Availability Analysis of Fusion Reactor Plants with Degraded States

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FUSION TECHNOLOGY INSTITUTE

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ABSTRACT

A computer program PROPA is used to analyze the availability of the STARFIRE tokamak fusion reactor plant by taking into account degraded states of systems. While the model is more realistic than binary state models, at this stage we are unable to make quantitative predictions of the plant availability because of lack of data. Data on frequencies of system degradation, and, in addition, the relationship among inputs and outputs of gates in systems trees for multiple state systems must be obtained.

1. INTRODUCTION

Very large and complex systems such as future fusion reactor plants are not likely to always perform in their normal state, but most failures may not be complete, i.e. lead to total failure but only to degraded performance states. Such states can be easily included in a Monte Carlo simulation for system availability. The basic methodology of such a simulation has been developed in a previous report [1].

In the present paper, the application of the PROPA computer program to an availability analysis of the STARFIRE tokamak reactor plant [2] is described. In Section 2 we shall establish analysis procedures utilizing the PROPA program. The procedures will be applied to the analysis of STARFIRE in Sections 3 and 4. In this work, we do not attempt to obtain a very detailed model of the reactor and its operation. Our objective is to demonstrate the analysis procedures for a fusion reactor plant. We shall show how to construct a systems tree and how to obtain transfer functions which represent relations among inputs and outputs of gates. First, only 14 components will be included in the model. This model will be used to examine sensitivity of the plant availability to the availabilities of components and transfer functions. Then some of the components will be further decomposed into smaller systems so that more realistic repair strategies are included in the model. Sensitivity analysis will be performed for this model. Section 5 will conclude this work. Future work related to reliability data, plasma physics, and system models will be suggested.

2. ANALYSIS PROCEDURES

In this section the procedures of availability analysis are discussed.

Objectives: Determine the objectives of the analysis.

A. Modeling

1. Define the outer boundary of the system being analyzed; functional relations with the outside world must be specified.
2. Make a list of subsystems of the system.
3. Draw a block diagram indicating the functional connections among the subsystems; the subsystems can be related to one another through energy, particles, mass (gas or fluid), and data (information) flows.
4. If necessary, the subsystems are further decomposed into smaller systems. Procedures 2 and 3 are repeated. To describe the system completely, components at the lowest level should be included in the model. However, such a detailed modeling is usually not allowed because of the lack of manpower, data, and computational tools. Rules for where the decomposition process is stopped may be given as follows:
   - stop at a level where reliable data on state transition probabilities is available. Usually the statistical accuracy of data increases for elements at lower levels since there is usually far more data at the component level.
   - stop at a level where desired simulations can be performed; for example, if a repair is performed for a component at a certain level, decompositions must be made down to this level so that the repair strategy is included in the model.
5. Determine the state variables of elements and define three states: normal, degraded, and failed states.

6. Construct a systems tree by using the block diagram. At this stage, the following rules are useful:
   - The top gate represents the entire system.
   - The second level of the tree consists of elements that directly affect the state of the entire system. These elements should be as large as possible.
   - For subsystems at lower than the second level, the above procedure is repeated until finally the level reaches components or where one wants to stop the decomposition process.
   - Different elements in different branches of the tree must be independent of one another. Note that this is a restriction of the current PROPA program and not of the general analysis process.
   - A subsystem need not necessarily correspond to a physical system. If several subsystems interact closely with one another, treating these as one subsystem may be helpful.
7. Obtain suitable transfer functions for the gates. This may require solution of a set of equations.

<u>B. Data Collection</u>

1. Collect state transition probability data: λ_{ij} and μ_{ij} for the components.
2. Determine appropriate scheduled maintenance frequency and timelines.
3. Collect economic data for the components: the capital cost of a unit and maintenance cost.

<u>C. Computer Simulation</u>

1. Determine the timestep size and the total time length of a history. The timestep size should be set by the shortest characteristic time length:

$\min\{1/\lambda_{ij}, 1/\mu_{ij}\}$. The total time length of a history should be the longest interval of periodicity of operation such as the longest interval between scheduled maintenances.

2. Run the PROPA computer program for a small number of histories.
3. If the accuracy of the solution is not enough, continue the run until satisfactory results are obtained.

D. Analysis

1. Sensitivity Analysis. Identify critical elements; critical elements are those having low availabilities and large importances. Importance indicates the degree of contribution of a particular element to the availability of the entire system. Thus increasing the availabilities of critical elements leads to a higher availability of the entire system.

   To determine the importance of elements, a sensitivity analysis should be carried out. One of the ways to carry out such analyses is to vary the reliability parameters (failure rates and repair times) of components and see their influence on the system availability. This approach is, however, very costly for large systems.

2. Optimization. Increasing the availabilities of critical elements certainly leads to a high availability of the system, but such a system may be more costly than less available systems. Thus we should find the best system from both the economics and availability point of views. Such a tradeoff between system cost and system availability can be performed by computing the system cost for many different cases with different system parameters such as:

   - the number of redundant components.

- repair strategy: replacement, immediate repair, deferred repair, repair in state 0 or 1.
- the schedule of scheduled maintenance (frequency and timeline).
- operating points of systems: the transfer functions of gates.
- reliability of components.

In the course of the analysis, it may be better to optimize each subsystem separately. As the last step, optimize the entire system using the optimized subsystems. This procedure allows us to save computing cost and obtain better and more detailed models of the subsystems than analyzing an entire large system.

3. Uncertainty Analysis. Uncertainty analysis is another expression for error analysis. Availability analysis by a Monte Carlo method is associated with several errors:

- error in reliability data.
- error due to system modeling.
- error associated with the construction of systems trees.
- error in transfer functions of gates.
- statistical uncertainty stemming from the use of a Monte Carlo method.

Sensitivity analysis could give estimates of uncertainty of the system availability due to these errors.

3. MODELING AND DATA COLLECTION

We shall analyze the STARFIRE fusion reactor plant by following the procedures described in Section 2.

Objectives: Obtain a rough estimate of the plant availability without sophisticated repair strategies and identify critical components. The model should represent specific features of STARFIRE.

A. Modeling

1. The primary input is deuterium as well as tritium for the initial startup; the primary outputs of the plant are 1200 MW of electric power and 2600 MW of thermal heat.
2. The subsystems of the plant are the following:
    1. plasma
    2. vacuum system
    3. magnets
    4. first wall/blanket
    5. heat transport system
    6. RF system
    7. fueling system
    8. radiation shield
    9. cryogenics system
    10. instrumentation and control system (I/C)
    11. balance of plant (BOP)
    12. ECRH system

    In order to clarify the specific features of STARFIRE, subsystems 2, 3 and 7 should be further decomposed as follows:

2. vacuum system

    i. limiter

    ii. exhaust system (vacuum pumps)

3. magnets

    i. TF S/C magnets

    ii. EF S/C magnets

    iii. CF normal magnets

    iv. OH S/C magnets

7. fueling system

    i. gas puffing system

    ii. fuel supply system

This analysis is carried out for steady state operation; hence, the OH magnets and the ECRH system can be ignored in the following model. Note, however, that even for steady state operation, startup procedures are necessary after a complete failure of the plant or a scheduled maintenance shutdown. Demand failures of these systems should be taken into account to make the model more realistic.

3. The block diagram of the plant is given in Fig. 1, where the flows of energy (neutrons and gammas, heat, and electricity), particles (D and T), and fluid (liquid He) are indicated. Control data flow, which is significant in terms of system availability, is not indicated; obviously all subsystems are connected to the I/C system.

4. State variables and the ranges of three states are defined in Table 1.

5. A systems tree is constructed as illustrated in Fig. 2. There are 14 components indicated by circles in the figure. There are six gates indicated by the symbol ⬭ in the figure. The output of the top gate is

Table 1. Definitions of States*

Element Name	Variable	State 0	State 1	State 2
Plasma	D-T reaction rate	0-50%	50-90%	90-100%
Limiters	impurity control eff.	0-50	50-90	90-100
Exhaust	exhaustion rate	0-50	50-90	90-100
TF magnets	magnetic field	0-50	50-90	90-100
EF magnets	magnetic field	0-50	50-90	90-100
CF magnets	magnetic field	0-50	50-90	90-100
FW/blanket	energy conversion eff.	0-50	50-90	90-100
Heat transport	energy transport eff.	0-50	50-90	90-100
RF system	power injection rate	0-50	50-90	90-100
Gas puffing	fuel injection rate	0-50	50-90	90-100
Fuel supply	fuel supply rate	0-50	50-90	90-100
Shield	shielding eff.	0-50	50-90	90-100
Cryogenics systems	fluid supply rate	0-50	50-90	90-100
I/C	I/C success rate	0-90	90-95	95-100
BOP	energy conversion eff.	0-50	50-90	90-100
Plasma/vacuum	neutron power	0-50	50-90	90-100
Plasmas	D-T reaction rate	0-50	50-90	90-100
Magnets	magnetic field	0-50	50-90	90-100
Fueling systems	fuel supply rate	0-50	50-90	90-100
Vacuum systems	impurity density	0-50	50-90	90-100
Plant	electric power	0-50	50-90	90-100

*States are determined by setting the design point (or normal) operating point to 100%

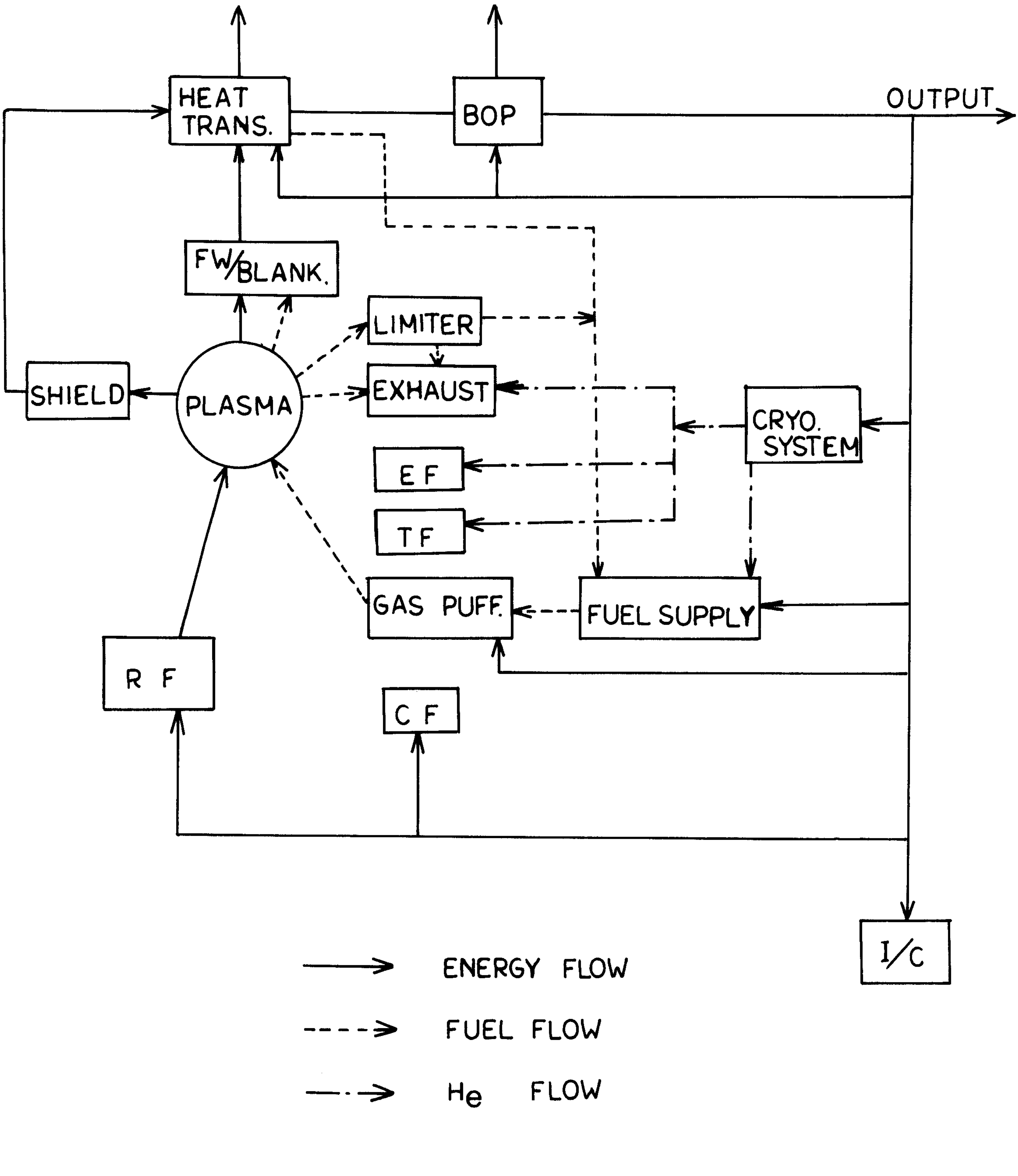

Figure 1. Block diagram of STARFIRE.

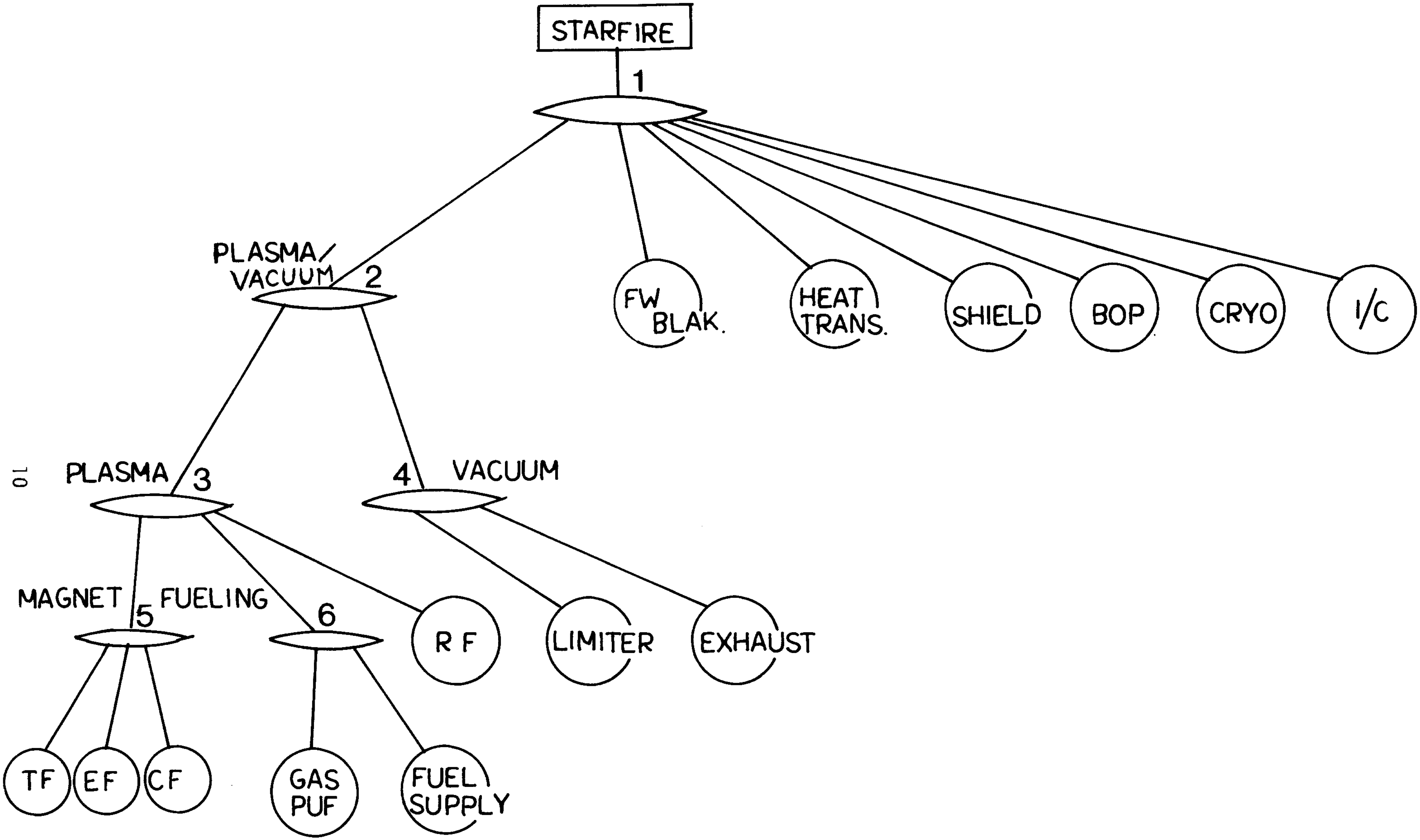

Figure 2. Systems tree of STARFIRE (Model I).

electric power from the entire plant. There are 7 inputs to the top gate. One of them is the output from the gate that represents the plasma/vacuum system. This output is neutron power. The amount of the neutron power is governed by the state of the plasma (temperature, particle density, and confinement time) and the density of impurity particles (i.e., the efficiency of impurity control). Hence, there are 2 inputs to this plasma/vacuum gate; one is the output from the gate that represents the state of the plasma, and another is the output from the gate that represents the state of the vacuum system. The state of the plasma is controlled by three variables: magnetic field, the injection rate of D and T fuels, and the injection rate of the RF power. The state of the vacuum system is determined by the efficiency of impurity control by the limiters and the exhaust rate by the vacuum pumps. Note here that the failures of the plasma itself, such as plasma disruption, are not taken into account in this model.

6. First, let us find a suitable transfer function for gate 1. Apparently, the output state is normal (2) if all the seven input states are 2. Also we see that the output state is in a failed state (0) if one of the seven input states is 0. It may be reasonable to say that the output state is degraded (1) if at least one of the inputs is 1. Therefore, we obtain the logic of the AND gate [1] for gate 1.

   The transfer function of gate 2 involves physics. If the state of the plasma (i.e., the output of gate 3) is 0 or 1, the neutron power output is in state 0 or 1, respectively. The dependence of the neutron power output on the impurity density may not be proportional. Since the temperature of the burning plasma is very high and the impurity radiation from the plasma is well confined or reabsorbed by the plasma, a 50% increase of impurity density, which corresponds to the degraded state of the vacuum system, may not affect the D-T reaction rate or the neutron power output. This argument leads to the transfer function given in Table 2.

The transfer function of gate 4 (vacuum system) and gate 6 (fueling system) can be represented by that of the AND gate.

As for gate 5 (magnets), we assume that of the AND gate. In fact, the transfer function of gate 3 should be obtained by considering three magnets (TF, EF and CF), separately because the roles of these magnets on the plasma are different. In the present model, we use one state from these three magnets by introducing gate 5. More detailed analysis is left for the future.

Now we discuss the transfer function of gate 3 (the plasma) in detail. First suppose the impurity of the plasma is sufficiently controlled. The output of gate 3 is neutron power density, P_n [MW/m^3]. The inputs are magnetic field strength, B [tesla], D-T fuel injection rate, S_{in} [1/m^{3}s], and RF power injection rate, P_{in} [MW/m^3]. Note that the role of the RF system is not only plasma heating but also the current drive for poloidal magnetic field formation. The latter role is not taken into account by the present plasma model.

The neutron power output P_n is obtained by finding the solution of the following equations.

$$\frac{n^2}{4} \langle \sigma v \rangle_{DT} E_\alpha + P_{in} - \frac{3nkT}{\tau_E} = 0 \qquad (1)$$

$$n = \tau_p S_{in} \qquad (2)$$

Table 2. The Transfer Function of Gate 2

gate 3 \ gate 4	0	1	2
0	0	0	0
1	0	1	1
2	0	2	2

$$P_n = \frac{n^2}{4} \langle\sigma v\rangle_{DT} E_n \tag{3}$$

where: n is the plasma density [1/m^3],

T is the plasma temperature [keV],

τ_E is the energy confinement time [s],

τ_p is the particle confinement time [s],

$\langle\sigma v\rangle_{DT}$ is the D-T fusion reaction rate,

E_α = 3.5 MeV,

E_n = 14.1 MeV

and $k = 1.6 \times 10^{-16}$ J/keV.

$\langle\sigma v\rangle_{DT}$ can be given by the formula in Ref. [3]:

$$\langle\sigma v\rangle_{DT} = AT^{-2/3} \exp(-BT^{-1/3}) \tag{4}$$

where $A = 3.68 \times 10^{-18}$ and $B = 19.94$. To derive the above equations (1), (2) and (3), we make several assumptions:

1. steady state, point plasma.

2. one component.

3. all α particles and radiation power are absorbed by the plasma.

4. impurity density is negligible compared to plasma density.

The energy confinement time is scaled with respect to B, T, and n by the following formula:

$$\tau_E = \tau_o \left(\frac{B}{1}\right)^a \left(\frac{T}{10}\right)^b \left(\frac{n}{10^{20}}\right)^{-c} \qquad (5)$$

where τ_o, a, b, and c are positive constants. Also, the particle confinement time is given by:

$$\tau_p = \eta\tau_E \qquad (6)$$

where η is a positive constant.

We solve Eqs. (1) and (2) with Eqs. (4), (5) and (6) numerically to obtain n and T, varying S_{in}, P_{in}, and B. Then P_n is computed by using Eq. (3). Since the plasma should be stable, the plasma β must be smaller than a certain value. Hence, the solution is obtained under this constraint. As an example of solutions, contours of β, T, $n\tau_E$, and P_n are plotted on the S_{in}-P_{in} plane. Figures 3, 4, and 5 show the contours for three different B's. For this example, we use a = 1, b = 3/2, c = 1/2, τ_o = 0.5, and η = 1.0.

To choose operating parameters, first look at the plasma parameters for STARFIRE given in Table 3. By referring to these values, the following operating parameters are chosen for the present model:

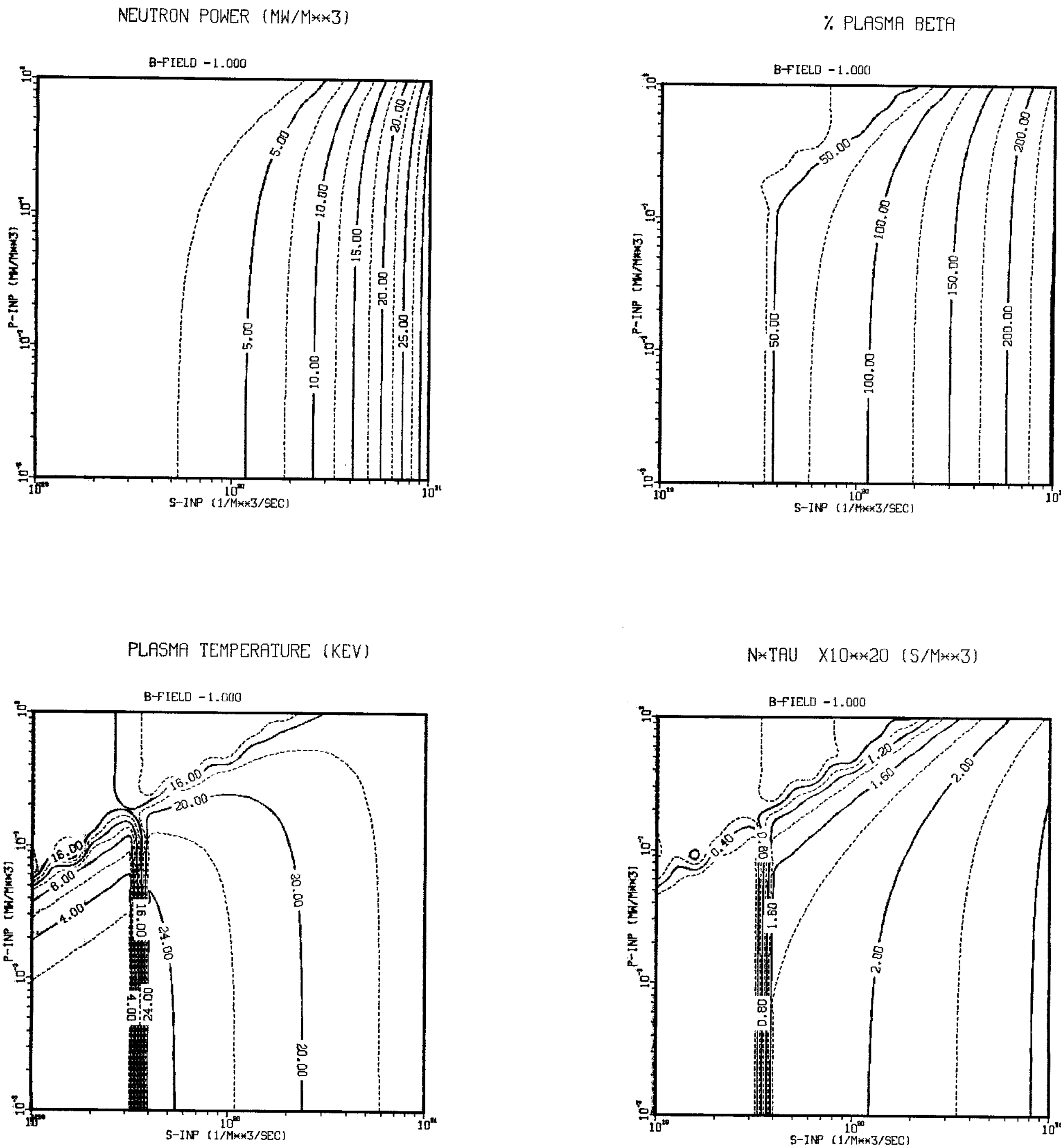

Figure 3. Contour plots for the case of B = 1.0 tesla.

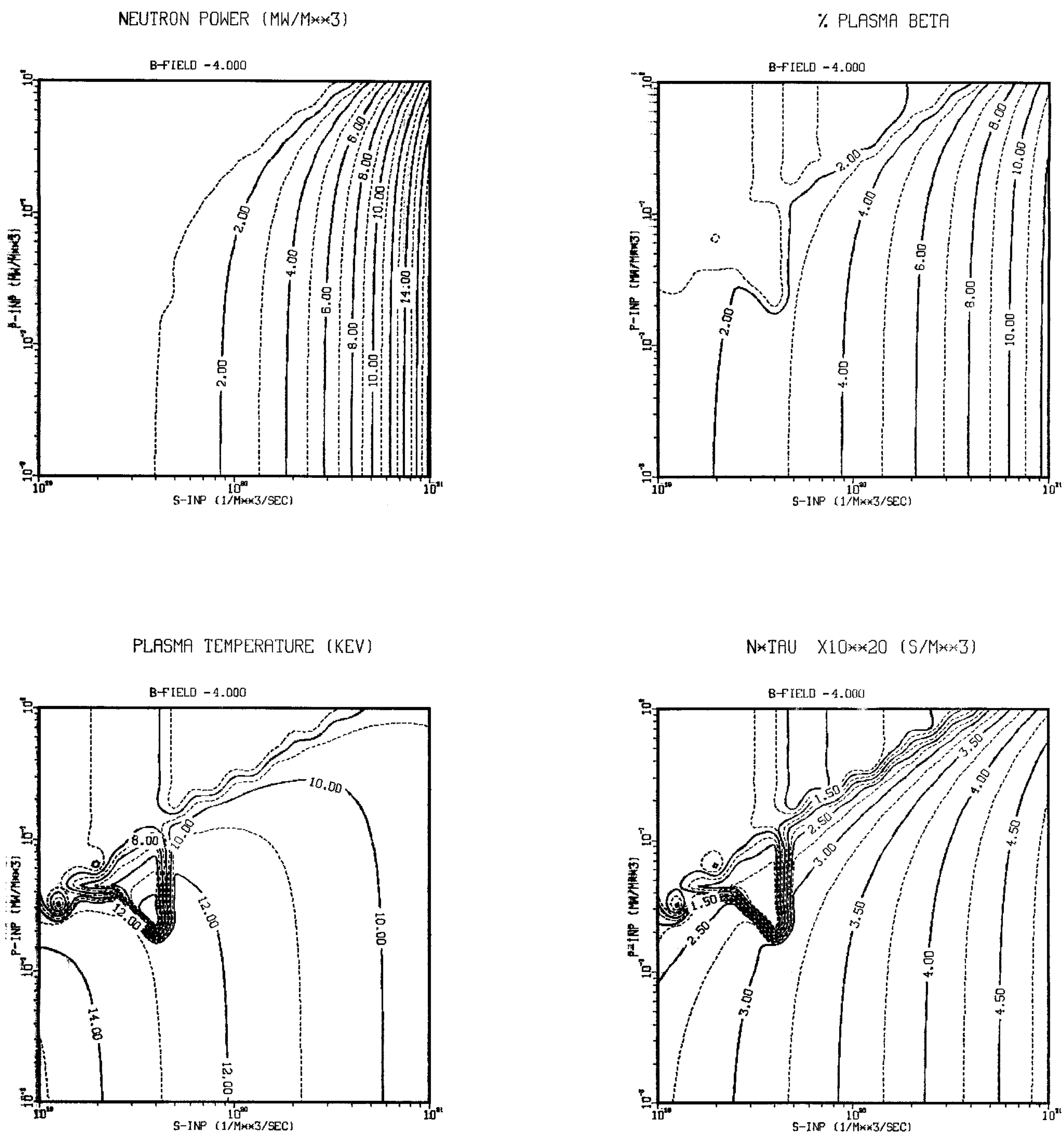

Figure 4. Contour plots for the case of B = 3.0 tesla.

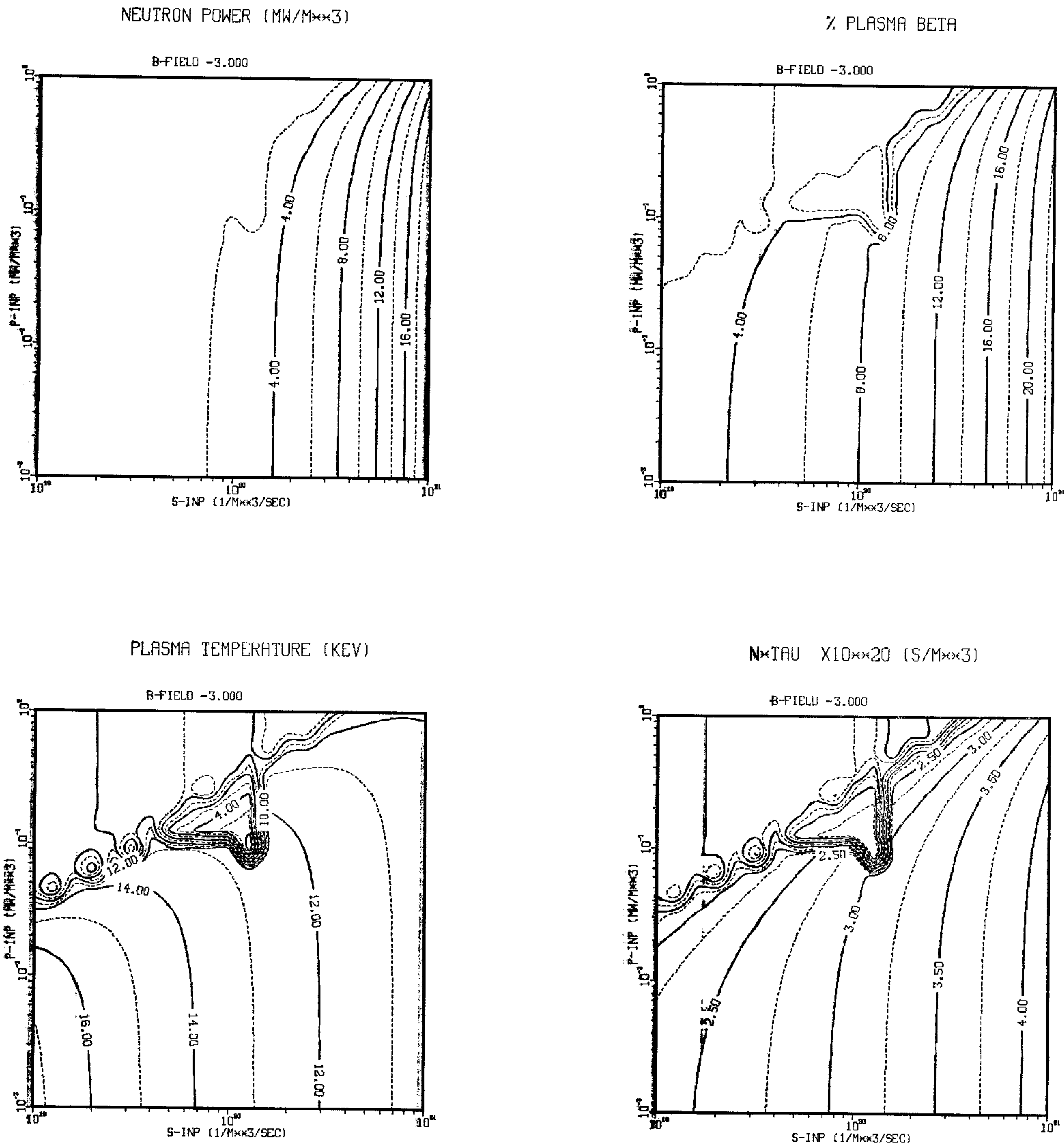

Figure 5. Contour plots for the case of B = 4.0 tesla.

Table 3. STARFIRE Plasma Parameters

Plasma minor radius	1.94 m
Major radius	7.0 m
Elongation	1.6
Plasma volume	832 m^3
Neutron power	3510 MW
Neutron power density	4.2 MW/m^3
RF power	90 MW
RF power density	0.11 MW/m^3
Toroidal field at center	5.8 T
Electron temperature	17.3 keV
Ion temperature	24.1 keV
Ion density (average)	$0.8 \times 10^{20}/m^3$
Plasma β (average)	6.7%

$$S_{in} = 3.2 \times 10^{20}$$

$$P_{in} = 0.13 \ MW/m^3$$

$$B = 4 \text{ tesla.}$$

For these inputs, we have the plasma parameters:

$$\beta = 6.9\%$$

$$T = 10.4 \text{ keV}$$

$$Q_p = 46$$

$$P_n = 5.8 \text{ MW/m}^3 \ .$$

By varying S_{in}, P_{in} and B, β, T, $n\tau_E$, and P_n are computed. The results are given in Table 4. The values of S_{in}, P_{in}, and B correspond to 100%, 70% and 25% of the normal values. The states of P_n are given in the last column in the table. The states 0, 1, and 2 correspond to P_n values of 0 to 2.4, 2.4 to 5.2, and 5.2 to 5.8, respectively.

Since the plasma with β larger than the maximum β, which is 8% in this case, is not stable, such cases are considered to have state 0 as P_n. If one of 3 input variables are 0, P_n is also 0. Thus we obtain the transfer function for gate 3 shown in Table 5 (column of uncontrollable). Although cases 14, 15, 17, and 18 have β's which are too large, it may be assumed that the β can be decreased below 8% by reducing either S_{in} or P_{in}. After such controls are made, however, the output neutron power is no longer the normal value; it may be a degraded value. Under these assumptions we obtain the transfer function of gate 3 given in the column (controllable) of Table 5. This function will be used in later computation.

The systems tree given in Fig. 2 does not show that in fact there is more than one TF magnet. As shown in Table 6, there are several components consisting of many identical units. In this analysis, a group of identical units is considered to have one output. For example, 12 TF magnets produce one output state. To construct a state from the states of

Table 4. Neutron Power Output as a Function of Particle Injection Rate, RF Power Injection Rate and Magnetic Field Strength

	S_{in} x $10^{-20}/m^3s$	P_{in} MW/m^3	B T	β %	T keV	nτ x $10^{-20}s/m^3$	P_n MW	State of P_n*
27	3.2	0.13	4.0	6.9	10.4	3.5	5.8	2
26	2.0	0.13	4.0	5.4	10.7	2.7	3.6	1
25	0.8	0.13	4.0	3.1	10.9	1.5	1.2	0
24	3.2	0.09	4.0	7.0	10.4	3.6	6.0	2
23	2.0	0.09	4.0	5.5	10.8	2.7	3.8	1
22	0.8	0.09	4.0	3.3	11.4	1.5	1.4	0
21	3.2	0.03	4.0	7.2	10.5	3.6	6.3	2
20	2.0	0.03	4.0	5.7	11.0	2.8	4.1	1
19	0.8	0.03	4.0	3.7	11.9	1.9	2.1	0
18	3.2	0.13	3.0	12.8	11.7	3.3	6.6	2
17	2.0	0.13	3.0	10.1	12.1	2.5	4.1	1
16	0.8	0.13	3.0	0.4	3.3	0.4	0.002	0
15	3.2	0.09	3.0	13.0	11.7	3.3	6.8	2
14	2.0	0.09	3.0	10.4	12.2	2.5	4.3	1
13	0.8	0.09	3.0	6.3	12.9	1.5	1.6	0
12	3.2	0.03	3.0	13.3	11.9	3.3	7.1	2
11	2.0	0.03	3.0	10.7	12.4	2.6	4.7	1
10	0.8	0.03	3.0	6.9	13.5	1.5	1.9	0
9	3.2	0.13	1.0	150.	19.0	2.6	11.1	2
8	2.0	0.13	1.0	120.	20.0	2.0	7.2	2
7	0.8	0.13	1.0	76.	21.5	1.2	2.8	0
6	3.2	0.09	1.0	150.	19.1	2.6	11.4	2
5	2.0	0.09	1.0	122.	20.1	2.0	7.4	2
4	0.8	0.09	1.0	79.	22.0	1.2	3.0	0
3	3.2	0.03	1.0	152.	19.3	2.6	11.7	2
2	2.0	0.03	1.0	125.	20.3	20	7.7	2
1	0.8	0.03	1.0	83.	22.6	1.2	3.3	0

*State of P_n is determined by: state 0: 0 ~ 2.4
1: 2.4 ~ 5.2
2: 5.2 ~ 5.8

Table 5. Transfer Functions of Gate 3

Case	S_{in}	P_{in}	B	P_n Uncontrollable	P_n Controllable	P_n AND Gate
1	0	0	0	0	0	0
2	1	0	0	0	0	0
3	2	0	0	0	0	0
4	0	1	0	0	0	0
5	1	1	0	0	0	0
6	2	1	0	0	0	0
7	0	2	0	0	0	0
8	1	2	0	0	0	0
9	2	2	0	0	0	0
10	0	0	1	0	0	0
11	1	0	1	0	0	0
12	2	0	1	0	0	0
13	0	1	1	0	0	0
14	1	1	1	0	1	1
15	2	1	1	0	1	1
16	0	2	1	0	1	1
17	1	2	1	0	1	1
18	2	2	1	0	1	1
19	0	0	2	0	0	0
20	1	0	2	0	0	0
21	2	0	2	0	0	0
22	0	1	2	0	0	0
23	1	1	2	1	1	1
24	2	1	2	1	1	1
25	0	2	2	0	0	0
26	1	2	2	1	1	1
27	2	2	2	2	2	2

Table 6. The Number of Identical Units of Components

Component Name	Number of Units	Virtual Gate Type
TF magnets	12	SUM (s_1 = 12, s_2 = 21)
EF magnets	6	AND
CF magnets	4	AND
Gas puffing	1	
Fuel supply	1	
RF system	6	SUM (s_1 = 6, s_2 = 10)
Limiters	96	SUM (s_1 = 96, s_2 = 172)
Exhaust, pumps	48	SUM (s_1 = 48, s_2 = 86)
FW/Blanket	24 sectors	SUM (s_1 = 24, s_2 = 43)
Heat transport	1	
Shield	1	
BOP	1	
Cryogenic	1	
I/C	1	

those 12 units, we use a virtual gate [1]. The transfer functions of virtual gates must be determined by taking into account the physics involved in the system.

As for systems such as RF systems, limiters, vacuum pumps and FW/blanket systems, these work like batteries connected in series. The units are indistinguishable from one another. Only the sum of a certain quantity affects the other system. For example, if only 12 sectors of 24

FW/blanket sectors are working properly, the outcome, i.e. heat deposition, may be half the normal value. Even if one of the units completely fails, the system is still working as a group. Therefore, the transfer functions of virtual gates for these systems can be well represented by that of a SUM gate. For convenience, we give the transfer function for SUM gates below:

$$\text{output } z = \begin{cases} 2 & \text{for } s_2 < y < 2n \\ 1 & \text{for } s_1 \leq y \leq s_2 \\ 0 & \text{for } 0 \leq y \leq s_1 \end{cases}$$

where $y = \sum_{i=1}^{n} x_i$, x_i is the state of unit i, and n is the number of identical units. The constants s_1 and s_2 must be determined. s_1 and s_2 for RF systems, limiters, FW/blanket systems, and vacuum pumps are given in Table 6. These numbers are determined by

$$s_1 = 0.5 \times 2n$$

and

$$s_2 = 0.9 \times 2n$$

Twelve TF magnets behave in a similar manner, however, the failure of two magnets at the opposite side from each other is different from the failure of two placed side by side because the symmetry of the magnetic field geometry has a significant effect on plasma confinement. Thus the TF magnets cannot be treated in the same way as the FW/blanket systems and others. A suitable transfer function should be obtained by carefully analyzing the effect of states of magnets on the confinement. For the present analysis, we use the SUM gate whose s_1 and s_2 are given in Table 6.

As for the EF and CF magnets, each of these units plays a different role from a geometrical point of view. The failure of one unit significantly affects the performance of the magnets as a group. Hence, it is reasonable to use the AND gate for these systems.

B. Data Collection

1. At present there are a few data sources for the reliability of fusion reactor systems. Since the objective of the present analysis is not accuracy but methodology, we can use the very crude estimates of reliability collected in Ref. [4]. This reference contains most of the data necessary for the present analysis. In Table 7, the failure rate λ_{20} (for failure from state 2 to 0) and the repair time τ_{02} (for repair from state 0 to 2) are given for the systems being analyzed. For 3-state availability analysis, we need the data on λ_{21} and λ_{10}. τ_{01} and τ_{12} are also needed if a repair is performed to bring a system up from a degraded state.

Since failure data is collected for any modes which bring a system from the normal state to off normal states, λ_{21} can be obtained as one of the failure data from standard data sources. For example, Ref. [5] contains the reliability data for degraded states. The data λ_{10}, τ_{01} and τ_{12} is completely lacking.

To proceed with the analysis, we make very crude assumptions. First we consider that all systems are repaired from state 0 to 2. The second assumption is that the sum of λ_{20} and λ_{21} is equal to the λ_{20} given in Table 7. Let the λ_{20} for 2-state models be denoted by λ'_{20}. Then λ_{ij} for the 3-state model is given by $\lambda_{20} = \lambda_{21} = \lambda_{10} = 0.5\ \lambda'_{20}$.

Table 7. Reliability Data

Component Name	λ_{20}	τ_{02}	Reference Page No. in UWFDM-532	Comments
TF magnet	4.5E-6	720	60	
EF magnet	4.5E-6	720	60	
CF magnet	1.1E-5	240	60	
Gas puffing	1.9E-5	38.0	---	STARFIRE Report p. 19-101 (1)
Fuel supply	1.7E-5	2.0	60	See note (2)
RF system	2.5E-3	40	60	
Limiter	1.1E-4	720	35	
Exhaust	4.6E-5	96	60	Data of vacuum pumps
FW/Blanket	5.7E-5	120.0	57	
Heat transport	1.7E-5	72.0	---	STARFIRE Report p. 19-99 (3)
Shield	2.5E-5	168.0	60	
BOP	2.5E-4	240.0	60	
Cryogenic	7.6E-5	52.0	60	See note (4)
I/C	2.0E-4	48.0	60	

(1) λ_{20} is calculated as follows:
estimated forced outage frequency/unit outages oper. Year a = 0.15;
then $\lambda_{20} = -\ln(1 - a)/T$ where T = 8760 hours.

(2) λ_{20} = sum of the failure rates of T_2 extraction (5.7E-6) and fuel preparation (1.1E-5)
$\tau_{02} = (1/\tau_1 + 1/\tau_2)^{-1}$ where $\tau_1 = 24$ for T_2 extraction, and $\tau_2 = 2$ for fuel preparation

(3) Only primary coolant pumps/motors are considered

(4) λ_{20} = sum of the failure rates of compressors (3.8E-5) and turbo-expanders (3.8E-5)
$\tau_{02} = (1/\tau_1 + 1/\tau_2)^{-1}$ where $\tau_1 = \tau_2 = 52$ for both compressors and turbo-expanders

2. The plant is shut down for 28 days annually. During these maintenance periods all subsystems except magnets are maintained. Maintenances for the magnets are performed for 120 days every 10 years. We do not specify particular timelines of the scheduled maintenances. It is simply assumed that all the systems are in state 0 during the maintenance.

4. SIMULATION AND ANALYSIS

A. Computer Simulation

1. The maximum mean time to failure of components is that of the S/C magnets and it is about 50 years. It is assumed that the scheduled maintenance for the S/C magnets, which is performed every 10 years, makes the magnets totally new; in other words, a periodicity of 10 years for the plant availability can be assumed. Taking this into account, we perform simulations only over 10 year periods.

   The minimum mean time to repair (or fixed repair time) is 2 hours as we see in Table 2. Hence, the timestep of simulation must be 2 hours. However, we choose 24 hours as the timestep length in order to reduce the computing time. By doing this, we will underestimate the availabilities of systems whose repair time is shorter than 24 hours.

   It turns out that the CPU time is about 2.5 minutes for the above parameters and 20 histories, and the 95% confidence interval for the effective availability of the entire system is about ±2.4% of the sample mean. In order to perform sensitivity analysis as well as optimization the error must be reduced further; but performing computation for many cases is very costly. Thus, instead of using 10 years of simulation time, we shall use one year and increase the total number of histories in most of the following analyses.

B. Analysis

1. Sensitivity Analysis. In order to obtain critical components, a simulation is performed for 10 year periods by using 1 day timestep and 20 histories. The effective availabilities (e-avails), which are computed as $A_2 + 0.7\ A_1$ (A_i is the i-th state availability in percent), and their 95%

confidence intervals are given in Table 8. In the same table results based on a 2-state model are also given. The statistical errors are small. The smallest e-avail is that of the RF system. This is obvious because this system has the largest failure rate. The limiter system has the second lowest e-avail even though the failure rate is rather small. This is because there are many limiters, i.e. 96 units; it is very likely that this system is in a degraded state as a group. When the state availabilities by the 3-state model, which are not shown in the table, are examined, it is found that the plant is in the normal state only for 16% of the entire operation time and it is in a degraded state for about 67% of the time.

Comparing the results by 3-state and 2-state models, we see that both models point out that the RF system and the limiter system have the lowest and the second lowest e-avail; but the 2-state model predicts smaller plant availability than that by the 3-state model.

Next we examine the sensitivity of e-avails to gate transfer functions, in particular those of gate 3 and the virtual gate of TF magnets. As we discussed in Section 3.A.7, the transfer function of gate 3, which represents the relation among the magnetic field strength, the fuel and RF power injection rates, and the neutron power output, was chosen by assuming that increase of plasma β due to the degradation of magnets can be compensated by reducing the fuel and RF power injection rates. Eventually a stable plasma is obtained even though the neutron power output is in a degraded state. Now suppose this control is impossible; the plasma becomes unstable. This leads to the gate transfer function given in Table 5

Table 8. Effective Availability of the Systems*

	Effective Availability	
	3-State Model	2-State Model
TF magnets	95.3 ± 1.74	96.7 ± 0.06
EF magnets	84.7 ± 5.08	95.1 ± 0.48
CF magnets	90.3 ± 0.77	91.4 ± 0.21
Gas puffing system	91.9 ± 0.40	92.3 ± 0.02
RF system	65.6 ± 0.33	66.1 ± 0.30
Limiters	74.7 ± 0.57	80.3 ± 0.97
Vacuum pumps	91.6 ± 0.26	92.3 ± 0.00
FW/Blanket	88.4 ± 0.89	92.2 ± 0.06
Heat transport system	91.2 ± 0.66	92.2 ± 0.04
Rad. shield	91.1 ± 0.38	92.0 ± 0.11
BOP	80.1 ± 1.1	87.8 ± 0.57
Cryogenics system	88.1 ± 1.1	91.9 ± 0.08
Whole plant	62.6 ± 1.50	50.7 ± 0.86

*T = 87600 hrs, Δt = 24 hrs, and number of histories = 20.

Table 9. Sensitivity to the Transfer Function of Gates*

Case	Effective Availability (%)		Comments
	Whole Plant	Gate 3	
Base	68.7 ± 2.05	83.5 ± 2.23	controllable gate 3
1	65.3 ± 3.73	80.0 ± 4.58	uncontrollable gate 3
2	60.5 ± 0.85	63.7 ± 0.76	gate 3 = AND
3	67.5 ± 2.21	80.9 ± 2.58	TF magnets = AND

*T = 8760 hrs, Δt = 24 hrs, number of histories = 50.

(uncontrollable P_n). Case 1 in Table 9 shows this case. The e-avail of gate 3 is somewhat lower and consequently the plant availability is lower.

As with the second case (case 2), the AND logic is used for gate 3. This logic is shown in Table 5. The use of this logic implies that the degradation of one of 3 subsystems (magnets, fueling systems, and RF systems) leads to a degraded plasma. Table 9 shows that this case results in a very low e-avail of gate 3 as well as the entire plant. The errors in the e-avails are small enough to justify this conclusion. Thus we can say that the choice of an operating point in the B-S_{in}-P_{in} space of the plant parameters has a significant impact on the plant availability. An operating point should be chosen so that the degradation of the RF injection rate has less effect on the neutron power output.

We assumed that a group of 12 TF magnets work as if these were batteries connected in series; in other words, the SUM gate was used for the virtual gate. Now instead use the AND gate. Then the plant availability becomes a little smaller as shown in Table 9 (case 3); but the change is negligible. This is because the magnets are very reliable.

Our next goal is to maximize the plant availability by changing system parameters other than failure rates and repair times. Since RF systems and limiters are the lowest availability subsystems, as shown in Table 8, we attempt to increase the availabilities of these systems.

First, introduce redundant RF systems; that is, the number of units is increased from 6 to 10 units, but s_1 and s_2 for the SUM gate are kept constant. For this case the e-avails of the RF systems and the plant are given in Table 10 (case 1). This certainly increases the availability of the RF systems.

Table 10. Enhancement of Availability of RF and Limiter Systems*

Case	Effective Availability (%)			Comments
	RF System	Limiter System	Plant	
Base	64.8 ± 0.73 (1) 64.8 ± 0.36	74.3 ± 1.01 74.5 ± 0.46	68.7 ± 2.05 69.0 ± 0.96	
1	92.3 ± 0.10	75.2 ± 0.97	70.1 ± 2.50	redundant RFs 6 → 10 units
2	87.7 ± 0.15	74.7 ± 0.93	71.6 ± 1.92	repair degraded RFs
3	64.8 ± 0.97	92.3 ± 0.00	56.8 ± 2.32	redundant limiters 96 → 120 units
4	92.1 ± 0.06 (1) 92.1 ± 0.03	92.3 ± 0.00 92.3 ± 0.00	71.9 ± 2.22 71.3 ± 1.07	redundant RFs and limiters

*T = 8760 hrs, Δt = 24 hrs, number of histories = 50.

(1) These rows are for 200 histories.

Second, let the RF systems be repaired while these are in a degraded state instead of adding redundant units. The repair is performed by shutting down a degraded unit with the same repair time as that for repair from state 0 to 2. This strategy also increases the availability of the RF systems.

Third, add redundant limiters; the number of limiters is increased from 96 to 120 units, while s_0 and s_1 are kept the same. The availability of limiters significantly increases by this action as shown in Table 10 (case 3). The effect on the plant availability, however, is negligible. The reason is the transfer function of gate 2. Here we assume that the degradation of the vacuum system (gate 4), which is equivalent to that of the limiters in this case, has little effect on the output state of gate 2 (see Table 2).

Case 4 in Table 10 shows the availabilities when redundant RF systems and limiters are added at the same time. A difference in the plant availability between the base case and this case exists; but, it is within the error limits. To clarify the difference, 200 histories are simulated for both cases. Now the difference is clear as shown in Table 10.

For a more detailed modeling, we further decompose the RF and heat transport systems. Also, the cryogenic system is now considered to provide an input to the magnets, the fueling system, and the vacuum system to obtain more realistic effects of the system on these systems. The systems tree and an output from the PROPA program for this model (Model II) are reproduced in Figs. 6 and 7, respectively.

In this model, two primary loops are utilized. Four components of the RF systems are explicitly included so that some of the components, for example, amplifiers and klystrons, can be quickly replaced instead of being repaired in order to reduce downtime.

The results given in Fig. 7 are for the base case; no special repair strategy is performed. To increase the plant availability, we take the five actions for the primary coolant loops, the limiter systems, and the RF systems. This is summarized in Table 11.

Table 11. Enhancement of the Plant Availability for Model II*

Case	Effective Availability (%)				Actions
	Primary Coolant Loops	Limiter Systems	RF Systems	Plant	
0	76.6 ± 3.32 (1) 72.9 ± 2.88	75.1 ± 0.87 75.2 ± 0.54	76.3 ± 2.23 77.5 ± 1.39	62.0 ± 2.05 59.6 ± 2.16	case shown in Fig. 7
1	80.2 ± 2.56	75.1 ± 0.87	76.3 ± 2.23	65.4 ± 1.24	logic of gate 8 is (ii) in Table 12
2	77.7 ± 2.71	92.3 ± 0.00	74.0 ± 1.50	64.8 ± 1.50	no. of redundant limiters are increased from 96 to 120 units
3	76.7 ± 2.81	92.3 ± 0.00	76.1 ± 2.29	64.7 ± 1.22	amplifiers and klystrons in RF systems are replaced within 24 hours
4	78.4 ± 2.95 (1) 79.0 ± 1.53	92.3 ± 0.00 92.3 ± 0.00	87.6 ± 2.31 88.3 ± 0.71	65.2 ± 1.70 65.8 ± 0.93	degraded amplifiers and klystrons are replaced within 24 hours
5	92.2 ± 0.24	92.3 ± 0.00	87.6 ± 1.46	66.9 ± 1.61	logic of gate 8 is (iii) in Table 12

* T = 8760 hrs, Δt = 24 hrs, number of histories = 50

(1) These columns are for 200 histories.

Table 12. Transfer Function of Primary Coolant Loop Gate (Gate 8)

Input States		Output State		
Loop 1	Loop 2	Case (i)	Case (ii)	Case (iii)
0	0	0	0	0
1	0	0	0	1
2	0	0	1	2
0	1	0	0	1
1	1	0	1	2
2	1	1	1	2
0	2	0	1	2
1	2	1	1	2
2	2	2	2	2

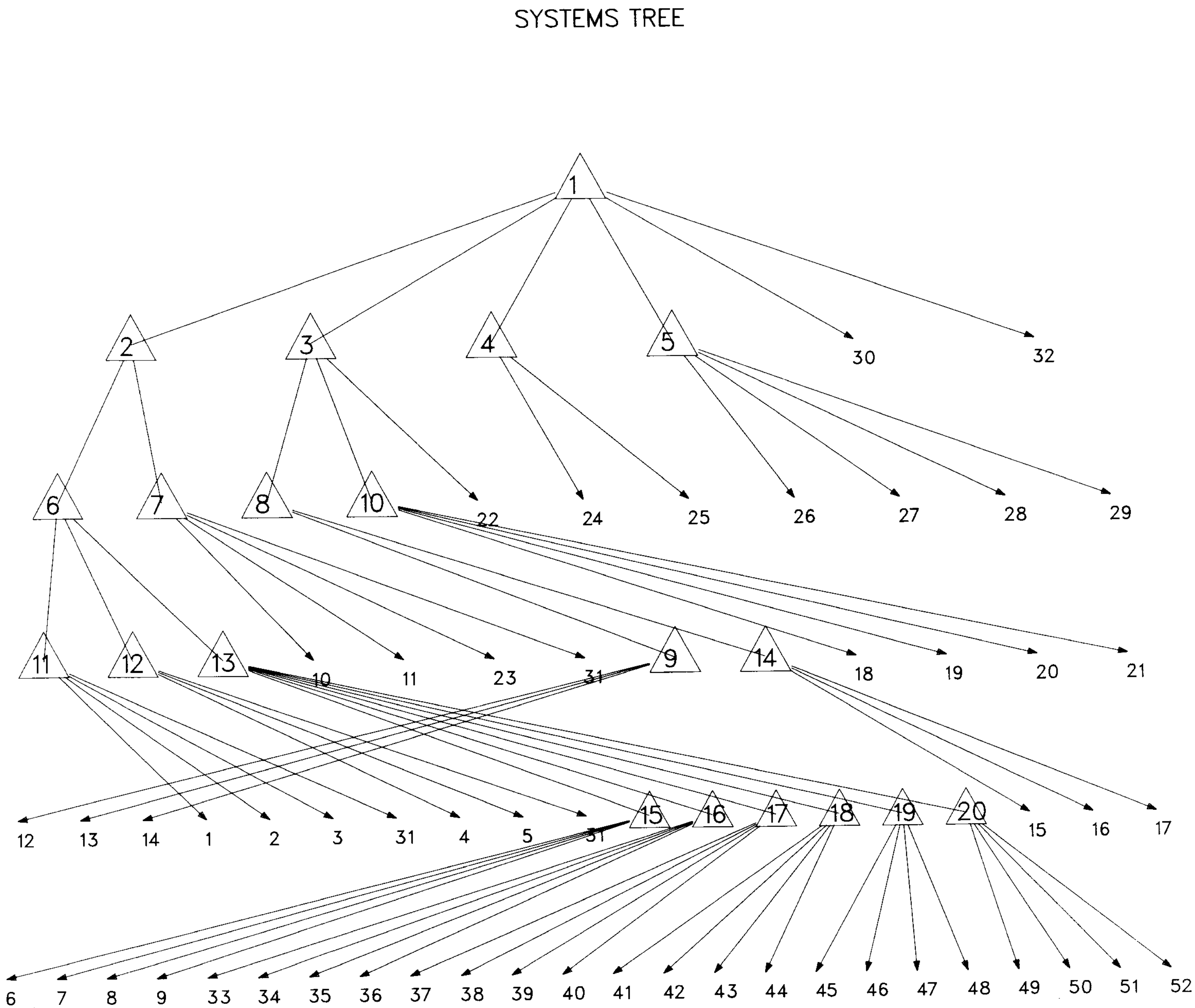

Figure 6. Systems tree of STARFIRE (Model II).

Figure 7. PROPA output for Model II.

****

*** program propal.5 (Ø8/Ø1/85) *

- problem Ø2 -starfire model-(case 71Ø) Ø8/Ø4/85

(ncomp/ngate/level/nhist)= 52/ 2Ø/ 5/ 5Ø/

- time step for simulation = 24.ØØØ hours
- total time interval for simulation = 876Ø.ØØØ hours

- no variance reduction is utilized

- gate information -

(gate logic type -1/1/2/3 = user sepcified/AND/SUM/MAX)

id	name	level	input no.	type	nsumg for Ø	nsumg for 1	replace opt. for Ø/1	number of spares	time for replace. hrs	coefg Ø	coefg 1	coefg 2
1	whole plant	1	6	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
2	vacuum vess	2	2	-1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
3	heat transp	2	3	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
4	blankets	2	2	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
5	bop	2	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
6	burn plasma	3	3	-1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
7	vacuum syst	3	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
8	prim cool s	3	2	2	2	3	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
9	prim cool 1	4	3	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
1Ø	heat remove	3	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
11	magnets	4	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
12	fueling sys	4	3	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
13	rf system	4	6	2	6	1Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
14	prim cool 2	4	3	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
15	rf system 1	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
16	rf system 2	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
17	rf system 3	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
18	rf system 4	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
19	rf system 5	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ
2Ø	rf system 6	5	4	1	Ø	Ø	Ø	Ø	Ø.ØØ	Ø.ØØ	Ø.7Ø	1.ØØ

- gate logic input -

gate id	gate output
2	Ø Ø Ø Ø 1 2 Ø 1 2
6	Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø 1 1 Ø 1 2 Ø Ø Ø Ø 1 1 Ø 1 2

- systems tree data -

gate id input gate id/ input comp. id

```
 1        2  3  4  5
         3Ø 32
 2        6  7

 3        8 1Ø
         22
 4
         24 25
 5
         26 27 28 29
 6       11 12 13

 7
         1Ø 11 23 31
 8        9 14

 9
         12 13 14
1Ø
         18 19 2Ø 21
11
          1  2  3 31
12
          4  5 31
13       15 16 17 18 19 2Ø

14
         15 16 17
15
          6  7  8  9
16
         33 34 35 36
17
         37 38 39 4Ø
18
         41 42 43 44
19
         45 46 47 48
2Ø
         49 5Ø 51 52
```

- component data -

(virtual gate logic type Ø/1/2/3=non/AND/SUM/MAX)

id	name	number of units	logic type	nsum for Ø	nsum for 1	replacement type for state Ø	and 1	number of sch. maint.	no. of spares	coefc(*,*) Ø	1	2	import. factor
1	tf s/c magn	12	2	12	21	2	Ø	Ø	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
2	ef s/c magn	6	1	Ø	Ø	2	Ø	Ø	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
3	cf n-magnet	4	1	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
4	gas puff sy	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
5	fuel supply	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
6	klystron	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
7	amplifier	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
8	wave guides	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
9	power suppl	1	Ø	Ø	Ø	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
1Ø	limiter sys	96	2	96	172	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ
11	cryo pumps	48	2	48	86	2	Ø	1	Ø	Ø.ØØ	Ø.7Ø	1.ØØ	Ø.ØØØØ

12	h2o pump 1	2	2	2	3	2	0	1	0	0.00	0.70	1.00	0.0000
13	valves 1	10	2	10	19	2	0	1	0	0.00	0.70	1.00	0.0000
14	steam gen 1	2	2	2	3	2	0	1	0	0.00	0.70	1.00	0.0000
15	h2o pump 2	2	2	2	3	2	0	1	0	0.00	0.70	1.00	0.0000
16	valves 2	10	2	10	19	2	0	1	0	0.00	0.70	1.00	0.0000
17	stram gen 2	2	2	2	3	2	0	1	0	0.00	0.70	1.00	0.0000
18	reservoir	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
19	heat exchan	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
20	pumps 3	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
21	valves 3	7	2	7	13	2	0	1	0	0.00	0.70	1.00	0.0000
22	pressurizer	2	2	2	3	2	0	1	0	0.00	0.70	1.00	0.0000
23	first wall	24	2	24	40	2	0	1	0	0.00	0.70	1.00	0.0000
24	blankets	24	2	24	40	2	0	1	0	0.00	0.70	1.00	0.0000
25	reflectors	24	2	24	40	2	0	1	0	0.00	0.70	1.00	0.0000
26	turbine	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
27	condenser	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
28	generator	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
29	bop auxilia	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
30	rad. shield	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
31	cryogenics	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
32	c/i	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
33	klystron	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
34	amplifier	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
35	wave guides	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
36	power suppl	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
37	klystron	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
38	amplifier	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
39	wave guides	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
40	power suppl	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
41	klystron	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
42	amplifier	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
43	wave guides	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
44	power suppl	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
45	klystron	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
46	amplifier	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
47	wave guides	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
48	power suppl	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
49	klystron	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
50	amplifier	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
51	wave guides	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000
52	power suppl	1	0	0	0	2	0	1	0	0.00	0.70	1.00	0.0000

- 3 states transition matrices (input) -

id	(0,0)	(1,0)	(2,0)	(0,1)	(1,1)	(2,1)	(0,2)	(1,2)	(2,2)	data base
1	0.0000	2.2500e-06	2.2500e-06	0.0000	0.0000	2.2500e-06	720.0000	0.0000	0.	fdm532,p60
2	0.0000	2.2500e-06	2.2500e-06	0.0000	0.0000	2.2500e-06	720.0000	0.0000	0.	fdm532,p60
3	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	240.0000	0.0000	0.	fdm532,p60
4	0.0000	8.5000e-06	8.5000e-06	0.0000	0.0000	8.5000e-06	38.0000	0.0000	0.	guess
5	0.0000	8.5000e-06	8.5000e-06	0.0000	0.0000	8.5000e-06	2.0000	0.0000	0.	guess
6	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
7	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
8	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
9	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34
10	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	720.0000	0.0000	0.	fdm532,p35
11	0.0000	2.3000e-05	2.3000e-05	0.0000	0.0000	2.3000e-05	96.0000	0.0000	0.	fdm532,p60
12	0.0000	8.0000e-06	8.0000e-06	0.0000	0.0000	8.0000e-06	336.0000	0.0000	0.	fdm532,p60
13	0.0000	5.0000e-06	5.0000e-06	0.0000	0.0000	5.0000e-06	48.0000	0.0000	0.	guess

14	0.0000	1.0000e-05	1.0000e-05	0.0000	0.0000	1.0000e-05	72.0000	0.0000	0.	guess
15	0.0000	8.0000e-06	8.0000e-06	0.0000	0.0000	8.0000e-06	336.0000	0.0000	0.	fdm532,p60
16	0.0000	5.0000e-06	5.0000e-06	0.0000	0.0000	5.0000e-06	48.0000	0.0000	0.	guess
17	0.0000	1.0000e-05	1.0000e-05	0.0000	0.0000	1.0000e-05	72.0000	0.0000	0.	guess
18	0.0000	5.0000e-06	5.0000e-06	0.0000	0.0000	5.0000e-06	168.0000	0.0000	0.	guess
19	0.0000	1.0000e-05	1.0000e-05	0.0000	0.0000	1.0000e-05	168.0000	0.0000	0.	guess
20	0.0000	8.0000e-06	8.0000e-06	0.0000	0.0000	8.0000e-06	336.0000	0.0000	0.	fdm532,p60
21	0.0000	5.0000e-06	5.0000e-06	0.0000	0.0000	5.0000e-06	48.0000	0.0000	0.	guess
22	0.0000	1.0000e-05	1.0000e-05	0.0000	0.0000	1.0000e-05	168.0000	0.0000	0.	guess
23	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	760.0000	0.0000	0.	guess
24	0.0000	1.9000e-05	1.9000e-05	0.0000	0.0000	1.9000e-05	288.0000	0.0000	0.	fdm532,p60
25	0.0000	3.8000e-06	3.8000e-06	0.0000	0.0000	3.8000e-06	960.0000	0.0000	0.	fdm532,p60
26	0.0000	1.1000e-04	1.1000e-04	0.0000	0.0000	1.1000e-04	68.0000	0.0000	0.	nercgads
27	0.0000	3.1500e-05	3.1500e-05	0.0000	0.0000	3.1500e-05	50.0000	0.0000	0.	nercgads
28	0.0000	2.4500e-05	2.4500e-05	0.0000	0.0000	2.4500e-05	115.0000	0.0000	0.	nercgads
29	0.0000	1.3000e-04	1.3000e-04	0.0000	0.0000	1.3000e-04	64.0000	0.0000	0.	nercgads
30	0.0000	1.2500e-05	1.2500e-05	0.0000	0.0000	1.2500e-05	168.0000	0.0000	0.	fdm532,p60
31	0.0000	3.5000e-05	3.5000e-05	0.0000	0.0000	3.5000e-05	52.0000	0.0000	0.	guess
32	0.0000	1.0000e-04	1.0000e-04	0.0000	0.0000	1.0000e-04	48.0000	0.0000	0.	fdm532,p60
33	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
34	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
35	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
36	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34
37	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
38	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
39	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
40	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34
41	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
42	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
43	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
44	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34
45	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
46	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
47	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
48	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34
49	0.0000	2.8500e-05	2.8500e-05	0.0000	0.0000	2.8500e-05	48.0000	0.0000	0.	fdm532,p35
50	0.0000	5.5000e-05	5.5000e-05	0.0000	0.0000	5.5000e-05	72.0000	0.0000	0.	fdm532,p35
51	0.0000	5.5000e-06	5.5000e-06	0.0000	0.0000	5.5000e-06	336.0000	0.0000	0.	fdm532,p35
52	0.0000	9.5000e-06	9.5000e-06	0.0000	0.0000	9.5000e-06	24.0000	0.0000	0.	fdm532,p34

- scheduled maintenace data -

(state/start time/end time)

n\id		1			2			3			4			5			6	
1	0	8784.0	8808.0	0	8784.0	8808.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0

n\id		7			8			9			10			11			12	
1	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0

n\id		13			14			15			16			17			18	
1	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0

n\id		19			20			21			22			23			24	
1	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0	0	8088.0	8760.0

n\id		25			26			27			28			29			30	

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  1  Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø

n\id       31                       32                       33                       34                       35                       36
  1  Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø

n\id       37                       38                       39                       4Ø                       41                       42
  1  Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø

n\id       43                       44                       45                       46                       47                       48
  1  Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø

n\id       49                       5Ø                       51                       52
  1  Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø   Ø    8Ø88.Ø    876Ø.Ø

 - time interval for spare supply =   Ø.ØØØ hrs


*** simulation starts ***

     history no.  availability and uncertainty of top event
                  state Ø                  state 1                  state 2
            2     1.3836e-Ø1 (3.6986e-Ø2)  6.6712e-Ø1 (2.Ø411e-Ø1)  1.9452e-Ø1 (1.6712e-Ø1)
            4     1.5ØØØe-Ø1 (1.8795e-Ø2)  7.Ø479e-Ø1 (8.6235e-Ø2)  1.4521e-Ø1 (7.4Ø66e-Ø2)
            6     1.3927e-Ø1 (1.4812e-Ø2)  7.26Ø3e-Ø1 (5.7838e-Ø2)  1.347Øe-Ø1 (4.8ØØ6e-Ø2)
            8     1.4521e-Ø1 (1.2329e-Ø2)  7.2Ø21e-Ø1 (4.6946e-Ø2)  1.3459e-Ø1 (3.8417e-Ø2)
           1Ø     1.5753e-Ø1 (1.6979e-Ø2)  6.9863e-Ø1 (4.1886e-Ø2)  1.4384e-Ø1 (3.9456e-Ø2)
           12     1.57Ø8e-Ø1 (1.41Ø5e-Ø2)  7.Ø183e-Ø1 (3.4733e-Ø2)  1.411Øe-Ø1 (3.2862e-Ø2)
           14     1.7789e-Ø1 (2.4647e-Ø2)  6.7886e-Ø1 (3.3493e-Ø2)  1.4325e-Ø1 (3.1489e-Ø2)
           16     1.899Øe-Ø1 (2.3173e-Ø2)  6.4914e-Ø1 (3.5888e-Ø2)  1.6Ø96e-Ø1 (3.1Ø22e-Ø2)
           18     1.9619e-Ø1 (2.3614e-Ø2)  6.3973e-Ø1 (3.3Ø63e-Ø2)  1.64Ø8e-Ø1 (2.7911e-Ø2)
           2Ø     1.9ØØØe-Ø1 (2.163Øe-Ø2)  6.5Ø82e-Ø1 (3.1Ø37e-Ø2)  1.5918e-Ø1 (2.5921e-Ø2)
           22     1.9527e-Ø1 (2.2651e-Ø2)  6.5392e-Ø1 (3.Ø634e-Ø2)  1.5Ø81e-Ø1 (2.4236e-Ø2)
           24     1.9144e-Ø1 (2.Ø976e-Ø2)  6.5651e-Ø1 (2.9132e-Ø2)  1.52Ø5e-Ø1 (2.2948e-Ø2)
           26     1.8419e-Ø1 (1.9979e-Ø2)  6.6185e-Ø1 (2.75Ø8e-Ø2)  1.5395e-Ø1 (2.1597e-Ø2)
           28     1.8513e-Ø1 (1.9Ø77e-Ø2)  6.5744e-Ø1 (2.6495e-Ø2)  1.5744e-Ø1 (2.Ø267e-Ø2)
           3Ø     1.8521e-Ø1 (1.7796e-Ø2)  6.642Øe-Ø1 (2.5191e-Ø2)  1.5Ø59e-Ø1 (1.96Ø9e-Ø2)
           32     1.8211e-Ø1 (1.6854e-Ø2)  6.7363e-Ø1 (2.4495e-Ø2)  1.4426e-Ø1 (1.8987e-Ø2)
           34     1.8Ø66e-Ø1 (1.5892e-Ø2)  6.6398e-Ø1 (2.46Ø1e-Ø2)  1.5536e-Ø1 (2.ØØ36e-Ø2)
           36     1.8Ø29e-Ø1 (1.5Ø16e-Ø2)  6.6994e-Ø1 (2.3669e-Ø2)  1.4977e-Ø1 (1.9348e-Ø2)
           38     1.7945e-Ø1 (1.4311e-Ø2)  6.7361e-Ø1 (2.2874e-Ø2)  1.4694e-Ø1 (1.8563e-Ø2)
           4Ø     1.8Ø55e-Ø1 (1.3692e-Ø2)  6.65ØØe-Ø1 (2.2538e-Ø2)  1.5445e-Ø1 (1.8416e-Ø2)
           42     1.7776e-Ø1 (1.3179e-Ø2)  6.6275e-Ø1 (2.2635e-Ø2)  1.5949e-Ø1 (1.93Ø4e-Ø2)
           44     1.8225e-Ø1 (1.3166e-Ø2)  6.589Øe-Ø1 (2.1772e-Ø2)  1.5884e-Ø1 (1.8492e-Ø2)
           46     1.85Ø5e-Ø1 (1.2944e-Ø2)  6.59[illegible]e-Ø1 (2.Ø839e-Ø2)  1.5545e-Ø1 (1.7893e-Ø2)
           48     1.8179e-Ø1 (1.2613e-Ø2)  6.6Ø84e-Ø1 (2.ØØ29e-Ø2)  1.5736e-Ø1 (1.7281e-Ø2)
           5Ø     1.7962e-Ø1 (1.22Ø6e-Ø2)  6.663Øe-Ø1 (1.9617e-Ø2)  1.54Ø8e-Ø1 (1.6748e-Ø2)

***  final results print **

  (state Ø = failure/state 1 = degraded/state 2 = normal)

 -     gate id                             availability
                               state Ø                  state 1                  state 2
        1    whole plant       1.7962e-Ø1 (1.22Ø6e-Ø2)  6.663Øe-Ø1 (1.9617e-Ø2)  1.54Ø8e-Ø1 (1.6748e-Ø2)
        2    vacuum vess       9.38Ø8e-Ø2 (3.6662e-Ø3)  2.3989e-Ø1 (4.4686e-Ø2)  6.663Øe-Ø1 (4.4529e-Ø2)
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3	heat transp	1.3753e-Ø1	(1.29Ø6e-Ø2)	4.6247e-Ø1	(3.75Ø5e-Ø2)	4.ØØØØe-Ø1	(3.6362e-Ø2)
4	blankets	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	2.2466e-Ø3	(1.1992e-Ø3)	9.21Ø4e-Ø1	(1.1992e-Ø3)
5	bop	9.5726e-Ø2	(1.5916e-Ø3)	4.9951e-Ø1	(3.7Ø82e-Ø2)	4.Ø477e-Ø1	(3.6748e-Ø2)
6	burn plasma	9.38Ø8e-Ø2	(3.5662e-Ø3)	2.3989e-Ø1	(4.4686e-Ø2)	6.663Øe-Ø1	(4.4529e-Ø2)
7	vacuum syst	7.8959e-Ø2	(6.44Ø2e-Ø4)	5.9277e-Ø1	(1.7598e-Ø2)	3.2827e-Ø1	(1.7634e-Ø2)
8	prim cool s	1.3118e-Ø1	(1.25Ø4e-Ø2)	3.4186e-Ø1	(4.Ø661e-Ø2)	5.2696e-Ø1	(4.1566e-Ø2)
9	prim cool 1	8.3Ø68e-Ø2	(2.249Øe-Ø3)	1.9852e-Ø1	(3.9457e-Ø2)	7.1841e-Ø1	(3.9178e-Ø2)
1Ø	heat remove	8.1918e-Ø2	(1.5874e-Ø3)	1.5474e-Ø1	(3.3151e-Ø2)	7.6334e-Ø1	(3.313Øe-Ø2)
11	magnets	8.9918e-Ø2	(3.4Ø64e-Ø3)	2.11Ø1e-Ø1	(4.4221e-Ø2)	6.99Ø7e-Ø1	(4.4121e-Ø2)
12	fueling sys	7.95Ø7e-Ø2	(6.935Øe-Ø4)	1.3962e-Ø1	(3.7691e-Ø2)	7.8Ø88e-Ø1	(3.773Øe-Ø2)
13	rf system	8.ØØ55e-Ø2	(1.46Ø9e-Ø3)	5.2258e-Ø1	(3.5962e-Ø2)	3.9737e-Ø1	(3.6387e-Ø2)
14	prim cool 2	8.7452e-Ø2	(5.8Ø36e-Ø3)	2.2214e-Ø1	(3.8254e-Ø2)	6.9Ø41e-Ø1	(3.8399e-Ø2)
15	rf system 1	8.2849e-Ø2	(1.1Ø3Øe-Ø3)	2.8844e-Ø1	(4.7641e-Ø2)	6.2871e-Ø1	(4.7561e-Ø2)
16	rf system 2	8.29Ø4e-Ø2	(1.4828e-Ø3)	2.Ø356e-Ø1	(4.Ø611e-Ø2)	7.1353e-Ø1	(4.Ø691e-Ø2)
17	rf system 3	8.4329e-Ø2	(1.3766e-Ø3)	2.4942e-Ø1	(4.3411e-Ø2)	6.6625e-Ø1	(4.3397e-Ø2)
18	rf system 4	8.3178e-Ø2	(1.1813e-Ø3)	3.1479e-Ø1	(4.9168e-Ø2)	6.Ø2Ø3e-Ø1	(4.9299e-Ø2)
19	rf system 5	8.4822e-Ø2	(1.5Ø97e-Ø3)	2.7359e-Ø1	(4.35ØØe-Ø2)	6.4159e-Ø1	(4.3353e-Ø2)
2Ø	rf system 6	8.18Ø8e-Ø2	(1.2671e-Ø3)	3.9414e-Ø1	(4.6764e-Ø2)	5.24Ø5e-Ø1	(4.6765e-Ø2)

- component id availability

		state Ø		state 1		state 2	
1	tf s/c magn	Ø.	(Ø.)	1.4411e-Ø2	(7.8928e-Ø3)	9.8559e-Ø1	(7.8928e-Ø3)
2	ef s/c magn	8.2192e-Ø3	(3.5225e-Ø3)	7.9726e-Ø2	(3.3396e-Ø2)	9.12Ø5e-Ø1	(3.3181e-Ø2)
3	cf n-magnet	8.ØØØØe-Ø2	(1.2719e-Ø3)	4.8932e-Ø2	(2.26Ø8e-Ø2)	8.71Ø7e-Ø1	(2.2499e-Ø2)
4	gas puff sy	7.7151e-Ø2	(2.6383e-Ø4)	1.2329e-Ø2	(9.3Ø49e-Ø3)	9.1Ø52e-Ø1	(9.2968e-Ø3)
5	fuel supply	7.6822e-Ø2	(7.6696e-Ø5)	3.1945e-Ø2	(1.79Ø9e-Ø2)	8.9123e-Ø1	(1.79Ø5e-Ø2)
6	klystron	7.7479e-Ø2	(2.7161e-Ø4)	1.48Ø5e-Ø1	(4.Ø516e-Ø2)	7.7447e-Ø1	(4.Ø497e-Ø2)
7	amplifier	8.12Ø5e-Ø2	(8.8131e-Ø4)	1.183Øe-Ø1	(3.2484e-Ø2)	8.ØØ49e-Ø1	(3.2391e-Ø2)
8	wave guides	7.7479e-Ø2	(7.6712e-Ø4)	3.3973e-Ø2	(2.3781e-Ø2)	8.8855e-Ø1	(2.3771e-Ø2)
9	power suppl	7.6822e-Ø2	(7.6696e-Ø5)	4.7288e-Ø2	(2.3498e-Ø2)	8.7589e-Ø1	(2.3493e-Ø2)
1Ø	limiter sys	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	5.7425e-Ø1	(1.46Ø2e-Ø2)	3.49Ø4e-Ø1	(1.46Ø2e-Ø2)
11	cryo pumps	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	1.5397e-Ø2	(6.Ø85Øe-Ø3)	9.Ø789e-Ø1	(6.Ø85Øe-Ø3)
12	h2o pump 1	8.2Ø82e-Ø2	(2.1945e-Ø3)	2.1973e-Ø2	(1.1Ø52e-Ø2)	8.9595e-Ø1	(1.1133e-Ø2)
13	valves 1	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	1.6718e-Ø1	(4.Ø154e-Ø2)	7.5611e-Ø1	(4.Ø164e-Ø2)
14	steam gen 1	7.7699e-Ø2	(4.48Ø3e-Ø4)	1.6767e-Ø2	(9.16Ø1e-Ø3)	9.Ø553e-Ø1	(9.1843e-Ø3)
15	h2o pump 2	8.6137e-Ø2	(5.75Ø2e-Ø3)	4.7945e-Ø2	(2.Ø687e-Ø2)	8.6592e-Ø1	(2.1211e-Ø2)
16	valves 2	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	1.3Ø74e-Ø1	(3.6682e-Ø2)	7.9255e-Ø1	(3.6682e-Ø2)
17	stram gen 2	7.8192e-Ø2	(6.Ø74Øe-Ø4)	7.5781e-Ø2	(2.1986e-Ø2)	8.46Ø3e-Ø1	(2.2Ø32e-Ø2)
18	reservoir	7.7Ø96e-Ø2	(3.8356e-Ø4)	1.Ø63Øe-Ø2	(1.Ø63Øe-Ø2)	9.1227e-Ø1	(1.Ø629e-Ø2)
19	heat exchan	7.9397e-Ø2	(1.Ø973e-Ø3)	2.1315e-Ø2	(1.2255e-Ø2)	8.9929e-Ø1	(1.22Ø9e-Ø2)
2Ø	pumps 3	7.8849e-Ø2	(1.2159e-Ø3)	2.811Øe-Ø2	(1.6456e-Ø2)	8.93Ø4e-Ø1	(1.6426e-Ø2)
21	valves 3	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	1.Ø849e-Ø1	(2.9328e-Ø2)	8.1479e-Ø1	(2.9328e-Ø2)
22	pressurizer	7.7863e-Ø2	(6.5Ø65e-Ø4)	6.2521e-Ø2	(3.Ø679e-Ø2)	8.5962e-Ø1	(3.Ø638e-Ø2)
23	first wall	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	Ø.	(Ø.)	9.2329e-Ø1	(3.1951e-Ø8)
24	blankets	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	2.2466e-Ø3	(1.1992e-Ø3)	9.21Ø4e-Ø1	(1.1992e-Ø3)
25	reflectors	7.6712e-Ø2	(3.8Ø8Øe-Ø9)	Ø.	(Ø.)	9.2329e-Ø1	(3.1951e-Ø8)
26	turbine	8.4274e-Ø2	(9.9188e-Ø4)	2.2762e-Ø1	(3.9686e-Ø2)	6.8811e-Ø1	(3.9593e-Ø2)
27	condenser	7.8356e-Ø2	(4.6967e-Ø4)	1.5923e-Ø1	(4.ØØØØe-Ø2)	7.6241e-Ø1	(3.9941e-Ø2)
28	generator	7.863Øe-Ø2	(6.79Ø4e-Ø4)	4.4877e-Ø2	(1.9248e-Ø2)	8.7649e-Ø1	(1.92Ø3e-Ø2)
29	bop auxilia	8.4712e-Ø2	(1.Ø38Øe-Ø3)	2.7238e-Ø1	(3.6971e-Ø2)	6.429Øe-Ø1	(3.68Ø5e-Ø2)
3Ø	rad. shield	8.Ø164e-Ø2	(1.Ø526e-Ø3)	6.8767e-Ø2	(2.8Ø86e-Ø2)	8.51Ø7e-Ø1	(2.8144e-Ø2)
31	cryogenics	7.8959e-Ø2	(6.44Ø2e-Ø4)	1.Ø296e-Ø1	(3.3326e-Ø2)	8.18Ø8e-Ø1	(3.3415e-Ø2)
32	c/i	8.3Ø14e-Ø2	(7.Ø992e-Ø4)	2.5184e-Ø1	(3.6711e-Ø2)	6.6515e-Ø1	(3.6462e-Ø2)
33	klystron	7.8Ø27e-Ø2	(3.3431e-Ø4)	6.7123e-Ø2	(2.6697e-Ø2)	8.5485e-Ø1	(2.6632e-Ø2)
34	amplifier	7.9178e-Ø2	(5.87Ø8e-Ø4)	1.1348e-Ø1	(3.3794e-Ø2)	8.Ø734e-Ø1	(3.3765e-Ø2)
35	wave guides	7.9Ø14e-Ø2	(1.3Ø13e-Ø3)	5.863Øe-Ø3	(4.6336e-Ø3)	9.1512e-Ø1	(4.7553e-Ø3)
36	power suppl	7.6822e-Ø2	(7.6696e-Ø5)	3.3589e-Ø2	(1.8683e-Ø2)	8.8959e-Ø1	(1.8679e-Ø2)
37	klystron	7.8575e-Ø2	(4.3188e-Ø4)	8.18Ø8e-Ø2	(3.1547e-Ø2)	8.3962e-Ø1	(3.1495e-Ø2)

38	amplifier	8.Ø438e-Ø2	(6.538Øe-Ø4)	1.5638e-Ø1	(3.6Ø28e-Ø2)	7.6318e-Ø1	(3.5975e-Ø2)
39	wave guides	7.8521e-Ø2	(1.Ø6Ø7e-Ø3)	3.15Ø7e-Ø2	(2.Ø445e-Ø2)	8.8997e-Ø1	(2.Ø416e-Ø2)
4Ø	power suppl	7.6932e-Ø2	(1.Ø618e-Ø4)	3.7753e-Ø2	(2.2157e-Ø2)	8.8532e-Ø1	(2.215Øe-Ø2)
41	klystron	7.7918e-Ø2	(3.2426e-Ø4)	1.6132e-Ø1	(4.2Ø52e-Ø2)	7.6Ø77e-Ø1	(4.196Øe-Ø2)
42	amplifier	8.Ø822e-Ø2	(3.2192e-Ø4)	1.7551e-Ø1	(3.963Øe-Ø2)	7.4367e-Ø1	(3.9416e-Ø2)
43	wave guides	7.7479e-Ø2	(7.6712e-Ø4)	1.2767e-Ø2	(1.2767e-Ø2)	9.Ø975e-Ø1	(1.2775e-Ø2)
44	power suppl	7.7Ø96e-Ø2	(1.3581e-Ø4)	3.1671e-Ø2	(1.9713e-Ø2)	8.9123e-Ø1	(1.97Ø1e-Ø2)
45	klystron	7.8Ø27e-Ø2	(3.6915e-Ø4)	9.1288e-Ø2	(3.1812e-Ø2)	8.3Ø68e-Ø1	(3.1853e-Ø2)
46	amplifier	8.1151e-Ø2	(8.5352e-Ø4)	2.Ø515e-Ø1	(4.Ø728e-Ø2)	7.137Øe-Ø1	(4.Ø583e-Ø2)
47	wave guides	7.9Ø14e-Ø2	(1.3Ø13e-Ø3)	7.5Ø68e-Ø3	(7.5Ø68e-Ø3)	9.1348e-Ø1	(7.5724e-Ø3)
48	power suppl	7.6767e-Ø2	(5.4795e-Ø5)	4.3562e-Ø2	(2.Ø497e-Ø2)	8.7967e-Ø1	(2.Ø494e-Ø2)
49	klystron	7.8Ø27e-Ø2	(3.6915e-Ø4)	9.2548e-Ø2	(3.Ø341e-Ø2)	8.2942e-Ø1	(3.Ø314e-Ø2)
5Ø	amplifier	7.9452e-Ø2	(8.61Ø6e-Ø4)	2.6427e-Ø1	(4.5911e-Ø2)	6.5627e-Ø1	(4.5952e-Ø2)
51	wave guides	7.7479e-Ø2	(7.6712e-Ø4)	4.6466e-Ø2	(2.1587e-Ø2)	8.76Ø5e-Ø1	(2.1567e-Ø2)
52	power suppl	7.7Ø41e-Ø2	(1.2719e-Ø4)	6.8438e-Ø2	(2.7994e-Ø2)	8.5452e-Ø1	(2.7978e-Ø2)

- effective availability of whole system = 62.Ø493 %

- ranking of effective availability -

rank	gate id	name	% eff-avail	error
1	4	blankets	92.2614	Ø.Ø71232
2	12	fueling sys	87.86Ø8	2.249517
3	1Ø	heat remove	87.166Ø	1.9826Ø8
4	9	prim cool 1	85.7375	2.318249
5	16	rf system 2	85.6Ø27	2.44Ø56Ø
6	11	magnets	84.6778	2.667369
7	14	prim cool 2	84.59Ø7	2.49363Ø
8	17	rf system 3	84.Ø844	2.585858
9	6	burn plasma	83.4225	2.692489
1Ø	2	vacuum vess	83.4225	2.692489
11	19	rf system 5	83.31Ø1	2.5669Ø9
12	15	rf system 1	83.Ø619	2.819947
13	18	rf system 4	82.2384	2.953Ø17
14	2Ø	rf system 6	79.9951	2.7859ØØ
15	8	prim cool s	76.6263	3.316522
16	13	rf system	76.3173	2.232365
17	5	bop	75.4422	2.152187
18	7	vacuum syst	74.3211	1.Ø57884
19	3	heat transp	72.3726	2.922482
2Ø	1	whole plant	62.Ø493	2.Ø54156

rank	comp. id	name	% eff-avail	error
1	1	tf s/c magn	99.5677	Ø.468833
2	2	ef s/c magn	96.7863	2.Ø266Ø7
3	25	reflectors	92.3288	Ø.ØØØØØ6
4	23	first wall	92.3288	Ø.ØØØØØ6
5	24	blankets	92.2614	Ø.Ø71232
6	18	reservoir	91.9715	Ø.63444Ø
7	35	wave guides	91.9227	Ø.368328
8	4	gas puff sy	91.9151	Ø.552836
9	47	wave guides	91.8734	Ø.5Ø6879
1Ø	43	wave guides	91.869Ø	Ø.77Ø383
11	11	cryo pumps	91.8668	Ø.36145Ø
12	14	steam gen 1	91.7271	Ø.55389Ø

13	19	heat exchan	91.42Ø8	Ø.741388
14	5	fuel supply	91.3595	1.Ø63132
15	44	power suppl	91.34Ø3	1.168787
16	36	power suppl	91.31Ø1	1.1Ø9Ø77
17	2Ø	pumps 3	91.2718	Ø.992252
18	8	wave guides	91.2329	1.416295
19	39	wave guides	91.2Ø27	1.221328
2Ø	4Ø	power suppl	91.1742	1.3148Ø7
21	12	h2o pump 1	91.1326	Ø.764428
22	48	power suppl	91.Ø164	1.217Ø84
23	9	power suppl	9Ø.8992	1.394946
24	51	wave guides	9Ø.8581	1.284595
25	28	generator	9Ø.79Ø7	1.139934
26	3	cf n-magnet	9Ø.5321	1.337794
27	22	pressurizer	9Ø.3381	1.817375
28	52	power suppl	9Ø.2427	1.659764
29	33	klystron	9Ø.1836	1.5738ØØ
3Ø	15	h2o pump 2	89.9479	1.635749
31	3Ø	rad. shield	89.92Ø5	1.6889Ø4
32	17	stram gen 2	89.9Ø74	1.318888
33	37	klystron	89.6882	1.864873
34	45	klystron	89.4586	1.899766
35	49	klystron	89.42Ø8	1.79794Ø
36	21	valves 3	89.Ø74Ø	1.742Ø89
37	31	cryogenics	89.Ø153	1.9999Ø7
38	34	amplifier	88.6778	2.ØØ4Ø13
39	16	valves 2	88.4Ø66	2.178893
4Ø	7	amplifier	88.33Ø4	1.916698
41	6	klystron	87.81Ø4	2.4Ø3353
42	27	condenser	87.3874	2.365612
43	41	klystron	87.3688	2.48Ø321
44	13	valves 1	87.3134	2.385728
45	38	amplifier	87.2647	2.1324Ø5
46	42	amplifier	86.6526	2.31543Ø
47	46	amplifier	85.73Ø4	2.394671
48	26	turbine	84.7441	2.344564
49	32	c/i	84.1436	2.134Ø97
5Ø	5Ø	amplifier	84.1266	2.73891Ø
51	29	bop auxilia	83.3573	2.169971
52	1Ø	limiter sys	75.1Ø14	Ø.867379

* computing time in seconds *
(cpu/i&o/sys)= 64.79654/ 11.73Ø88/ Ø.ØØ987/

5. CONCLUSIONS AND FUTURE WORK

The PROPA computer program has been used to analyze the availability of the STARFIRE tokamak fusion reactor plant by taking into account degraded states of systems. The program allows us to make more realistic models of the plant performance. However, it is still early to conclude its usefulness for design of fusion reactor plants until we accomplish the work discussed below.

The following reliability data must be collected:

- failure modes and rates both for failures from a normal state to a degraded state and from a degraded state to a failed state;
- repair time both for repairs from a failed state to a degraded state and from a degraded state to a normal state.

Gate transfer functions in system trees must be determined; in particular, the gate logic associated with plasmas makes significant impact on the estimate of plant availability. Typical problems are:

- effects of magnetic field (both its strength and geometry) on the state of the plasma;
- response of the plasma to degradation of fueling, heating (and current drive), and impurity control systems;
- selection of the best operating parameters for the plasma from the system reliability point of view by taking account of plasma control systems.

There are many system models that still need to be added to the PROPA program. Among them the following capabilities of modeling are being implemented:

- demand failures for transient system behavior such as startup and shutdown;
- dependent failures;
- effects on other systems during repair of a particular system;

- limited resources for maintenance (equipment and personnel);
- limited availability of spare parts for system replacement.

The last two features will allow a user to predict the necessary maintenance facilities and spare parts to be stored.

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APPENDIX A. TERMINOLOGY

System: everything in this world

Component: a part of the system being analyzed whose internal structure is not considered

Subsystem: a part of the system being analyzed but not a component

Element: a component or a subsystem

Unit: one of identical components

State transition probability (STP): the probability that a system changes its state at a particular time

Failure: any change of state from the normal state

Failed State: state in which a system does not perform its function

Critical Failure: the state changes into a failed state

Degraded State: state in which a system performs its role partially

Degradation: state change into a degraded state

Repair: an action by which a system in a degraded or failed state is brought to a normal state

Effective Availability: $\alpha A_2 + \beta A_1 + \gamma A_0$ where $0 < \alpha, \beta, \gamma < 1$ and A_i $(i = 0, 1, 2)$ is the i-th state availability

Systems Tree: a tree structure representing a system and consisting of gates and components

Transfer Function (Logic): a function associated with a gate; it represents a relation between the output state and input states

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