Resum

El camí cap a la fusió nuclear com a font d'energia neta i abundant ha de superar una gran quantitat d'obstacles tècnics. Un dels principals problemes amb què s'han topat els enginyers que treballen en el disseny de reactors de fusió són els materials, que quan el reactor entri en funcionament estaran sotmesos a un gradient tèrmic, una fluència d'energia i una irradiació de neutrons majors a les que s'ha treballat fins ara.

Per tal d'escollir els materials més idonis per a la construcció de futurs reactors de fusió s'està dissenyant la planta IFMIF. Aquesta planta permetrà irradiar materials en condicions semblants a les del reactor i així poder estudiar l'efecte de la irradiació sobre les seves propietats. Per complir eficientment els seus objectius, és necessari que IFMIF tingui una gran disponibilitat. Aquest treball analitza els estudis de Fiabilitat, Disponibilitat i Manteniment (RAM) existents per a IFMIF i proposa el camí a seguir els propers anys en aquest camp.

Summary

The way to nuclear fusion as a clean and abundant energy source is full of technical obstacles. One of the main problems engineers have to face are the materials. Inside the reactor, materials are subject to thermical gradients, energy fluencies and neutron irradiation greater than in any plant before.

In order to choose the most suitable materials to build fusion reactors, the IFMIF is in its design phase. This facility will allow irradiate materials in similar conditions to the ones inside a reactor, and study the effect of irradiation on their properties. To fulfil its goals, IFMIF must have a very high availability. This paper analyzes the existing Reliability, Availability and Maintainability (RAM) works on IFMIF and suggests the steps to follow the next few years in this field.

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1. Acronyms

ALARA	As Low As Reasonably Available
AP1000	Advanced Pressurized Water Reactor
CDA	Conceptual Design Activity
CERN	European Organization for Nuclear Research
DEMO	DEMOnstration Power Plant
DESY	Deutsches Elektronen Synchrotron
DTL	Drift Tube Linac
EPR	European Pressurized Reactor
ESRF	European Synchrotron Radiation Facility
EVEDA	Engineering Validation and Engineering Design Activity
FCFR-Db	Fusion Components Failure Rate Database
HEBT	High Energy Beam Transport
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEA FPCC	IEA Fusion Power Coordinating Committee
IFMIF	International Fusion Materials Irradiation Facility
IPN	Institut de Physique Nucléaire
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KEP	Key Element technology Phase
LEBT	Low Energy Beam Transport
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PIE	Post Irradiation Examination
PSA	Probabilistic Safety Assessment
RAM	Reliability, Availability and Maintainability
RAMS	Reliability, Availability, Maintainability and Security
RF	Radiofrequency
RFQ	Radiofrequency Quadrupoles
SLAC	Stanford Linear Accelerator Centre
TFTR	Tokamak Fusion Test Reactor
VIT	Vertical Irradiation Tubes
VTA	Vertical Test Assembly

2. Introduction

In January 2007 the Fusion Energy Engineering Laboratory (FEEL), belonging to the Nuclear Engineering Section, was asked to carry out a study concerning the IFMIF project, focusing on its Availability goals. I was given the chance to take part of this international project in cooperation with Ciemat. The opportunity to work with a team specific for fusion energy and to be part of a worldwide project at the time I wrote the master thesis project was too good to reject.

2.1. Objectives

The main objective of this project is to analyse the current state of RAM studies in the IFMIF project and to suggest the steps to follow during the IFMIF Engineering Validation and Engineering Design Activity (EVEDA) in order to achieve the availability budget.

The secondary objective is to convince the IFMIF joint team that the suggested steps are important to follow in order to let IFMIF fulfil its overall availability goals, and the final objective of the report is to bring the IFMIF/RAM task to be performed by Spanish engineers.

This project intends to settle the guidelines to be followed by those working on the RAM issue during the EVEDA phase that started in March 2007. It is based on previous RAM works concerning IFMIF and other fields of nuclear and non nuclear engineering.

Finally, a RAM analysis was completed on one of the main IFMIF systems to prove the need to recalculate the other systems with updated methodology, but also to get familiar with RAM methodologies and learn how they work and the differences they have.

3. Fusion, energy from the stars

3.1. The Nuclear Fusion

Nuclear fusion is the process by which multiple nuclei join together to form a heavier nucleus (see Fig 3.1). It is accompanied by the release or absorption of energy depending on the masses of the nuclei involved. The fusion of two nuclei lighter than iron or nickel generally releases energy while the fusion of nuclei heavier than iron or nickel absorbs energy. The resulting mass is less than the unbound components mass in case of light nuclei fusion. The amount of energy released follows the Einstein equation $E = m \cdot c^2$. These reactions are the origin of the Sun and all the other stars energy.

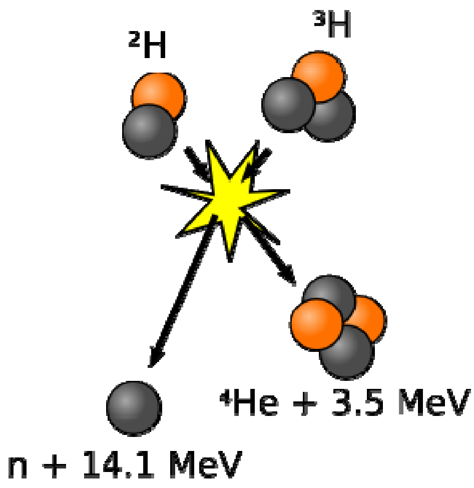


Fig. 3.1 Deuterium-Tritium Fusion

Produce artificially this reaction is a hard task. The nuclei have to be very close to each other so that the nuclear force can overcome the electrostatic repulsion between their positively charged protons. The nuclear force attracts nucleons (protons and neutrons) to their immediate neighbours due to the short range of the force. The electrostatic force, on the other hand, is an inverse-square force, so a proton added to a nucleus will feel an electrostatic repulsion from all the protons in the nucleus. In short distances the nuclear force is stronger than the electrostatic, allowing nuclei being stable.

Nuclei must be given a great amount of energy to overcome the electrostatic repulsion. In case the goal is having an energetically interesting reaction (i.e. the energy released in the reaction is larger than the energy introduced to produce it), nuclei must be under very high pressure and temperature conditions during a period of time long enough to let fusions happen in a high frequency. Lawson criterion (Eq. 3.1) defines the conditions needed for a fusion reactor to reach ignition, that is, that the heating of the plasma by the products of the fusion reactions is sufficient to maintain the temperature of the plasma against all losses without external power input.

$$n_e \cdot T \cdot \tau_e \geq 10^{21} \frac{KeV \cdot s}{m^3} \qquad \text{(Eq. 3.1)}$$

where

n_e is the electron density

T is the electron temperature when all the ions are assumed to be at the same temperature

τ_e is the confinement time

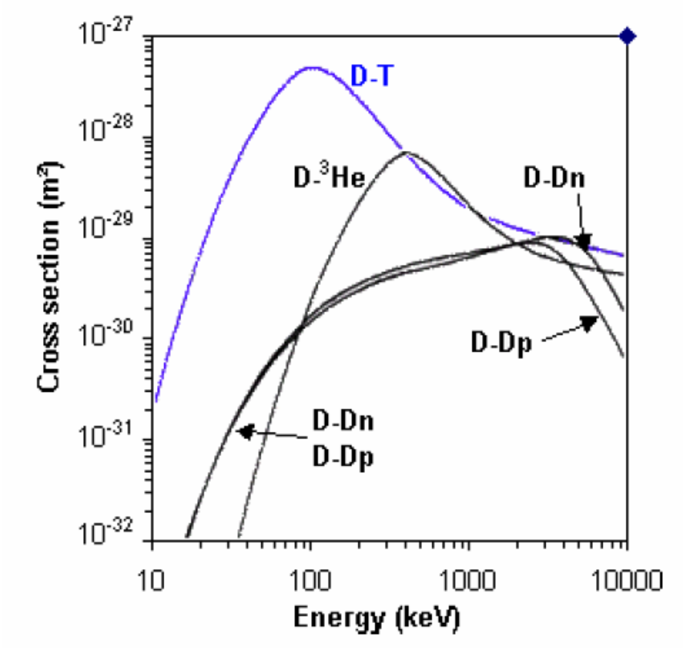


Fig. 3.2 Cross section for different fusion reactions

The reaction Deuterium-Tritium is the easiest one to achieve, as it requires a relatively low energy of the components, at about 70 KeV, to reach the maximum value in the cross section, which means the highest probability to react (see Fig. 2.2). Deuterium (D) is a very common species on the Earth's crust. It is present in the sea water with a concentration of 0.034 g/l. On the other hand, Tritium (T) doesn't exist in nature as it is radioactive with 12.5 years mean life. However, it can be easily created from lithium, another common element, as shown in Eq. 3.2:

$$n + {}^{6}_{3}Li \rightarrow {}^{4}_{2}He + T \qquad \text{(Eq. 3.2)}$$

Neutrons produced in the fusion process can be used to produce tritium to be used in the reactor. This will allow future fusion reactors produce the lithium they need in the reactor itself.

3.2. Fuel Confinement Methods

There are different ways to reach the density and temperature conditions necessary to produce fusion reactions.

3.2.1. Gravitational

One force capable of confining the fuel well enough to satisfy the Lawson criterion is gravity. The mass needed, however, is so great that gravitational confinement is only found in stars (the smallest of which are brown dwarfs). Even if the more reactive fuel deuterium were used, a mass greater than that of the planet Jupiter would be needed.

3.2.2. Inertial

Another confinement principle is to apply a rapid pulse of energy to a large part of the surface of a pellet of fusion fuel, causing it to simultaneously "implode" and heat to very high pressure and temperature. Deuterium and tritium are put into small spheres to create the fuel cells. If the fuel is dense enough and hot enough, the fusion reaction rate will be high enough to burn a significant fraction of the fuel before it has dissipated. To achieve these extreme conditions, the initially cold fuel must be explosively compressed. This compression is done by laser, ion or x-ray beams, which put a huge amount of energy in a very short time to the fuel cell.

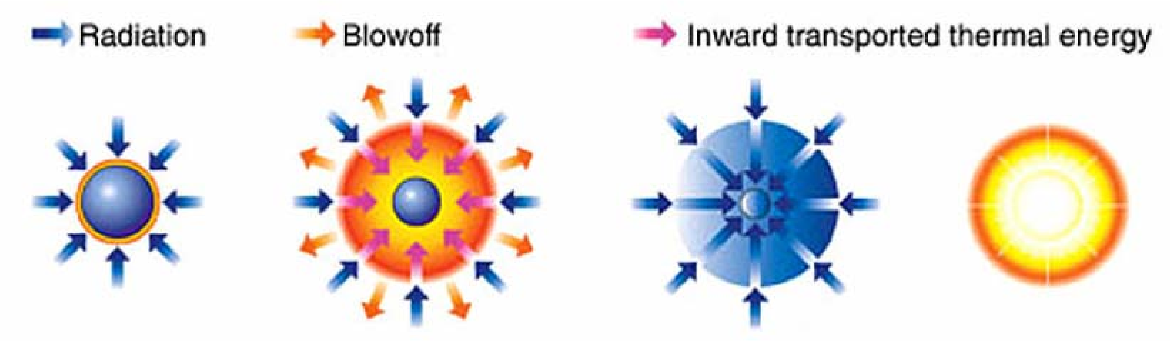


Fig. 3.3 Inertial confinement

3.2.3. Magnetic

Under the temperature conditions required to produce fusion reactors matter is in plasma state, that is, completely ionized gas. Since plasmas are very good electrical conductors, magnetic fields can also confine fusion fuel. A variety of magnetic configurations can be used, the most basic distinction being between mirror confinement and toroidal confinement, especially tokamaks and stellarators.

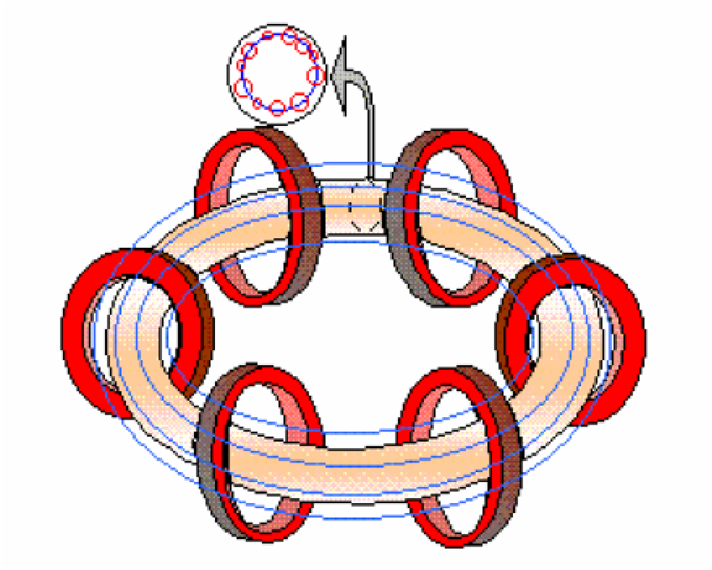


Fig. 3.4 Magnetic confinement in toroidal vessel

Nowadays the most developed technology for civilian use is the toroidal magnetic confinement. The two main research lines are tokamak and stellarator. Charged particles describe a helix trajectory around the magnetic field lines. Closing the field lines in a torus shaped confinement can be obtained. However, a toroidal magnetic field is not enough to get a good confinement due to the mass difference between electrons and ions. To solve this problem a poloidal magnetic field to improve the confinement, resulting in a helix-shaped magnetic field.

Tokamak and stellarator are two different strategies to create this magnetic field. In tokamaks coils only produce a toroidal magnetic field and the electric current generated in the plasma by unloading a transformer induces a poloidal field which improves the plasma confinement.

In stellarators helicoidal coils generate the magnetic field required to improve the confinement.

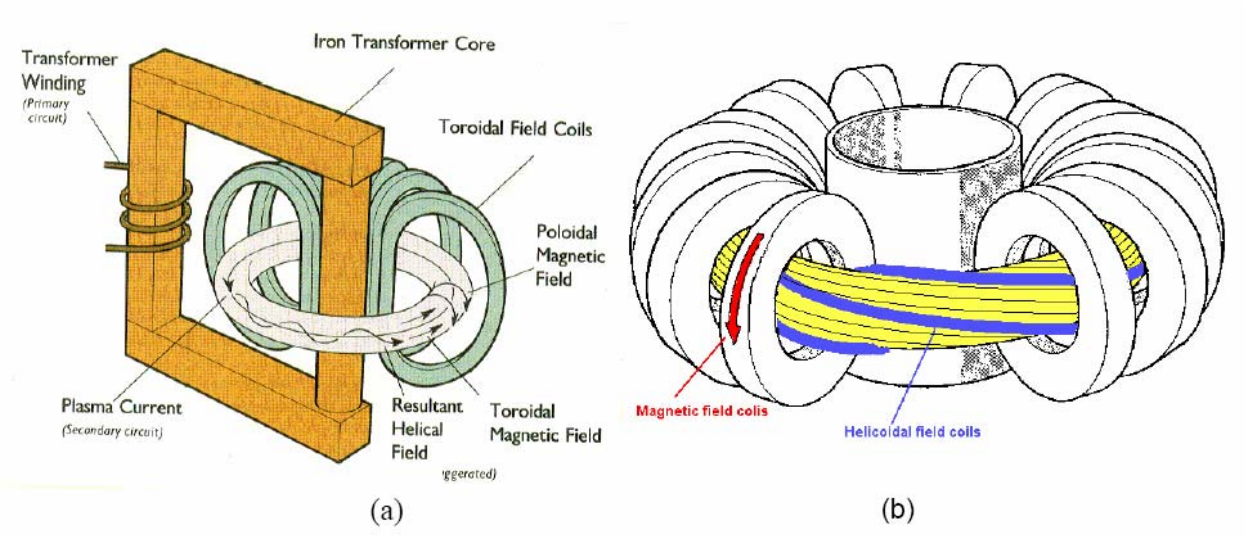


Fig. 3.5 Tokamak (a) and Stellarator (b) technologies of plasma confinement

Nowadays tokamak technology is more used because making helicoidal coils used in stellarators is so difficult. However, the tokamak technology has a handicap. Tokamak works by pulses, as the transformer has to be recharged every time it is completely unloaded. On the other hand, stellarators can work continuosly.

The main tokamak reactors currently working are JET (United Kingdom) and TFTR (USA), and the main stellarators are LHD (Japan) and Wendelstein 7-X (Germany). Up to now, only JET and TFTR are the only two reactors that have produced fusion power, reaching 16 MW and 10.7 MW respectively. These are the two only reactors which have operated with deuterium and tritium plasmas.

3.3. Fusion as Energy Source

Modern society requires access to a reliable and abundant energy supply to keep the welfare state. Current energy sources are mainly fossil fuels, but nuclear fission, hydroelectric and other renewable energy sources are also used.

UN estimation predicts that the energy demand will double in the next 50 years due to the increasing of the population and the consumption per capita. Demand will increase specially in the developing countries which will need to greatly increase their generating capacity by building power plants. Environmental requirements will favour low and zero CO_2 emission energy sources. Nuclear fusion is projected to be an energy source in the middle term. It will have a significant role in the energy generation, as it is reliable, safe and clean. Therefore, fusion might be a solution to the energy requirements worldwide.

Fusion has several advantages concerning safety, environmental issues and performance:

- Basic fusion fuel (deuterium and lithium) are abundant and can be found almost everywhere on the Earth.
- Resulting waste of the fusion process is helium, which isn't radioactive.
- The intermediate fuel (tritium) is produced from lithium in the reactor's blanket. This means that there is no need to transport radioactive products for fusion power plants to work normally.
- Fusion power plants are inherently safe. Runaway accidents (i.e. a reaction out of control) or Meltdown accidents (i.e. melting of the fuel elements) are not possible in this kind of reactors.
- By building the reactor with low activation materials no long-life radioactive waste will be created.

- Fusion power plants don't emit greenhouse effect gases
- Fusion is an energy source environmentally respectful and independent from the region's climate conditions.

Each D-T fusion produces a high energy (14 MeV) neutron. These neutrons can escape the magnetic confinement as they are non-charged particles. The interaction of the high energy neutrons with the walls results in a heating of the blankets that cover the vessel. Blankets are cooled down by a water-based heat rejection system and the steam produced in that process is used to generate electricity in a conventional turbine.

But besides heating, neutron irradiation has other effects on the blanket materials. Due to the irradiation, materials are activated, becoming radioactive themselves. After fusions have been produced have been produced inside a reactor’s vessel, radioactivity doesn’t allow hands-on maintenance inside the vessel. Atoms are displaced from their positions in the Bravais lattice. Massive irradiation like can significantly alter material's mechanical and electrical properties.

3.3.1. The ITER project

The International Thermonuclear Experimental Reactor (ITER) is the last step before the construction of commercial fusion power plants. Located in Cadarache, France, ITER is currently on its early construction phase. It will be a tokamak which will produce 500 MW fusion power during 500 seconds, with Q>5, where Q is the ratio between produced power and injected power. The first plasma operation is planned for 2016.

ITER will be the first fusion reactor to operate regularly with D-T plasmas. The main objectives for this plant are learning about the plasma and testing materials for future fusion plants.

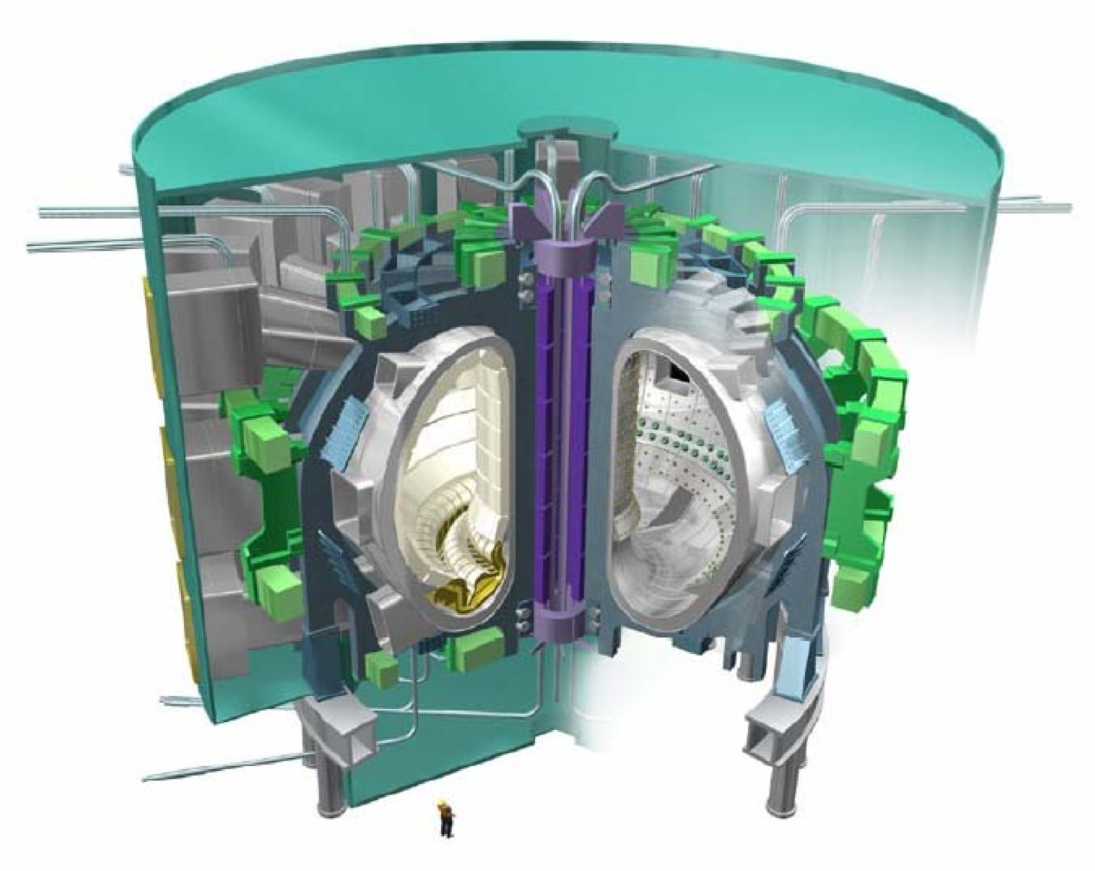


Fig. 3.6 The ITER reactor

3.3.2. DEMO

The Demonstration Power Plant (DEMO) will be the first commercial fusion power plant. It will be able to produce continuously 2000 MW fusion power. DEMO's 2 gigawatt will be on the scale of a modern electric power plant.

3.4. The International Fusion Materials Irradiation Facility

Continued progress toward the development of a fusion commercial power plant will require addressing a bread set of issues regarding environmental acceptability, safety, and economic viability. Among such issues, the development and qualification of radiation-resistant and low-activation materials will be a key factor. These low-activation materials must survive exposure to damage from neutrons having an energy spectrum peaked near 14 MeV with annual radiation doses in the range of 20 displacements per atom (dpa). To test and fully qualify candidate materials up to the expected doses of a fusion power reactor, a high flux source of high energy neutrons, presently not existing, has to be built and operated.

The International Fusion Materials Irradiation Facility (IFMIF) has the mission to provide an accelerator-based Deuterium-Lithium neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to abort a full lifetime of anticipated use in fusion energy reactors. The IFMIF would generate a base of material-specific activation and radiological properties data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning and waste disposal systems.

3.4.1. Plant Requirements

The design concept for IFMIF is based on input from the materials community on the estimated test volume required to obtain useful irradiation data in a reasonably short operating time. Providing a flux equivalent to 2 MW/m^2 ($0.9 \cdot 10^{18}\ n/m^2 s$ uncollided flux) is required to irradiate a volume of about 0.5 l. A fraction of this volume, of 0.1 l, will be irradiated at 5 MW/m^2 for accelerated testing.

Two accelerated systems combined will provide a continuous wave of 250 mA of 40 MeV deuterons. An estimate of the test volume and the corresponding displacement rate in a test assembly with iron-based specimens per year of facility operation is as follows:

$$0.1l > 50\,dpa/fpy$$

$$0.5l > 20\,dpa/fpy$$

$$6.0l > 1\,dpa/fpy$$

Assuming a total facility availability of 70%, these displacement numbers which represent a full power year (fpy), have to be multiplied by a factor of 0.7.

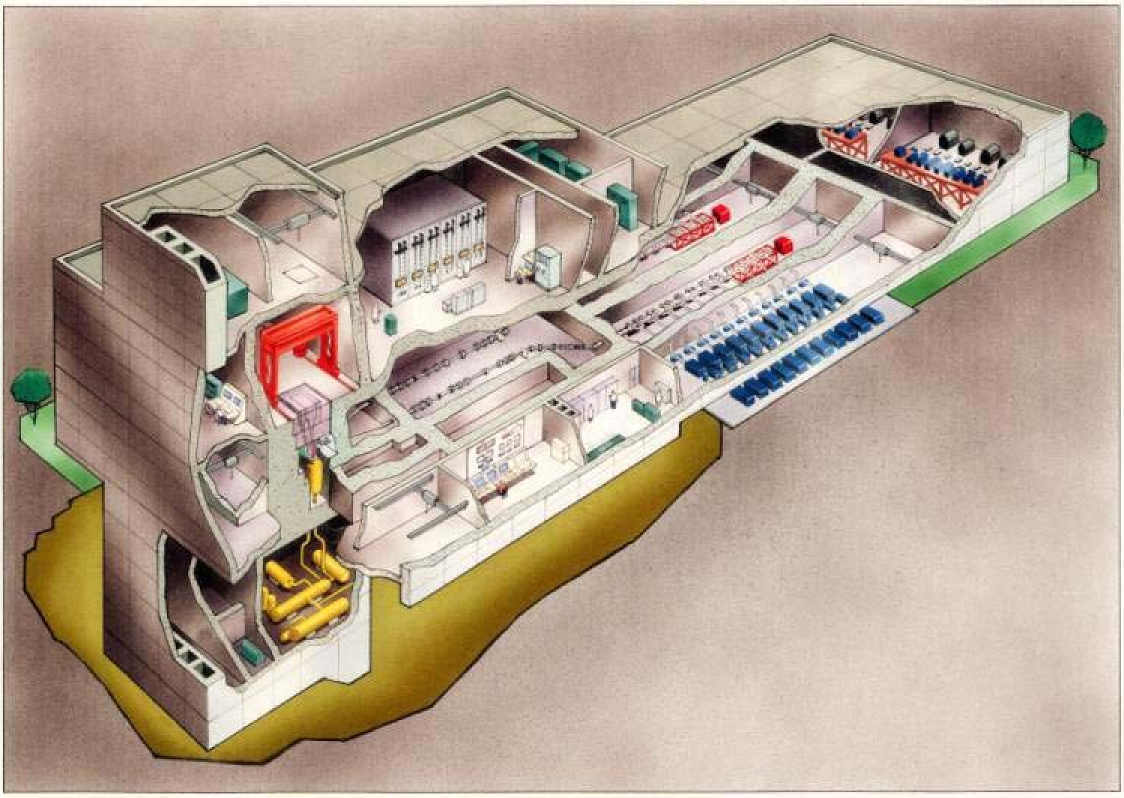


Fig. 3.7 IFMIF 3D view

The IFMIF is divided in 5 main systems:

- Test Facilities
- Target Facilities
- Accelerator Facilities
- Conventional Facilities
- Central Control System and Common Instrumentation

3.4.2. Test Facilities

The test facilities include the Test Cells, where the wide range of environments associated to fusion materials is reproduced, and the post irradiation examination (PIE) facilities, including hot cells for high-activity irradiated materials, shielded glove boxes for tritium-containing materials and shielded glove boxes for conventional irradiated materials.

The Test Cell is composed of two Vertical Test Assemblies (VTA) for high and mid-flux and two vertical orientated assemblies, referred as Vertical Irradiation Tubes (VIT) for low and very low-flux.

The facility will be capable of irradiation temperatures of 250 to 1000 ºC in the high and medium-flux regions, 80 K to 500 ºC in the low-flux regions and 4 K to 300 ºC in the very low-flux regions. It will also be capable of testing irradiated materials' mechanical and electrical properties in-situ.

3.4.3. Target Facilities

The Target Facilities provide a stable lithium jet in the target assembly to react with the deuteron beam to produce high energy neutrons for the irradiation of materials but also to remove 10 MW of beam power.

The system includes the main lithium loop, the chemistry purification loop, the impurity monitoring loop, the lithium transfer system, and all loop components. The lithium systems are confined in lithium cells below the test cell.

Liquid lithium reacts with air and water resulting in fire. Therefore, the most signifcant event to be considered is a major leak of the lithium and the possibility of a fire if the lithium loop components were installed in an environment that supported combustion. Although the probability of such a leak, with subsequent combustion, is very low, and measures could be taken to control any releases to the environment, the loop has been designed nonetheless to completely eliminate the possibility of a lithium fire. A vacuum condition of 10^{-3} will be maintained in front of the lithium jet both to prevent lithium evaporation and interference with the deuteron beam. Vacuum environment is also provided in the test cell and the HEBT in order to prevent lithium fire in case of leakage.

3.4.4. Accelerator Facilities

Two linear particle accelerators of 125 mA working in parallel will provide a combined deuteron beam of 250 mA. A 155-mA deuteron beam is extracted from the ion source at 100 keV. A Low Energy Beam Transport (LEBT) guides the deuteron beam from the source to an RFQ. The RFQ bunches the beam and accelerates 125 mA to 8 MeV. The 8 MeV RFQ beam is injected directly into a Room Temperature (RT), where it is accelerated 40 MeV. The DTL beam is directed to either of the two targets or the tune-up beam calibration station by a High Energy Beam Transport (HEBT).

3.4.5. Conventional Facilities

The Conventional Facilities will provide housing for the three process Facilities (Test, Target and Accelerator) in a single main building centered around the test cells. Smaller separate structures house the support services. The process Facilities are functionally largely independent and require buildings for many subsystems. As a consequence of the independence of these Facilities it is possible to group their buildings in separate complexes.

Besides housing for the main process facilities, Conventional Facilities also include other systems:

- Heat rejection system, which is required to reject the heat generated by accelerators, RF generators and lithium loop for a total heat rejection of about 40 MW,
- Electrical power distribution system, needed to supply electric power from the grid to each facility with a degree of reliability to operate the plant, protect the facility from damage and ensure the safety of plant, staff, and the public under all conditions
- Heating ventilation and Air conditioning system, which must provide sufficient air throughput to ensure acceptable air quality for continuous access of the personnel to some selected areas of the facility. In potentially contaminated areas it also has a safety function to protect both the personnel and the environment from uncontrolled releases of radioactive materials. Therefore, they must be designed for high availability and easy maintenance.
- Service water system, required to supply plant process and domestic uses, and to collect and discharge liquid waste. Separate systems are required for potable water, for fire protection water and for process water.
- Liquid and solid radioactive waste handling facility, where radioactive waste will be packaged in a waste form suitable for final disposal

3.4.6. Central Control System and Common Instrumentation

The Central control system and Common instrumentation will provide operational and functional control capability to the IFMIF. The control function will be centralized in a single control room. It will be supported by an array of instrumentation, monitors and sensors as required to supplement those provided by the individual facilities. The IFMIF will be operated from a single, integrated central Control System that will perform all data acquisition and control tasks during the facility life.

3.4.7. Current state of the IFMIF

The IFMIF project started in 1996 with the Conceptual Design Activity (CDA). In this document IFMIF's specifications and the basic design were set. In 2003 started a 3-year Key Element technology Phase. During this phase the most critical elements in the IFMIF were deeply analysed to check their technical feasibility and the best design alternatives for each one of them.

In February 2007 the IFMIF – Engineering Validation and Engineering Design Activity (EVEDA) phase was officially launched. This phase will last the next 5 years and will settle the final design for all the systems and components in the IFMIF. The construction of the IFMIF will start after the EVEDA phase finishes, in 2013, and the first irradiation is planned for 2020 with one accelerator (125 mA deuteron beam). The plant will be fully functional in 2022, with the installation of the second accelerator, which will provide the required 250 mA.

Figure 3.8 Shows the IFMIF construction planning from now until the plant is fully functional in 2023.

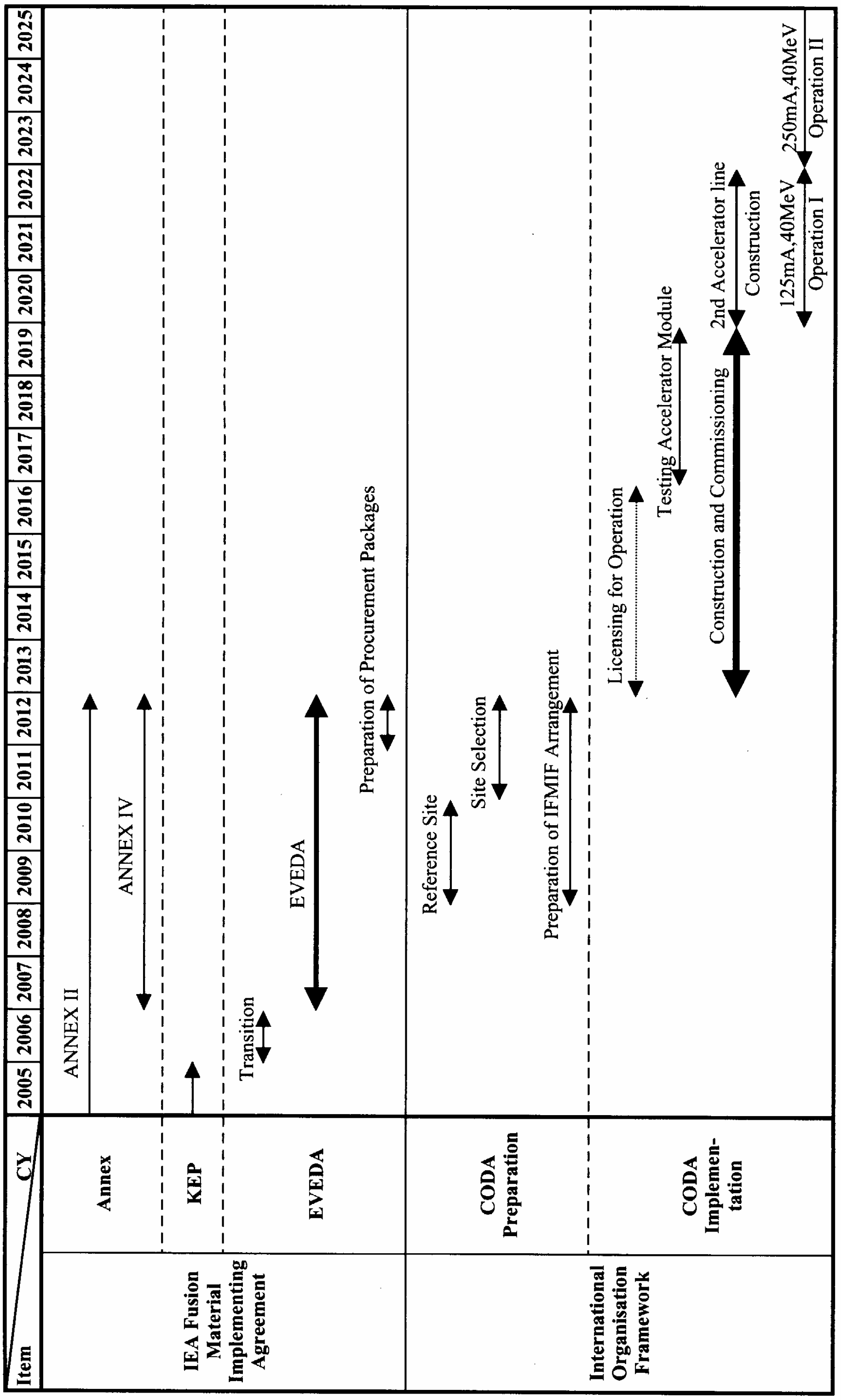


Fig. 3.8 IFMIF time planning

4. Reliability, Availability and Maintainability

One of the obsessions of most of the facilities all over the world is achieving a high availability level, that is, increase the production time as much time as possible. In order to reach this goal Reliability, Availability and Maintainability (RAM) has been a very active field of research.

Availability is defined as the degree to which a system, subsystem, or equipment is operable and in a committable state at the start of a mission, when the mission is called for at an unknown, i.e., a random, time. Simply put, availability is the proportion of time a system is in a functioning condition. It is calculated by the ratio of the total time a functional unit is capable to work during an interval to the length of the interval. Therefore, its value is between 0 and 1. An example of availability is 100/168 if the unit is capable of being used for 100 hours in a week (1 week = 168 hours).

There are basically two ways to get a high availability: high reliability and good maintainability.

For engineering purposes, reliability is defined as the probability that a system will perform its intended function during a specified period of time under stated conditions. Mathematically,

$$R(t) = \int_t^\infty f(x)dx \qquad \text{(Eq. 4.1)}$$

this may be expressed as,

where $f(x)$ is the failure probability density function. Reliability is a probability and it is calculated for a certain time period t. Its value shows the chance that the system will operate without failure before time t.

Reliability can be increased in several ways. In components, selecting better materials or improving the design for higher reliability are two common ways to do it. To increase systems reliability a usual thing to do is using redundancies, that is, put more than one component doing the same function so that if one fails the other can keep the system working. There are different kinds of redundancy strategies. In hot redundancies, components are working in parallel and in case on of them fails the others can keep the system running. In cold redundancies, spares start working when the working component fails, so that the system doesn't stop.

Maintainability includes the maintenance program, the spares strategy and the tasks to do during scheduled and unscheduled outages. An accurate maintenance program can avoid failures before they occur by replacing components at the end of their life cycle, keeping systems in good state, etc. An easy-maintenance design lowers repair times in case a failure occurs and makes maintenance tasks easier and more efficient.

Therefore, focusing on rising system's reliability and maintainability efficiency will lead to high availability rates.

4.1. System modelling

In RAM analysis, elements are modeled by two parameters: Mean time between failures (MTBF) and Mean time to repair (MTTR). MTBF is the mean time between failures of an element or system, the reciprocal of the failure rate in the special case when the failure rate is constant. Calculations of MTBF assume that a system is renewed, i.e. set to its original properties, after each failure, and then returned to service immediately after failure. MTTR is the mean time an element or system will need to be fully functional after a failure. It is, therefore, the main system’s downtime in case of failure of the element or system.

4.2. Calculation methods

The most common methodologies used in RAM are Fault trees and Markov chains. The fault trees method is based in Boolean algebra and logic gates. The subject of study is outlined in a tree-shaped diagram (hence the name) where components, elements, subsystems and systems are in different levels. Bye means of logic gates and Boolean algebra, components are grouped in elements, elements in subsystems and so on, until the whole system is assembled with a single global MTBF and MTTR, and its corresponding availability and reliability values.

The Markov chains approach is a mathematical approach to the RAM issue. In Markov chains theory, the next state of a system only depends on the current state of the system. Systems can be modelled into matrix using their parameters and following the Markov chains rules system’s MTBF and MTTR can be obtained.

Both systems have advantages. Modelling by fault trees is easier and more intuitive than by matrix. This is especially important in large systems. However, Markov chains method allows performing sensitivity analysis faster than fault tress. In case of very complex systems, this can result in a gain of computation hours.

Sensitivity analyses are used to evaluate the importance of certain parameters in the global availability of the system. MTBF and MTTR are probabilistic parameters, often based on estimation or experience. That why sometimes the values assigned to certain elements are not accurate. By multiplying and divining the estimated value, generally by 3 or 10, it is intended to know the effect of bad MTBF and MTTR estimations.

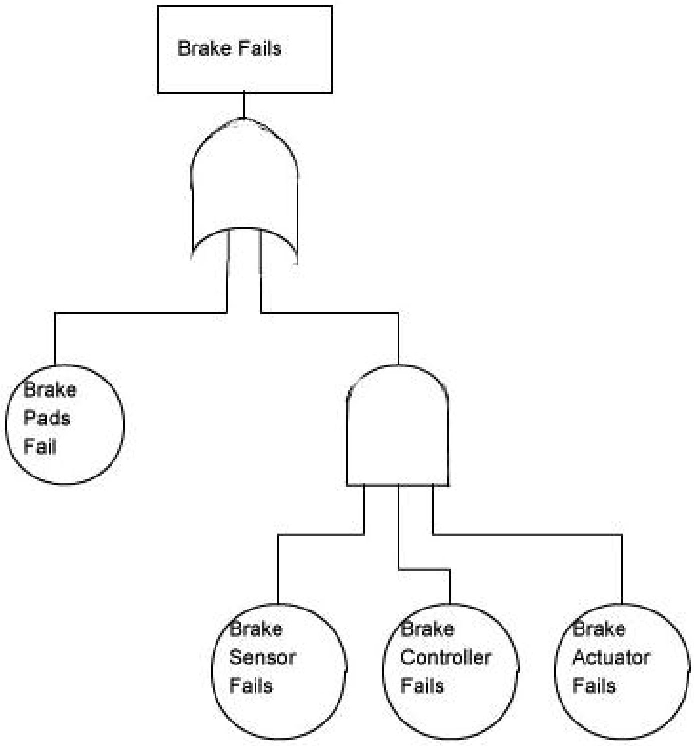


Fig. 4.1 Example of a simple fault tree for a break system

5. Proposal for a RAM plan in the IFMIF

5.1. Current state of RAM studies

Reliability, Availability and Maintainability are essential concepts for the IFMIF project. One of the most critical requirements for IFMIF is to have an overall irradiation capacity of at least 70% of the time after the first 12 months of operation, as is set in the CDA document. It is only scheduled a shut down for maintenance up to 60 days per year within its 30-year operation life.

It is also said in CDA document that all systems shall be designed to achieve optimum availability, by means of high reliability of every component and/or setting redundancy. Maintainability programs are also another way to achieve high availability, but some of these maintenance tasks will have to be done with Remote Handling.

5.1.1. Conceptual Design Activity (1996)

In this document [1] availability and maintainability requirements are set. Facility down-time will occur either as scheduled or unscheduled maintenance. The current assumption includes scheduled maintenance equivalent to one month off (31 d × 24 h = 744 h) once a year (or two periods of two weeks each, or a similar combination with the same total duration) and 8 h off once a week (52 weeks × 8 h = 416 h), leaving 7600 h for scheduled operation. The inherent system availability design requirement is 6132 h/7600 h = 80.7%.

Based on this top level requirement, the availability has been allocated to the main IFMIF subsystems as follows:

Table 5.1: IFMIF RAM specifications

IFMIF RAM specifications	Minimum required
Test Facilities:	97.5%
Target Facilities:	95.0%
Accelerator Facilities:	88.0%
Conventional Facilities:	99.5%
Central Control System and Common Instrumentation:	99.5%
Total (product):	80.7%

Preliminary fault trees of every system were performed referring to the conceptual design. Fault rates were extracted from previous studies [2], engineering evaluation and operating experience. Continuous and highly reliable operation was established as a basic design criterion for the IFMIF. Specifically, the overall requirement for IFMIF calls for an average of 70% on-line performance (6132 h) over a calendar year (8760 h). In order to achieve this goal a comprehensive RAM model for all the systems in the IFMIF facility, including the three process Facilities (Test, Target and Accelerator), Central Control System and Common Instrumentation, and Conventional Facilities was developed. This model includes an allocation of the availability to all the major components of the subsystems.

The RAM model is performed using fault trees (FT) and tables. Tables show the individual MTBF (Mean Time Between Failure) and MTTR (Mean Time To Repair) values (in hours) used for every component. The number of components, number of spares (if any), type of redundancy (number 1 indicates a hot, or operational redundancy, while number 2, indicates a cold, or standby redundancy), annual number of replacements, average amount of time spent annually for repairs, availability, and reliability over a period of one week (168 hours) are also indicated.

Results obtained fulfil the requirements in all IFMIF systems except the Accelerator. However, the availability margin in the other systems is not so wide, especially in the Target Facilities, as shown in Table 5.2:

Table 5.2: Analysis results vs. Design specifications

System	**Required**	**Achieved**
Test facilities	0.9750	0.9830
Target facilities	0.9500	0.9508
Accelerator facilities	0.8800	0.8765
Conventional facilities	0.9950	0.9973
Central control system and Common instrumentation	0.9950	0.9950

These results are not conclusive as there have been many changes in the IFMIF design since this analysis was performed. For example, the test facilities are not refrigerated by liquid metal (NaK) as it was in the first design, but by He. Component reliability data and equations used to calculate availability have also been updated.

Therefore, RAM analyses in CDA are not useful to take conclusions in this field, but they are a good basis to perform future studies and set work guidelines.

5.1.2. Conceptual Design Evaluation (1998)

During the CDE [3], the subsystem and component RAM database was systematically developed by obtaining voluminous data from a number of operating accelerator facilities, and by beginning the task of translating the information into a consistent format and performing the required analyses. The initial objectives were to study the operating procedures employed in these facilities to achieve the recorded availability, and to collect performance data. It was found that the organization of operations across the facilities is remarkably similar, with differences mainly reflecting more or less formality depending on the facility size. A preferred database format for future data capture was proposed and endorsed by a number of facilities.

5.1.3. Conceptual Design Activity. Reduced Cost Report. A Supplement to the CDA by the IFMIF Team (2000)

In 1999 the IEA Fusion Power Coordinating Committee (FPCC) requested a review of IFMIF design with focus on cost reduction without changing its original mission. The main modifications introduced with the reduced cost design as compared to CDA design are listed hereafter:

1. Reducing the number of target locations.

The number of target locations have been reduced from 3 (two Li target and the dump target) to 1.

Two legs for each accelerator of HEBT and a fixed beam dump have been removed

2. Removing the HEBT cavities

The EDC (Energy Dispersion Cavities) and the buncher cavities installed in the HEBT line are removed and the associated RF power source with RF transport is also removed

3. Shortening the HEBT system

The layout of the HEBT is changed from the 90-deg beam turning line to the two-bends translation line

4. Shortening RF transport

The Accelerator Vault and the RF power bay are located at the same level and the length of the RF transport is reduced to about 40% of the original design. The coaxial size is necessary to be changed from air cooled 19" diameter to the water cooled 9" diameter for penetrating through the shielding wall between the two rooms easily.

5. Removing the circulator at output of RF source module

The circulator at the exit of the final RF amplifier are removed by changing the protection scheme for the reflected RF power (if it is removed the reliability of the RF power system will be improved, however a careful protection scheme for the sudden reflection of RF power is necessary).

6. Changing the RFQ-DTL transition energy and DTL tanking

   The output energy of RFQ is reduced from 8 MeV to 5 MeV and the DTL tanking is changed to 9-, 16-, 24-, 32- and 40 MeV.

   The materials of RFQ will be 2/3 of the original CDA estimates (2 segments instead of 3). The DTL tanks have been reduced from 8 to 5.

All these changes have an effect on the IFMIF availability and must be taken in account in further RAM analyses. Therefore, after the CDA Rationalized was released [4], the RAM study performed in CDA became out of date.

5.1.4. Key Element Technology Phase (2003)

In 2000, a three year Key Element Technology Phase (KEP) was undertaken to reduce the key technology risk factors. The results of the three-year KEP activities [5] include many works in the major project areas: accelerator, target and test facilities, as well as design integration.

Regarding the accelerator, a RAM analysis was performed [DI81-JA: RAM Analysis for the Rationalized IFMIF Design]. Three different DTL configurations were analysed using updated equations for the calculation:

- Original IFMIF design, with 8 DTL tanks
- Rationalized design, with 5 DTL tanks
- Author suggestion, with 5 DTL tanks and a different maintenance policy

The only changes among the three analyses were the DTL tanking, so some of the changes included in the Rationalized design were not considered.

Data used in this calculation is supposed to be taken from the CDA report. However, some of the data used doesn't match with the data listed in CDA. Under these conditions, the availability achieved in the first two cases doesn't reach the minimum of 88% stated in the design conditions as shown in Table 5.3

Table 5.3: KEP analysis results

Configuration origin	Achieved availability
Original design	0.8760
Rationalized design	0.8720
Author suggestion	0.8920

5.1.5. FZKA7080 (2005)

The Adjoint Sensitivity Analysis Procedure (ASAP) of Markov Chains is developed in this PhD Thesis [6] to perform RAM and sensitivity analyses. The availability obtained using ASAP of Markov Chains is very similar to the one obtained using traditional methods (fault trees). This method also allows performing sensitivity analysis demanding much less calculation power.

As an example the IFMIF accelerator's availability is recalculated and compared to the one obtained in CDA. Obviously, the design used in this example is the one before the rationalized design, so that the results can be compared.

However, the point of developing this method is to allow fast calculation of sensitivity. A complete sensitivity analysis on the Accelerator Facilities is performed, with 4 different perturbations on both essential parameters (MTBF and MTTR) of each one of the accelerator components.

ASAP of Markov Chains is a powerful tool that must be considered in future RAM and sensitivity works.

5.1.6. Know-how: People and Work

Many tasks concerning accelerators availability in general and IFMIF's accelerator in particular, and other tasks concerning the other main IFMIF systems have been done since 1997. This list shows some of them:

- Accelerator Reliability, Availability, and Maintainability, C. Piaszczyk, Maintainability and Reliability Conference, Knoxville, TN, May 1997

- Accelerator Systems Model (ASM) - a Powerful Tool for Parametric Studies of Emerging High Power Accelerator Applications, C. Piaszczyk, et al., American Nuclear Society Winter Conference, Albuquerque, NM, Nov.1997

- IFMIF RAM Proposal, C. Piaszczyk, March 1997

- Reliability Survey of Accelerator Facilities, C. Piaszczyk, M. Rennich, Maintainability and Reliability Conference, Knoxville, TN, May 1998

- C. M. Piaszczyk and M. Rennich, “Reliability Analysis of the IFMIF’, AccApp ‘98, 2nd Topical Meeting on Nuclear Applications of Accelerator Technology, Sept. 20-23, 1998, Gatlinburg, TN

- M. Eriksson, C. M. Piaszczyk, “Reliability Assessment of the LANSCE Accelerator System”, AccApp ‘98, 2nd Topical Meeting on Nuclear Applications of Accelerator Technology, Sept.20-23, 1998, Gatlinburg, TN

- C. M. Piaszczyk, “Operational Experience at Existing Accelerator Facilities”, NEA Workshop on Utilization and Reliability of High Power Accelerators, Mito, Japan, Oct.1998

- C. M. Piaszczyk and M. Rennich, “Reliability Survey of Accelerator Facilities”, Maintenance and Reliability Conference Proceedings, May 12-14, 1998, Knoxville, Tennessee

- L. Burgazzi, IFMIF Lithium Target Safety, ENEA Report FIS-P127-015, 2003.

- L. Burgazzi, IFMIF Plant Safety Analysis, ENEA Report FIS-P127-011, 2003.

It is fair to see that Mr. Piaszczyk is a great expert in the field of accelerators reliability. Unfortunately, he is not part of the IFMIF project anymore. The same problem happens concerning Mr. Burgazzi and the other main IFMIF systems. Know-how and experience has been lost and this can slow down the whole process.

5.1.7. Comments

- The only complete RAM analysis for all the IFMIF systems is the one in CDA.
- Later analyses are focused on the Accelerator, based on CDA design and data.
- No RAM analyses on the rationalized design have been performed.
- Reliability data used in different studies doesn't always match, even when the source is said to be the same.
- RAM studies have been performed by people that now are out of IFMIF. Know-How lost

5.2. Methodology used in NPPs, ITER and Particle Accelerators

There are several different possible approaches to the RAM issue depending on the kind of facility and its goals. Experimental facilities traditionally care less about availability as their scheduled work times are reduced and unscheduled outages are not major problems. This concept, however, has been changing the last years, and that kind of facilities are trying to boost their availability.

On the other side, commercial facilities need to achieve very high availability to fulfil their commercial purposes: the more time the plant is working, the more money it gets.

5.3. RAM in Nuclear Power Plants

The main goal of RAM works on NPPs used to be guaranteeing the safety of the plant. Regulatory bodies are very strict in this sense and don't give licences unless a detailed deterministic study is performed. The economical aspect is also important in NPPs, and that's the reason why availability has been rising, achieving very high levels in third generation plants. The ultimate goal is to work as many hours as possible.

There has been a change in the RAM approach between second and third generation plants. In second generation plants the Probabilistic Studies Assessment (PSA) was post-design, as in third generation plants PSA is pre-design. PSA works have a three level structure:

- PSA Level I (RAM)
- Core Melting risk analysis
- PSA Level II (Security)
- Ultimate Barrier Failure risk
- PSA Level III (Security + Action)

5.3.1. Exposition risk beyond the exclusion area

This approach allows higher availability rates in new plants. The high availability goal means few or none scheduled and unscheduled outages apart from the fuel charging. The main issue in NPPs reliability and availability works is, therefore, maintenance during operation to guarantee the correct functioning of the plant with no need to stop it. Large number of redundancies (for second generation plants) and component reduction (third generation) are the main strategies followed to achieve safety and availability goals.

Nowadays 441 NPPs are operational. This means that there is a huge operative and design experience, with design manuals and technical recommendations generally accepted for the nuclear community, and a well established spare market, where components are widely tested. This gives designers and operators a solid base to work on.

5.4. RAM in ITER

As an experimental facility, a high availability rate is not a design specification in ITER. As a consequence, RAM was not taken in account during the design process. Good performance of the facility is to be guaranteed by component quality assurance, security and the scheduled maintenance outages.

PSA works have been performed for security and licensing questions, and have been possible thanks to the international Fusion Component Failure Rate Database (FCFR-Db) and the security culture which is present in the nuclear sector. There are some “issues” to implement a RAM plan linked to security studies:

- Assessment of maintenance scenarios
- Rules for study of accidents and internal and external hazards
- Need for a Reliability, Availability and Maintainability Framework
- Establishing links between the Reliability, Availability and Maintainability Framework and the ITER Safety Case
- Need to minimise unnecessary system diversity
- Estimating ITER Shutdown Durations
- 9.1-06 The component design process needs to consider installation and maintenance requirements.
- ITER Dependability Analysis
- ITER "Corporate" QA Program

5.5. RAM in Accelerators

In the world there are a lot of particle accelerators working in many different purposes, from CERN's big synchrotron to small medical accelerators. In the late 1990s accelerator operators started to raise their availability rates by improving maintenance policies or fixing design mistakes. At that time availability had become an important parameter even for experimental facilities. Since then RAM methods in the field of particle accelerators has been developing so quickly. Component failure rate databases were collected and workshops for design on high availability were organised (e.g. Accelerator Reliability Workshop ESRF Grenoble 2002, Groemitz 2005). These workshops allowed operators to share operative experience and lessons learnt among the years. Acts like those ones bring to the creation of recommendations on the design of new accelerators, which might be taken as design rules for high availability. However, there isn't still any RAM standard.

5.6. Existing Failure rate Databases and Operative experience

Operative experience in fields related to the different IFMIF systems is very different depending on the system:

5.6.1. Central Control System and Common Instrumentation and Conventional Facilities

The Central Control System and Common instrumentation will provide overall and functional control capability to the IFMIF. The control function will be centralized in a single control room. It will be supported by an array of instrumentation, monitors and sensors as required to supplement those provided by the individual facilities.

The Conventional Facilities will provide housing for the three process Facilities (Test, Target and Accelerator) in a single main building centred on the test cells. Smaller separate structures house the support services. The process Facilities are functionally largely independent and require buildings for many subsystems. As a consequence of the independence of these Facilities it is possible to group their buildings in separate complexes. Conventional Facilities also include the Heat rejection system for the accelerator and the Lithium loop, the Electrical power distribution system, the Air conditioning system, Service water, Radioactive waste handling facility and other plant services.

More than 50 years and 441 operating nuclear power plants give a solid experience to design and operate these systems. Furthermore, the systematic data collection following IAEA and NRC standards provides a reliable database on all the components used in these systems.

5.6.2. Accelerator Facility

There are a great number of particle accelerators of many kinds all over the world, built with different purposes. Mainly are dedicated to perform particle physics research or have a medical use in hospitals, but there are also some commercial irradiation plants.

Reaching a high availability rate wasn't traditionally a primary goal in accelerator designing. That's why there isn't a global and standardized accelerator component failure rate database. Some of the main particle accelerators like CERN, IPN or APS have their own private databases. However, in the last years a great effort on improving accelerators' availability is being done. Prove of this are the high accelerator reliability workshops ESRF or NEA where lessons learnt and solutions taken among the years were shared.

Work groups on accelerator reliability have been created. The collaborative development of a common approach for reliability, availability and safety in European accelerators, created by CERN, DESY and ESRF will start working on 2008.

The main conclusions achieved are.

- Lighten design stress
- Design margins (~10%). Working at the limit of a device's capability shortens its life and increases its failure rate.
- Reduce the amount of components ($R \alpha r^N$)
- Total reliability (R) depends on each component's reliability (r) and on the number of components (N). Therefore, the more components, the more failures ($r \leq 1$, $N > 1$, $R \leq r$).
- Spares, redundancy and MTTR (Mean Time To Repair) policy
- ALARA – *As Low As Reasonably Available*
- Hands on repairs are preferred. Avoid activation as much as possible.
- Radiation-Hard Components
- Small failure events involving radiation might be much more severe if nearby components are easily affected by radiation.
- Classify components on their risk to cause long stops

In the same way in security components are classed on their risk to cause damage or injuries, in RAM works it is necessary to know which failures lead to the most time of stop:

Availability risk = Probability * Stop time

For example, an electric and electronic connector failure may lead to a relatively long stop without safety risk. As there are many connectors in the facility, their failure rate and time to repair must be minimized (improving contacts or making them easier to find and repair) to minimize the Availability risk.

5.6.3. Target Facility

Two lithium loops similar to the one to be built in IFMIF, one in IPPE, Russia, and the other in Osaka, Japan, are working nowadays. The information taken in these lithium loops will be directly used to improve IFMIF's target design.

5.6.4. Test Facility

There are no other facilities like the one to be built in IFMIF in the world. However, hot cells used in IFMIF are conventional so the experience in using them is large. The main question in the test facility will be the Test cell itself, including the VTA1, VTA2 and VIT.

5.7. Global Evaluation

There is a large experience and existing databases concerning the main systems of the IFMIF, but there is still a long way to go.

As previous works show, the accelerator is the most critical system in the RAM aspect. Therefore, there is the need to create a standardized accelerator failure rate database by unifying the existing databases into a single international database. This is already being done in the Fusion Component Failure Rate Database, where all the groups working on fusion have access.

The operating experience must be condensed into design rules to avoid repeating past mistakes.

Availability can be improved in many ways. Improving component reliability, increasing the redundancies or making more strict maintenance and spare policies are some of them. All these solutions increase construction costs, operation costs or even both, increasing the factory's life cycle cost. There must be an agreement on how much is the availability goal worth and find the economically optimal solution.

RAM and security integration is a necessary step as methodology used in those two disciplines is very similar and their goals are close to each other. Security as well as availability is tied to reliability and maintenance policies. RAM-Security integration will avoid repeating work and increasing the efficiency of the work done.

5.8. Methodology to implement a RAM program

5.8.1. IFMIF Peculiarities

One of the main IFMIF's design specifications is an overall availability of 70% including scheduled outages. This means that the requirement is 80.7% of scheduled working time. As a consequence, RAMS must interact with the design process. A constant RAMS-Design feedback process during the EVEDA phase is the only way to guarantee the fulfilment of the specifications.

The IFMIF is made up of 5 systems, which are designed separately. A process of design integration is needed to unify methodology and design criterion. RAMS must take part of the design integration in order to assure common RAMS methodology for all the systems and a global view of the plant, considering the interrelations between systems. In order to successfully implement design integration, experience in similar projects, like the EPR and AP1000 nuclear power plants, must be taken in account.

5.8.2. Regulatory Framework: IAEA Guidelines

A correct RAMS methodology election to evaluate the design will simplify the process to obtain the construction and operation licences. Methodology chosen must be validated for the regulatory body (IAEA, NRC...) ruling in the country where the plant will be placed. This will also make necessary to define a regulatory framework where to recourse when necessary. Local and international laws concerning radioactive installations will be an important design and RAMS limitation. Furthermore, a licensing study was performed during the KEP phase [DI91-JA: Examination of Licensing and Regulations] in case the IFMIF location is in Japan.

During the EVEDA phase a quality control of the RAMS works must be carried out in order to check that all the works fulfil the methodology and rigour that this task demands. A central RAMS group coordinating all the groups working on IFMIF's RAMS might be a good way to do this checking.

In this direction, the IAEA gives some guidelines which are interesting to fulfil:

- IAEA-TECDOC-478

Component Reliability data for use in Probabilistic Safety Assessment

- IAEA-TECDOC-504

Evaluation of Reliability Data Sources

- IAEA-TECDOC-508

Survey of Ranges of Component Reliability Data for use in Probabilistic Safety Assessment

- IAEA-TECDOC-636

Manual on reliability data collection for research reactor PSAs

- IAEA-TECDOC-930

Generic component reliability data for research reactor PSA

- IAEA-TECDOC-952

Advanced control systems to improve nuclear power plant reliability and efficiency

- IAEA-TECDOC-1048

Collection and classification of human reliability data for use in probabilistic safety assessments

- IAEA-TECDOC-1494

Case studies in the application of probabilistic safety assessment techniques to

5.8.3. Synergies: Similar Projects

Comparing and learning with similar projects is a basic part of any engineering project.. There are currently some examples of RAMS design integration in major projects:

- Nuclear Industry: EPR, AP1000
- Aeronautics: Airbus 380
- Space Program: ESA, ISA, NASA
- Accelerators: CERN, LHC (Burgazzi)

Contact teams working on these projects and learn from their experience will give the IFMIF RAMS team a base to work from. This experience will be useful to:

- Create Design Rules
- Improve RAMS quality
- Improve RAMS-Design integration

These three aspects are balanced in importance and will have similar dedication.

5.9. Proposal of a Basic Implementation

The proposed RAMS structure includes a RAMS work group which works separately from the engineering groups, checking and reviewing the evolutions in the design process. This RAMS group will integrate the inputs coming from the existing and future databases, the methodology chosen and the know-how/operating experience from one side and the engineering work from the other to guarantee the fulfilment of the availability specifications. Know-how, operative experience and design rules are also a very important input in the engineering groups (see Fig. 5.1).

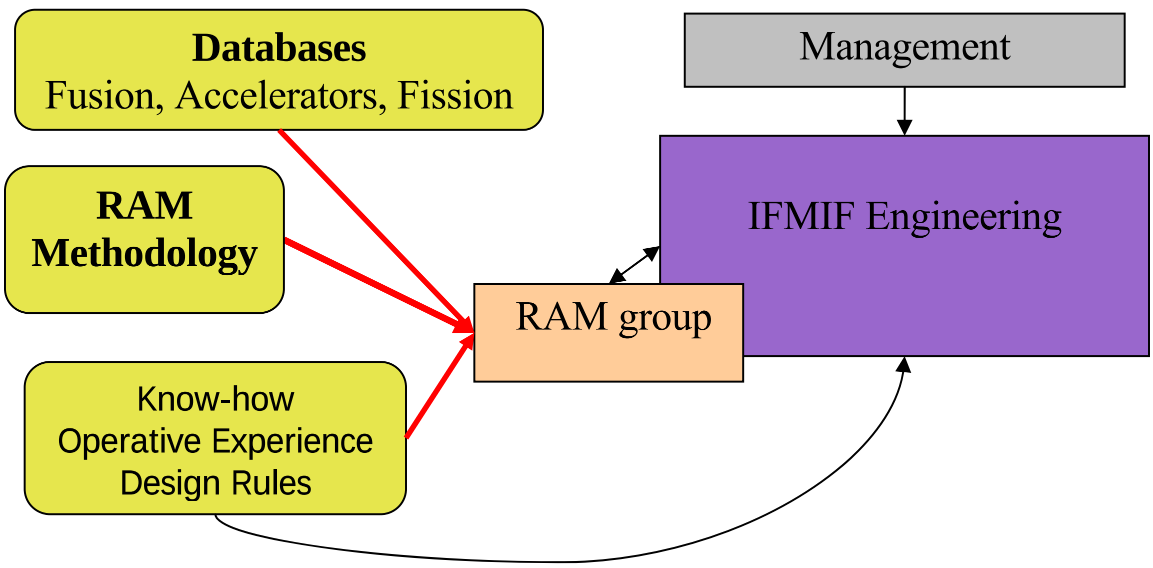


Fig. 5.1 RAM group location

The inner structure of the RAMS group is the one shown in Fig. 5.2.

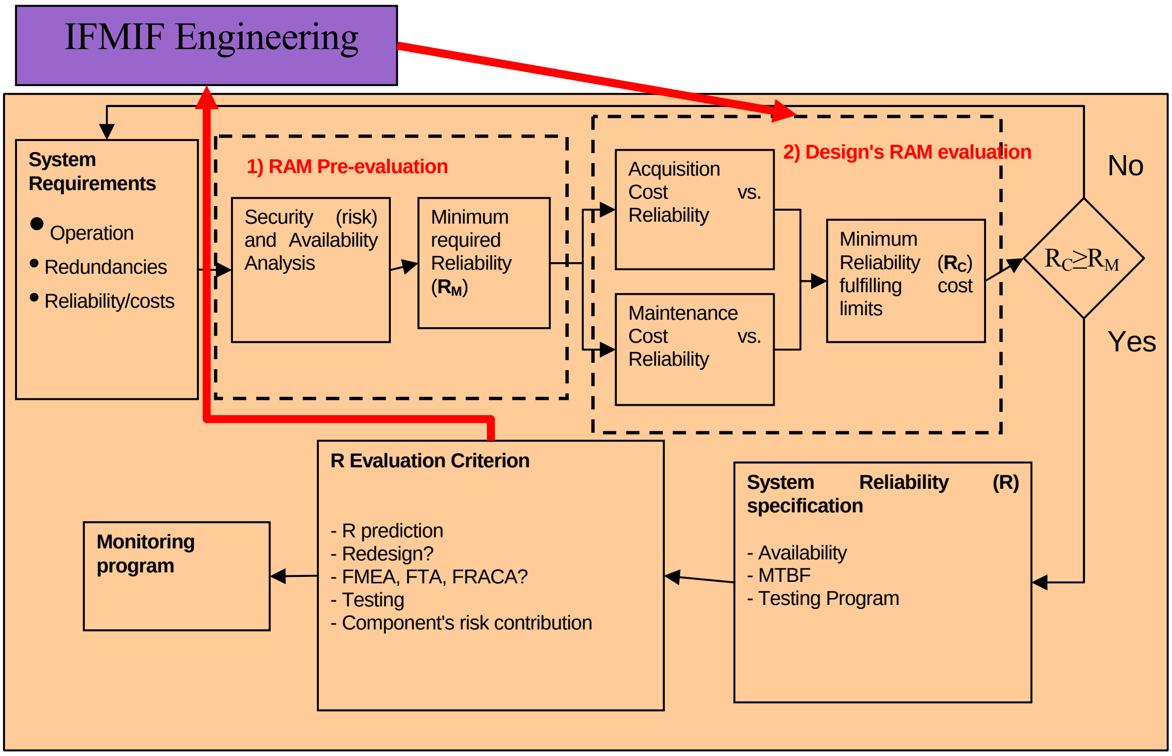


Fig. 5.2 Inner structure of the RAM group

A RAM pre-evaluation after the system requirements is the step previous to working on the conceptual design. In the second step the system requirements and the available solutions are checked and compared with the budget. If the estimated acquisition or operation cost is too high or the availability achieved doesn't reach the specifications ($R_C \leq R_M$) some changes in the design, the goal or the budget will be necessary. Otherwise ($R_C \geq R_M$), the conceptual design is approved and the reliability specifications for the system's components, how it will be predicted, tested and measured, will be set and sent to the engineering workgroups. From then on a monitoring process on the design process will be performed by the RAMS workgroups.

5.10. RAM Working proposals for 1st year

- Create a RAMS workgroup

The first and most important step is to create a workgroup dedicated only to RAMS. This group should be stable and will be operating during the whole EVEDA phase. The early creation of this group is essential to launch all the RAM workgroups and tasks.

Once the group is created, the following steps are deciding the most convenient RAMS structure linked to the engineering. The fact that different countries with many engineering workgroups each and belonging to different joint teams makes it hard to have an overall vision of the state of the design and the interactions between the different systems. A correct location of the RAMS workgroups in one or more of the engineering levels is important in order to work efficiently, both engineering and RAMS workgroups. The main levels to consider are:

- Joint Team level
- Legal entities level
- Engineering workgroups level

The way information is collected and managed, and the communication between RAMS workgroups is also something in charge of the main workgroup.

- Agreements with Failure Rate Databases

Failure rate databases are one of the main tools RAMS workgroups will use while performing their tasks. That's why having access to those containing component data that can be used in the IFMIF is necessary. Arranging the necessary agreements to let IFMIF engineers and RAMS workgroups consult main component failure rate databases is a first priority task for the IFMIF main RAMS workgroup.

Databases to consider are:

- Nuclear Power Plants

- Fusion Facilities (Fusion Component Failure Rate Database)

- Accelerator Facilities (CERN, SLAC, DESY, ESRF, …)

However, databases are not always comparable as data has been taken in different conditions and/or different formatting. This non standardized data has to be used carefully, as it might lead to calculation mistakes. Creating a standardized database for IFMIF is also a task to perform by the RAMS workgroup.

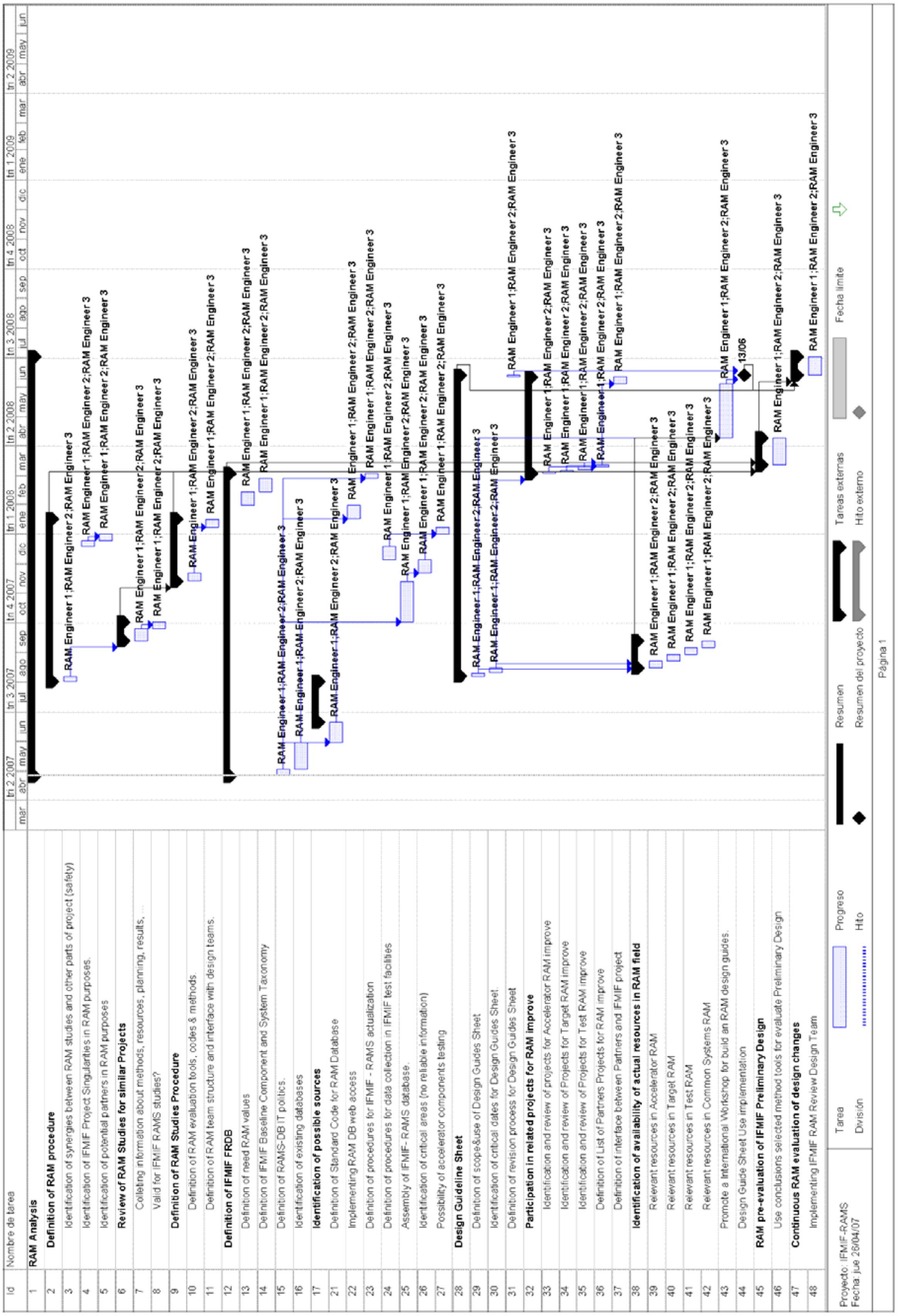
- Operational Experience

Know-how and professional experience are two essential aspects to succeed in engineering process and achieving the required availability. Contact groups with proved experience in the fields concerning IFMIF and learn from them:

- Mr. Cadwallader, from INL, has wide experience integrating RAM within the design process

- Mr. Burgazzi, Mr. Piaszczyk and Mr. Pinna have wide experience in fusion, CERN and other accelerators' reliability and availability

Tasks to be done next year are summarized in detail in the Gantt chart.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Nombre de tarea
1 RAM Analysis
2 Definition of RAM procedure
3 Identification of synergies between RAM studies and other parts of project (safety)
4 Identification of IFMIF Project Singularities in RAM purposes.
5 Identification of potential partners in RAM purposes
6 Review of RAM Studies for similar Projects
7 Colleting information about methods, resources, planning, results, ...
8 Valid for IFMIF RAMS studies?
9 Definition of RAM Studies Procedure
10 Definition of RAM evaluation tools, codes & methods.
11 Definition of RAM team structure and interface with design teams.
12 Definition of IFMIF FRDB
13 Definition of need RAM values
14 Definition of IFMIF Baseline Component and System Taxonomy
15 Definition of RAMS-DB IT politics.
16 Identification of existing databases
17 Identification of possible sources
21 Definition of Standard Code for RAM Database
22 Implementing RAM DB web access
23 Definition of procedures for IFMIF - RAMS actualization
24 Definition of procedures for data collection in IFMIF test facilities
25 Assembly of IFMIF- RAMS database.
26 Identification of critical areas (no reliable information)
27 Possibility of accelerator components testing
28 Design Guideline Sheet
29 Definition of scope&use of Design Guides Sheet
30 Identification of critical dates for Design Guides Sheet
31 Definition of revision process for Design Guides Sheet
32 Participation in related projects for RAM improve
33 Identification and review of projects for Accelerator RAM improve
34 Identification and review of Projects for Target RAM improve
35 Identification and review of Projects for Test RAM improve
36 Definition of List of Partners Projects for RAM improve
37 Definition of interface between Partners and IFMIF project
38 Identification of availability of actual resources in RAM field
39 Relevant resources in Accelerator RAM
40 Relevant resources in Target RAM
41 Relevant resources in Test RAM
42 Relevant resources in Common Systems RAM
43 Promote a International Workshop for build an RAM design guides.
44 Design Guide Sheet Use implementation
45 RAM pre-evaluation of IFMIF Preliminary Design
46 Use conclusions selected method tools for evaluate Preliminary Design
47 Continuous RAM evaluation of design changes
48 Implementing IFMIF RAM Review Design Team
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Progreso
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Resumen
Resumen del proyecto
Tareas externas
Hito externo
Fecha límite
Página 1

6. Methodology application on the IFMIF Target facility

To check whether the changes in the design after the first CDA [1] design affected significantly the availability in the main IFMIF systems RAM has been recalculated for one of them, the Target Facility. This analysis is based in the CDA design without taking in account the second target assembly, eliminated from the design after the CDA Reduced Cost Report [4]. MTBF and MTTR values are taken from the CDA report.

Methodology used is the same as the one used in KEP report [5] to recalculate the Accelerator facility's availability. It is a set of Markov chains-based equations which allows calculating element, system consisting of only working parts, system consisting of working parts and spare parts, and system consisting of subsystems.

6.1. Calculation method for Reliability, Availability, MTBF and MTTR of the system

6.1.1. Definitions

Generally, MTBF is defined as:

$$MTBF \equiv T = \int_0^\infty R(t)dt \qquad \text{(Eq. 6.1)}$$

Where R is Reliability and t is time. As assumed in the RAM analysis of the CDA, R of an element is given as an exponential function:

$$R = e^{-F \cdot t} \qquad \text{(Eq. 6.2)}$$

where F is the failure rate, so $T = 1/F$. Availability, A, is defined as:

$$A = \frac{T}{T + \tau} \qquad \text{(Eq. 6.3)}$$

where $\tau = MTTR$.

6.1.2. Subsystem consisting of only working parts

Defined a subsystem S_1 consisting of m_1 working parts with common F , T , τ values and no spare parts, the subsystem failure rate, reliability, and availability (respectively F_1, R_1 and A_1) are given by the following equations:

$$F_1 = m_1 \cdot F \qquad \text{(Eq. 6.4)}$$

$$T_1 = \frac{1}{F_1} = \frac{T}{m_1} \qquad \text{(Eq. 6.5)}$$

$$R_1 = R^{m_1} = e^{-m_1 \cdot F \cdot t} = e^{-F_1 \cdot t} \qquad \text{(Eq. 6.6)}$$

$$A_1 = \frac{T_1}{T_1 + \tau} = \frac{(T/m_1)}{(T/m_1) + \tau} \qquad \text{(Eq. 6.7)}$$

6.1.3. Subsystem consisting of Working parts and Spare parts

Defined a subsystem S_2 consisting on m_2 working parts and p_2 spare parts, the subsystem reliability R_2 and availability A_2 are given by:

$$R_2 = e^{-m_2 \cdot F \cdot t} \left\{ \sum_{k=0}^{p_2} \frac{(m_2 \cdot F \cdot t)^k}{k!} \right\} = e^{-F_2 \cdot t} \left\{ \sum_{k=0}^{p_2} \frac{(F_2 \cdot t)^k}{k!} \right\} \qquad \text{(Eq. 6.8)}$$

$$A_2 = \frac{\{(p_2 + 1)/m_2\}T}{\{(p_2 + 1)/m_2\}T + \tau} = \frac{T_2}{T_2 + \tau} \qquad \text{(Eq. 6.9)}$$

6.1.4. System consisting of Subsystems

Defined a system consisting of n subsystems: S_1, S_2, …, S_n, reliability R_S, availability A_S, MTBS T_S and MTTR τ_S are given by:

$$R_S = \prod_{i=1}^{n} R_i \qquad \text{(Eq. 6.10)}$$

$$A_S = \prod_{i=1}^{n} A_i \qquad \text{(Eq. 6.11)}$$

$$T_S = \int_0^\infty \prod_{i=1}^{n} \left[e^{-F_i t} \left\{ \sum_{k=0}^{p_i} \frac{(F_i \cdot t)^k}{k!} \right\} \right] dt = \frac{1}{F_S} \int_0^\infty e^{-x} \left[\prod_{i=1}^{n} \left\{ \sum_{k=0}^{p_i} \frac{1}{k!} \left(\frac{F_i}{F_S} x \right)^k \right\} \right] dx \qquad \text{(Eq. 6.12)}$$

where the system fiability F_S is given as

$$F_S = \sum_{i=1}^{n} F_i \qquad \text{(Eq. 6.13)}$$

Using a function $g(x)$:

$$g(x) = \prod_{i=1}^{n} \left\{ \sum_{k=0}^{p_i} \frac{1}{k!} \left(\frac{F_i}{F_S} x \right)^k \right\} = \sum_{j=0}^{\left(\sum_{i=0}^{n} p_i\right)} c_j \cdot x^j \qquad \text{(Eq. 6.14)}$$

equation 5.12 is given as

$$T_S = \frac{1}{F_S} \int_0^\infty e^{-x} g(x) dx = \frac{1}{F_S} \sum_{j=0}^{\left(\sum_{i=0}^{n} p_i\right)} \left(j! c_j \right) \qquad \text{(Eq. 6.15)}$$

According to Eq. 5.3, MTBF τ_S is

$$\tau_S = T_S \left(\frac{1}{A_S} - 1 \right) \qquad \text{(Eq. 6.16)}$$

6.2. RAM analysis of the IFMIF Target Facility

In this project, a RAM analysis and a sensitivity analysis was completed. The subject of study is the IFMIF Target facility. It was chosen because there are no RAM analyses for that facility after CDA, even it suffered a major modification in the cost reduction, when the second target assembly was eliminated.

However, the design and the data used in this analysis are the same as used in CDA report. It must be taken in account that the system structure and the element quantity used, especially for the number of valves in each subsystem, is based in the Figure 6.1, extracted from CDA and modified to eliminate the second target assembly.

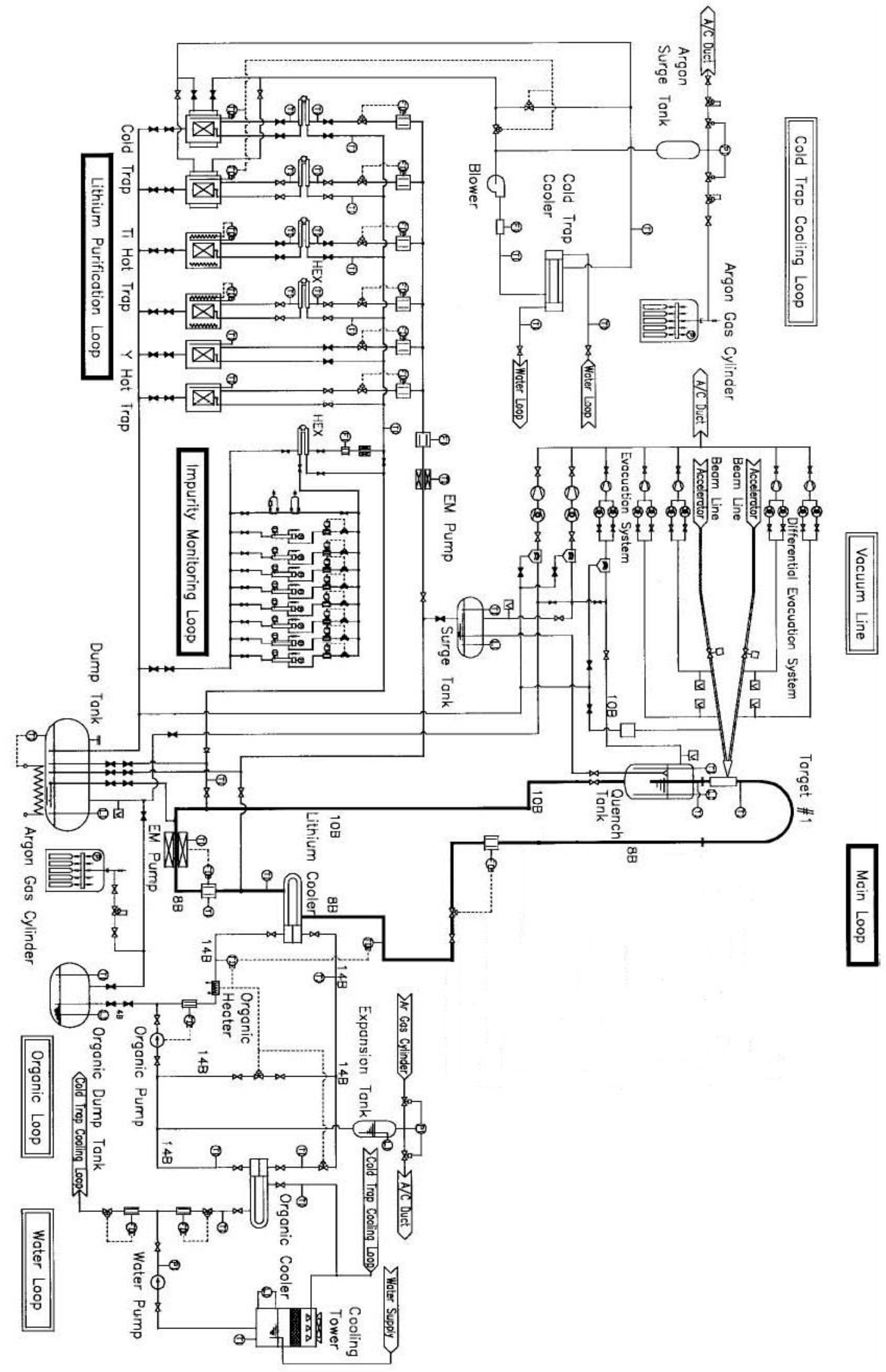

Fig. 6.1 Diagram of the Target Facility. The second target assembly has been erased after the cost reduction.

The system has been modelled as shown in Fig. 6.2 and 6.3. The fault trees are used just to show the element and system hierarchy used to describe the plant.

The IFMIF Target Facility is composed of 4 main subsystems at the same level: the primary loop, including the target assembly and the main lithium loop, the impurity removal loop, the organic loop, and the water loop. The impurity removal loop is used to keep the lithium in the lithium main loop in the desired level of purity by removing the undesired products of the interaction between Li and the deuteron beam, mainly ^{7}Be and tritium. The organic and water loops are the primary and secondary loops of the heat rejection system. They have to remove the 10 MW introduced to the Li loop by the deuteron beam. The water loop is also used to cool down the cold traps in the impurity removal loop.

The impurity removal loop is the most interesting in terms of RAM analysis, as it contains different levels of elements and redundancies (see Fig. 6.3).

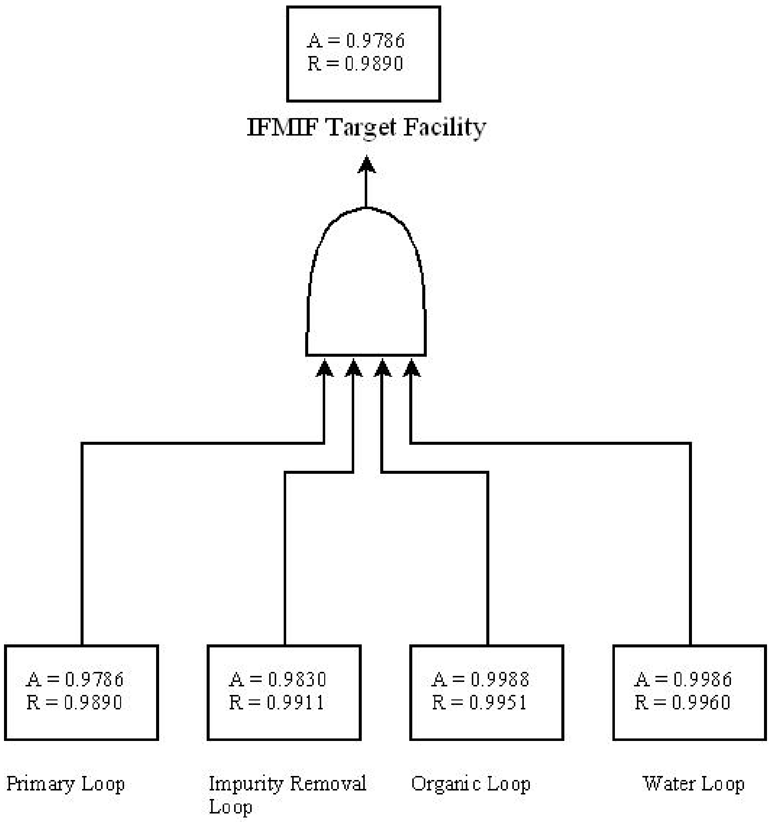

Fig. 6.2 Target Facility Diagram

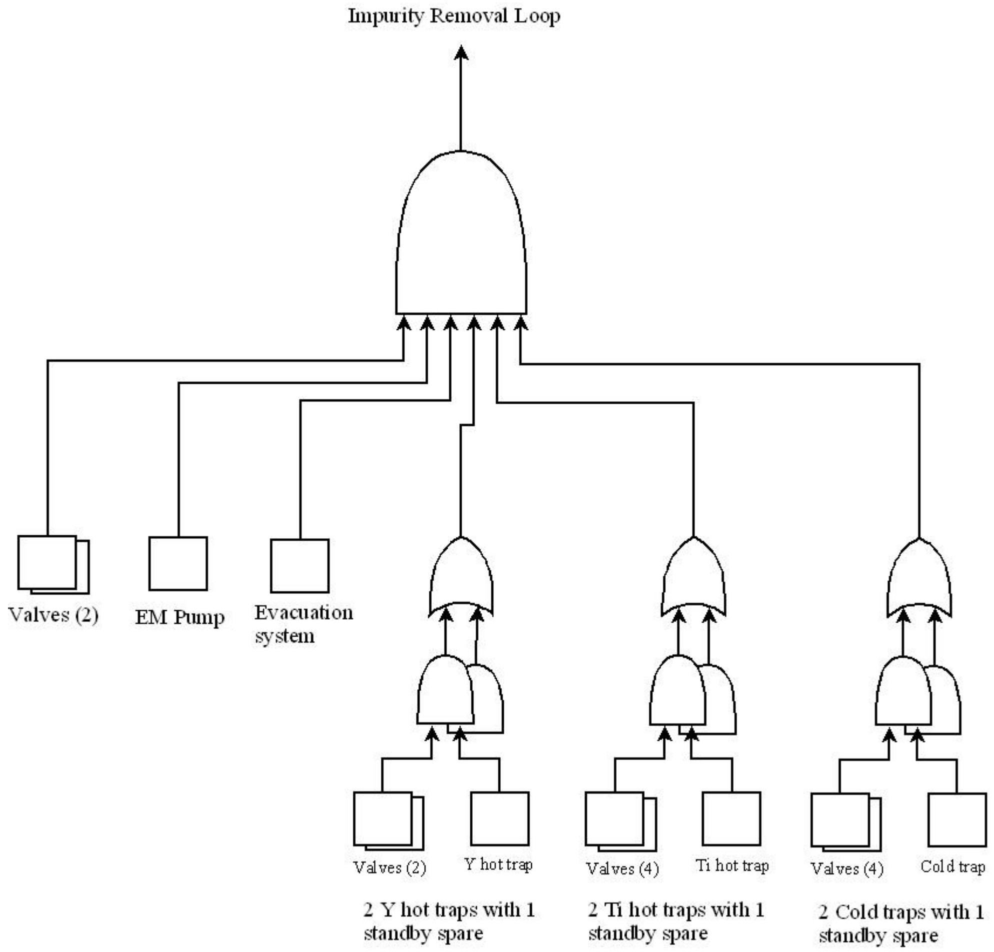

Fig. 6.3 Impurity Removal Loop

Table 6.1: RAM analysis for the IFMIF Target Facility

System	Component	number	spares	MTBF [h]	MTTR [h]	A	R
IMPURITY REMOVAL LOOP							
	Valves	2	0	175000	336	0.9981	0.9990
	EM pump	1	0	71500	168	0.9977	0.9977
	Evacuation system	1	0	30000	168	0.9944	0.9944
	Cold trap assembly						
	Cold trap	1	0	100000	168	0.9983	0.9983
	Valves	4	0	87500	336	0.9962	0.9981
	Cold trap assembly	1	0	46667	258	0.9945	0.9964
	2 cold trap assembly w/ redundancy	1	1	93333	258	0.9972	1.0000

Y hot trap assembly						
Y hot trap	1	0	100000	168	0.9983	0.9983
Valves	2	0	175000	336	0.9981	0.9990
Y hot trap assembly	1	0	63636	229	0.9964	0.9974
2 Y hot trap assembly w/ redundancy	1	1	127273	229	0.9982	1.0000
Ti hot trap assembly						
Ti hot trap	1	0	100000	168	0.9983	0.9983
Valves	4	0	87500	336	0.9962	0.9981
Y hot trap assembly	1	0	46667	258	0.9945	0.9964
2 Ti hot trap assembly w/ redundancy	1	1	93333	258	0.9972	1.0000
TOTAL IMPURITY REMOVAL LOOP			14776	256	0.9830	0.9911
PRIMARY LOOP						
Target assembly	1	0	259200	336	0.9987	0.9994
Quench tank	1	0	5000000	8760	0.9983	1.0000
Lithium dump tank	1	0	5000000	8760	0.9983	1.0000
Main EM pump	1	0	71500	336	0.9953	0.9977
Valves	4	0	87500	336	0.9962	0.9981
Surge tank	1	0	5000000	8760	0.9983	1.0000
Evacuation System	1	0	30000	168	0.9944	0.9944
Lithium-organix hx	1	0	350000	336	0.9990	0.9995
TOTAL PRIMARY LOOP			15137	331	0.9786	0.9890
ORGANIC LOOP						
Organic loop coolant dump tank	1	0	5000000	336	0.9999	1.0000
Organic pump	1	0	350000	5	1.0000	0.9995
Expansion pot	1	0	5000000	336	0.9999	1.0000
Organic-water hx	1	0	350000	336	0.9990	0.9995
Valves	8	0	43750	5	0.9999	0.9962
TOTAL ORGANIC LOOP			34517	42	0.9988	0.9951

WATER LOOP							
	Water pump	1	0	350000	4	1.0000	0.9995
	Cooling tower	1	0	259200	336	0.9987	0.9994
	Valves	6	0	58333	4	0.9999	0.9971
TOTAL WATER LOOP				41915	58	0.9986	0.9960
TOTAL IFMIF TARGET FACILITY				5360	226	0.9595	0.9715
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)						0.95	

The results obtained are similar to those in CDA, as shown in table 6.2. However, availability obtained with the new analysis is almost 0.9% higher. This remarkable increase in the system availability is caused by the design updates, but also to the updated methodology. The availability value obtained using the original design, with 2 target assemblies and the same number of all the other elements, is lower than in 1996: $A = 0.9461$ (see Annex A).

Table 6.2: Comparison between results obtained and the ones in CDA

	CDA (1996)	Genís Riba (2007)
Availability	0.9508	0.9595
Reliability	0.9690	0.9715
MTBF [h]	5034	5360
MTTR [h]	260	226

6.3. Sensitivity Analysis

Parameters used to characterize each one of the elements in the system, MTBF and MTTR, have a statistical origin. They are calculated by testing the elements or from operational experience and put in databases for further RAM analyses. The accuracy in a RAM analysis depends on how accurate is the source of statistical data. Sensitivity analyses are used to minimize the impact of this uncertainty in the global result by modifying MTBF and MTTR values, multiplying or dividing them for a 3 or 10 factor randomly.

In our case, MTBF and MTTR values were not taken as estimation but as design goals. Parameters used were considered to be the feasible ones that fulfilled the availability overall objectives.

The sensitivity analyses completed here takes the two worst situations for the availability. In case A all the components' MTBF was divided and multiplied by 3 and in case B MTTR was multiplied and divided by 3. Besides the two extreme cases, a third scenery was calculated, dividing and multiplying the valves' MTBF by 3. Valves have a big impact on our system's availability because of their number, 30 in the whole system. Results are summarized in table 6.3. See Annex A for the entire analysis.

Table 6.3: Sensitivity Analysis

Case	A $(MTBF/3)$ - $(MTBF \cdot 3)$	B $(MTTR \cdot 3)$-$(MTTR/3)$	C $(MTBF/3)$-$(MTBF \cdot 3)$
A	0.8836 – 0.9863	0.8836 – 0.9863	0.9392 – 0.9664
R	0.9170 – 0.9904	0.9715 – 0.9715	0.9531 – 0.9778
$MTBF$ [h]	1787 - 16080	5360 - 5360	3173 - 6958
$MTTR$ [h]	235 - 224	706 - 75	206 - 242

Results show that the system is more likely to lose availability increasing MTTR or decreasing MTBF than to gain it in the reverse process. It is also interesting to point that the maintenance program has a great effect on the availability. A more active maintenance program (MTTR/3) doesn't affect the reliability of the system but produces a great increase in the overall availability.

The system is working above the limit but with almost no margin.

Conclusions and Recommendations

IFMIF is an international project with a budget over 3.000 M€. Its objective is testing materials for the future construction of commercial fusion reactors. In order to fulfil its goals, a high availability rate, over 80% of scheduled operating time, is demanded.

IFMIF is currently on its Engineering Validation and Engineering design phase, which has just started and will last the next 5 years.

Concerning IFMIF RAM program

1. IFMIF design isn't nowadays defined
2. RAMS studies are not updated, are partial, and use different methodologies
3. Availability goals will not be achieved unless a RAM effort is done
4. Failure Rates data isn’t homogeneous. It is necessary to use a standard data collection and storing methodology
5. Need for RAMS and Design interaction. Work protocols must be strict and well defined. Need for a Regulatory framework
6. It will be very useful to establish synergies with other disciplines where RAMs are an input to the Design

The main tasks to do are:

1. Create a RAM group for IFMIF
    - Create RAM working group for EVEDA phase.
    - Define organization and engineering structure, in order to allocate RAM working groups.

2. Agreements with Failure Rate Data Base

    - Arrange the necessary agreements to consult FCFR-db, CERN-db, SLAC-db, Other-accelerators-db

    - Normalize Failure Rates Databases to make them comparable

3. Operational Experience

    - Contact Mr. Cadwallader, Mr. Burgazzi, Mr. Piaszczyk and Mr. Pinna, who have wide experience on RAM concepts and design integration

Concerning RAM methodology

1. Choosing a proper RAM methodology and being consistent with the election is a key point in any RAM study.

2. Different methodologies lead to different results.

3. In complex systems with a large number of components, software will be required. It must be validated and contrasted as a reliable RAM calculation software.

4. Each methodology has its weaknesses and strengths. Knowing them will help selecting the most suitable for the system to analyze.

5. Sensitivity analyses are a powerful tool to prevent wrong results due to bad parameter estimations.

6. Small miscalculation in some element's MTBF can lead to noticeable differences in the final result. Therefore, having access to reliable databases is very important for any RAM analysis.

7. Even though there is a close relation between RAM and safety, safety issues are not taken in account in this project. However, for the licensing process safety studies will be necessary.

Acknowledgments

I want to thank my tutors, Javier Dies and Carlos Tapia, to let me be active part of IFMIF, an international project with worldwide dimension and relevance. Thanks to them I have been able to do my bit in the development of nuclear fusion technology. I also want to thank them for their support and help in the difficult moments I had to pass through during the elaboration of this project.

I also want to give special thanks to my colleagues, Miquel Dapena and Rubén Lopez. Without them this project would have never been possible. Their help in the key points of the report and the good ambient they created in the office have been fundamental to reach a satisfactory end of these 4-month work.

Finally I want to thank my parents, my brother and my sister for their unconditional support.

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ANNEX

A. Original Design RAM and Sensitivity Analysis

Table A.1: RAM calculation for the original CDA design with the updated equations

	component	number	spares	MTBF [h]	MTTR [h]	A	R
IMPURITY REMOVAL LOOP							
	Valves	7	0	50000	336	0.9933	0.9966
	EM pump	1	0	71500	168	0.9977	0.9977
	Evacuation system	1	0	30000	168	0.9944	0.9944
	Cold trap assembly						
	Cold trap	1	0	100000	168	0.9983	0.9983
	Valves	3	0	116667	336	0.9971	0.9986
	Cold trap assembly	1	0	53846	246	0.9955	0.9969
	2 cold trap assembly w/ redundancy	1	1	107692	246	0.9977	1.0000
	Y hot trap assembly						
	Y hot trap	1	0	100000	168	0.9983	0.9983
	Valves	3	0	116667	336	0.9971	0.9986
	Y hot trap assembly	1	0	53846	246	0.9955	0.9969
	2 Y hot trap assembly w/ redundancy	1	1	107692	246	0.9977	1.0000
	Ti hot trap assembly						
	Ti hot trap	1	0	100000	168	0.9983	0.9983
	Valves	3	0	116667	336	0.9971	0.9986
	Y hot trap assembly	1	0	53846	246	0.9955	0.9969
	2 Y hot trap assembly w/ redundancy	1	1	107692	246	0.9977	1.0000
TOTAL IMPURITY REMOVAL LOOP				12308	267	0.9788	0.9888
PRIMARY LOOP							
	Target assembly	2	0	129600	336	0.9974	0.9987
	Quench tank	2	0	5000000	8760	0.9983	0.9999
	Lithium dump tank	1	0	5000000	8760	0.9983	1.0000
	Main EM pump	1	0	71500	336	0.9953	0.9977
	Valves	7	0	50000	336	0.9933	0.9966
	Surge tank	1	0	5000000	8760	0.9983	1.0000

	Evacuation System	1	0	30000	168	0.9944	0.9944
	Lithium-organix hx	1	0	350000	336	0.9990	0.9995
TOTAL PRIMARY LOOP				12708	332	0.9746	0.9869
ORGANIC LOOP							
	Organic loop coolant dump tank	1	0	5000000	336	0.9999	1.0000
	Organic pump	1	0	350000	5	1.0000	0.9995
	Expansion pot	1	0	5000000	336	0.9999	1.0000
	Organic-water hx	1	0	350000	336	0.9990	0.9995
	Valves	6	0	58333	336	0.9943	0.9971
TOTAL ORGANIC LOOP				42998	296	0.9932	0.9961
WATER LOOP							
	Water pump	1	0	350000	4	1.0000	0.9995
	Cooling tower	1	0	259200	336	0.9987	0.9994
	Valves	4	0	87500	4	1.0000	0.9981
TOTAL WATER LOOP				55115	75	0.9986	0.9970
TOTAL IFMIF TARGET FACILITY				4967	283	0.9461	0.9690
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)						0.95	

Table A.2: MTBF divided by 3

	component	**number**	**spares**	**MTBF [h]**	**MTTR [h]**	**A**	**R**
IMPURITY REMOVAL LOOP							
	Valves	2	0	58333	336	0.9943	0.9971
	EM pump	1	0	23833	168	0.9930	0.9930
	Evacuation system	1	0	10000	168	0.9835	0.9833
	Cold trap assembly						
	Cold trap	1	0	33333	168	0.9950	0.9950
	Valves	4	0	29167	336	0.9886	0.9943
	Cold trap assembly	1	0	15556	259	0.9837	0.9893
	2 cold trap assembly w/ redundancy	1	1	31111	259	0.9918	1.0000
	Y hot trap assembly						

Y hot trap	1	0	33333	168	0.9950	0.9950
Valves	2	0	58333	336	0.9943	0.9971
Y hot trap assembly	1	0	21212	230	0.9893	0.9921
2 Y hot trap assembly w/ redundancy	1	1	42424	230	0.9946	1.0000
Ti hot trap assembly						
Ti hot trap	1	0	33333	168	0.9950	0.9950
Valves	4	0	29167	336	0.9886	0.9943
Y hot trap assembly	1	0	15556	259	0.9837	0.9893
2 Y hot trap assembly w/ redundancy	1	1	31111	259	0.9918	1.0000
TOTAL IMPURITY REMOVAL LOOP			4925	260	0.9499	0.9736
PRIMARY LOOP						
Target assembly	1	0	86400	336	0.9961	0.9981
Quench tank	1	0	1666667	8760	0.9948	0.9999
Lithium dump tank	1	0	1666667	8760	0.9948	0.9999
Main EM pump	1	0	23833	336	0.9861	0.9930
Valves	4	0	29167	336	0.9886	0.9943
Surge tank	1	0	1666667	8760	0.9948	0.9999
Evacuation System	1	0	10000	168	0.9835	0.9833
Lithium-organix hx	1	0	116667	336	0.9971	0.9986
TOTAL PRIMARY LOOP			5046	337	0.9374	0.9673
ORGANIC LOOP						
Organic loop coolant dump tank	1	0	1666667	336	0.9998	0.9999
Organic pump	1	0	116667	5	1.0000	0.9986
Expansion pot	1	0	1666667	336	0.9998	0.9999
Organic-water hx	1	0	116667	336	0.9971	0.9986
Valves	8	0	14583	5	0.9997	0.9885
TOTAL ORGANIC LOOP			11506	42	0.9963	0.9855
WATER LOOP						
Water pump	1	0	116667	4	1.0000	0.9986
Cooling tower	1	0	86400	336	0.9961	0.9981
Valves	6	0	19444	4	0.9998	0.9914
TOTAL WATER LOOP			13972	58	0.9959	0.9880

TOTAL IFMIF TARGET FACILITY			1787	235	0.8836	0.9170
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)					0.95	

Table A.3: MTBF multiplied by 3

component	number	spares	MTBF [h]	MTTR [h]	A	R
IMPURITY REMOVAL LOOP						
Valves	2	0	525000	336	0.9994	0.9997
EM pump	1	0	214500	168	0.9992	0.9992
Evacuation system	1	0	90000	168	0.9981	0.9981
Cold trap assembly						
Cold trap	1	0	300000	168	0.9994	0.9994
Valves	4	0	262500	336	0.9987	0.9994
Cold trap assembly	1	0	140000	258	0.9988	0.9893
2 cold trap assembly w/ redundancy	1	1	280000	258	0.9991	1.0000
Y hot trap assembly						
Y hot trap	1	0	300000	168	0.9994	0.9994
Valves	2	0	525000	336	0.9994	0.9997
Y hot trap assembly	1	0	190909	229	0.9988	0.9991
2 Y hot trap assembly w/ redundancy	1	1	381818	229	0.9994	1.000
Ti hot trap assembly						
Ti hot trap	1	0	300000	168	0.9994	0.9994
Valves	4	0	262500	336	0.9987	0.9994
Ti hot trap assembly	1	0	140000	258	0.9988	0.9893
2 Y hot trap assembly w/ redundancy	1	1	280000	258	0.9991	1.0000
TOTAL IMPURITY REMOVAL LOOP			44329	255	0.9943	0.9970
PRIMARY LOOP						
Target assembly	1	0	777600	336	0.9996	0.9998

	Quench tank	1	0	15000000	8760	0.9994	1.0000
	Lithium dump tank	1	0	15000000	8760	0.9994	1.0000
	Main EM pump	1	0	214500	336	0.9984	0.9992
	Valves	4	0	262500	336	0.9987	0.9994
	Surge tank	1	0	15000000	8760	0.9994	1.0000
	Evacuation System	1	0	90000	168	0.9981	0.9981
	Lithium-organix hx	1	0	1050000	336	0.9997	0.9998
TOTAL PRIMARY LOOP				45411	329	0.9928	0.9963
ORGANIC LOOP							
	Organic loop coolant dump tank	1	0	15000000	8760	0.9994	1.0000
	Organic pump	1	0	1050000	5	1.0000	0.9998
	Expansion pot	1	0	15000000	336	1.0000	1.0000
	Organic-water hx	1	0	1050000	336	0.9997	0.9998
	Valves	8	0	131250	5	1.0000	0.9987
TOTAL ORGANIC LOOP				103550	42	0.9996	0.9984
WATER LOOP							
	Water pump	1	0	1050000	4	1.0000	0.9998
	Cooling tower	1	0	777600	336	0.9996	0.9998
	Valves	6	0	175000	4	1.0000	0.9990
TOTAL WATER LOOP				125744	58	0.9995	0.9987
TOTAL IFMIF TARGET FACILITY				16080	224	0.9863	0.9904
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)						0.95	

Table A.4: MTTR multiplied by 3

	component	**number**	**spares**	**MTBF [h]**	**MTTR [h]**	**A**	**R**
IMPURITY REMOVAL LOOP							
	Valves	2	0	175000	1008	0.9943	0.9990
	EM pump	1	0	71500	504	0.9930	0.9977
	Evacuation system	1	0	30000	504	0.9835	0.9944
	Cold trap assembly						
	Cold trap	1	0	100000	504	0.9950	0.9983
	Valves	4	0	87500	1008	0.9886	0.9981
	Cold trap assembly	1	0	46667	776	0.9837	0.9964
	2 cold trap	1	1	93333	776	0.9918	1.0000

	assembly w/ redundancy						
	Y hot trap assembly						
	Y hot trap	1	0	100000	504	0.9950	0.9983
	Valves	2	0	175000	1008	0.9943	0.9990
	Y hot trap assembly	1	0	63636	689	0.9893	0.9974
	2 Y hot trap assembly w/ redundancy	1	1	127273	689	0.9946	1.0000
	Ti hot trap assembly						
	Ti hot trap	1	0	100000	504	0.9950	0.9983
	Valves	4	0	87500	1008	0.9886	0.9981
	Y hot trap assembly	1	0	46667	776	0.9837	0.9964
	2 Y hot trap assembly w/ redundancy	1	1	93333	776	0.9918	1.0000
TOTAL IMPURITY REMOVAL LOOP				14776	779	0.9499	0.9911
PRIMARY LOOP							
	Target assembly	1	0	259200	1008	0.9961	0.9994
	Quench tank	1	0	5000000	26280	0.9948	1.0000
	Lithium dump tank	1	0	5000000	26280	0.9948	1.0000
	Main EM pump	1	0	71500	1008	0.9861	0.9977
	Valves	4	0	87500	1008	0.9886	0.9981
	Surge tank	1	0	5000000	26280	0.9948	1.0000
	Evacuation System	1	0	30000	504	0.9835	0.9944
	Lithium-organix hx	1	0	350000	1008	0.9971	0.9995
TOTAL PRIMARY LOOP				15137	1010	0.9374	0.9890
ORGANIC LOOP							
	Organic loop coolant dump tank	1	0	5000000	1008	0.9998	1.0000
	Organic pump	1	0	350000	15	1.0000	0.9995
	Expansion pot	1	0	5000000	1008	0.9998	1.0000
	Organic-water hx	1	0	350000	1008	0.9971	0.9995
	Valves	8	0	43750	15	0.9997	0.9962
TOTAL ORGANIC LOOP				34517	127	0.9963	0.9951
WATER LOOP							

Water pump	1	0	350000	12	1.0000	0.9995
Cooling tower	1	0	259200	1008	0.9961	0.9994
Valves	6	0	58333	12	0.9998	0.9971
TOTAL WATER LOOP			41915	173	0.9959	0.9960
TOTAL IFMIF TARGET FACILITY			5360	706	0.8836	0.9715
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)					0.95	

Table A.5: MTTR divided by 3

component	number	spares	MTBF [h]	MTTR [h]	A	R
IMPURITY REMOVAL LOOP						
Valves	2	0	175000	112	0.9994	0.9990
EM pump	1	0	71500	56	0.9992	0.9977
Evacuation system	1	0	30000	56	0.9992	0.9944
Cold trap assembly						
Cold trap	1	0	100000	56	0.9994	0.9983
Valves	4	0	87500	112	0.9987	0.9981
Cold trap assembly	1	0	46667	86	0.9982	0.9964
2 cold trap assembly w/ redundancy	1	1	93333	86	0.9991	1.0000
Y hot trap assembly						
Y hot trap	1	0	100000	56	0.9994	0.9983
Valves	2	0	175000	112	0.9994	0.9990
Y hot trap assembly	1	0	63636	76	0.9988	0.9974
2 Y hot trap assembly w/ redundancy	1	1	127273	76	0.9994	1.0000
Ti hot trap assembly						
Ti hot trap	1	0	100000	56	0.9994	0.9983
Valves	4	0	87500	112	0.9987	0.9981
Y hot trap assembly	1	0	46667	86	0.9982	0.9964
2 Y hot trap assembly w/ redundancy	1	1	93333	86	0.9991	1.0000

TOTAL IMPURITY REMOVAL LOOP			14776	85	0.9943	0.9911
PRIMARY LOOP						
Target assembly	1	0	259200	112	0.9996	0.9994
Quench tank	1	0	5000000	2920	0.9994	1.0000
Lithium dump tank	1	0	5000000	2920	0.9994	1.0000
Main EM pump	1	0	71500	112	0.9984	0.9977
Valves	4	0	87500	112	0.9987	0.9981
Surge tank	1	0	5000000	2920	0.9994	1.0000
Evacuation System	1	0	30000	56	0.9981	0.9944
Lithium-organix hx	1	0	350000	112	0.9997	0.9995
TOTAL PRIMARY LOOP			15137	110	0.9928	0.9890
ORGANIC LOOP						
Organic loop coolant dump tank	1	0	5000000	112	1.0000	1.0000
Organic pump	1	0	350000	2	1.0000	0.9995
Expansion pot	1	0	5000000	112	1.0000	1.0000
Organic-water hx	1	0	350000	112	0.9997	0.9995
Valves	8	0	43750	2	1.0000	0.9962
TOTAL ORGANIC LOOP			34517	14	0.9996	0.9951
WATER LOOP						
Water pump	1	0	350000	1	1.0000	0.9995
Cooling tower	1	0	259200	112	0.9996	0.9994
Valves	6	0	58333	1	1.0000	0.9971
TOTAL WATER LOOP			41915	19	0.9995	0.9960
TOTAL IFMIF TARGET FACILITY			5360	75	0.9863	0.9715
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)					0.95	

Table A.6: Valves MTBF divided by 3

component	number	spares	MTBF [h]	MTTR [h]	A	R
IMPURITY REMOVAL LOOP						
Valves	2	0	58333	336	0.9943	0.9971
EM pump	1	0	71500	168	0.9977	0.9977
Evacuation system	1	0	30000	168	0.9944	0.9944
Cold trap assembly						

Cold trap	1	0	100000	168	0.9983	0.9983
Valves	4	0	29167	336	0.9886	0.9943
Cold trap assembly	1	0	22581	299	0.9870	0.9926
2 cold trap assembly w/ redundancy	1	1	45161	299	0.9934	1.0000
Y hot trap assembly						
Y hot trap	1	0	100000	168	0.9983	0.9983
Valves	2	0	58333	336	0.9943	0.9971
Y hot trap assembly	1	0	36842	274	0.9926	0.9955
2 Y hot trap assembly w/ redundancy	1	1	73684	274	0.9963	1.0000
Ti hot trap assembly						
Ti hot trap	1	0	100000	168	0.9983	0.9983
Valves	4	0	29167	336	0.9886	0.9943
Y hot trap assembly	1	0	22581	299	0.9870	0.9926
2 Y hot trap assembly w/ redundancy	1	1	45161	299	0.9934	1.0000
TOTAL IMPURITY REMOVAL LOOP			10708	332	0.9699	0.9892
PRIMARY LOOP						
Target assembly	1	0	259200	336	0.9987	0.9994
Quench tank	1	0	5000000	8760	0.9983	1.0000
Lithium dump tank	1	0	5000000	8760	0.9983	1.0000
Main EM pump	1	0	71500	336	0.9953	0.9977
Valves	4	0	29167	336	0.9886	0.9943
Surge tank	1	0	5000000	8760	0.9983	1.0000
Evacuation System	1	0	30000	168	0.9944	0.9944
Lithium-organix hx	1	0	350000	336	0.9990	0.9995
TOTAL PRIMARY LOOP			11246	334	0.9712	0.9852
ORGANIC LOOP						
Organic loop coolant dump tank	1	0	5000000	336	0.9999	1.0000
Organic pump	1	0	350000	5	1.0000	0.9995
Expansion pot	1	0	5000000	336	0.9999	1.0000
Organic-water hx	1	0	350000	336	0.9990	0.9995
Valves	8	0	14583	5	0.9997	0.9885

TOTAL ORGANIC LOOP			13389	19	0.9986	0.9875
WATER LOOP						
Water pump	1	0	350000	4	1.0000	0.9995
Cooling tower	1	0	259200	336	0.9987	0.9994
Valves	6	0	19444	4	0.9998	0.9914
TOTAL WATER LOOP			17199	26	0.9985	0.9903
TOTAL IFMIF TARGET FACILITY			3173	206	0.9392	0.9531
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)					0.95	

Table A.7: Valves MTBF multiplied by 3

component	**number**	**spares**	**MTBF [h]**	**MTTR [h]**	**A**	**R**
IMPURITY REMOVAL LOOP						
Valves	2	0	525000	336	0.9994	0.9997
EM pump	1	0	71500	168	0.9977	0.9977
Evacuation system	1	0	30000	168	0.9944	0.9944
Cold trap assembly						
Cold trap	1	0	100000	168	0.9983	0.9983
Valves	4	0	262500	336	0.9987	0.9994
Cold trap assembly	1	0	72414	215	0.9970	0.9977
2 cold trap assembly w/ redundancy	1	1	144828	215	0.9985	1.0000
Y hot trap assembly						
Y hot trap	1	0	100000	168	0.9983	0.9983
Valves	2	0	525000	336	0.9994	0.9997
Y hot trap assembly	1	0	84000	195	0.9977	0.9980
2 Y hot trap assembly w/ redundancy	1	1	168000	195	0.9988	1.0000
Ti hot trap assembly						
Ti hot trap	1	0	100000	168	0.9983	0.9983
Valves	4	0	262500	336	0.9987	0.9994

	Ti hot trap assembly	1	0	72414	215	0.9970	0.9977
	2 Y hot trap assembly w/ redundancy	1	1	144828	215	0.9985	1.0000
TOTAL IMPURITY REMOVAL LOOP				16919	216	0.9874	0.9918
PRIMARY LOOP							
	Target assembly	1	0	259200	336	0.9987	0.9994
	Quench tank	1	0	5000000	8760	0.9983	1.0000
	Lithium dump tank	1	0	5000000	8760	0.9983	1.0000
	Main EM pump	1	0	71500	336	0.9953	0.9977
	Valves	4	0	262500	336	0.9987	0.9994
	Surge tank	1	0	5000000	8760	0.9983	1.0000
	Evacuation System	1	0	30000	168	0.9944	0.9944
	Lithium-organix hx	1	0	350000	336	0.9990	0.9995
TOTAL PRIMARY LOOP				17110	329	0.9811	0.9902
ORGANIC LOOP							
	Organic loop coolant dump tank	1	0	5000000	336	0.9999	1.0000
	Organic pump	1	0	350000	5	1.0000	0.9995
	Expansion pot	1	0	5000000	336	0.9999	1.0000
	Organic-water hx	1	0	350000	336	0.9990	0.9995
	Valves	8	0	131250	5	1.0000	0.9987
TOTAL ORGANIC LOOP				72816	84	0.9989	0.9977
WATER LOOP							
	Water pump	1	0	350000	4	1.0000	0.9995
	Cooling tower	1	0	259200	336	0.9987	0.9994
	Valves	6	0	175000	4	1.0000	0.9990
TOTAL WATER LOOP				80454	107	0.9987	0.9979
TOTAL IFMIF TARGET FACILITY				6985	242	0.9664	0.9778
IFMIF TARGET SYSTEM AVAILABILITY GOAL (MINIMUM)						0.95	

B. Budget

B.1 Personnel Cost

This project tries to be a step in the way to the construction of the IFMIF. It synthesises previous work concerning IFMIF RAM and it proposes a list of things to do the next year for IFMIF to achieve its goals. There is also an example of RAM calculation on one of the main IFMIF systems.

The stages followed in the elaboration of this master thesis project are:

1. *Analysis of the existing documentation concerning the IFMIF*

   Existing documentation was studied to get familiar with the plant and its structure

   Time: 60 hours

2. *Comprehensive analysis of the previous RAM works*

   Documents IFMIF's and other facilities RAM were deeply analysed to be aware of the current state-of-the-art

   Time: 100 hours

3. *Proposal for a RAM planning in the IFMIF*

   A proposal for the steps to follow the next years during the IFMIF EVEDA phase was prepared

   Time: 150 hours

4. *Example of the method application*

   The Target Facility's RAM was recalculated following the methodology used so far in the IFMIF as an example of a RAM analysis

   Time: 50 hours

5. *Results analysis and conclusions*

The results obtained were evaluated and the conclusions taken

Time: 50 hours

6. Writing the project's report

   The report was written and some of the figures drawn

Time: 80 hours

The cost of an Engineer is estimated in 45 €/h.

B.2 Materials Cost

The only materials used during this project were office supplies: paper, ink, printers, computers, etc.

The estimated cost for all this is 70€

B.3 Project Budget

Item	Time [h]	Unit Cost [€/h]	Cost [€]
Personnel			
Analysis of the existing documentation concerning the IFMIF	60	45	2700
Comprehensive analysis of the previous RAM works	100	45	4500
Proposal for a RAM planning in the IFMIF	150	45	6750
Example of the method application	50	45	2250
Results analysis and conclusions	50	45	2250
Writing the project's report	80	45	3600
TOTAL PERSONNEL			22050

Material			
Office Supplies			70
TOTAL MATERIAL			70

TOTAL	22120

C.Environmental impact assessment

The development of this project doesn't have any major environmental impact. Only mention the use of office supplies like printer's ink and paper to print the documentation, apart from the usual electricity consumption associated to working with a personal computer.

Finally, it must be said that this project will help in the way to nuclear fusion as a clean energy source, without generation of greenhouse effect gases.