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RAMI: the Main Challenge of Fusion Nuclear Technologies

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RAMI (Reliability, Availability, Maintainability and Inspectability) is one of the most severe challenges of Fusion Technologies, and it is probably the engineering branch where the fusion community is the least competent. This paper summarizes the RAMI statistics in existing fusion machines, the RAMI approaches adopted in ITER and in DEMO, and the expected availability targets in these two machines. The paper then discusses these approaches and targets and recommends adopting a Reliability Growth program for future fusion devices.

Keywords: Fusion technology, Fusion power plant, Availability, Reliability, RAMI

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1. Introduction and definitions

The main challenges of Fusion Technologies quoted in the literature are usually the blanket & first wall, power exhaust, materials, and RAMI (Reliability, Availability, Maintainability and Inspectability) [1]. RAMI is often quoted in fusion papers, but it is probably the branch of Systems Engineering where the fusion community is the least competent. This is reflected by the limited number of published papers on RAMI devoted to fusion.

The term systems engineering appeared in the 1940s. The need to identify and manipulate the properties of a system as a whole, which in complex engineering projects may greatly differ from the sum of the parts' properties, motivated various industries to develop this discipline.

Reliability engineering is a branch of System Engineering. It is closely associated with maintainability, availability, and logistics engineering. Reliability engineering is a critical component of Safety and of Security engineering, and is a key element in Risk Management.

1.1 Availability

Availability is the proportion of time a system is in a functioning condition or, in other words, its mission capable rate. Availability is defined as the ratio of the total time a functional unit is capable of being used during a given interval to the length of the interval. Different definitions exist, depending on the time interval considered:

- Inherent availability (A_i): the probability that an item will operate satisfactorily at a given point in time when used under stated conditions in an ideal support environment (i.e., personnel, tools, spares, etc. are instantaneously available). It includes corrective maintenance downtime but it excludes preventive maintenance downtime.
- Achieved availability (A_a) includes, in the 'time interval', preventive maintenance downtime.
- Operational availability (A_o): the probability that an item will operate satisfactorily in realistic operating and support environment. The main difference with A_a is that A_o includes logistics time and waiting or administrative downtime.

A key parameter in Power Engineering is the load factor, or capacity factor, i.e. the ratio between the actual energy output over the maximum possible energy output of a given installation, assuming continuous operation at full nominal capacity, over a specified period of time. By definition the load factor can never exceed the operational availability factor. The load factor is a very important key performance indicator (KPI) for a power plant. As discussed later in the paper, it will be an important KPI for DEMO but not for an experimental device such as ITER.

1.2 Reliability

Reliability describes the ability of a system or component to function under stated conditions for a specified period of time. This is different from the availability, which describes the ability of a system or component to function under stated conditions at a specified moment or interval of time. Reliability is theoretically defined as the probability of success.

A reliability assessment provides a set of qualitative and quantitative evidence to perform a risk assessment, in order to check that use of a component or system will not be associated with unacceptable risk, risk being defined as a combination of probability and severity of the failure occurring. The severity of a failure includes, on the one hand, aspects of interest to the operator or owner of the systems, e.g. loss of revenue when the system is not in operation and, on the other hand, the effects for the public and the environment. What is acceptable in this case is discussed, for a nuclear facility, with the regulatory authority.

Reliability and safety use common methods for their analyses. Generally speaking, reliability engineering focuses on costs of failure whilst safety engineering focuses on preserving life and the environment, and therefore deals only with particular dangerous system-failure modes.

1.3 Evaluation and improvement of availability

The achieved and operational availabilities are defined as follows:

A_a= MTBF/(MTBF+MTTR)

A_o= MTBF/(MTBF+MDT)

where MTBF is the 'mean time between failure,' MTTR the 'mean time to repair', and MDT the 'mean downtime.'

To improve the availability of a system it is necessary either to improve its reliability, i.e. to increase MTBF, and/or to improve its testability and maintainability, i.e. to decrease MTTR, and/or to decrease the waiting and administrative downtime lost during maintenance operations, i.e. to decrease MDT.

Improving the maintainability of a system is generally easier than increasing its reliability. Maintainability estimates, i.e. repair rates, are also generally more accurate. However, because the uncertainties in the reliability estimates are in most cases very large, they are likely to dominate the availability calculation, even when maintainability levels are very high. When reliability is not under control, more complicated issues may arise, like manpower, spare parts availability etc. Focusing only on maintainability is not enough. Moreover, if failures could be prevented, none of the other issues would be relevant. Reliability is therefore the most important part of availability. This is particularly true in fusion devices where the MTTR is anticipated to be large, typically several weeks.

1.4 Reliability requirements and predictions

Analyses are required to make predictions, and requirements are required to make analyses. For any complex system one of the first tasks is to specify the reliability and maintainability requirements. Setting only RAMI targets, e.g. maximum failure rates, is not appropriate because, often, it will not be possible to assess with sufficient accuracy whether the targets can be met.

One fundamental reason is that the full validation of a quantitative reliability allocation can often not be made because of the high level of uncertainties involved for showing compliance with these requirements, but also because reliability is a function of time, so that accurate estimates become available only late in the project, sometimes after several years of in-service use. This is particularly true for prototype or novel systems, which is the case for all fusion devices build to date, and this will also be the case for ITER, DEMO, and the first fusion power plant.

Prediction of reliability from historic data can be very misleading. Even minor changes in design, manufacturing process, operating loads etc. can have major effects on reliability. Furthermore, the most unreliable and important items are most likely to be modified and re-engineered since historical data was gathered, making the statistical methods less effective.

Another surprising — but logical — argument is that to be able to accurately predict reliability the exact mechanisms of failure must be known and, therefore, could in principle be prevented!

1.5 Maintenance and Inspection

Maintenance is either preventive or corrective. Preventive maintenance is the care and servicing of equipment for the purpose of maintaining it in satisfactory operating condition by providing for systematic inspection, detection, and correction of incipient failures either before they occur or before they develop into major defects. Preventive maintenance tends to follow planned guidelines. It includes tests, measurements, adjustments, parts replacement and cleaning, performed specifically to prevent faults from occurring. Corrective Maintenance involves fixing the equipment should it become out of order or broken.

The complete maintenance package includes inspection, required either to confirm that a system/component is fully functional, e.g. back to its nominal condition before resuming operation; or whether it needs to be replaced before the occurrence of a failure because of, e.g., wear; or to identify a failed system/component and to plan it repair or replacement; or to locate a failure within a failed system, e.g., a vacuum leak.

Preventive maintenance can, and must, be planned to ensure the reliable operation of a system. Corrective maintenance can be prepared for, although not for all possible failures, but it cannot be planned. Scheduled outages of a system are manageable because of their predictable nature. Unscheduled outages are, instead, often a major disturbance and can have dramatic consequences. The scheduled outage of a power plant is ideally planned during the summer, whilst an unscheduled stoppage of a power plant on a cold winter day at 7 am, corresponding to the time of the peak power demand, can be a catastrophe. To the owners of many facilities, in particular Utilities, the unscheduled nature of failure – and its consequences – is often more disturbing that the associated loss of production.

1.6 The 'bathtub' curve

The so-called 'bathtub curve' (fig. 1) is widely used in reliability engineering. It describes a particular form of the hazard function which comprises three parts. The first part is a decreasing failure rate, known as early failures or infant mortality; the second part is a constant failure rate, known as random failures; the third part is an increasing failure rate, known as wear-out failures.

Infant mortality failures occurs typically when a product is first introduced in the market or during the early operation of a novel system, the rate of random failures correspond to failures occurring during the useful life of the product or system, and the rate of wear-out failures corresponds to failures occurring when the product or system operates beyond its design lifetime.

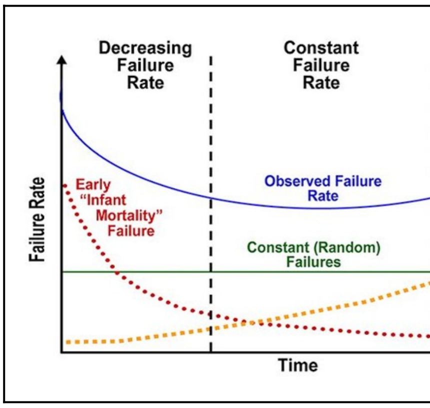

Fig. 1. The bathtub curve, summarizing *the three main* causes of failure in many components and systems.

Not all products or systems follow the bathtub failure rate curve, but it is applicable to most prototype components or systems. In reliability engineering, the three distribution functions of a bathtub curve may be analyzed using Weibull charts, corresponding to continuous probability distribution functions.

2. RAMI in existing fusion facilities

2.1 Statistics on existing facilities before 2010

RAMI of fusion facilities has not been the subject of many publications before 2010. There are, in addition, a few publications on the operational experience of specific systems. Most of these publications are listed as references in an excellent paper by T. Pinna and colleagues [2]. The facilities reviewed are the tokamaks JET (UK), AUG (Germany), TS (France), DIII-D (USA) and TFTR (USA), and the tritium facilities TLK (Germany), TSTA (USA) and TPL (Japan).

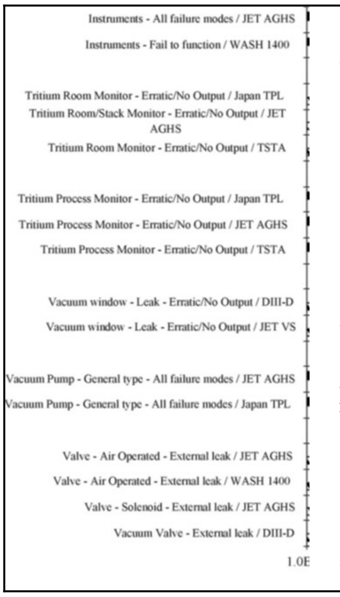

Fig. 2. Comparison between components failure rates from different sources (from [3]).

As reported in the paper: 'historical data have been searched in various sources […] such as hand-written log-books, electronic databases, incident investigation reports […] and from plant personnel interviews.' Indeed, finding reliability and availability data in existing facilities constitutes a significant undertaking since few machines keep proper statistics, and these statistics only record a limited amount of information.

The paper compared the reliability data from these different facilities and also with data from nuclear power plants, and concluded that they were generally 'fair to good, giving confidence that the collected data are yielding valuable failure rate information that can be pooled for use in probabilistic safety assessment and system reliability analysis.' Examples of comparison of reliability data of similar components in the different facilities are given in fig. 2.

The reliability database put together by Pinna and co-workers also records Operational Radiation Exposure (ORE) from existing machines, where JET and TFTR experience is particularly noteworthy because of their DT operations. The main conclusion of this analysis was that a significant part of the Work Effort (i.e., the total number of man-hours needed to perform a given task) – between 30 and 50% – spent on maintenance activities was 'to prepare the zone and the tools for the task, then to clear the area after intervention.' This is consistent with the experience in fission plants, where a significant reduction in intervention time and in ORE is achieved by training on representative mock-ups before interventions in-situ [3]. The analysis also indicated that traditional worker safety was 'very similar' to the situation in other industries.

All tokamak devices in operation today are experimental machines, and the criterion used to assess their availability is the time during experimental campaigns when the facility is ready to operate without taking into account the time required between plasma pulses, e.g. to recharge the central solenoid or to allow the TF coils to cool down. This calculation method is acceptable because the most important KPI for existing tokamaks is probably the number of successful pulses per experimental session.

A delay during an experimental session will be recorded together with the system that caused it only if the delay exceeds a certain duration, typically between 10 and 30 minutes. In case of delay the session still takes place, but not as many pulses as planned will be realized during that session. Pinna's analysis concluded that the availability is not so different between the different tokamaks assessed, with an average A_i of 75% during planned experimental campaigns, which account for about 30% of the total calendar time with 10-14 operation hours per day. TS, the only machine assessed with actively cooled PFCs, had an A_i lower than average because of the additional delays caused by in-vessel leaks.

When an experimental campaign is stopped because of a failure resulting in a modification of the overall program, it is recorded separately. This is another very important KPI but the exploitation of current records is difficult. For instance, if a major sub-system fails, the experimental program will be amended and experiments that do not require the failed sub-system will be performed. It is however difficult to decide if and how to consider this kind of failures in the calculation of the machine availability: the machine will operate, but the experimental program is not the one originally foreseen and the quality and/or interest of the research undertaken until the failure is repaired may be affected.

2.2 JET availability during 2000-2016

JET has recently completed a very comprehensive and detailed analysis of its performance during the period 2000-2016. The inherent availability and the main causes for delay are consistent with the analysis of Pinna and co-workers as shown in figure 3 [4].

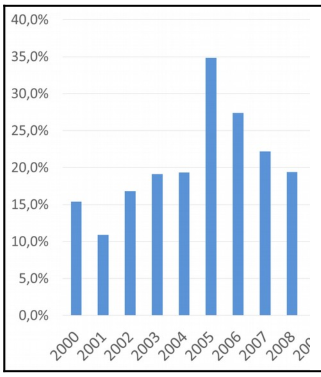

Fig. 3. Average delay per year during JET sessions over the period 2000-2016. The average delay over the period was 1.36 hours/shift, with shifts of 7.5 hours, corresponding to a loss of availability of 18.1% (from [4]).

The 3 main causes for delays are the same in all existing machines (fig. 4): pulsed power supplies, Control and Data Acquisition Systems (CODAS) and H&CD (primarily beams). Considering the complexity of the technologies involved, the complexity of the many sub-systems that have to operate simultaneously, and that the H&CD systems are usually expected to operate close to, or at full power, the availability of existing fusion facilities is quite remarkable.

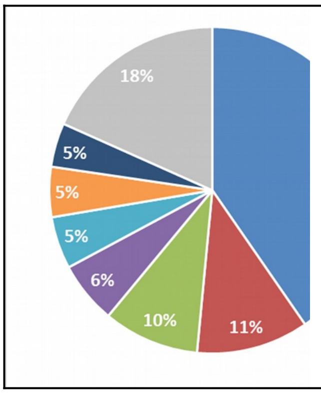

Fig. 4. Main causes of delays in JET over the period 2000-2016. The main causes, as in other tokamaks, are the pulsed power supplies, followed by CODAS and H&CD systems (from [4]).

Another important parameter is the number of 'good pulses' realized. Indeed, plasma disruptions, trips of essential systems, wrong setting and other causes lead to the failure of the pulse from the experimental standpoint. Fig. 5 and 6 show the average number of pulses per session and the average number of 'good' pulses per session in JET over the period 2000-2016. Out of an average of 11.8 pulses per session, only a few more than half of them were 'good' over the period 2006-2016.

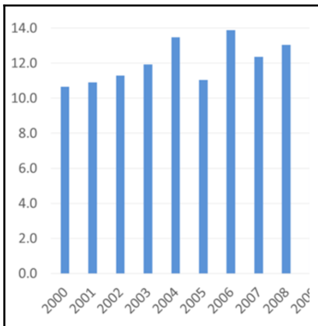

Fig. 5. Average number of pulses per session in JET over the period 2000-2016 (from [4]).

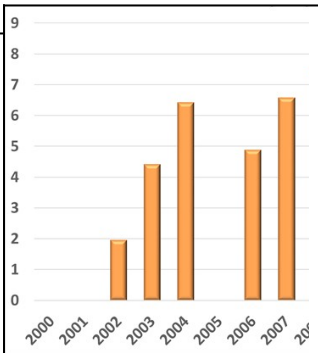

Fig. 6. Average number of 'good physics pulses' per session in JET over the period 2000-2016 (from [4]).

3. RAMI in ITER

Early during the design phase the ITER Organization developed an approach to assess the RAMI of all its main components and systems [5]. The RAMI process includes Functional Analysis (FA), Failure Modes, Effects and Criticality Analysis (FMECA) and risk mitigation actions, allowing the definition of RAMI requirements and their integration into the systems specifications. The key step in this approach is, after the initial FMECA and the classification of the various risks identified, to decide whether the risk is acceptable or whether mitigating actions are required.

One of the first systems analyzed was the Tokamak Cooling Water System (TCWS), and the outcome of the initial FMECA is shown in fig. 7. Following a series of mitigating actions, e.g. implementation of redundant sensors and definition of a preventive maintenance plan for critical components such as the pumps, the criticality of all failure modes identified was reduced below the required threshold (fig. 8).

Similar analyses have been carried out for several ITER systems since the adoption of this RAMI approach, and the definition of the 'criticality level' is crucial. The severity of each failure mode identified is rated according to a scale that is used for all systems to ensure consistency between the different analyses. The severity level depends on the duration of the machine outage resulting from the occurrence of the failure. The latest revision of this scale allocates a severity level of 1 if the outage is less than 1 day and a severity level of 6 if the outage is more than 6 months [6]. If the intervention to recover from the failure requires human intervention in hostile environment, then the severity level is 4 or higher even if the machine outage is very small. The failure rate of most of the events considered in the analysis for the various subsystems are not know with any accuracy, and a range of 1-10 is considered and adopted based on known data and/or engineering judgement. For instance, a failure rate between 0.5 and 5 per year is categorized a 'probable' and allocated an occurrence level of 3.

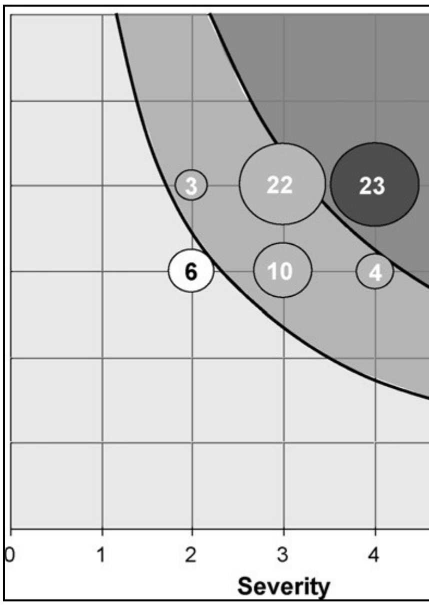

Fig. 7. Initial criticality chart for the ITER TCWS. Numbers and size of circles represent the number of failure modes identified for each set of coordinates: severity and frequency of

occurrence. Criticality thresholds (7 and 13) separate the different risk zones (minor, medium, major) (from [5]).

These analyses have also been used to estimate the overall availability of the machine during the first 11.5 years of operation, i.e. between 'first plasma' and completion of the 'fusion power operation' phase (goal: several hundred MWs of fusion power for several tens of seconds at Q=5-10). For planning purposes ITER foresees an operation pattern consisting of batches of 2 weeks, with 12 days of 2 shifts operation and 2 days of short-term maintenance. With a repetition rate of 30 minutes this will result in a maximum of 32 pulses per day. Assuming an A_i of 60%, ITER considers that it will achieve 13 'good' plasma pulses per operational day [7]. During these initial 11.5 years of operation ITER foresees a total of 1,460 operation days, corresponding to 35% of the total calendar time.

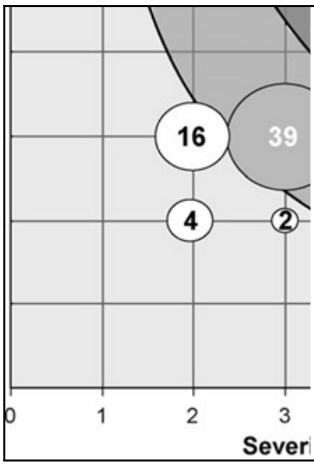

Fig. 8. Expected criticality chart for the ITER TCWS after implementing mitigating actions to reduce the criticality level of all failure modes identified below 13 (from [5$).

4. RAMI in DEMO

RAMI is considered one of the most severe technological challenges to be faced during the design of DEMO [8], but only limited work has been performed to date within the DEMO studies in progress. In additional to some general considerations [9], only the analyses of two breeding blanket concepts have been published. The methodology is similar to the one used by ITER and the analyses are very preliminary since the blanket concept designs considered have not yet been revised following these analyses. In other words, some failures with unacceptable criticality levels still need to be resolved. For instance, the assessment of the European HCPB blanket concept cooling system [10] suggests that the 'inherent availability goals proposed for the European DEMO Primary Heat Transfer System and Tokamak auxiliaries are potentially achievable but challenging for the secondary loop'. Indeed, the target A_o for the Tokamak auxiliaries and PHTS was 84% and the analysis indicated 71%, the numbers for the secondary loop being 94% and 74% respectively.

The preliminary analysis of the European DEMO WCLL blanket [11] is also a source of concern. Contrary to the HCPB, the analysis is not limited to the heat transfer systems but assessed the whole blanket, i.e. all modules and all connections until the valves of the main inlet and outlet feeders. The preliminary value of 27.5% for A_o could be increased to 55% by reducing the number of penetrations per segments. Other design modifications are suggested to further increase this value, which is much too low. These studies also warn that there is a risk of overestimating the availability by neglecting possible failures, and further work is clearly necessary during the on-going DEMO design studies.

The difficulty of estimating the reliability of future DEMO components and the overall DEMO availability is reflected in the wide range of operational availability targets considered: 30% in Europe and 60% in Japan [12].

5. RAMI and the Nuclear Regulator

Nuclear Regulators are not directly interested in the RAMI of a plant, but they will use a number of results from the analyses performed for the RAMI assessment of the plant. The Regulator will consider in particular the unreliability of all Safety Important Components (SICs). Indeed, if a SIC is expected to fail frequently, its failure will be considered a regular event and the consequences of this failure cannot result in a degraded level of safety. This might not be the case if the expected frequency of failure was lower. The Regulator will also consider FMECAs to provide inputs for the safety analyses.

The owner of a nuclear plant or facility must define the Operating Rules, which must be analyzed by the Regulator. These rules specify all operations foreseen, including in-service inspections and maintenance interventions. Any intervention in a radiologically controlled area and/or affecting a SIC not foreseen in the Operating Rules cannot be executed. In other words, should a failure require an intervention not foreseen in the Operating Rules, the appropriate remedial procedure will have to be approved by the Regulator before it can be executed. Considering that this approval is likely to require a few months, it is in the Owner interest to (i) maximize the reliability of all systems and (ii) develop Operating Rules covering the widest possible range of interventions.

ITER is the first fusion device that requires a nuclear license, indeed it is classified as 'Installation Nucléaire de Base n. 174' by the French Nuclear Safety Authority. ITER will provide invaluable experience for the licensing and operation of future fusion plants and some initial feedback by the Regulators has already been published [13].

6. Discussion

6.1 Infant mortality

ITER foresees plasma operation 35% of the calendar time, a slight increase compared to the average 30% of exiting machines. ITER also considers a similar operation pattern than in JET, aiming to achieve 13 good pulses per day, to be compared to the 12 to 14 achieved routinely in JET. To assume slightly better performance in ITER than in existing tokamaks is very reasonable, but the challenge in ITER during its first years of operation will be to address infant mortality issues of its numerous systems. Indeed, the JET statistics of 'good pulses' per day are calculated over the last 10 years, i.e. when infant mortality effects have all been resolved.

Existing statistics do not record properly the time required between commissioning and reliable operation of any given system. For instance, JET operations with the ITER-like wall were foreseen to take place in 2014-2018. Due to difficulties in reaching full NBI power after a major upgrade of the system and in developing modes of operation compatible with the new metal wall, the program is now scheduled to be completed at the end of 2020 – a delay of 2 years, or an increase of 40% of the calendar time required to execute the program originally foreseen [14]. This 2 year delay is not only attributable to the NBI, although it is clear that the 2 key factors are the shakedown from ‘perturbations’ following the upgrade of the system and unplanned failures, but especially a combination of both (Fig. 9).

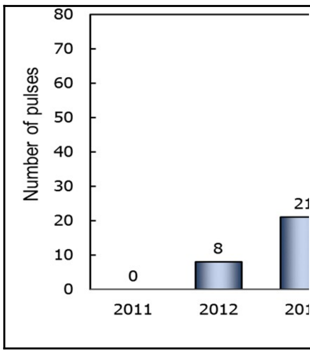

Fig. 9. Number of pulses achieved in JET with more than 25 MW of NBI power following the upgrade of the NBI system (from [14]).

6.2 Number of pulses vs. load factor

As discussed in section 2, the most important KPI in existing machines is the number of good pulses per session. The load factor that would be achieved in ITER, assuming optimistic assumption about pulse durations – 1,040 operation days with 13 good pulses 100s long and 420 operation days with 13 good pulses 400s long – is 2.4% during the planned experimental days or less than 1% over the corresponding calendar time of 11.5 years.

These values demonstrate that the 'load factor' is not a relevant KPI for experimental fusion machines. Availability targets have been defined for DEMO (see section 4) but not for the load factor. Assuming a considerably larger load factor in DEMO than in ITER will alter the nature of the technical challenges to be faced in both machines. DEMO will have to cope with a much larger neutron fluence, with a requirement on the DEMO blanket to resist at least 50dpa, to be compared to the maximum target in ITER of 3dpa. This fluence requirement in DEMO is necessary for the qualification of the Tritium Breeding Modules.

6.3 RAMI in DEMO and in FPPs

To achieve an acceptable availability in DEMO and in future FPPs it will be essential to consider RAMI requirements early during the design stage and throughout the life of the project. High availability will only be achieved by putting less emphasis on the maximum performance of the various systems, as is usually the case in experimental devices, and by putting more emphasis on robust, i.e. simpler, design concepts with more margins. Moreover, RAMI requirements should be given more credits during the selection between competing concepts.

As an example let us consider H&CD systems. From the RAMI perspective the comparison if fairly clear cut: Electron Cyclotron systems look very convenient: the front-end of the system close to the plasma is likely to be an open wave guide – current machines use metallic mirrors, whilst all complex sub-systems – the gyrotrons and the power supplies – can be located relatively far away in a radiologically non-controlled area. To ensure the high availability of an EC system will be primarily a problem related to spare parts management.

A Neutral Beam system look much worse from the maintenance standpoint: it is a very large and complex system located close to the main vacuum vessel though a large opening. Neutron streaming will activate the whole system, thereby requiring full remote maintenance. Furthermore, the large opening through the vessel affects negatively the shielding of the TF coils and weakens the vessel structure.

The situation of Ion Cyclotron systems is somewhat in-between, the final assessment depending on the complexity of the antenna to be installed facing the plasma.

Neutral Beams are the workhorses of today's machine for many good reasons, in particular because other systems cannot inject the same amount of power into the plasma. However, when considering RAMI, it is clear that a DEMO or a FPP will have a significantly higher availability with an EC system instead of an NBI system, assuming that either can drive the same amount of power into the plasma. The CD efficiency of the different systems will obviously be another very important parameter to be considered in the selection of the final system(s) for DEMO.

6.4 Reliability growth

In general, the first prototypes produced during the development of a new system contain design, manufacturing and/or engineering deficiencies. During the first phases of a product's development, the estimate of the product's final reliability is typically called the 'reliability goal.' To reach this goal, the product must undergo comprehensive testing and appropriate corrective or redesign actions must be implemented. The process of finding reliability problems and monitoring the increase of the product's reliability is called 'reliability growth.'

The work of Pinna and co-workers [3] constitutes the first step of the reliability growth process necessary to achieve the very challenging DEMO availability targets. The collection, processing and storage of reliability data from existing machines must be resumed. Furthermore, it would be advantageous to collect the data generated during the commissioning tests of ITER components and, later, during ITER operation.

7. Conclusions

Today's tokamaks are experimental machines working in non-nuclear conditions with a very low availability. ITER is the first fusion nuclear facility and will demonstrate the scientific viability of fusion. ITER, however, will also operate with a low availability and with a load factor of the order of 1%. DEMO, the machine to be built after ITER to demonstrate the technological and economic viability of fusion, will face severe technological and engineering challenges because it will have to operate with a significantly higher availability, between 30 and 60%, and with a much higher load factor than ITER.

A RAMI approach must be developed and implemented very early during the design stage to achieve these goals, and RAMI requirements must be given more credits than they are given today in the selection between alternative concepts.

To succeed, RAMI should be everybody's business, from the top of the management structure down to the individual draughtsman and workwoman.

Disclaimer

The views expressed in this paper reflect only the author's views and the European Commission is not responsible for any use that may be made of the information it contains.

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