Three-State Model for Fusion Reactor Plant Availability Analysis

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ABSTRACT

An availability simulation methodology and a computer program (PROPA) have been developed for systems subject to three states: normal, degraded, and failed. The program is used to analyze the STARFIRE tokamak fusion reactor plant. The new program extends our modeling capability for complex systems; while it is found that significant improvements are needed in the areas of reliability data, understanding of system behavior, and the computing speed.

INTRODUCTION

Availability analysis of engineering systems has been performed by assuming that the state of systems is either normal (success) or failed. In many cases, however, the use of three or more states enables us to model the realities better than the 2-state model. For example, the behavior of a system with a continuous state variable can be modeled appropriately.

The need for a multistate model is reflected in many published papers concerning this subject (for example, see bibliographies cited in Ref. 1). Most of these authors discuss only mathematical methods of analysis. An exception is a paper by an Italian group;[2] they consider the modeling of multiple failures in nuclear fission reactor safety systems. Another is a paper from EPRI;[3] the authors have developed a computer program (UNIRAM) to calculate the availability of coal fired plants by including a number of states of the plant power output. However, its modeling capability is limited because the program takes a deterministic approach.

We have developed a computer simulation program (AVSYS) and applied it to a conceptual fusion reactor, MARS.[4,5] The work has demonstrated the great flexibility of the Monte Carlo simulation approach. To enhance the modeling capability, we are undertaking inclusion of a multistate model. In the present paper, we shall describe the methodology used in a new computer program (PROPA) and its application to the STARFIRE fusion reactor plant availability analysis. In particular, the problems associated with such a modeling and simulation will be clarified.

SYSTEMS MODEL

A <u>system</u> carries certain functions. A system can be partitioned into smaller parts according to the functions and these are called <u>subsystems</u>. A subsystem can be further partitioned. Finally we reach a subsystem, for which further partitioning is undesirable. Such a subsystem is called <u>component</u>. Subsystems and components together are called <u>elements</u> of the system. In a system there may be a number of identical components. In this case a component is called <u>unit</u>. Identical units are sometimes <u>redundant</u> and exist to increase the reliability.

Components are interconnected to one another via flows of power, materials (gas or liquid), and control signals. The functional relationship can be represented by means of a <u>functional diagram</u>. The system interacts with the outside through some input/output ports. Components are also related to one another via forces such as stress, electric/magnetic forces, sound, heat, and radiation. This is represented by means of a <u>force field diagram</u>.

A system and its elements are associated with one or more state parameters representing functional outputs. These parameters vary in time. Undesirable changes occur when the elements fail to operate properly. Any unintended occurrence of a departure from its normal state is called <u>failure</u>. If an element achieves its specified function partially, its state is <u>degraded</u> and a transition from a normal to a degraded state is called <u>degradation</u>. Failures other than degradation are called <u>critical failures</u> and the state is <u>failed</u>. Actions to bring the elements from a failed to a degraded or a normal state, and a degraded to a normal state are called <u>replacement</u> if it is done by replacing the element by a new unit; otherwise, it is called repair. For replacement, spares must be supplied. In addition to unintended changes, there are planned state transitions such as scheduled maintenance and testing.

In the 3-state model, we denote the normal, degraded, and failed states by 2, 1, and 0, respectively. Furthermore, we define the state-availability of a system as the ratio of the length of time during which the system is in a particular state to the total length of time being considered.

PROPA COMPUTER PROGRAM

A new computer program, PROPA, has been developed[1,6] by including the model described in the above section. A Monte Carlo simulation method is utilized. Time is advanced by a specific amount and for a time period the states of elements and the system are calculated by playing a Monte Carlo game. It is assumed that the state transition probability for degradation is constant in time (equivalent to assuming a constant failure rate in the 2-state model) and fixed repair times are used instead of probability distributions. The transition paths among three states can be specified by users. To compute the state of the system, a systems tree must be provided. A systems tree is a tree-representation of the functional diagram and the force field diagram and consists of gates and events. An event is either a state of a component or an external event. A gate is associated with an output and several inputs. The relation among the output and inputs is represented by a transfer function (we may call it a decision table or multivalued logic table). For the user's convenience, three types of transfer functions are implemented in the program in addition to transfer functions specified by the user. The AND gate is such that the output state is failed if one of input states is failed, the output is normal if all inputs are normal, and for all other cases the output is degraded. If a gate has n inputs, the sum of input state variables varies between 0 and 2n. The range is partitioned into three subintervals. Then the output state of the SUM gate is determined by identifying a subinterval where the sum of input variables lies. The three subintervals must be specified by the users. The MAX gate is such that the output state is equal to the maximum value of input states. Furthermore, the concept of a virtual gate is introduced. A virtual gate represents the output state of identical units as a whole.

Other major features of the program are a simulation capability for maintenance personnel and equipment and spare inventories. The PROPA program is currently being used on the CRAY-1 computers at the National Magnetic Fusion Energy Computer Center (NMFECC), Livermore, CA.

STARFIRE

STARFIRE is a steady-state D-T tokamak reactor producing 1200 MWe.[7] The main features of this reactor are the use of radio frequency wave systems to drive the toroidal current, limiters for impurity control of the plasma, and solid-breeder blankets with water as the coolant.

The functional diagram is given in Fig. 1. There are 17 major subsystems, which can be called components in the present analysis: the plasma itself, the radio frequency wave (RF) system, the electron cyclotron resonance heating (ECRH) system, the fueling (GAS PUFF) system, the limiters, the vacuum pumps and ducts (EXHAUST) system, the ohmic heating (OH) coils, the toroidal field (TF) coils, the equilibrium field (EF) coils, the control field (CF) coils, the radiation shields (SHIELD), the first wall and blankets (FW/BLANKET), the heat transport system (HEAT TRANS.), the balance of plant (BOP) including turbine-generators and switch yards, the cryogenics (CRYO.) system, the fuel supply system, and the instrumentation and control (I/C) system. The connections among components are illustrated by solid lines for energy (heat and electric power) flows, dotted lines for fuel (Tritium and Deuterium) flows, and dashed lines for cryogenics (helium and nitrogen) flows. The I/C signals are not given since this was not designed in the STARFIRE study. We simply assume

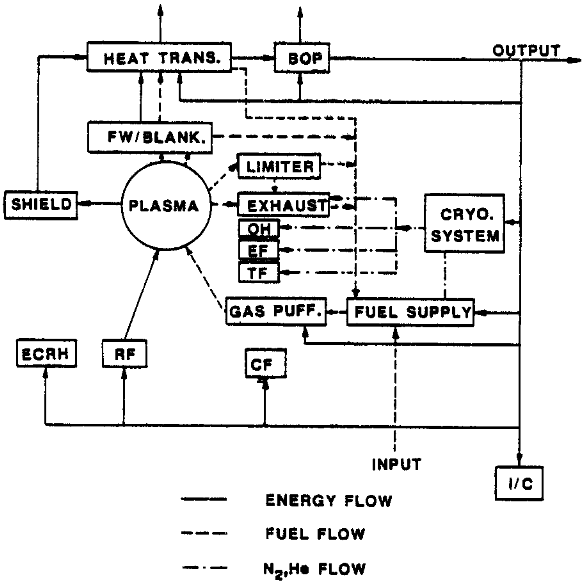

Fig. 1. Functional diagram of STARFIRE.

that the I/C system is connected with all the components.

For further analysis, we neglect OH, ECRH, and the plasma by making the following assumptions. The effects of the OH and ECRH systems on the plant availability are negligible because these are used only for plant start-up. Plasma disruptions rarely occur.

Now we define the three states of the components. The state parameter for the RF system is the electromagnetic wave power injected into the plasma. The toroidal current induced is proportional to the injected RF power. There are 48 RF units. A 50% or greater loss of the power is regarded as critical failure. A 2% or greater loss leads to a degraded state. The state parameter of GAS PUFF is the flow rate of D and T particles injected into the plasma. A 50% or more loss of the fueling rate is regarded as a critical failure. A 10 to 50% loss results in a degraded state. From the functional point of view, the state parameter of the limiters should be the reflection ratio defined as the ratio of the number of particles hitting the limiter to the number of particles returning into the plasma. Once the geometry of the limiters is determined, the ratio depends only on the exhaust capability of the vacuum pumps. The most likely failure mode of the limiters is coolant loss. Thus, the leakage rate of the coolant into the vacuum chamber is a more suitable state parameter. No leak, small leak, and large leak are regarded as normal, degraded, and failed, respectively. There are 96 limiters. If all units are normal, the system is normal. If the sum of the 96 state variables is smaller than 96, it is failed. Otherwise, it is degraded. The state parameter of the EXHAUST system is the vacuum pumping rate. There are 12 vacuum ducts behind limiters. Each duct is connected to two cryopumps. We look at this as 12 identical exhaust units. If one of the units fails, the system is still normal. If the sum of the 12 state variables becomes smaller than 24, it is failed. Otherwise, it is in a degraded state. The state parameter of the magnets is the magnetic field strength and spatial distribution of the field. Since change of spatial positions of the magnets is unlikely, the field strength can represent the state of a magnet. There are 12 superconducting (S/C) TF coils and these are connected in series. This configuration ensures the axial symmetry of the toroidal field when a coil fails, while it eliminates redundancy. There are six S/C EF coils and four normal conductor CF coils. The TF, EF, and CF systems can be represented appropriately by using AND gates. The state parameter of SHIELD is the attenuation of radiation. A 10% loss of the attenuation is regarded as degradation. A 50% or greater loss results in a failed state. The state parameters of the FW/BLANKET are the tritium breeding ratio and the energy conversion ratio (ECR), which represents the ratio of neutron and gamma energy entering the system to the heat removed from the system. The tritium can be provided from an outside supplier whenever it is necessary; hence we regard the ECR as the state parameter. The ECR depends mainly on the water coolant flow rate and the inlet temperature. A loss of coolant occurs because of the leak from tubes in the blanket. No leak, small leak, and large leak are considered as normal, degraded and failed states. Although there are 12 separate blanket units, none of these is redundant. Since all units are subject to the same amount of neutron heat load, the degradation of one unit is likely to result in the degradation of the system. Thus the AND gate is used as the gate. The state parameter of the HEAT TRANSPORT system is the ratio of the heat removed from the blankets to the steam energy transported to the turbines. The state parameter of the BOP is the thermal efficiency representing the ratio of the steam power entering the turbines to the electricity generated. The state parameter of CRYO. and the fuel supply systems are the cryogenic fluid supply rate and the D and T fuel supply rate. The state parameter of I/C is the success rate of detection and response of control signals. To improve reliability, a great number of redundant units are provided in the STARFIRE design.

A systems tree is given in Fig. 2. There are 14 components represented by circles and six gates. More than one gate is used to reduce the size of the decision table. The output of gate 1 represents the state of the plant (electric power). Gate 3 represents the neutron power output from the plasma. Gates 4, 5, and 6 represent the vacuum control, magnetic field, and fueling qualities, respectively. TF, EF, and CF coils make up the magnets' quality. GAS PUFF and FUEL SUPPLY make up the fueling quality. LIMITER and EXHAUST make up the vacuum control quality. Gate 2 is used to separate the effects of the vacuum control system from other systems affecting the plasma quality. TF, CF, EF, RF, LIMITER, EXHAUST, and FW/BLANKET are accompanied by virtual gates since these consist of a number of identical units. As a base case we use the AND transfer functions for all six gates. Strictly speaking, the transfer functions must be determined by thoroughly analyzing the systems.

DATA COLLECTION

At present there are few data sources for the reliability of fusion reactor systems. For this study we use the very crude estimates of reliability collected in Refs. 7 and 8. In Table 1, 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 components included in this analysis. For the 3-state availability analysis, we need data for

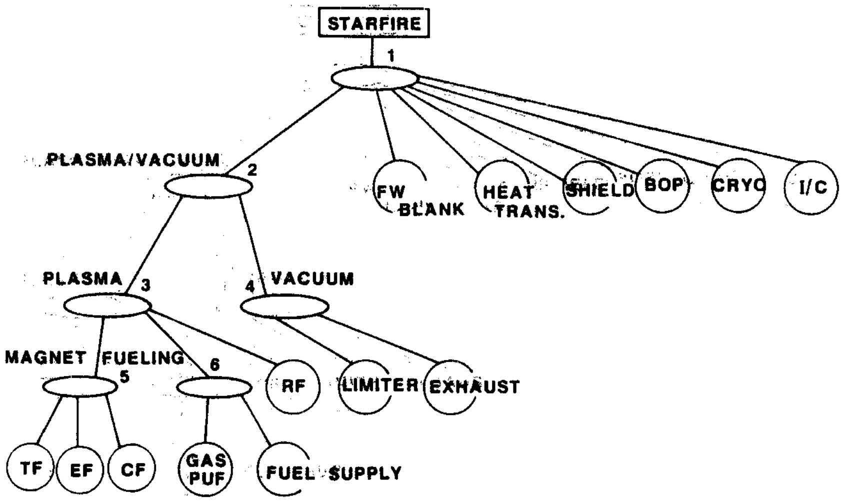

Fig. 2. Systems tree of STARFIRE.

Table 1. Reliability Data

Component Name	λ_{20} [1/hrs]	τ_{02} [hrs]	Reference Page No. in Ref. [8]	Comments
TF magnet	4.5E-6	720.0	60	
EF magnet	4.5E-6	720.0	60	
CF magnet	1.1E-5	240.0	60	
Gas puffing	1.9E-5	38.0	---	Ref. [7], pp. 19-101 (1)
Fuel supply	1.7E-5	2.0	60	See note (2)
RF system	2.5E-3	4.0	60	
Limiter	1.1E-4	720.0	35	
Exhaust	4.6E-5	96.0	60	Data of vacuum pumps
FW/Blanket	5.7E-5	120.0	57	
Heat transport	1.7E-5	72.0	---	Ref. [7], pp. 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 operation year a = 0.15; then $\lambda_{20} = a/(T - a\tau_{02})$ 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.

Table 2. Availabilities in %

	Failed	Degraded	Normal	e-avail
TF magnets	5.5	70.0	24.5	73.5 ± 3.08
EF magnets	4.5	20.7	74.8	89.3 ± 4.10
CF magnets	8.0	7.2	84.8	90.0 ± 0.60
Gas puffing	7.7	1.4	90.9	91.9 ± 0.32
Fuel supply	7.7	3.0	89.3	91.4 ± 0.54
RF system	7.7	91.6	0.7	64.8 ± 0.02
Limiters	7.7	91.3	1.0	64.9 ± 0.04
Exhaust	7.7	10.4	81.9	89.2 ± 0.78
FW/Blanket	14.2	71.8	14.0	64.3 ± 0.63
Heat transport	7.7	2.1	90.2	91.6 ± 0.51
Rad Shield	7.8	4.9	87.3	90.7 ± 0.78
BOP	10.4	25.2	64.4	73.5 ± 3.08
CRYO. system	7.9	9.7	82.4	89.2 ± 0.94
I/C	8.1	19.6	72.3	86.0 ± 0.72
Plant	22.6	77.3	0.1	54.2 ± 0.44

λ_{21} and λ_{10}. τ_{01} and τ_{12} are also needed if a repair is performed to bring a system up to a degraded state.

Since failure data is collected for all 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 such as Ref. 9. The data on λ_{10} and τ_{01} is completely lacking.

To proceed with the analysis, we must make assumptions. First, we consider that all components 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 1. Let the λ_{20} for the 2-state model be denoted by λ'_{20}. Then λ_{ij} for the 3-state model is given by $\lambda_{20} = \lambda_{21} = \lambda_{10} = 0.5\ \lambda'_{20}$.

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

SIMULATION AND ANALYSIS

The maximum mean-time-to-failure of the 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 as good as 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 repair time is two hours. Hence the timestep of simulation must be smaller than two hours. However, we choose 24 hours as the timestep length in order to reduce computing time. It turns out that the CPU time is about three minutes for the above parameters and 20 histories, and the 95% confidence interval for the effective availability of the entire system is less than ±0.1% of the sample mean.

A simulation is performed for 10 year periods by using a one day timestep and 20 histories. The state availabilities and the effective availabilities (e-avails), which are defined by $A_2 + 0.7\ A_1$ (A_i is the i-th state availability in percent), and their 95% confidence intervals are given in Table 2. The statistical errors are small. The smallest e-avail is that of the RF system. This can be expected 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. When the state availabilities by the 3-state model are examined, it is found that the plant is in the normal state only for 0.1% of the operation time and it is in a degraded state for about 80% of the time. The e-avails of the base configuration are given as case 1 in Table 3. Now we shall perform a sensitivity analysis to see the effects of different configurations on the availability. For this analysis 50 histories

Table 3. Sensitivity Analysis Results

CASE	e-avail, %			
	Limiter	RF	GATE 3	PLANT
1	64.9	64.9	62.8	56.6 ± 1.00
2	80.2	64.8	63.5	56.3 ± 0.98
3	65.0	72.8	68.8	55.5 ± 1.00
4	64.9	92.3	84.7	56.7 ± 1.01
5	64.9	64.9	84.7	56.7 ± 1.01
6	64.9	64.9	54.0	48.5 ± 4.24

are simulated for one day timesteps and a one year period. There are 96 limiters. By increasing the number of limiters to 110 units, the same impurity control capability can be achieved with more failed units. The result given in Table 3 (case 2) shows the improvement of the e-avail. There are 48 RF units. By increasing the number of units up to 60 units, the same injection power can be obtained for less reliable components. The result is given in Table 3 as case 3. Another way to improve the availability of the RF system is to repair degraded units. As seen in Table 3 (case 4) this significantly increases the e-avail of the component. The relation between the fusion power output and availabilities of magnets, RF systems, and the fueling system is of particular interest. Case 1 is obtained for the transfer function of Gate 3 such that a degradation of one of three inputs results in degradation of the plasma. If the degradation of the RF system does not affect the plasma, the availability may be higher. This is seen as case 5 in Table 3. However, if degraded magnets lead to a critical failure of the plasma, it should become smaller. This is seen as case 6 in Table 3.

The present analysis suffers three types of uncertainties: uncertainties in the reliability data, the models of the systems, and the statistical errors inherent in the Monte Carlo simulation. Currently the first error is very large and can be significantly reduced as more systems are placed in operation and a large amount of data is collected. The second error will not be easily reduced. A systematic way to check such errors must be developed. The third error source is reduced by simply performing more simulations.

CONCLUSIONS

The 3-state model described in this paper enhances our modeling capability and will consequently lead to better estimates of the fusion reactor plant availability. The computer program developed can be used not only for availability analysis but also to predict necessary maintenance personnel and equipment, simulate spare inventories in a plant, and estimate the operating cost of the plant.

In spite of these advantages, we cannot obtain good predictions until sufficient data with high quality is collected. For the 3-state modeling, data regarding system degradations must be obtained. Simulation is expensive although it is much cheaper than other computations routinely performed at the NMFECC. Significant improvement in computing speed is needed. A possibility of using computer languages suitable for simulation should be taken into account to incorporate more detailed models effectively. A correct model can be obtained only by doing thorough analysis of systems comparable to large conceptual reactor design studies.

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