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THE AVAILABILITY ANALYSIS OF FUSION POWER PLANTS AS APPLIED TO MARS

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ABSTRACT

The computer program AVSYS has been developed to analyze the availability of fusion power plants. A parametric study has been conducted on MARS. In order to bring up the availability to acceptable levels redundancy is needed in the neutral beam injection, ECRH, ICRH, direct convertor, and the central cell magnet coils (one coil/side redundant). At the same time, an improvement in quality, maintenance, design (hence failure rates and repair times) is needed for the magnets, as well as the neutral beam subsystem and the direct convertor.

INTRODUCTION

The proposed fusion power plant designs may have availability problems due to the new and complex engineering systems utilized.

We have developed a computer program (AVSYS) to calculate approximate availability of a given design, compare different designs, suggest design improvements and component quality improvements for optimum cost of electricity, identify the availability drivers and apportion availabilities of individual subsystems so that an overall availability can be achieved.

The computer model has an availability and a cost component. It can handle redundancy, m-out-of-n operation, maintenance timelines, etc., as well as transient analysis and aging of components (if data can be found). Each subsystem's status is computed at each time interval using a Monte Carlo method. The status of the plant is obtained by combining this information in the logic diagram of the power plant.

LOGIC DIAGRAM OF POWER PLANT

The power plant is broken up into subsystems (see Table 1 as an example) which are combined into a logic diagram using logic gates (AND, OR and NOT). Figure 1 represents a very simplified (for illustration purposes only) diagram of the MARS plant. In order to analyze the availability, some of the numbers in Table 1 are varied, as well as the logic diagram of the plant and the failure data of subsystems.

TABLE 1. Subsystems of MARS[1,2]

Subsystem	Number of Units	Standby Redundancy	On-line Redundancy
Cryogenic	1	0	0
Central Cell (CC) Magnet	48	0	0
Choke Magnet	1/side	0	0
Tweak Magnet	1/side	0	0
Transition Magnet	1/side	0	0
Anchor Magnet	2/side	0	0
Plug Magnet	2/side	0	0
Recircularization Magnet	1/side	0	0
Direct Convertor Magnet	1/side	0	0
Direct Convertor	1/side	0	0
4 MW ICRH anchor	1/side	0	0
3 MW ECRH,plug	1/side	0	0
40 MW ECRH,plug	1/side	0	0
475 keV NB,plug	1/side	0	0
Fueling	1/side	0	0
Vacuum	1	0	0
Shield	1	0	0
Blanket	1 (84 modules)	0	0
Balance of Plant (BOP)	1	0	0
Control and Instrumentation	1	0	0

THE MODEL[3]

Our model employs a Monte Carlo analysis of availability. In this analysis, instantaneous reliability, $R_i = \exp(-\Lambda_i \Delta t)$, of each subsystem i is calculated for each time step Δt. R_i is

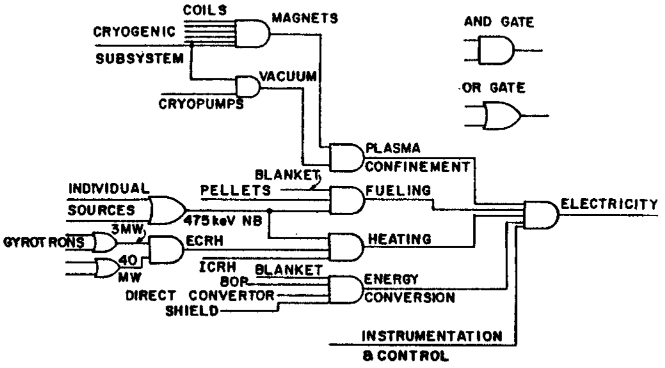

Fig. 1. Very simplified logic diagram for MARS.

compared to a random number between 0. and 1., generated by the congruential recursive method. The component fails in Δt if and only if the random number is greater than R_i.

In order to increase the efficiency of the program and decrease the variance, the failure rates are biased by multiplying by certain weight factors, such that the quantity $\Lambda_i * \mathrm{MTTR}_i$ remains constant for each subsystem (MTTR_i is the mean time to repair of subsystem i).[10] This can be justified by noting that the total downtime of a component in a given history has to remain constant. Using this variance reducing scheme a percentage relative standard deviation of less than 10% can be achieved.

Once failed, the component enters the repair routine where its downtime is increased until it equals the MTTR_i.

This information is employed to find the status of each logic gate output of all the time intervals.

Employing the availability model, one can test different design options for their impact on the availability, as well as quality control (decrease in Λ_i) or faster maintenance (decrease in MTTR_i).

The preceeding analysis is combined with a cost code; an increase in availability that decreases the operating costs is usually brought about by methods that increase capital costs (better quality control, redundancy, etc.). An optimum availability exists where the busbar cost of electricity (COE) is at a minimum:

$$\mathrm{COE}^{(11)} = \frac{\left[\overset{\text{Capital Cost}}{* \ \mathrm{CCF}} \ \overset{\text{Operations \&}}{+\text{Maintenance}} \ \overset{\text{Component}}{+\text{Replacement}} + \text{Fuel}\right]}{P * 8760 \text{ hrs/yr} * A} \underline{* \ 1000 \text{ mills/\$}}$$

where P is the station power rating in kWe
CCF is the carrying charge factor (usually 0.10 for the constant dollar mode)
A is the availability.

This formula assumes 100% capacity factor when the plant is operating.

FAILURE DATA

Table 2 shows the failure data used at the start of the analysis of MARS.

Some of the data have been obtained from the literature (e.g. STARFIRE report, ETF availability apportionment study), some have been solicited from the workers familiar with individual subsystems. Understandably, there is much of uncertainty in some of the data, because little is known about failure mechanisms and frequency of occurence for many subsystems. Not much is known about the maintenance timelines of such subsystems, either. Some of the numbers in

TABLE 2. Failure Data[3]

Subsystem	$\Lambda(\mathrm{hr}^{-1})$	MTTR (hrs)
Cryogenic[a,9]	1.1E-4	200.
All Magnets[a,b,4,8]	4.E-5	1000.
Direct Convertor[a,4]	2.3E-4	950.
ECRH, ICRH[a,4]	4.6E-4	240.
Neutral Beam[a,7]	1.4E-3	240.
Fueling[4]	1.1E-4	200.
Vacuum[4]	5.7E-5	200.
Shield[c,5]	2.3E-5	240.
Blanket[6]	1.7E-4	240.
BOP[5]	2.5E-4	240.
Control & Instrumentation[c,4,5]	2.E-4	48.

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[a] Private communication.

[b] We have found an estimate of 4.6E-6 from private communications and the ETF report, but used an order of magnitude higher estimate due to conservatism, and to the fact that not much is known about the failure of these coils.

[c] A reasonable estimate on MTTR was employed, based on accessibility considerations, range of data reported in literature and MTTR of similar subsystems.

the table may seem too high, but we decided to start from a conservative set of values in view of the uncertainties involved. Runs have been made with more optimistic data (order of magnitude improvement).

In this analysis, these failure data are subject to change, as we search for the ways to achieve a reasonable plant availability, at a reasonable cost. We can then recommend which subsystems need to be fabricated and designed to meet more stringent failure and maintenance criteria, and, perhaps, also suggest the ways in which the needed changes can be brought about.

RESULTS

The code AVSYS has been run on several fusion power plant designs, the latest one of which is the MARS tandem mirror reactor, and the MARS results will be presented here.

The highlights of the system are given in Table 1. At first, no redundancy is assumed for any of the subsystems. Later on we will assume that it is possible to operate the plant with one CC coil on either side failed.

The goal has been to alter the system design and failure data in such a way as to achieve a reasonable availability including a four week scheduled maintenance period. The parameters to be changed to achieve this goal are: Λ's (failure rates), MTTR's (mean times to repair), redundancy (on-line and standby) and number of units operating (e.g. number of central cell coils or neutral beam subsystems).

Using the data in Table 2 and Table 1, a very low availability is achieved (2%). (Using the optimistic data, an availability of 60% results, but we cannot base our design on the optimistic data.) Assuming one CC coil per side can fail without impairing the operation of the plant, the availability rises to 3.4%. These low availabilities are unacceptable, but not very surprising, since failure in almost any subsystem will shut down the plant. Hence, a two pronged approach is devised to improve this number. In the first stage, we tried to improve the failure rates and repair times of critical subsystems to what we felt were achievable values, or, in the case of magnets necessary values. In the second stage, redundancy of appropriate subsystems was considered.

In the first stage, we felt that the most critical subsystems were the magnets, because no redundancy of bulk magnets is possible and there are so many of them. Also, it was assumed that the dominant mode of failure was the conductor failure (due to spurious local loss of superconductivity, or mechanical failure). Auxiliary equipment such as the power supplies can always be made sufficiently redundant. For instance, assuming failure data for magnet power supplies given in the literature, an on-line redundancy of 1 results in the availability of these supplies of 0.99988, while only fractionally increasing the cost of the magnets. Therefore, the assumption is that the failure rate is proportional to the conductor volume of the magnet. As an example, the direct convertor magnet must undoubtedly be much simpler to design and fabricate than the plug yin-yang magnets, and can be expected to fail less often. So, in order to increase the power plant availability, we felt it necessary to decrease the failure rate of the plug magnets about 10 times (to 4.E-6 hr^{-1}), and adjust the failure rate of other magnets (except for the central cell coil) according to the ratio of conductor volume[1,12,13] of the particular magnet to that of one plug magnet. The central cell coils are very big and there are so many of them, so their failure rate was kept on the order of 4.E-6 hr^{-1}

as well.

These lower failure rates can be achieved in several ways. One example is quality control. It is difficult to estimate how much this option would cost. Another example may be to have several (e.g. 2) windings in each coil connected to the same power supply, so that in case of failure of one of them, the other ones can take up the load. For illustration purposes, for $\Lambda = 4.E\text{-}5\ hr^{-1}$ per winding, and employing two such independent windings would reduce the effective failure rate roughly an order of magnitude. Hence, an order of magnitude improvement in the magnet Λ is possible by doubling the magnet cost.

The MTTR of the magnets was also changed, to half its previous value. This can be achieved by designing the magnets in such a way as to minimize the cryogenic cooldown and warmup time during magnet replacement. Smaller magnets may be able to accomplish this more easily.

The new data improved the availability to 11%. The availability drivers are now the direct convertor, the neutral beams, the ECRH and the ICRH subsystems (see Table 3).

By employing an on-line redundancy of one for each end NB system, the availability increased to 17%. By decreasing the MTTR of the direct convertor to 200 hrs (comparable to the blanket replacement time), the availability increased to 28%. Decreasing the NB failure rate 10 times brought it up further to 32%. This decrease in the Λ of the NB can again be accomplished by better quality or by internal redundancy, e.g. of the ion source electrodes. For example, two electrodes with $\Lambda = 1.4E\text{-}3\ hr^{-1}$, MTTR = 240. hr, yields an effective Λ of $2.8E\text{-}4\ hr^{-1}$. With these changes, the availability drivers are now the RF heating subsystems. Employing a standby redundancy of one for each operating ECRH and ICRH system raised the availability to 60% (including a 4 week scheduled shutdown period).

For the plasma heating subsystems, it may not be possible to bring in additional beam or RF heating ports into the reactor. This is especially true of such congested regions as the anchor (ICRH is there). However, assuming that the critical parts are the gyrotrons for the ECRH, the oscillators and the amplifiers for the ICRH, and the ion sources, accelerator grids and ion beam dumps for the neutral beam injection subsystem, it is possible to build in the redundancy of such parts. Several beams would enter the reactor through the same port, while effectively achieving the redundancy of the whole subsystem. This means that the antennas and waveguides will have to be made for high reliability, or else be replaceable at scheduled maintenance downtime.

TABLE 3. Availability Drivers

Subsystem	New Λ/old Λ	New MTTR/old MTTR
Magnets	0.1 max	0.5
Direct Convertor	1.	0.2
Neutral Beams	0.1	1.
ECRH, ICRH	1.	1.
Cryogenic	1.	0.5

An availability of 71% was achieved by introducing an on-line redundancy of the direct convertor. By the redundancy of the direct convertor, we mean the system is designed to tolerate the loss of one direct convertor on either end of the machine, hence it is on-line redundancy.

Introducing a standby redundancy of the NB system and the fueling system, and on-line redundancy of the vacuum and the cryogenic systems increased the availability to 78%. Any further increases in redundancy would likely not be cost effective.

In order to see what effect the number of central cell coils has on the availability, this number was reduced from 48 to 30. There was no significant change in the availability.

Table 4 summarizes these steps in designing a more reliable system. These steps are cost effective, because a net reduction of the COE results.

Redundancy is a very potent tool for increasing the availability. It can obviate the need for unreasonably low failure rates or the need to know the failure data accurately. A redundancy of one unit can equal improvement in the failure rate of an order of magnitude, or better. Redundancy can be cost effective, since it may be less expensive to put in and maintain a medium quality component than to build a very high quality one.

These points can be seen from the following examples:

1. At the availability of 78%, increasing the MTTR of the direct convertor 2.5 times and its Λ 2 times, brought about no significant

TABLE 4. Final System Design

Action		Availability
1.	Data & system when started	2%
2.	On-line redundancy of CC coils	3.4%
3.	↓ Λ of magnets (10* min) & weighted according to winding volume ↓ MTTR of magnets (2*)	11%
4.	On-line redundancy of NBI	17%
5.	↓ MTTR (5*) of direct convertor	28%
6.	↓ Λ of NBI (10*)	32%
7.	Standby redundancy for ECRH, ICRH	60%
8.	On-line redundancy for direct convertor	71%
9.	Redundancy of: NBI (standby) fueling (standby) vacuum (on-line) cryogenic (on-line)	78%

TABLE 5. Cost Comparisons for the Plasma Heating Systems With and Without Standby Redundancy

Action	Decrease in Capital Cost[a]	New Availability	Change in COE[b]
No standby redundancy for ECRH, ICRH	$190 M	41%	+63%
No standby redundancy for NBI	$ 22 M	78%	- 0.6%

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[a] Assuming $2/Watt for all plasma heating subsystems[11]

[b] Assuming capital and operating[11] costs = these costs for WITAMIR-I reactor[11] and plant operating at 100% capacity when up.

TABLE 6. Sensitivity of Availability

Action (change from final design)		Availability (final value = 78%)
	Redundant Subsystems	
1.	↑ MTTR direct convertor (2.5*) ↑ Λ direct convertor (2*)	78%
2.	↑ Λ of NB (10*)	69%
3.	↑ Λ of CC coil (10*)	78%
4.	No standby spares for NBI	78%
	Nonredundant subsystems	
5.	No on-line redundancy for direct convertor	34%
6.	↑ Λ magnets (10*)	34%
7.	↑ MTTR magnets (2*)	78%
8.	No spare (on-line) for CC coils, 48 coils	71%
9.	↑ Λ of CC coils (10*) and no spare for CC coils, 48 coils	35%
10.	No on-line spare for CC coils, 30 coils	74%
11.	Entry 9. for 30 CC coils	46%
12.	No cold spares for ICRH, ECRH	41%

change in the availability. However, removing the redundancy of this subsystem and with the new data caused the availability to drop to 34%.

2. Moderately increasing the MTTR of the magnets (2 times) did not change the availability. However, increasing the magnet Λ 10 times decreased the availability to 34% (the magnets have no redundancy except for the CC magnet).

3. A 10-fold increase in the failure rate of the NB system, decreased the availability to 69% (from 78%).

4. A 10-fold increase in the failure rate of the CC magnet coils didn't have a significant impact.

In the case that no on-line redundancy is possible for the CC coils, the availability of the plant drops to 71% (to 35% with 10-fold increase in the CC coil failure rate) for the case of 48 CC coils and to 74% (46% with 10 fold increase in Λ) for the case of 30 CC coils.

The ECRH and ICRH heating subsystems need a standby redundancy. Having no cold spares for any of the 3 RF heating subsystems reduces the availability to 41%. However, taking out the cold spares of the neutral beam subsystem didn't influence the availability significantly. This is due to on-line redundancy of the NB subsystem, in spite of its longer MTTR. It can be deduced, as in Table 5, that the standby redundancy of the ECRH and ICRH heating subsystems reduces the busbar COE, and hence is cost effective. The same is not true for the NBI system.

Table 6 summarizes the discussion on the sensitivity of the availability to these different perturbations.

In conclusion, reasonable availability of fusion power plants seems achievable by increasing the quality of the magnets and the neutral beams, faster maintenance of the direct convertor, the magnets and the cryogenics, as well as the redundancy in the ECRH, ICRH, NB and one CC coil/side. Even higher availability is gained by redundancy in the fueling, vacuum and the cryogenic subsystems. Redundancy can also be employed in case of high uncertainty in failure data. Decreasing the number and size of magnets will also improve the availability.

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