RELIABILITY AND AVAILABILITY ANALYSIS OF FUSION POWER PLANTS

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Abstract Major efforts are underway to develop fusion energy for use in electric power production in the furture. While fusion reactor concepts are being developed, appropriate attention must be given to problems relvant to the utility requirements which are likely to be encountered in the commercialization phase. In this paper the expected fusion plant availability is assessed in detail due to the importance of power plant availability in the commercialization of the use of any energy source. The reliability and availability of fusion plants are analyzed by using the PREP, KITT–1, and KITT–2 codes (1). Analysis of computer output yields the availability of 82–82.9 percent for a fusion power plant under investigation during one year operation by assuming that there would be two schedule outages for first wall replacement. Also, Exploration of those components which are prone to failure and which may increase the change for forced failures is made.

چکیده — سعی بر کوشش فراوان جهت استفاده از انرژی گداختهای هستهای به‌منظور تاءمین قدرت الکتریکی آینده درحال حاضر صورت می‌گیرد . همزمان با توسعهٔ طرحهای مختلف رآکتورهای گداخت هستهای لازم است مسائل مختلف که احتمالا "در مرحلهٔ تجارتی نمودن این منبع بزرگ انرژی ، تولیدکنندگان قدرت الکتریکی با آن مواجه خواهند شد بررسی گردد . از آن جمله مسائل می‌توان قابلیت اطمینان و دسترسی را نام برد که در این مقاله بطور مشروح مورد بررسی قرار می‌گیرد . نظر به اینکه ظرفیت قدرت الکتریکی مورد انتظار این واحدهای تولیدکننده حدود 2–5 GW میباشد لذا واضح است که باید این نیروگاهها از قابلیت دسترسی بیشتر و معقول برخوردار باشند . بدین‌منظور یک سیستم سیکل مستقیم توربین گازی گداخت هستهای انتخاب گردیده وجهت بررسی قابلیت اطمینان و دسترسی آن ازآنالیز درخت عیب (FAULT TREE) استفاده گردیده بدین ترتیب ضمن برآورد قابلیت اطمینان و دسترسی سیستم می‌توان نحوهٔ از کار افتادن (FAILURE) اجزاء مختلف سیستم را نیز بدست آورد . بدین‌منظور بعد از تشکیل (FAULT TREE) از سه کد کامپیوتری (Prep, Kitt – 1, Kitt2) استفاده گردیده و برای اجرای این برنامه‌ها اطلاعات شدت از کار افتادن (FAILURE) و مدت زمان لازم برای انجام تعمیرات هر المان از سیستم لازم است معلوم باشند چون تجربهٔ مستقیم از بهره‌برداری این سیستم‌ها وجود ندارند لذا از تجارب و اطلاعات موجود از بهره‌برداری نیروگاههای هستهای سیسیون (SUSION) و غیره استفاده گردیده تا این داده‌ها برای اجرای برنامهٔ کامپیوتری آماده گردد . خروجی این برنامه‌ها برای ما شدت از کار افتادن در هر زمان و غیرقابل دسترسی برحسب زمان و تعداد از مواد خارج‌شدن‌های قابل انتظار در هر لحظه از زمان و قابلیت اطمینان بودن سیستم را برحسب زمان فراهم می‌نماید . در این درون قابلیت دسترسی واحدهای گداخت هستهای حدود ۸۲ تا ۸۲/۹% محاسبه گردیده بشرطی که دو دفعه از مدار خارج شدن در سال به منظور جایگزینی دیوارهٔ اول رآکتور که در هر کدام حدود ۱۵ روز زمان درنظر گرفته شده است . این اعداد بطور خوشبینانه بنظر می‌رسد ولی با انتخاب مواد صحیح دیوارهٔ اول رآکتور و نیز با بکارگیری وبهبود روشهای تعمیراتی کنترل از راه دور این نتیجه واقع‌بینانه بنظر می‌رسد .

INTRODUCTION

The fact that the first generation of fusion plants is expected to have a large capacity, hence, reliability and availability are two of the important requirements for commercialization of fusion concepts which are being studied in this paper. Frequent changes of the irradiated wall of the plasma reaction chamber is expected to have major impact on plant availability. Also, failure of the magnetic field may interrupt the operation unless redundant and diversified system are used. Ohter factors which may cause forced outage are similar to other power plants. The duration of scheduled plant shutdown depends on ease of maintenance and system accessibility. In this regard, maintenance of the plant structure, vacuum system, and magnetic systems is of major importance (2), (3). Dividing the reactor into modules or segments is likely to shorten the duration of such maintenance activities. Nevertheless, this depends on the ability to fabricate a sagmented plant. Based on the operation experience with nuclear power plants, fusion plants are expected to have a limited availability of 71% unless specific plans are made to reduce scheduled outage duration (4), (5).

In order to analyze the reliability and availability of fusion system plants, the fault tree analysis technique may be used. For example, the technique is applied here to the direct cycle gas turbine fusion system shown in Figure 1. The fault tree itself is a graphical representation of Boolean logic associated with the development of a particular system failure, called the TOP event, to basic failures, called primary events (6), (7). The fault tree is shown in Figure 2. The top event is the outage of the fusion system due to loss of power generation with the primary events being failures of the individual components or some other causes which are related to the system. Tow assumption are used in evaluating the fault tree, namely the primary failures (or components) of the tree are independent; and the mode failures of the tree are known. To evaluate the fault tree analysis, the probabilistic information for each primary failure of the fault tree, each mode of failure, and top failure are needed (8).

Primary Failure Information

Consider and define a single primary failure,

$\lambda(t)dt$ = The probability of the failure occurring in time t to t + dt given that the failure does not exist at time t (1)

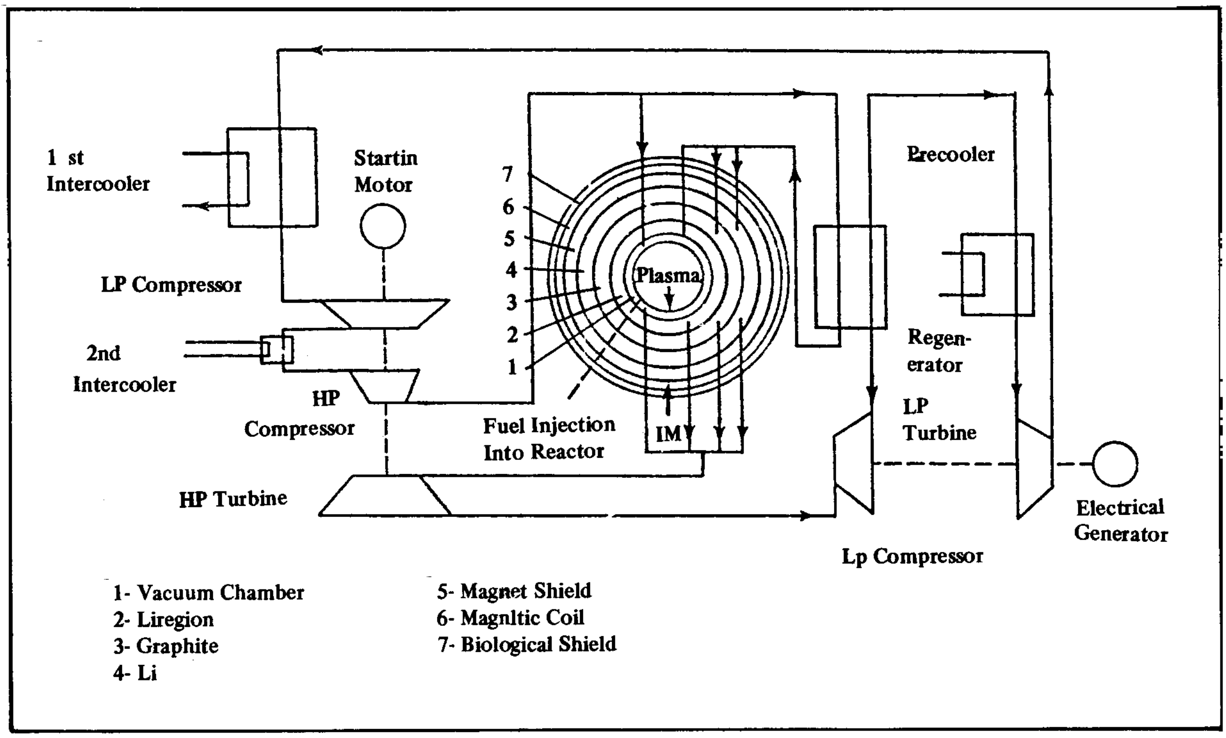

Figure 1. Direct cycle gas turbine with a rusion system

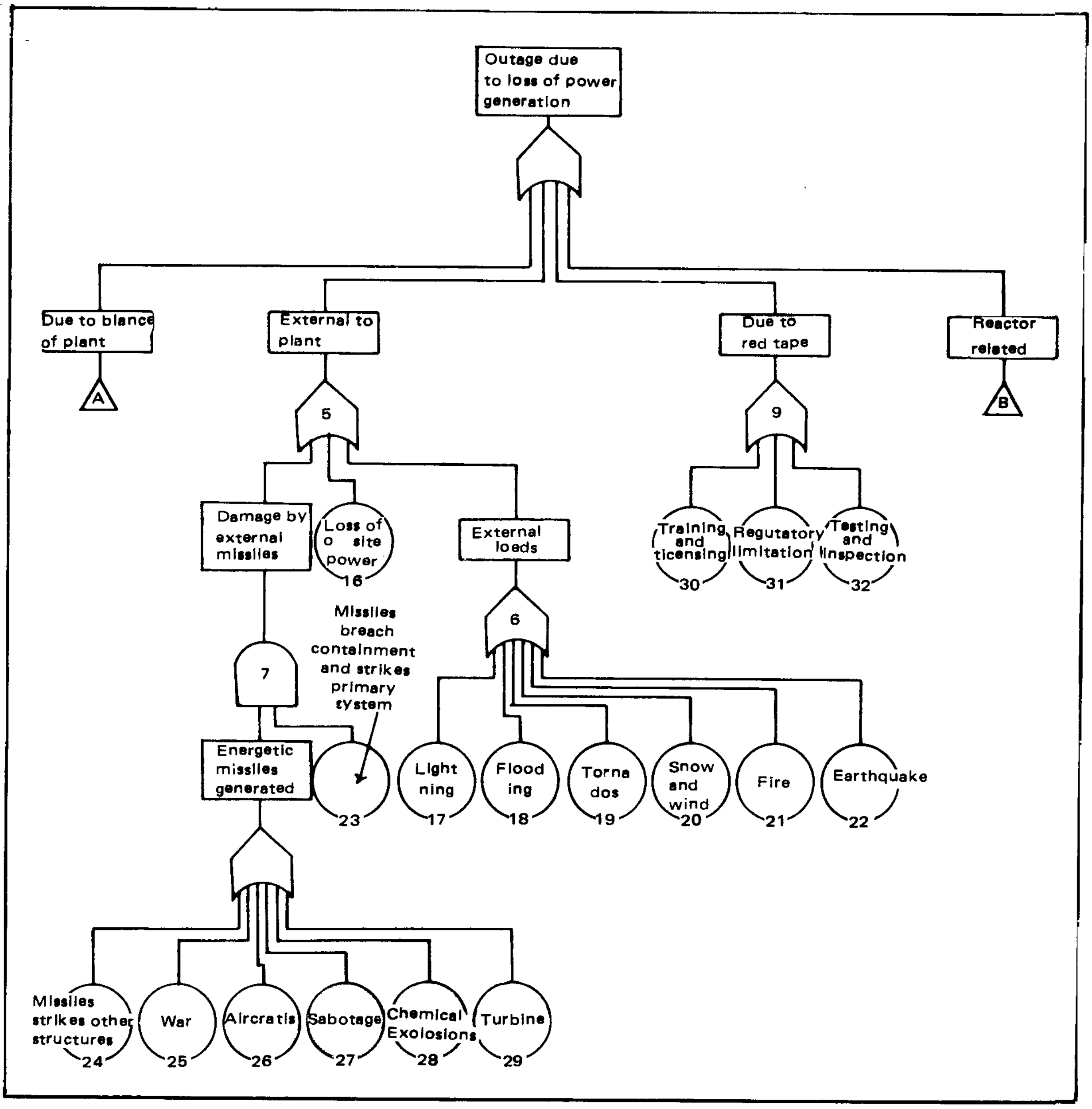

Figure 2. Fault tree analysis for the reliability of fusion system

$\mu(t)dt$ = The probability of the failure being repaired in time t to t + dt, given that the failure is exists at time t. (2)

The quantities $\lambda(t)$ and $\mu(t)$ are basic data in terms of fault tree analysis, and from these other probabilities are quantities may be obtained for the particular primary failure, that is

$f(t, t)$ = The non-occurrence or non-failure probability

or

$$f(t, t) = \exp\left(-\int_{t'}^{t} \lambda(t'')\, dt''\right); \; t' \leq t, \qquad (3)$$

$a(t, t)\,dt$ = The probability of the primary failure first occurring in time t to t + dt given that it does not exist at time t',

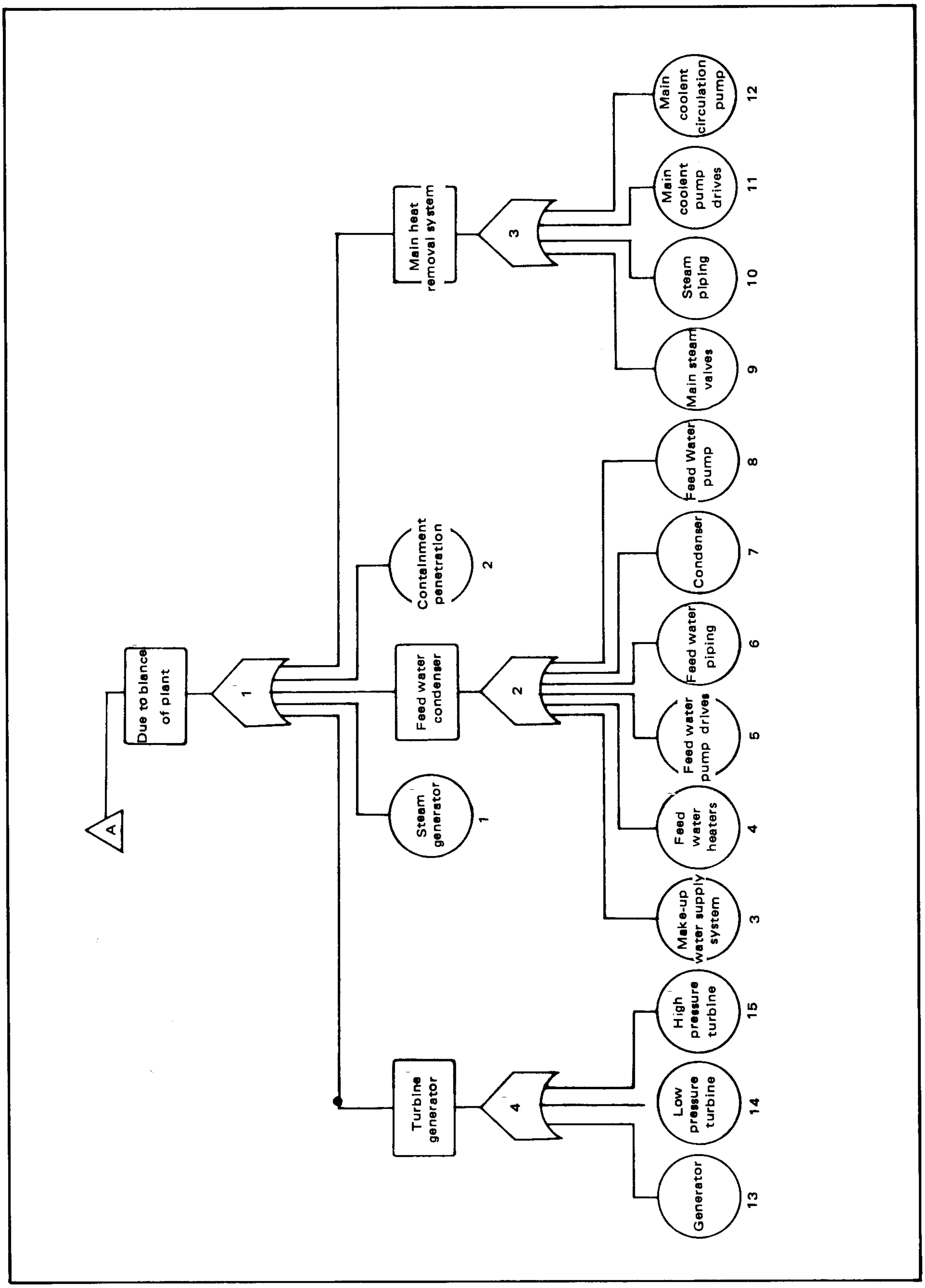

Figure 2. (Continued)

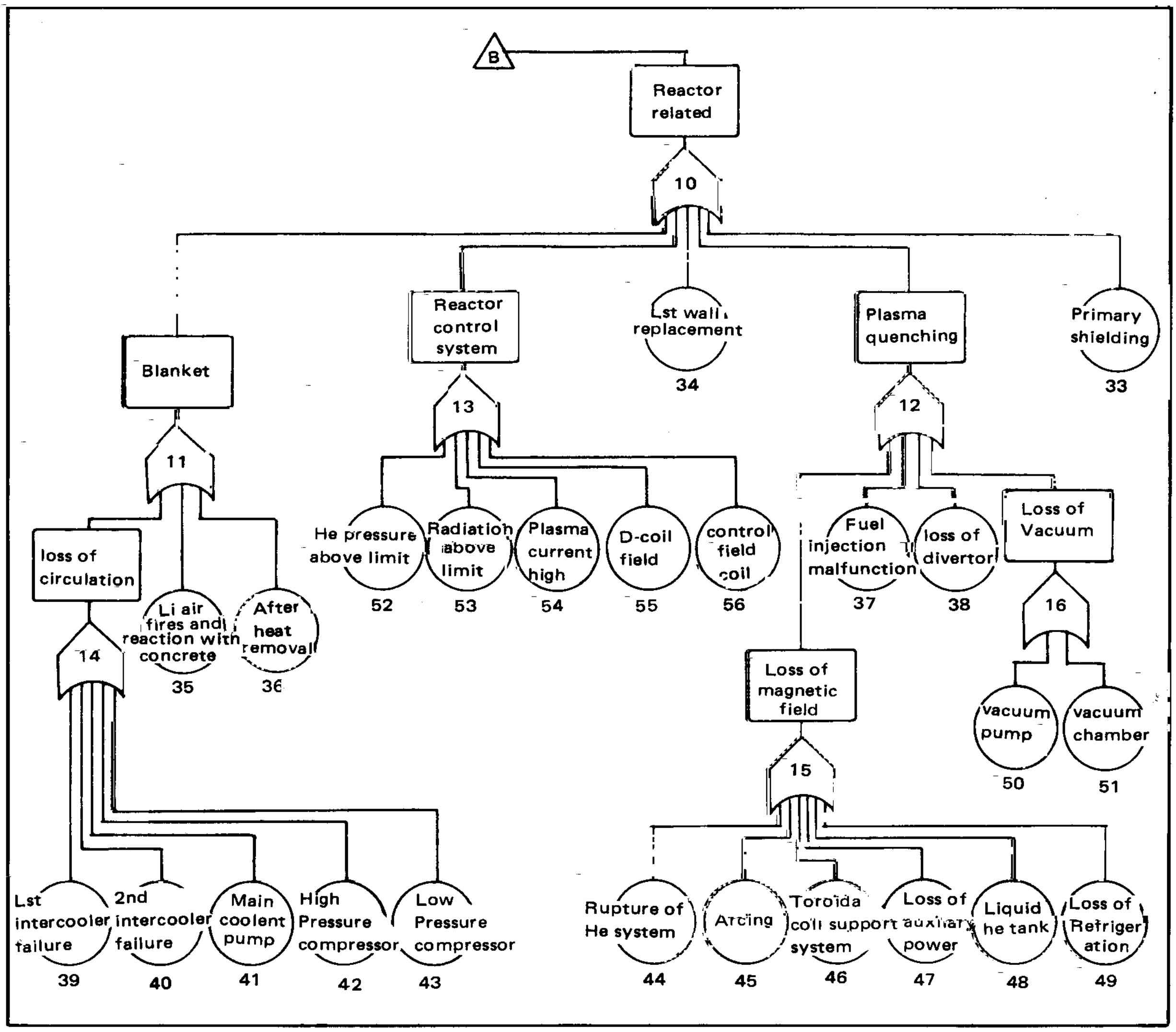

Figure 2. (Continued)

or

$$a(t', t)\,dt = f(t', t)\,\lambda(t)\,dt. \qquad (4)$$

and

$b(t', t)$ = The probability that the primary failure is repaired at time t to t+dt, given that it exists at time t',

or

$$b(t', t)\,dt = f(t', t)\,\mu(t)\,dt. \qquad (5)$$

There are also two other primary failure characteristics which are essential for any reliability study (8). The first characteristic is the primary failure intensity, w(t), which is defined as

$w(t)$ = The expected number of times that the primary failure occurs at time t per unit time

or

$$a(0, t) + \int_0^t dt''\, w(t'') \int_{t''}^t dt'\, b(t'', t')\, d(t', t) \qquad (6)$$

The second primary failure characteristic of interest is the primary failure existance probability, q(t);

$q(t)$ = The probability of the primary failure existing at time t

or

$$q(t) = 1 - \frac{w(t)}{\lambda(t)} \qquad (7)$$

From the primary failure's basic data, w(t) and q(t) can be simply obtained for each primary failure (8).

Mode Failure Information

Since mode failure is a "compounded" type of failure, the same probability characteristics which were obtained for a primary failure can be obtained for the mode failure. Consider a particular mode failure. Let is consist of n-primary failures and let these constituent primary failures be designated with indices from 1 through n. Assume the primary failure is independent and that at t=0 it does not exist (1). Thus

Q(t) = The probability that the mode failure exists at time t

If all primary failures exist at time t, then

$$Q(t) = \prod_{j=1}^{n} q_j(t). \tag{8}$$

The mode failure $\Lambda(t)$ is defined in the same way as for a primary failure;

$\Lambda(t)dt$=The probability of the mode failure occurring in time t to t + dt given that the mode failure does not exist at time t

$$\Lambda(t) = \frac{\sum_{j=1}^{n} w_j(t) \prod_{\substack{p=1 \\ \ell \neq j}}^{n} q(t)}{1 - Q(t)} \tag{9}$$

The mode failure may be experssed in terms of the mode failure intensity W(t). That is

W(t) = The expected number of times that the mode failure occurs at time t per unit time

or

$$W(t) = [1 \quad Q(t)]\, \Lambda(t) \tag{10}$$

and in terms of the constituent primary failure information,

$$W(t) = \sum_{j=1}^{n} w_j(t) \prod_{\substack{\ell=1 \\ \ell \neq j}}^{n} q_\ell(t). \tag{11}$$

The quantities Q(t), $\Lambda(t)$, and W(t), which characterize the mode failure are thus all simply determinable from the characteristics W(t) and q(t) of the primary failure which comprise the mode failure.

Top Failure Information

The top failure in this study is the plant outage probability $Q_0(t)$; thus

$Q_0(t)$ =The probability that outage exists at time t.

The availability of the plant is the complement of this quantity, that is,

$$A(t) = 1 - Q_0(t).$$

The exact value for $Q_0(t)$ can be determined as follows

$$Q_0(t) = \sum_{i=1}^{N} Q_i(t) - \sum_{i=2}^{N} \sum_{j=1}^{i-1} + \prod^{+i,\,j} q \quad t) +$$

$$. + (-1)^{N-1} + \prod^{+1 \ldots N} q(t)$$

where the values of Q_i and q(t), as mentioned before, are the i^{th} mode failure probability and the probability of primary failure existing at time t, respectively.

The outage intensity, $W_0(t)$, is the expected number of times that the outage occurs at time t per unit time, thus

$$W_0(t) = W_0^{(1)}(t) - W_0^{(2)}(t)$$

where

$$W_0^{(1)}(t) = \sum_{i=1}^{N} W_i(t) - \sum_{i=2}^{N} \sum_{j=1}^{i-1} W(t; i, j) \prod^{+i, j} q(t) + \sum_{i=3}^{N} \sum_{j=2}^{i-1} \sum_{k=1}^{j-1} W(t; i, j, k) \prod^{+i, j, k} q(t) \ldots , \qquad (15)$$

$$W_0^{(2)}(t) = \sum_{i=1}^{N} W_B(t, i) \sum_{i=2}^{N} \sum_{j-1}^{i-1} W_B(t; i, j) + \qquad (16)$$

$$W_B(t; t_1, \ldots, i_n) = \sum_{i'=1}^{N} W(t; i_1, \ldots, i_n - i') \prod_{i_1, \ldots i_n}^{i} \sum_{i'=2}^{i} \sum_{j'-1}^{i'-1} W(t; i \ldots i - i', j') \prod_{i, \ldots i}^{i', j'} q(t) + \qquad (17)$$

and

$W(t; 1, \ldots, m)$ = The outage intensity for a mode failure which has as its primary failures the primary failures which are common member to all the mode failures 1, ... , m.

If the outage rate $\Lambda_0(t)$ is known, the outage probability $Q_0(t)$ can be written as

$$W_0(t) = [\, 1 - Q_0(t)] \, \Lambda_0(t) \qquad (18)$$

Computer Program Description and Results

In order to carry out the fault tree analysis, three computer program have been considered, (PREP, KITT–1, and KITT–2). The codes are written in FORTRAN IV for the IBM 360/75 computer. The analysis requires identification

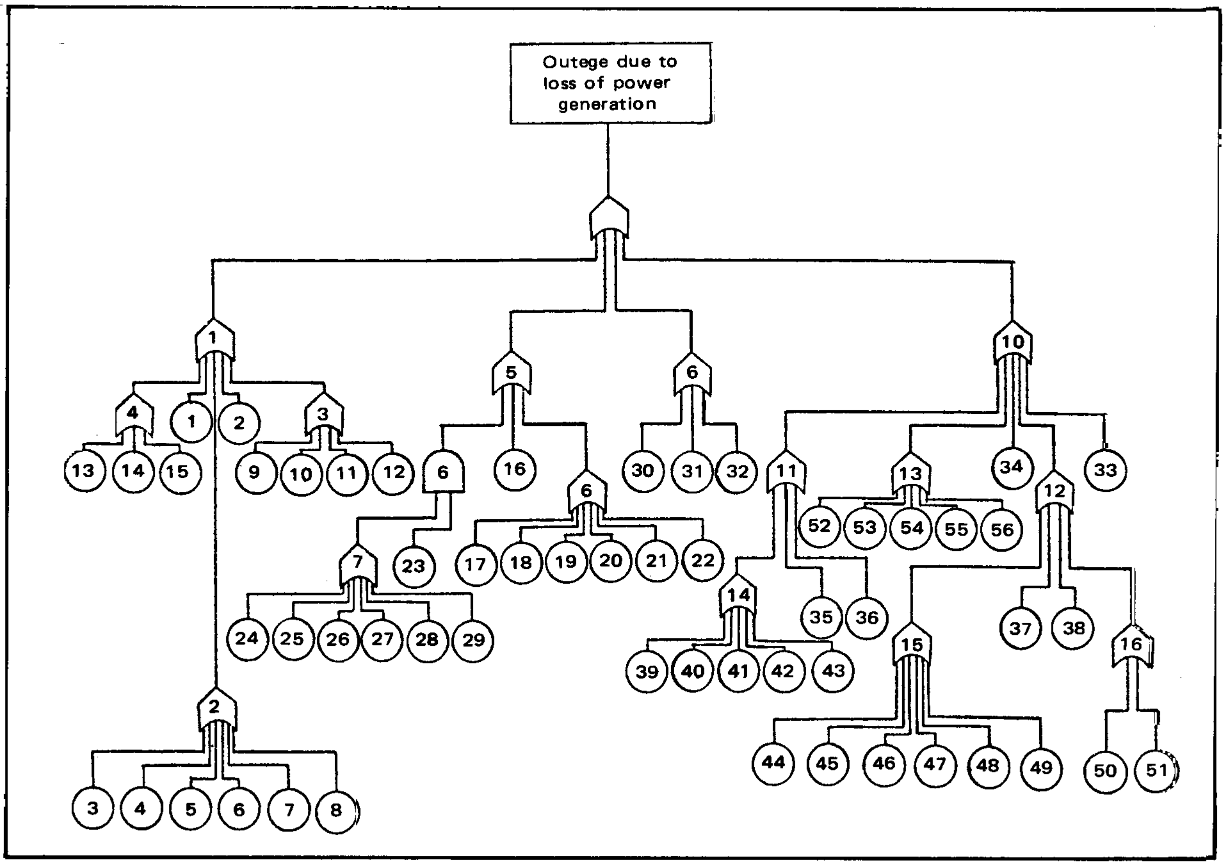

Figure 3. *Reduced fault tree for Figure 2.*

of the mode failures, or critical paths of the fault tree in order to obtain the top failure information. The code PREP obtains the mode failures either by Monte Carlo simulation or by deterministic testing. Having obtained the mode failures, KITT−1 or KITT−2 is then used to obtain the characteristics for the individual primary failures, mode failures, and top failure (1), (6).

Figure 3 shows the reduced fault tree for Figure 2, to make the calculation tractable, and it makes input data ready for the PREP code. The input data necessary to run the PREP codes are the component failure intensities (lambda, λ) and repair time τ, which is based on extrapolation of data from information and data of the operating experience of fission system. These values are listed in table 1.

The KITT−1 is a single phase computer code. It requires only one λ and τ for each component as an input with unique minimal cut sets of the fault tree or the unique minimal path sets of the fault tree. The KITT−1 code is run to obtain the probability characteristics of the components; such as the failure intensity at time, t(λ); unavailability, q(t); the expected number of outages occurring to time t (WSUM); reliability, R(t); and the outage rate at time t(W(t)).

After obtaining the minimal cut sets from the PREP code, the KITT−1 code is run to obtain the probability characteristics associated with the outage of fusion unit.

If n is assumed to be outages occurred in a total time, T(WSUM = n in program), then the total "down" time, or outage time, T_0 associated with a total time, T, is

$$T_0 = n\tau_r \tag{19}$$

where τ_r is a fixed time duration which represents the repair time or its equivalent. For this study, τ_r is assumed to be 15 days for any probable outage. The total time which the plant will be available or the "up" time, T_a, is

$$T_a = T - n\tau_r \tag{20}$$

The second term on the right hand side is the unavailability, P; that is

Table 1. Estimated values of the failure intensity and repair time for the components in Figure 3

Component	Failure intensity (λ)	Repair time τ (hours)
1	1.872×10^{-6}	72.0
2	1.141×10^{-10}	120.0
3	1.142×10^{-6}	50.0
4	1.895×10^{-6}	10.2
5	2.283×10^{-6}	45.0
6	1.142×10^{-6}	50.0
7	6.85×10^{-6}	72.0
8	3.65×10^{-6}	60.0
9	1.2557×10^{-6}	40.0
10	1.141×10^{-7}	50.0
11	2.28×10^{-6}	40.0
12	3.767×10^{-6}	60.0
13	1.2×10^{-6}	19.0
14	1.508×10^{-6}	70.0
15	1.6×10^{-6}	75.0
16	2.0×10^{-5}	15.0
17	1.141×10^{-9}	30.0
18	1.141×10^{-10}	35.0
19	1.141×10^{-10}	55.0
20	1.141×10^{-9}	30.0
21	1.141×10^{-7}	70.0
22	2.8×10^{-11}	24.0
23	1.0×10^{-7}	160.0
24	1.14×10^{-11}	100.0
25	1.14×10^{-8}	120.0
26	1.14×10^{-9}	100.0
27	1.14×10^{-8}	72.0
28	4.2×10^{-11}	100.0
29	1.14×10^{-9}	72.0

Table 1. (Continued)

Component	Failure intensity (λ)	Repair time c (hours)
30	1.0×10^{-4}	75.0
31	1.0×10^{-4}	200.0
32	1.2×10^{-4}	200.0
33	1.14×10^{-9}	70.0
34	2.283×10^{-4}	720.0
35	1.14×10^{-7}	120.0
36	1.14×10^{-7}	100.0
37	1.14×10^{-6}	20.0
38	1.14×10^{-8}	60.0
39	6.0×10^{-7}	72.0
40	6.0×10^{-7}	72.0
41	1.0×10^{-7}	62.0
42	1.0×10^{-6}	65.0
43	2.28×10^{-6}	65.0
44	1.141×10^{-6}	72.0
45	1.141×10^{-8}	72.0
46	1.141×10^{-9}	120.0
47	2.28×10^{-9}	10.0
48	1.141×10^{-8}	60.0
49	1.141×10^{-7}	15.0
50	1.141×10^{-6}	70.0
51	1.141×10^{-7}	60.0
52	1.142×10^{-8}	15.0
53	1.142×10^{-8}	20.0
54	1.142×10^{-8}	20.0
55	1.142×10^{-8}	70.0
56	1.142×10^{-8}	75.0

Then the mean availability will be

$$\hat{A} = \frac{T - n\tau_r}{T} \quad (21)$$

and the limiting case of the availability is

$$A = \lim_{T\to\infty} \frac{T - n\tau_r}{T} \quad (22)$$

or

$$A = 1 - \lim_{T\to\infty} \frac{n\tau_r}{T} \quad (23)$$

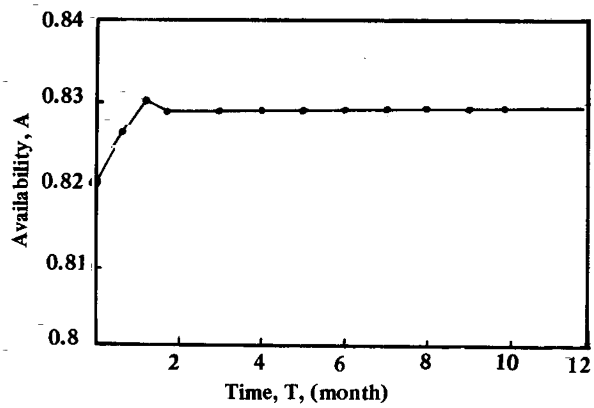

Figure 4. Availability of fusion plant during one year of operation.

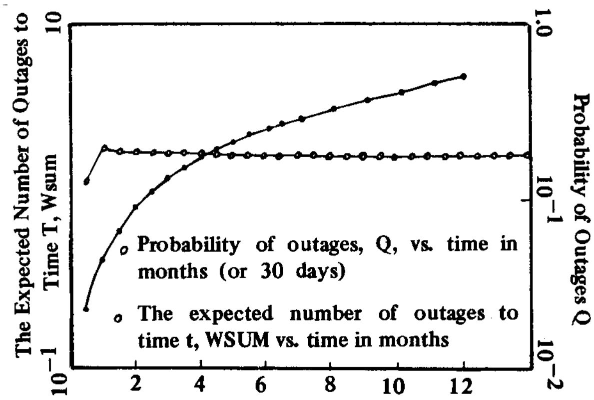

Figure 5. Reliability Intormation.

$$\hat{P} = \frac{n\tau_r}{} \quad (24)$$

or

$$P = \lim_{T\to\infty} \frac{n\tau_r}{T}$$

When an outage occurs only by chance, the number of outages will be

$$n = \lambda T_a$$

where λ is the expected number of outages the system will suffer per unit time.

Applying these relations to the computer, output yields Figure 4 which shows the availability of a fusion plant during one year's operation. Also, Figure 5 shows the expected number of outage to time t and the probability of outages during one year operation. From this analysis, the availability of a fusion unit can be expected to be about 82.0% to 82.9% which appears reasonable by assuming that there would be 2 outages for the first wall replacement per year, for 15-day periods each time. This assumption might be too optimistic, but, by choosing the right material for the first wall and decreasing at the time for improving remote maintenance, this assumption could be realistic.

CONCLUSIONS

In this paper the availability of a typical fusion plant is calculated based on fault tree system analysis. The probability of plant outage is estimated based on the effects of component failures. The results showed that, for a given plant, an availability as high as 82.9% is possible.

Since fusion plant sizes may exceed present plant sizes, integration of fusion plants in the electric grid poses several problems inlcuding the impact of outages on the network. The large size service areas can use fusion plants without any difficulty. However, it is unlikely that fusion systems will be viable options for small utility companies which generate their own electricity without pooling with neigh-boring utilities. Fusion power plants are expected to take operational precedence in a production system over thermal and fission plants but it would give way to hydro plants due to low operational cost. Also, with the development of high voltage dc transmission lines, power transfer capabilities will be sufficient to handle large fusion plant output. Since a generation reserve of 15% to 20% of the total operating capacity is usually required to cover periods of plant outage, the introduction of fusion plants would require relatively larger reserves than those currently required in the presence of smaller size plants (10), (11). Nevertheless, reserve requirements can be shared by members of power pools. In this case, institutional problems may arise since flexibility in plant ownerships may not continue to be possible.

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