software checks if it is more profitable to stop the accelerator and perform the repairs to bring the intensity back to 125 mA or to continue operation with this amount of degradation until the following scheduled maintenance period.

Beam parameter design and mean simulated values are shown in Table 3.

7.3.3. Maintenance actions

In Fig. 2, some failures lead to short corrective maintenance actions (every time that the parameters go to zero and back to its previous value). In these cases, the software does not decide to extend the maintenance period to repair all other components because the parameters' improvement would not compensate the time lost in it. Beam parameters return to nominal values after a long downtime caused by a failure that decreases the intensity too much.

7.3.4. Consequences in availability

These parameter degradations permit increased accelerator hardware availability at the expense of decreased beam effectiveness. Total availability performance is highly improved thanks to this degradation and to the balance done between the parameters.

8. Future work

Although it is not complex software; many improvements can be implemented to it in order to make it more accessible and user-friendly. Graphical interfaces, flexible input data and output data processing could highly improve it.

AvailSim only contemplates exponentially distributed failure probabilities. Other distributions should be included in future versions.

AvailSim 2.0 could be used to simulate all IFMIF facilities in order to see the relationship between them and to quantify the availability of the whole.

9. Conclusions

Updated AvailSim is suitable to simulate the whole IFMIF accelerator availability performances. AvailSim's capability to take

Please cite this article in press as: E. Bargalló, et al., Availability simulation software adaptation to the IFMIF accelerator facility RAMI analyses, Fusion Eng. Des. (2014), http://dx.doi.org/10.1016/j.fusengdes.2013.12.004

realistic maintenance decisions and to simulate degraded operation modes makes it the preferred software to analyze the behavior of a complex machine like IFMIF.

AvailSim 2.0 has been implemented in a generic way in order to allow simulating any other facility. However, some modifications and adaptations could be necessary to simulate them properly. The software will be publicly available.

Acknowledgments

We would like to express our special thanks to Professor Thomas Himel from Stanford University for allowing us to use and adapt the AvailSim software and for his advice and assistance in this process.

This work has been funded by the MINECO Ministry under projects AIC10-A-000441 and AIC-A-2011-0654.

References

[1] C. Tapia, J. Dies, V. Pesudo, J. Abal, Á. Ibarra, J.M. Arroyo, IFMIF accelerator: database, FMEA, fault tree and RAM, Fusion Engineering and Design 86 (9–11) (2011) 2722–2725.

[2] E. Bargallo, G. Martinez, J.M. Arroyo, J. Abal, P. Beauvais, F. Orsini, et al., RAMI analyses of the IFMIF accelerator facility and first availability allocation between systems, Fusion Engineering and Design 88 (9–10) (2012) 2728–2731.

[3] E. Bargallo, J.M. Arroyo, J. Abal, A. De Blas, J. Dies, C. Tapia, et al., IFMIF accelerator facility RAMI analyses in the engineering design phase, in: ICENES Proceedings, 2013.

[4] J.M. Arroyo, A. Ibarra, J. Mollá, J. Abal, E. Bargalló, J. Dies, et al., RAM methodology and activities for IFMIF engineering design, in: IPAC2011, 2011.

[5] T. Himel, J. Nelson, N. Phinney, M. Park, M. Ross, Availability and reliability issues for ILC, in: IEEE Particle Accelerator Conference (PAC), 2007.