A Preliminary Fusion Availability Data Base

Z. Musicki and C.W. Maynard

February 1984

UWFDM-532

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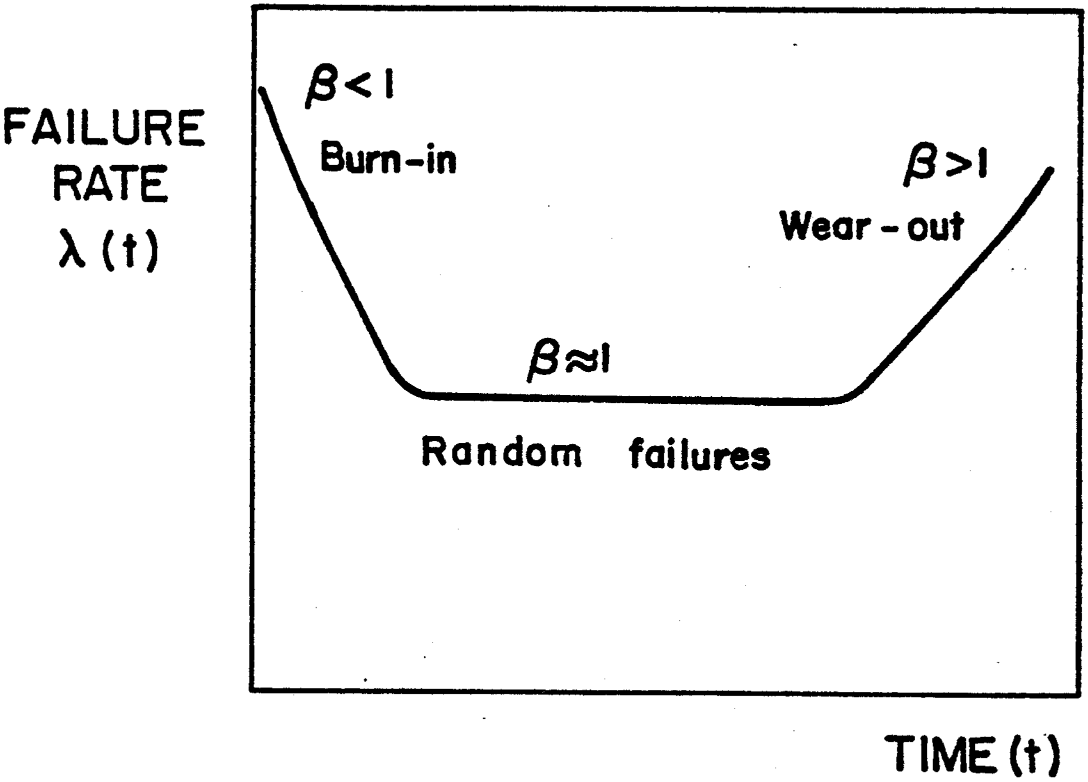
1. Introduction

We will describe the data needed in a fusion power plant availability analysis, and the methods employed to collect such data and estimate the errors in data and in the final system availability. Failure rates and repair times are the most basic information needed to estimate any system availability.

Since we are looking at the system availability, we will concentrate on the subsystem-level failure data.

Acquisition of good failure data is often the most difficult task in the availability analysis. Reliability and availability analysis is a relatively recent engineering discipline and only recently has increasing attention been paid to it. For many components and subsystems, data have simply not been compiled. Other equipment employed in fusion power plants is still in a development stage, thus no operating experience has accumulated on which to base a failure rate estimate. Determining a time dependent failure rate to fit a Weibull distribution (e.g., bathtub curve failure rate dependency, see Fig. 1), would be even more difficult, thus for the time being we are limiting our analysis to a constant failure rate.

Data for component and subsystem repair times are in better shape, since more is known (or can be learned) about the time spent in each maintenance operation, than about various failure mechanisms and their frequency. Timelines (i.e., step by step maintenance duration) have been developed for certain fusion reactor components in some recent fusion power plant designs (blanket and magnet overhauls have received the most attention).



Weibull distribution: $\lambda(t) = \lambda_c \beta t^{\beta-1}$, λ_c = constant, β = constant

Fig. 1. The bathtub curve.

2. Data Required for Availability Analysis

In order to more completely evaluate the availablity of a system, we have to know, in addition to the system configuration (e.g., number and type of units of each type, their interconnection, redundancy, operating conditions), the following information:

1) Failure modes and failure rates for each failure mode. Failure modes are types of failure for particular equipment (e.g., magnets can fail due to shorts, loss of superconductivity, power supply failure; valves can fail open, shut, etc.). The failure mode of equipment can represent a failure of one of its components. Also, ideally, some kind of uncertainty estimate associated with this data may be required. For failure rates following the Weibull distribution, time dependency should be specified.
2) Maintenance timeline for each failure mode and scheduled maintenance, with the maintenance equipment required at each stage.
3) Environmental and special operating conditions that may give rise to a different failure rate (e.g., high temperature and high radiation field may affect failure rates of magnetic coils).
4) Failure rates when the equipment is offline or idle.
5) Scheduled maintenance required and frequency.
6) Any tests required, duration and frequency.
7) Immediate or deferred repair (i.e., wait until a plant outage) upon failure.
8) Remote handling required for maintenance and repair (e.g., in high radiation field)?
9) Any data on burn-in and wearout; lifetime estimate.
10) Failure rates during transients, e.g., switch on and switch off.

Some of the data mentioned above may be very hard to obtain, so it will be either estimated or omitted. For instance, we may have only one "bulk" failure rate for a specific subsystem, without regard for failure modes or specific operating conditions. Hence, we can postulate an uncertainty to be associated with this particular failure rate that will include the unaccounted-for effects. This uncertainty can be estimated by looking at the changes that these effects entail in similar equipment (e.g., How much does elevated temperature increase some component's failure rate?. A similar component may be described in IEEE-Std 500-1977,(1) for instance, which has the failure rate multiplicative factors for changed environments.).

3. Failure Modes of Subsystems in a Magnetic Confinement Power Plant

The various failure modes of subsystems employed in a typical fusion power plant (specifically tandem mirrors), are presented in the report UWFDM-461,(2) among others, and will also be presented below in the section on the MARS data.

4. Operating Conditions of Fusion Power Plant Subsystems

Most data that we currently have do not specify the operating and environmental conditions under which they are applicable. Sometimes it is best to specify these conditions on the component level, because the component would be directly affected by changed conditions, or such data exist on the component level. Following is a list of parameters that may be important in estimating a subsystem failure rate:

Subsystem	Parameter(s)
Neutral beams	particle current, energy, radiation field
ECRH	power/gyrotron, frequency, radiation
ICRH	power, frequency, radiation

Magnets	current, temperatures, radiation field
Direct convertor	temperature, dpa rate
Steam generator, BOP	temperature, pressure, steam quality
Vacuum system	vacuum load
Cryogenic system	capacity, temperature
Control and instrumentation	varies with specific application
Blanket & first wall	temperature, radiation, dpa rate, type
Tritium system	capacity
Fueling system	capacity, pellet velocity
Shield	unknown
Power supply thyristor	current, voltage
Power supply transformer	current, voltage, type of coolant

5. Confidence Limits and Data Uncertainty

The data we are dealing with in this study are not known precisely, because they are estimates and because they are modified by insufficiently known factors, such as the environmental and operating conditions. Redundancy provisions can "desensitize" the system to a particular subsystem's data variations.

We can account for this data uncertainty in several ways:

1) Upper and lower bound. Estimate the worst and the best case failure rate (and/or repair times) for a particular subsystem. Run the system availability analysis for both cases and see how sensitive the final answer is to these variations. The bounds estimate may be revised if the system availability assumes an unacceptable value, but it must then be treated as a design requirement rather than an uncertainty.

The upper and lower bounds can be obtained from raw data as shown in IEEE Std 500-1977. Given that the accumulated data come from a single population with a failure rate λ, Epstein(3) has shown that twice the accumulated test hours times the failure rate follows the χ^2 distribution. The lower and upper confidence bounds are then given by:

$$\lambda_L = \frac{\chi^2_{\alpha/2;2n}}{2T^*} \; ; \qquad \lambda_u = \frac{\chi^2_{1-\alpha/2;2n+2}}{2T^*}$$

where: n = number of failures observed

α = 1 - confidence level desired.

The recommended value of λ is $\hat{\lambda} = n/T^*$, T^* = number of accumulated test hours.

The 5% and 95% confidence bounds can represent the upper and lower bounds in our case. The χ^2 values can be found in standard tables.(4)

The disadvantage of this process is that only a small probability would usually be associated with the extremes of a distribution, and hence would not be significant. For instance, a failure rate distribution may be depicted by Fig. 2. One can also take a failure rate midpoint between the two extremes, and thus arrive at a "best estimate."

2) From the range estimates in (1), one can arrive at a distribution of failure rates that may be used in assessing its effect on the system availability. For instance, a reasonable assumption would be that the data have a normal distribution (see discussion below). A normal distribution is specified by the mean value, m, and the standard deviation, σ. These parameters can be estimated as follows, assuming that the lower and upper bounds represent the 5% and 95% cumulative probability (confidence).

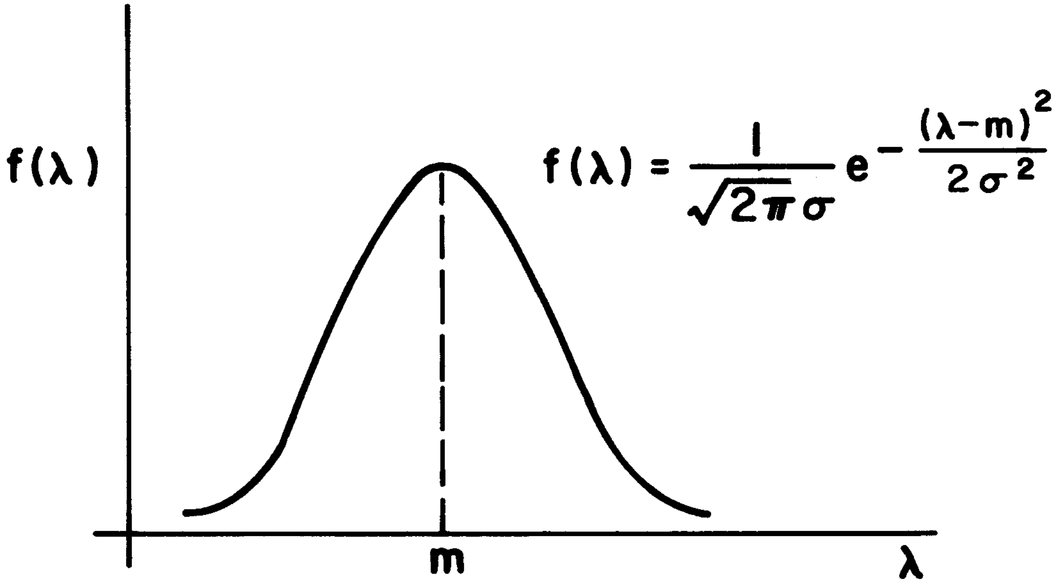


Fig. 2. A possible probability distribution of failure rates λ (normal distribution).

The normal distribution is given by:

$$f(\lambda) = \frac{1}{\sqrt{2\pi}\ \sigma}\ e^{-(\lambda-m)^2/2\sigma^2} .$$

Thus

$$\int_{-\infty}^{\lambda_u} \frac{1}{\sqrt{2\pi}\ \sigma}\ e^{-(\lambda-m)^2/2\sigma^2}\ d\lambda = 0.95 \quad \text{and} \quad \int_{-\infty}^{\lambda_L} \frac{1}{\sqrt{2\pi}\ \sigma}\ e^{-(\lambda-m)^2/2\sigma^2}\ d\lambda = 0.05 .$$

Changing variables to:

$$t = \frac{\lambda - m}{\sigma} , \qquad d\lambda = \sigma\ dt ,$$

the 95% confidence is represented on the new scale thus (distribution centered at 0. now):

$$\frac{1}{\sqrt{2\pi}} \int_{o}^{t_u} e^{-t^2/2}\ dt = 0.45$$

(since we are taking only the right half of the distribution); and

$$\frac{1}{\sqrt{2\pi}} \int_{t_L}^{o} e^{-t^2/2}\ dt = 0.45 .$$

From tables of the normal distribution:(5)

$$t_u = 1.64 , \qquad t_L = -1.64 .$$

Then $\frac{\lambda_u - m}{\sigma} = 1.64$ and $\frac{\lambda_L - m}{\sigma} = -1.64$.

This implies $$m = \frac{\lambda_u + \lambda_L}{2}$$

(the mean and median value). The standard deviation is given by:

$$\sigma = \frac{\lambda_u - \lambda_L}{2*1.64} .$$

3) We can ask our data sources to provide us with a confidence level that they have in the estimate offered. If the data is normally distributed, then a confidence level C (0 < C < 1.) would imply that fraction C of the data lies, say, within 10% on either side of this estimate, m, as depicted in Fig. 3. Hence:

$$\int_{0.9m}^{1.1m} f(\lambda)\, d\lambda = C \; ; \qquad t = \frac{\lambda - m}{\sigma} .$$

This implies $$\int_{-0.1m/\sigma}^{0.1m/\sigma} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt = C .$$

Hence $$\int_{0}^{0.1m/\sigma} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt = \frac{C}{2} .$$

Find σ from standard tables. For example, if C = 0.4, then

$$\frac{0.1\ m}{\sigma} = 0.53$$

and $$\sigma = \frac{0.1\ m}{0.53} .$$

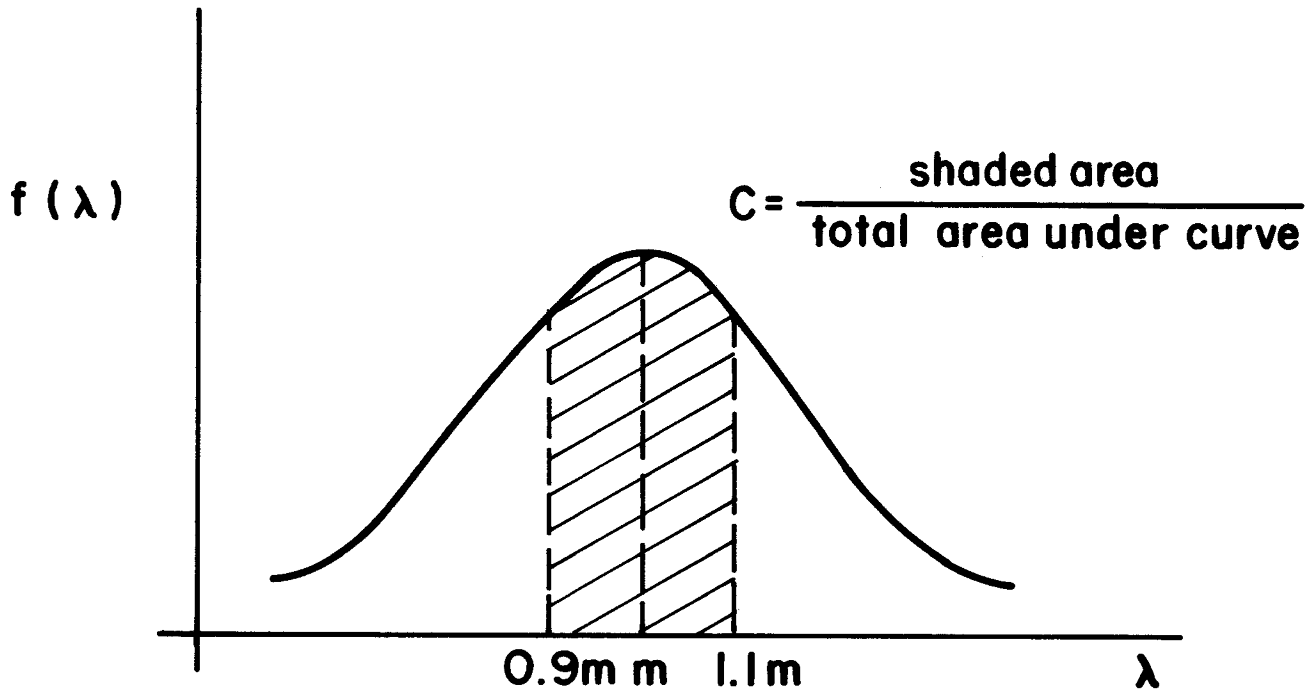


Fig. 3. An interpretation of confidence level C.

4) Once a data distribution is known or estimated, one can obtain the availability variation by sampling this distribution and running the availability program. For instance, a program called SAMPLE, described in Appendix II of WASH-1400,(6) can be employed for this purpose. SAMPLE is a Monte Carlo sampling program that, given the data distributions (normal, log-normal and log-uniform) and the functional relationship among the input data (e.g., a Boolean expression representing a logic gate), calculates the confidence levels of the output function. These confidence levels are the cumulative probabilities of the output function assuming values below the levels given by these confidences. Thus a spread of values is obtained which is indicative of the uncertainty in the calculated result (the spread between the 5% and the 95% confidence limits is usually used).

It is claimed in WASH-1400 that the log-normal distribution is appropriate for the data in reactor safety work, including both the failure rates and the repair times.(7) The log normal distribution is the normal distribution of the natural logarithm of data. In case of failure rates its use is justified by the fact that in reactor safety work, the uncertainty in data is high, with the extremes a factor of 10 away from the median value. For repair times, experience in nuclear power plants indicates that it usually takes a reasonably short time to repair certain equipment, but on a very few occasions the repair times are extremely long (for an example, see discussion of WASH-1400 data below). This is modeled by the positive skewness of the log-normal distribution and its long tail.

In this availability work, such wide error bands are unacceptable for critical components with no redundancy. For other components, however, the log-normal distribution may well be used.

The number of trials in the SAMPLE Monte Carlo code for adequate statistical error can be calculated as follows: the 5% to 95% range of the output function distribution consists of "successes" from a binomial distribution with a probability of success, $p = 0.9$, and the failure probability, $q = 1 - p = 0.1$. The standard deviation, σ, of this distribution is indicative of the absolute statistical error, the relative error being $\varepsilon = \sigma/(np)$, where n is the number of trials. From Ref. (5):

$$\sigma = \sqrt{npg}$$

and

$$\varepsilon = \frac{\sigma}{np} = \sqrt{\frac{g}{np}} .$$

For $\varepsilon = 1\%$, we will need $n = 1200$ trials.(6) In conjunction with a Monte Carlo availability model to calculate the output function, this is probably prohibitively many trials. However, for 2% relative error, only 300 trials are needed, and for 5% relative error, 48 trials are necessary.

6. Sources of Data

The failure data for fusion systems availability analysis are sometimes difficult to obtain for obvious reasons, and hence there is a need to rely on diverse sources of data:

1) Standards and data bases for conventional components and subsystems.
2) Reports and design studies of fusion plants.
3) Solicitation of opinion among experts in a particular subsystem.
4) Utilization of data for analogous equipment that may have similar failure data.

We will now describe some of these data sources.

6.1 Data Bases for Conventional Components and Subsystems

6.1.1 IEEE Std 500-1977(1)

This document is a guide to the collection and presentation of electrical, electronic and sensing component reliability data for nuclear power generating stations. Its purpose is to establish one method of collecting and presenting the data in the nuclear power industry in order to aid the reliability analysis of such plants, and in particular the safety equipment.

The report also presents the available failure rates for the appropriate nuclear power plant equipment. Some of the data can be used by us in the present application; the ideas and methodology presented herein are also very useful.

This work is intended to aid in reliability analysis and design of nuclear power plants. Hence, the numbers can be employed to evaluate the performance of an existing design, or to decide which strategies would be appropriate to improve this performance (alternate design, test intervals, maintenance and operating procedures).

The equipment described here is presented in terms of failure modes (catastrophic, degraded and incipient failures) and the types of failure impacting on the system status (e.g., "fails to run once started," "fails to start," "fails to run at rated speed," etc). For each of these categories, appropriate failure rates are given (if existing): the low and high, representing the best and the worst cases respectively, the recommended value and the maximum value that is the highest under all foreseen conditions (environmental, operator error, etc.). Sources of particular data are also indicated. See Table 1 for an example of a typical data matrix. For components where no data exists, appropriate failure modes and types are indicated.

Table 1. A Sample Table with Failure Data from IEEE Std 500-1977

Chapter: 9 - Instruments, Controls and Sensors **Section:** 9.1 Temperature **Subsection:** 9.1.3 Process Switches

Part Description (1)	Failure Mode (2)	Failure Rate (3)								Date of Last Revision (4)	Source (5)
		Failures/10^6 Hours				Failures/10^6 Cycles					
		Low	Rec	High	Max	Low	Rec	High	Max		
	ALL MODES	.3	1.34	1.959	28.49	.1	.75	1.5	2.0		Delphi and (15), (22)
	CATASTROPHIC	.105	.470	.687	9.989	.035	.263	.527	.702		
	Functioned without signal	.056	.252	.368	5.350	.019	.141	.282	.376		
	Failed to function when signalled	.049	.218	.319	4.639	.016	.122	.245	.326		
	DEGRADED	.195	.871	1.272	18.499	.065	.488	.975	1.30		
	Functioned at improper signal level	.150	.670	.979	14.230	.050	.375	.750	1.0		
	Intermittant Operation	.045	.201	.294	4.269	.015	.113	.225	.30		
	INCIPIENT	0	0	0	0	0	0	0	0		

At the beginning of each chapter describing a generic piece of equipment (e.g., transformers or motor-generators), there is given a failure mode matrix (see Table 2) and environmental factor matrix. The latter contains the factors by which to multiply the failure rates in case of extreme environmental conditions of the particular equipment in the chapter (Table 3). These conditions are usually high temperature, high radiation and high humidity. Of course, the degradation in performance will depend on the length of time that these conditions exist. A normal operating set of conditions is specified for some parts. Proper operating instructions and maintenance procedures are also noted.

The sources of data are: expert opinion (extensive use of the Delphi procedure) and reported occurrences in the literature (either of nuclear equipment or similar equipment in other industries).

For the purposes of the present study of availability of fusion power plants, specifically the recent tandem mirror concepts, we can use some of the data presented in IEEE Std 500-1977: the sections on compressors, steam-turbine driven generators, motors, transformers, cables and some of the instruments, controls and sensors. Some of the data may be too detailed for the present study, but may be of use in the near future. Environmental factors may be useful if we know how the conditions inside the fusion power plant differ from the normal operating conditions. Some of the data may be similar to that of another subsystem in a fusion power plant; e.g., the normal coil data might be similar to the dry, high voltage transformer data.

6.1.2 Nonelectronic Parts Reliability Data(8)

This report has been produced by the Reliability Analysis Center at the Rome Air Development Center. It gives the failure data for nonelectronic

Table 2. A Failure Mode Matrix from IEEE-Std 500-1977 (Only a Part of the Instruments, Controls and Sensors Matrix Shown Here)

Table D19
Ch 9 — Instruments, Controls, and Sensors
Failure Mode Matrix

Generic Listing	Catastrophic	Degraded	Incipient
9.1 9.1.1	Maximum output or zero output	Erratic output	Drift
9.1.2	No output (open circuit)	High output	
	No change of output with change of input	Low output	
9.1.3	Functioned without signal	Functioned at improper signal level	In-service problems
	Failed to function when signalled	Intermittant operation	
9.2	Zero or maximum output	Erratic output	Drift
9.2.1	No output	High output	
	No change of output with change of input	Low output	
9.2.2	Functioned without a signal	Functioned at improper signal level	In-service problems
	Failed to function when signalled	Intermittant operation	

Table 3. An Example of Environmental Matrix from IEEE Std 500-1977

Ch 9 — Instruments, Controls, and Sensors
Environmental Matrix

Generic Listing	Temperature	Radiation	Humidity	Vibration
9.1	1.75	1.25	1.5	2.0
9.1.1	1.0	1.0	2.0	2.0
9.1.2	2.0	1.5	1.5	—
9.1.3	1.5	1.0	1.5	2.0
9.2	1.75	1.0	1.38	1.5
9.2.1	2.0	1.25	1.25	—
9.2.2	1.5	1.0	1.5	1.5
9.3	1.67	1.15	1.32	2.0
9.3.1	1.5	1.2	1.2	—
9.3.2	2.0	1.25	1.25	—
9.3.3	1.5	1.0	1.5	2.0
9.4	1.53	1.03	1.13	1.2
9.4.1	2.0	1.1	1.1	1.2
9.4.2	1.1	1.0	1.1	—
9.4.3	1.5	1.0	1.2	—
9.5		no input		
9.6	1.5	1.0	1.2	1.2
9.6.1	1.5	1.0	1.2	1.2
9.6.2	1.5	1.0	1.2	—
9.7	1.2	1.0	1.2	—
9.8	5.0	1.2	1.5	1.5
9.9		no input		
9.11	1.5	1.0	1.35	5.0
9.11.3	1.5	1.0	1.35	5.0
9.12	5.0	1.0	4.0	—
9.13	1.0	1.0	1.5	—
9.14	1.5	1.0	1.0	—
9.15	2.0	1.0	1.5	wind lightning 5.0 10.0
9.16	1.2	1.0	1.2	—
9.17	2.0	1.0	2.0	—
9.18	2.0	1.2	1.5	—
9.19	3.5	1.0	1.25	—
9.20	1.25	1.0	1.75	—
9.21	3.5	1.0	1.25	—
9.23	1.6	1.0	1.6	—
9.24	2.0	1.2	1.5	—
9.25	3.5	1.0	1.5	—

parts commonly used in aircraft and other military applications. The format is such that each part's failure rates are documented for different environments (such as fighter based, ship based, ground based, etc.) and for either commercial or military applications. The failure rates are given as the mean value, the 60% upper single-sided confidence, the lower and upper bounds of the 60% confidence interval as well as the number of failures experienced and the total number of operating hours (see Table 4 for an example).

The document also contains a short discussion of failure modes and mechanisms for operational and dormant equipment described therein.

There is also data for parts commonly used in commercial equipment applications.

Some of the data presented here can be used in our present studies of fusion power plants: pumps, certain instruments, compressors.

6.1.3 Nuclear Plant Reliability Data System 1980; Annual Reports of Cumulative System and Component Reliability(9)

This document describes nuclear power plant experience in terms of system and component reliability. It is divided into two parts. The first part deals with system reliability data (e.g., air conditioning system, reactor trip system, etc.); generic system data are presented first, followed by specific vendor system data (i.e., W, GE, B&W, CE). The second part is devoted to component reliability data (e.g. generator, inverter, electric heater, etc.).

As an example of the failure data in the first part of report, see Table 5. System title and type are given, with the number of systems included in reports, operating hours, service hours, number of tests and number of failures, giving number of failures per million calendar hours. For the compo-

Table 4. Sample Table from Nonelectronic Parts Reliability Data

PART CLASS: VALVE

TYPE: HYDRAULIC

ENVIRONMENT	APPLICATION		FAILURE RATE/10^6 HOURS				NUMBER OF RECORDS	NUMBER FAILED	OPERATING HOURS ($\times 10^6$)
	MIL.	COML.	$\hat{\lambda}$	60% UPPER SINGLE-SIDED CONFIDENCE	60% CONFIDENCE INTERVAL				
					LOWER	UPPER			
DOR	X		0.005	---	0.001	0.015	7	1	208.651
GRF	X		---	9.253	---	---	1	0	0.099
GRM	X		7.302	---	6.320	8.452	2	40	5.478
AU	X		52.144	---	50.163	54.301	13	760	14.575
AUT		X	11.937	---	11.292	12.625	25	245	20.524
AUF	X		17.309	---	14.163	21.198	4	22	1.271

PART CLASS: VALVE

TYPE: NEEDLE

ENVIRONMENT	APPLICATION		FAILURE RATE/10^6 HOURS				NUMBER OF RECORDS	NUMBER FAILED	OPERATING HOURS ($\times 10^6$)
	MIL.	COML.	$\hat{\lambda}$	60% UPPER SINGLE-SIDED CONFIDENCE	60% CONFIDENCE INTERVAL				
					LOWER	UPPER			
GRF	X		1.362	---	0.842	2.164	2	5	3.671
GRF		X	---	1.176	---	---	1	0	0.779

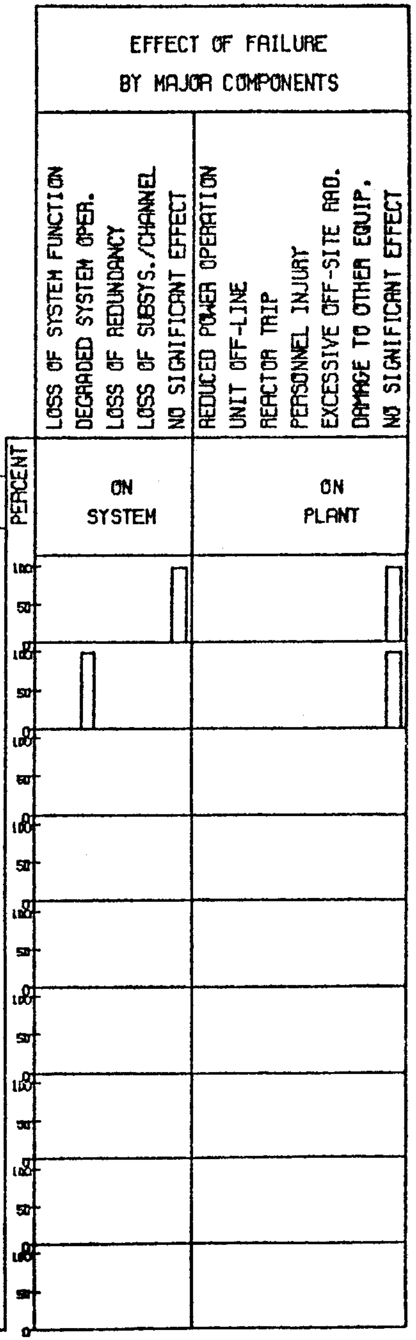
Table 5. Sample Subsystem Failure Data from Nuclear Plant Reliability Data System 1980

NPRD REPORT A02
PERIOD 7/74 - 12/80

ANNUAL REPORT OF CUMMULATIVE SYSTEM RELIABILITY
NUCLEAR PLANT RELIABILITY DATA SYSTEM
AAA AIR COND., HEATING, COOLING & VENT. SYS. &CONT

	SYSTEM							COMPONENT		
SYSTEM TITLE	TYPE OF UNIT	SYSTEMS	OPERATING HOURS (X1000)	CALENDAR HOURS (X1000)	TESTS	FAIL	FAILURES PER MIL. CALENDAR HOURS	REST. HOURS (AVG)	OUT-OF SERV. HOURS (AVG)	FAIL
REAC.BLDG. HEAT/VENT/AC	GE	5	89.4	212.7	3781	0	.00	122	122	3
TOTAL		5	89.4	212.7	3781	0				3

MAJOR COMPONENT TYPES AFFECTING AAA SYSTEMS CATEGORIES/FUNCTIONS	OP/CALENDAR HOURS (MILLION)	FAIL	COMPONENT FAILURES PER MILLION CALENDAR HOURS 0 5 10 15 20	OUT-OF-SERVICE HOURS ☐ (*=AVG.) RESTORATION HOURS ▨ (0=AVG.) 0 100 200 300 400
VALVE OPERATORS PNEUMATIC/DIAPHRAGM/CYLINDER	.3301 .3309	2	6.04	4 * 4 0
FILTERS/STRAINERS GAS	.2015 .2065	1	4.84	358 * 358 0



nents within each system, the tables show the average restoration hours, average out-of-service hours and number of failures. System failures are identified as such that "cause loss of system function." The second part of a typical table in this category shows major component types affecting a particular system, number of operating/calendar hours, number of failures, component failures per million calendar hours, range of out of service hours and restoration hours. The effects of failure of major components on the system and on the plant are also presented in terms of a bar chart. These can add up to a value different than 100% due to deficiencies in the reporting procedure.

The second part of this report (see Table 6 for an example) shows component accumulated failure data: failure modes, number of units, number of failures for each mode, operating and calendar hours. For the number of failures per million hours, several values are given: minimum, 25%, median, 75% and maximum. Also shown are the average number of restoration hours, and the lowest, average and highest out of service hours. At the beginning of each generic section (e.g., Instrumentation and Control) are presented summarized data of interest (see Table 7, for example): number of components in category, calendar hours, number of failures, out of service hours (highest, average, lowest); population size and number of failures for specified period for each type/category, application/function; number of failures for status at time of failure and failure detection method.

In this report, the useful data are the failure rates for assorted conventional components such as pumps, turbines, generators, specific control and instrumentation components (this last item has exhaustive data and can be particularly useful to us).

Table 6. Cumulative Component Failure Data from NPRDS Report

NPRD REPORT A03 (PART 2)
REPORT PERIOD: 7/74 -- 12/80

ANNUAL REPORT OF CUMULATIVE COMPONENT RELIABILITY
NUCLEAR PLANT RELIABILITY DATA SYSTEM

INSTRUMENTATION AND CONTROLS

THIS REPORT CONTAINS STATISTICS ON ALL COMPONENTS IN THE NPRDS ACCUMULATED BETWEEN 07/01/74 AND 12/31/80

COMPONENT CLASSIFICATION						COMPONENTS IN CATEGORY		OP/CALENDAR HOURS(MILLIONS)	TOTAL FAILURES	NUMBER OF SYSTEMS	NUMBER OF UNITS
			FAILURES PER MILLION CALENDAR HOURS					AVERAGE	OUT-OF-SERVICE HOURS		
FAILURE MODES	NO. FAILURES	NO. UNITS	* MINIMUM	25 TH PERCENTILE	MEDIAN	75 TH PERCENTILE	** MAXIMUM	RESTORATION HOURS	HIGHEST	AVERAGE	LOWEST
SENSOR/DETECTOR/ELEMENT THERMOCOUPLE						1145		43.101 ------ 50.212	35	98	26
LEAK	9	2	.00	.00	.00	.00	.84	376	1654	376	216
PHYSICAL DISPLACEMENT	1	1	.00	.00	.00	.00	.44	8	8	8	8
FRACTURE/BREAK	2	1	.00	.00	.00	.00	1.30	439	439	439	439
WON'T CLOSE	1	1	.00	.00	.00	.00	.11	23	23	23	23
OUT OF LIMITS	13	4	.00	.00	.00	.00	17.56	64	477	64	1
FALSE RESPONSE	9	2	.00	.00	.00	.00	.86	87	296	87	28
TOTAL	35	7	.00	.00	.00	.86	17.56	169	1654	169	1
SENSOR/DETECTOR/ELEMENT THERMISTOR						32		1.295 ------ 1.555	0	10	10
SENSOR/DETECTOR/ELEMENT POTENTIOMETIC						7		.133 ------ .387	2	4	4
WON'T START/MOVE	1	1	.00	.00	.00	.00	4.39	3	3	3	3
FALSE RESPONSE	1	1	.00	.00	.00	.00	15.21	8	8	8	8
TOTAL	2	2	.00	.00	.00	2.19	15.21	6	8	6	3
SENSOR/DETECTOR/ELEMENT HYGROSCOPIC						4		.228 ------ .228	0	1	1

* LOWEST CALCULATED FAILURE RATE FROM AN INDIVIDUAL UNIT
** HIGHEST CALCULATED FAILURE RATE FROM AN INDIVIDUAL UNIT

PLEASE REFER TO PAGE XXX FOR DESCRIPTION OF CALCULATION METHOD

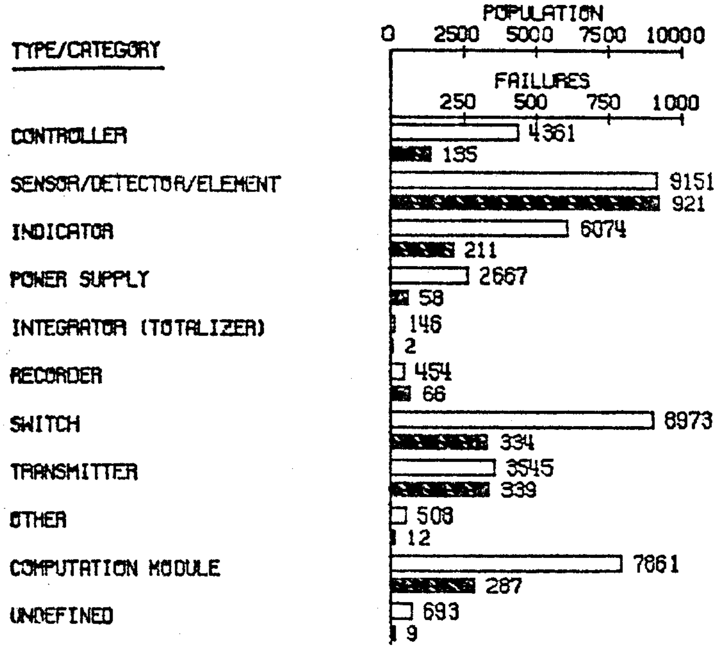
Table 7. Sample Generic Component Failure Data

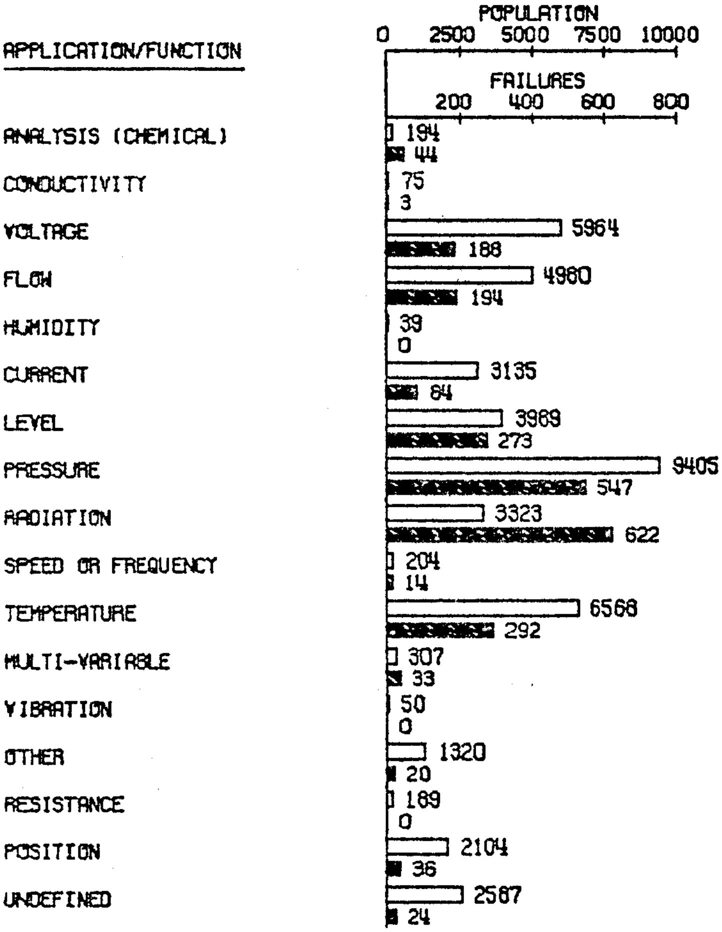
NPRD REPORT A03 (PART 1) ANNUAL REPORT OF CUMULATIVE COMPONENT RELIABILITY

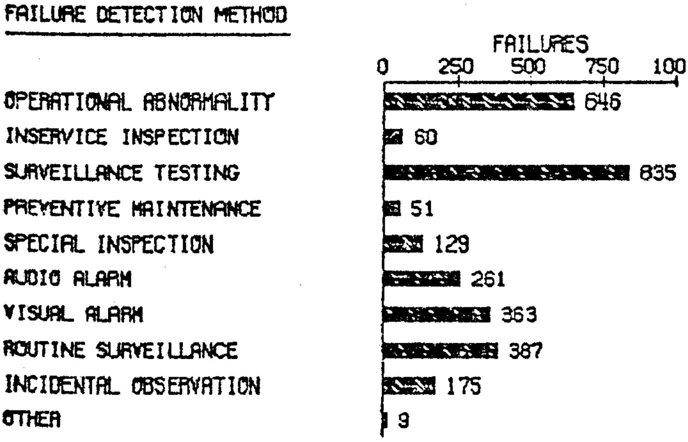
PERIOD: 7/74 - 12/80 NUCLEAR PLANT RELIABILITY DATA SYSTEM

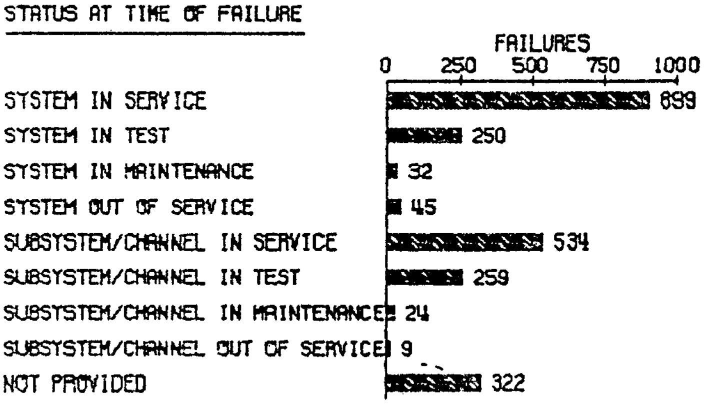
THIS REPORT CONTAINS STATISTICS ON ALL COMPONENTS IN THE NPRDS ACCUMULATED BETWEEN 7/1/74 THRU 12/31/80

COMPONENT CLASSIFICATION ALL FAILURE MODES	COMP IN CATEGORY	CALENDAR HOURS(MIL)	NUMBER OF FAILURES	OUT-OF-SERVICE HOURS HIGHEST	AVERAGE	LOWEST
INSTRUMENTATION AND CONTROLS	44433	1983.3754	2374	6645	352	0


TYPE/CATEGORY


APPLICATION/FUNCTION


FAILURE DETECTION METHOD


STATUS AT TIME OF FAILURE

FAILURES ▨ POPULATION ☐

6.1.4 Ten Year Review 1971-1980 Report on Equipment Availability, National Electric Reliability Council - Generating Availability Data System(10)

This report has outage statistics on generating units: by year, by power rating and by fuel (coal, oil, nuclear, etc.). Since these are plant statistics, and not detailed subsystem or component data, the report will be of little use as a source of failure data. However, it may be utilized in comparison studies between conventional and fusion power plants. It identifies major causes of forced outages, average times spent on scheduled and unscheduled maintenance and shows the availabilities attained in the past with a particular type of unit. A sample table from this compilation is shown in Tables 8 and 9.

6.1.5 Reactor Safety Study, Appendix III(7)

The Reactor Safety Study describes the reliability data for major safety related components of nuclear power plants. Some of the data for conventional components can be applicable for fusion design studies (e.g. pumps, steam generators, control and instrumentation). These data are not immediately useful, since the uncertainty is so large, but a median value can probably be used. Also included are the data on human operator error. For failure data see Table 10. Observed repair times and theoretical distributions for major components are also given (see Fig. 4). The theoretical distribution used was log normal, since a majority of repairs can be accomplished in a relatively short time, while a very few take a very long time (tail section of the log normal distribution). Common mode failures and methodology for estimating them are also presented. At this time, common mode failures will not be treated in fusion design studies.

Table 8. Nuclear Units Availability Data from the NERC's Ten Year Review, 1971-1980 (For Year 1976)

08/27/81

NATIONAL ELECTRIC RELIABILITY COUNCIL EQUIPMENT AVAILABILITY
COMPOSITE UNIT SUMMARY REPORT

ALL NUCLEAR UNITS FOR YEAR 1976

SELECTED NUCLEAR UNITS NO OF SYSTEMS 32 NO OF UNITS 53 NO OF UNIT YEARS 53

UNIT STATISTICS	CUMULATIVE
SERVICE HOURS	313469.58
SERVICE FACTOR-%	68.36
AVAILABLE HOURS	322162.52
CAPACITY FACTOR-%	58.98
OUTPUT FACTOR-%	88.13
EQUIV F.O.R.-%	19.66
SCHEDULED OUT RATE-%	22.56
FORCED OUT RATIO-%	41.27
F.O. INCIDENT RATE-%	70.00
EQUIV AVAILABILITY-%	65.62

CAUSE CODE	FORCED OUTAGE RATE CUMULATIVE-%	OPERATING AVAILABILITY CUMULATIVE-%	MEAN TIME BETWEEN FULL FORCED OUTAGES CUMULATIVE
REACTOR	6.8	77.2	1691.95
TURBINE	2.8	92.3	5038.68
COND.	0.3	97.0	13100.57
REGUL.	0.6	97.1	76420.00
GEN.	1.8	94.8	16982.22
OTHER	4.4	93.5	3758.36
UNIT	15.2	70.2	838.24

	FORCED OUTAGES								MAINTENANCE OUTAGE							
	UNIT YR AVG				CUMULATIVE				UNIT YR AVG				CUMULATIVE			
CAUSE CODE	NO OCC	OUTAGE HOURS	MAN HOURS	HRS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HOURS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HRS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HOURS WAIT
REACTOR	5	433.91	7571	0	270	22997.4	30285	21	1	304.49	5605	0	61	16137.9	22420	0
TURBINE	2	174.99	1237	0	90	9274.3	4949	13	1	150.97	15342	0	42	8001.5	61366	0
COND.	1	20.28	152	0	34	1074.8	606	0	0	52.93	327	0	11	2805.4	1306	0
REGUL.	0	41.11	0	0	5	2178.8	0	0	0	26.84	0	0	12	1422.6	0	0
GEN.	0	113.69	0	0	26	6025.4	0	0	0	90.04	20	0	10	4772.1	81	0
OTHER	2	277.90	1390	0	121	14728.4	5559	0	0	97.11	1066	0	20	5146.9	4262	0
UNIT	10	1061.87	10350	1	546	56279.2	41399	34	2	346.93	22359	0	123	18387.4	89435	0

	PLANNED OUTAGES								NONCURTAILING OUTAGES							
	UNIT YR AVG				CUMULATIVE				UNIT YR AVG				CUMULATIVE			
CAUSE CODE	NO OCC	OUTAGE HOURS	MAN HOURS	HRS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HOURS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HRS WAIT	NO OCC	OUTAGE HOURS	MAN HOURS	HOURS WAIT
REACTOR	1	1226.58	5240	1	67	65008.9	20960	78	2	88.08	0	0	90	4667.9	0	0
TURBINE	1	337.31	2307	0	29	17677.3	9226	0	0	173.75	0	0	18	9208.6	0	0
COND.	0	180.09	1202	0	9	9544.9	4809	0	0	157.63	0	0	25	8354.3	0	0
REGUL.	0	177.60	0	0	15	9412.9	0	0	0	2.51	0	0	2	132.9	0	0
GEN.	0	243.00	134	0	10	12879.0	535	0	0	6.34	0	0	1	336.0	0	0
OTHER	0	180.45	13262	0	10	9563.6	53047	0	1	45.04	0	0	29	2387.1	0	0
UNIT	2	1605.36	22144	1	111	85084.2	88577	78								

Table 9. Outage and Test Statistics for Nuclear Units from the NERC's Ten Year Review (For Year 1976)

```
                                  NATIONAL ELECTRIC RELIABILITY COUNCIL EQUIPMENT AVAILABILITY
08/27/81                                         COMPOSITE UNIT SUMMARY REPORT

ALL NUCLEAR UNITS FOR YEAR 1976

 SELECTED       NUCLEAR UNITS  NO OF SYSTEMS  32  NO OF UNITS    53  NO OF UNIT YEARS     53

                                                        PROBABILITY STATE - COMBINED UNIT
                    -----------------------------------------------------------------------------------------------------
                                   UNIT YR AVG                                             CUMULATIVE
                    ---------------------------------------------        ------------------------------------------------
                           FORCED                    SCHEDULED                     FORCED                      SCHEDULED
 PERCENTAGE         -------------------     -------------------        -------------------------    ---------------------
  AVAILABLE          NO   OUTAGE  PERCENT    NO   OUTAGE  PERCENT        NO  DUR  PER  PERCENT        NO  DUR  PER  PERCENT
 CATEGORIES         OCC   HOURS   OF YEAR   OCC   HOURS   OF YEAR       OCC   OUTAGE    PERIOD       OCC   OUTAGE    PERIOD
 ----------         ---  -------  -------   ---  -------  -------      -----  --------  -------     -----  --------  -------

 FULL OUTAGE         10  1061.87    12.27     4  1952.30    22.57        546    103.07    12.27       234    442.18    22.57

 00.1 - 19.9          1     3.63     0.04     0     7.68     0.08         27      7.12     0.04        17     23.95     0.08
 20.0 - 29.9          1    11.38     0.13     0     3.58     0.04         34     17.74     0.13        19      9.98     0.04
 30.0 - 39.9          1    36.59     0.42     1     6.00     0.06         53     36.59     0.42        33      9.64     0.06
 40.0 - 49.9          1    66.65     0.77     1    49.12     0.56         74     47.73     0.77        34     76.57     0.56
 50.0 - 59.9          1    61.47     0.71     1    19.08     0.22         79     41.23     0.71        41     24.65     0.22
 60.0 - 69.9          2   166.12     1.92     1    49.37     0.57        121     72.76     1.92        32     81.77     0.57
 70.0 - 79.9          4   289.39     3.34     2    59.77     0.69        201     76.30     3.34        87     36.41     0.69
 80.0 - 89.9          6   311.60     3.60     2    27.58     0.31        328     50.35     3.60        80     18.26     0.31
 90.0 - 99.9         13   609.49     7.04     6    50.79     0.58        675     47.85     7.04       323      8.33     0.58

 ECONOMY OUTAGE **     164.02 HOURS          1.89 % OF YEAR               8692.94 HOURS              1.89 % OF PERIOD
 FULL OPERATION       3643.83 HOURS         42.11 % OF YEAR             193123.17 HOURS             42.11 % OF PERIOD

                                                         UNIT STARTS NO. OF YEARS    20
                    -----------------------------------------------------------------------------------------------------
                                   UNIT YR AVG                                             CUMULATIVE
                    ---------------------------------------------        ------------------------------------------------
 ATTEMPTED                           15.80                                                    316
SUCCESSFUL                           13.55                                                    271

                                                       NUCLEAR SAFETY SYSTEMS TESTS
                   --------------------------------------------------------------------------------------------
                                 UNIT YR AVG                                         CUMULATIVE
                   --------------------------------------------  ----------------------------------------------
                      PARTIAL SUCCESS        UNSUCCESSFUL                PARTIAL SUCCESS       UNSUCCESSFUL
                   TEST ---------------  --------------------------  TEST  ---------------  ----------------------------
                   OCC   NO   MANHOURS   NO  MANHOURS  DURATION   OCC    NO  MANHOURS    NO  MANHOURS  DURATION
                   ---   ---  --------   ---  --------  --------   ----  ----  --------  ----  --------  --------
                    10    0          0    0         0      0.29    555     0         0     3        13      15.5

  ** ECONOMY OUTAGE HOURS DERIVED FROM AVAILABLE HOURS - SERVICE HOURS
    TOTAL ECONOMY OUTAGE OCCURANCES REPORTED      0
    TOTAL ECONOMY OUTAGE HOURS REPORTED          .00
```

Table 10. Hazard Rates, Failure Probabilities and Error Rates for Mechanical and Electrical Equipment and Human Operators from the Reactor Safety Study

Hazard Rates λ and Demand Failure Probabilities Q_d for Mechanical Hardware[a,b]

Components	Failure mode	Assessed range on probability of occurrence	Computational median	Error factor
1. Pumps (includes driver)	Failure to start on demand Q_d^c	$3 \times 10^{-4} - 3 \times 10^{-3}$/d	1×10^{-3}/d	3
	Failure to run, given start λ_o (normal environments)	$3 \times 10^{-6} - 3 \times 10^{-4}$/hr	3×10^{-5}/hr	10
	Failure to run, given start λ_o (extreme, post-accident environments inside containment)	$1 \times 10^{-4} - 1 \times 10^{-2}$/hr	1×10^{-3}/hr	10
	Failure to run, given start λ_o (post-accident, after environmental recovery)	$3 \times 10^{-5} - 3 \times 10^{-3}$/hr	3×10^{-4}/hr	10
2. Valves				
a. Motor operated:	Failure to operate (includes driver) Q_d^d	$3 \times 10^{-4} - 3 \times 10^{-3}$/d	1×10^{-3}/d	3
	Failure[e] to remain open (plug) Q_d	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3
	λ_o	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
b. Solenoid operated:	Failure to operate Q_d^f	$3 \times 10^{-4} - 3 \times 10^{-3}$/d	1×10^{-3}/d	3
	Failure to remain open, Q_d (plug)	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
c. Air-fluid operated:	Failure to operate Q_d^f	$1 \times 10^{-4} - 1 \times 10^{-3}$/d	3×10^{-4}/d	3
	Failure to remain open Q_d (plug)	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3
	λ_o	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
3. Check valves	Failure to open Q_d	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3
	Internal leak λ_o (severe)	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
4. Vacuum valve	Failure to operate Q_d	$1 \times 10^{-5} - 1 \times 10^{-4}$/d	3×10^{-5}/d	3
5. Manual valve	Failure to remain open Q_d (plug)	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
6. Relief valves	Failure to open Q_d	$3 \times 10^{-6} - 3 \times 10^{-5}$/d	1×10^{-5}/d	3
	Premature open λ_o	$3 \times 10^{-6} - 3 \times 10^{-5}$/hr	1×10^{-5}/hr	3
7. Test valves, flow meters, orifices,	Failure to remain open Q_d (plug)	$1 \times 10^{-4} - 1 \times 10^{-3}$/d	3×10^{-4}/d	3
	Rupture λ_o	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
8. *Pipes*				
a. Pipe ≤ 7.5 cm diam per section	Rupture/plug λ_o, λ_o	$3 \times 10^{-11} - 3 \times 10^{-8}$/hr	1×10^{-9}/hr	30
b. Pipe > 7.5 cm diam per section	Rupture λ_o, λ_o	$3 \times 10^{-12} - 3 \times 10^{-9}$/hr	1×10^{-10}/hr	30
9. Clutch, mechanical	Failure to operate Q_d	$1 \times 10^{-4} - 1 \times 10^{-3}$/d	3×10^{-4}/d	3
10. Scram rods (single)	Failure to insert	$3 \times 10^{-5} - 3 \times 10^{-4}$/d	1×10^{-4}/d	3

Table 10. Continued

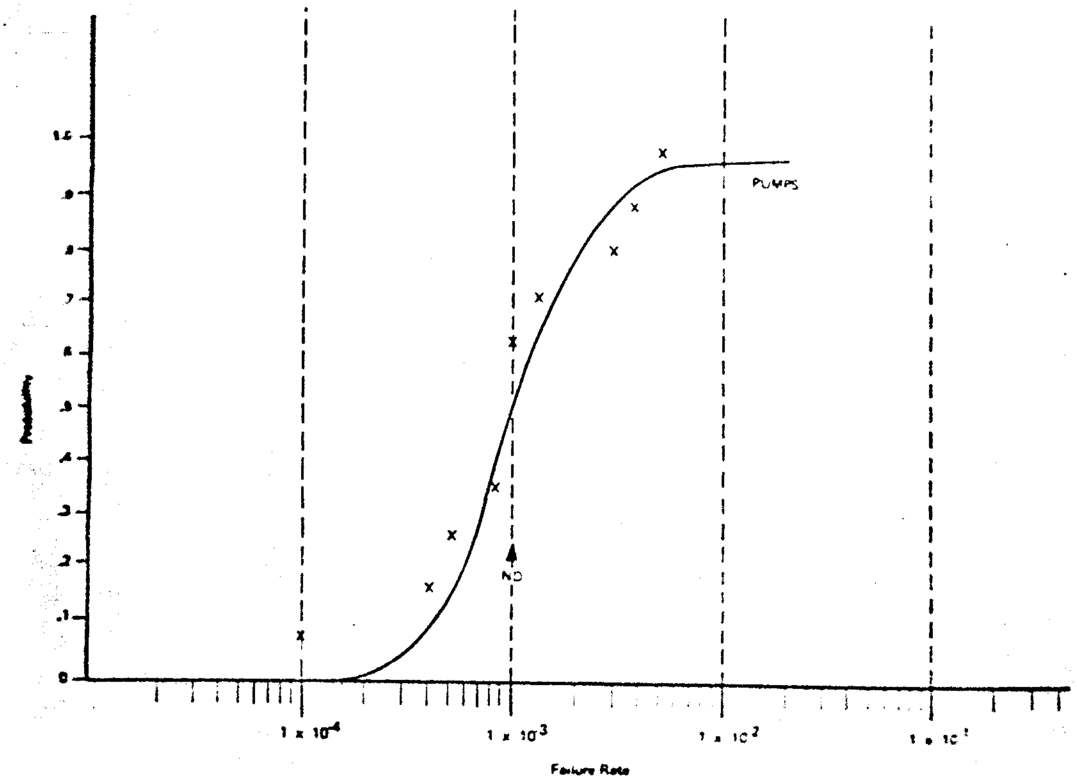
Hazard Rates λ and Demand Failure Probabilities Q_d for Electrical Equipment[a,b]

Component	Failure mode	Assessed range	Computational median	Error factor
1. Clutch, electrical	Failure to operate Q_d[c]	1×10^{-4}–1×10^{-3}/d	3×10^{-4}/d	3
	Premature disengagement λ_o	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
2. Motors, electric	Failure to start Q_d	1×10^{-4}–1×10^{-3}/d	3×10^{-4}/d	3
	Failure to run, given start λ_o (normal environment)	3×10^{-6}–3×10^{-5}/hr	1×10^{-5}/hr	3
	Failure to run, given start λ_o (extreme environment)	1×10^{-4}–1×10^{-2}/hr	1×10^{-3}/hr	10
3. Relays	Failure to energize Q_d	3×10^{-5}–3×10^{-4}/d	1×10^{-4}/d	3
	Failure of NO contacts to close, given energized λ_o	1×10^{-7}–1×10^{-6}/hr	3×10^{-7}/hr	3
	Failure of NC contacts by opening, given not energized λ_o	3×10^{-8}–3×10^{-7}/hr	1×10^{-7}/hr	3
	Short across NO/NC contact λ_o	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
	Coil open λ_o	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Coil short to power λ_o	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
4. Circuit breakers	Failure to transfer Q_d	3×10^{-4}–3×10^{-3}/d	1×10^{-3}/d	3
	Premature transfer λ_o	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
5. Switches				
a. Limit	Failure to operate Q_d	1×10^{-4}–1×10^{-3}/d	3×10^{-4}/d	3
b. Torque	Failure to operate Q_d	3×10^{-5}–3×10^{-4}/d	1×10^{-4}/d	3
c. Pressure	Failure to operate Q_d	3×10^{-5}–3×10^{-4}/d	1×10^{-4}/d	3
d. Manual	Failure to transfer Q_d	3×10^{-6}–3×10^{-5}/d	1×10^{-5}/d	3
6. Switch contacts	Failure of NO contacts to close given switch operation λ_o	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Failure of NC by opening, given no switch operation λ_o	3×10^{-9}–3×10^{-7}/hr	3×10^{-8}/hr	10
	Short across NO/NC contact λ_o	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
7. Battery power systems (wet cell)	Failure to provide proper output λ_o	1×10^{-6}–1×10^{-5}/hr	3×10^{-6}/hr	3
8. Transformers	Open circuit primary or secondary λ_o	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
	Short primary to secondary λ_o	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
9a. Solid state devices hi power applications (diodes, transistors, etc.)	Fails to function λ_o	3×10^{-7}–3×10^{-5}/hr	3×10^{-6}/hr	10
	Fails shorted λ_o	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
b. Solid state devices, low power applications	Fails to function λ_o	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
	Fails shorted	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
10a. Diesels (complete plant)	Failure to start Q_d	1×10^{-2}–1×10^{-1}/d	3×10^{-2}/d	3
	Failure to run, emergency conditions, given start λ_o	3×10^{-4}–3×10^{-2}/hr	3×10^{-3}/hr	10
b. Diesels (engine only)	Failure to run, emergency conditions, given start λ_o	3×10^{-5}–3×10^{-3}/hr	3×10^{-4}/hr	10
11. Instrumentation—general (includes transmitter, amplifier, and output device)	Failure to operate λ_o	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
	Shift in calibration λ_o	3×10^{-6}–3×10^{-4}/hr	3×10^{-5}/hr	10
12. Fuses	Failure to open Q_d	3×10^{-6}–3×10^{-5}/d	1×10^{-5}/d	3
	Premature open λ_o	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
13. Wires (typical circuits, several joints)	Open circuit λ_o	1×10^{-6}–1×10^{-5}/hr	3×10^{-6}/hr	3
	Short, to ground λ_o	3×10^{-8}–3×10^{-6}/hr	3×10^{-7}/hr	10
	Short to power λ_o	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
14. Terminal boards	Open connection λ_o	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Short to adjacent circuit λ_o	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10

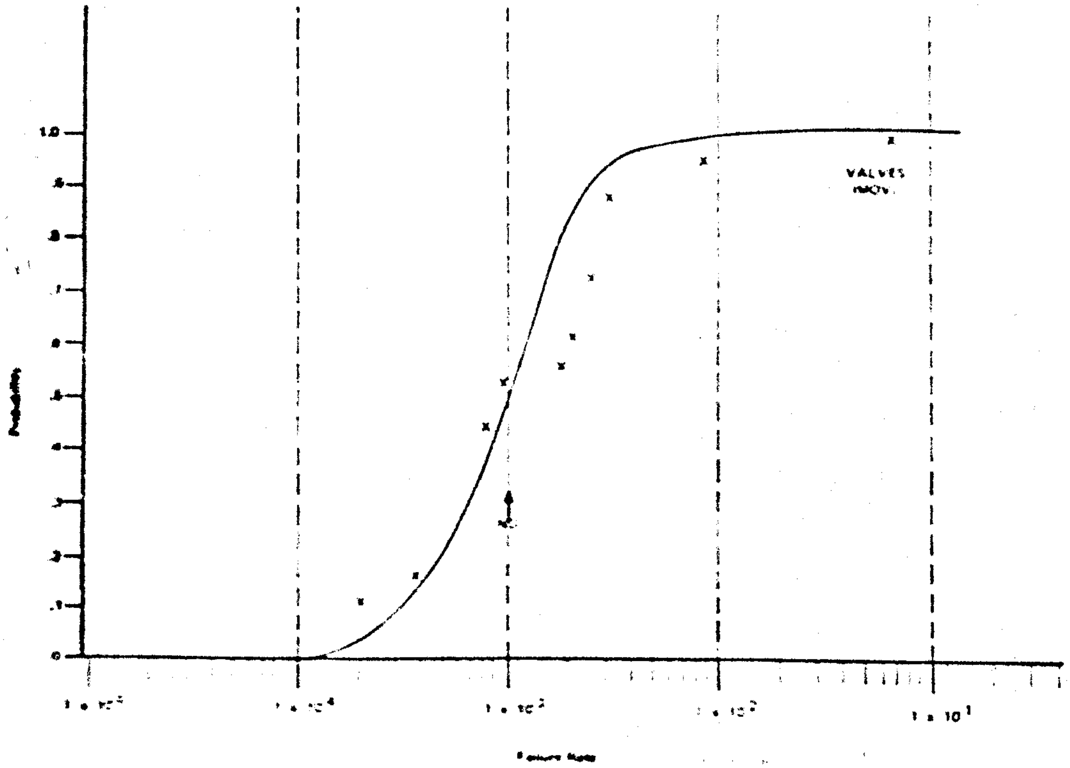
Table 10. Continued

Human Error Probabilities^{a,b}

Demand failure probability	Activity
10^{-4}	Selection of a key-operated switch rather than a nonkey switch. (This value does not include the error of decision where the operator misinterprets situation and believes key switch is correct choice.)
10^{-3}	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch.
3×10^{-3}	General human error of commission, e.g., misreading label and, therefore, selecting wrong switch.
10^{-2}	General human error of omission when there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance.
3×10^{-3}	Errors of omission where the items being omitted are embedded in a procedure rather than at the end as above.
3×10^{-2}	Simple arithmetic errors with self-checking but without repeating the calculation by redoing it on another piece of paper.
$1/x$	Given that an operator is reaching for an incorrect switch (or pair of switches), he or she selects a particular similar appearing switch (or pair of switches), where $x =$ the number of incorrect switches (or pairs of switches) adjacent to the desired switch (or pair of switches). The $1/x$ applies up to 5 or 6 items. After that point the error rate would be lower because the operator would take more time to search. With up to 5 or 6 items, the operator doesn't expect to be wrong and therefore is more likely to do less deliberate searching.
10^{-1}	Given that an operator is reaching for a wrong motor operated valve MOV switch (or pair of switches), he or she fails to note from the indicator lamps that the MOV(s) is (are) already in the desired state and merely changes the status of the MOV(s) without recognizing that he or she had selected the wrong switch(es).
~1.0	Same as above, except that the state(s) of the incorrect switch(es) is (are) *not* the desired state.
~1.0	If an operator fails to operate correctly one of two closely coupled valves or switches in a procedural step, he or she also fails to correctly operate the other valve.
10^{-1}	Monitor or inspector fails to recognize initial error by operator. Note: With continuing feedback of the error on the annunciator panel, this high error rate would not apply.
10^{-1}	Personnel on different work shift fail to check condition of hardware unless required by checklist or written directive.
5×10^{-1}	Monitor fails to detect undesired position of valves, etc., during general walk-around inspections, assuming no check list is used.
0.2–0.3	General error rate, given very high stress levels, where dangerous activities are occurring rapidly
$2^{(n-1)}x$	Given severe time stress, as in trying to compensate for an error made in an emergency situation, the initial error rate x, for an activity doubles for each attempt, n, after a previous incorrect attempt, until the limiting condition of an error rate of 1.0 is reached or until time runs out. This limiting condition corresponds to an individual's becoming completely disorganized or ineffective.
~1.0	Operator fails to act correctly in the first 60 seconds after the onset of an extremely high stress condition, e.g., a large LOCA.
9×10^{-1}	Operator fails to act correctly after the first 5 minutes after the onset of an extremely high stress condition.
10^{-1}	Operator fails to act correctly after the first 30 minutes in an extreme stress condition.
10^{-2}	Operator fails to act correctly after the first several hours in a high stress condition.
x	After 7 days after a large LOCA, there is a complete recovery to the normal error rate x, for any task.

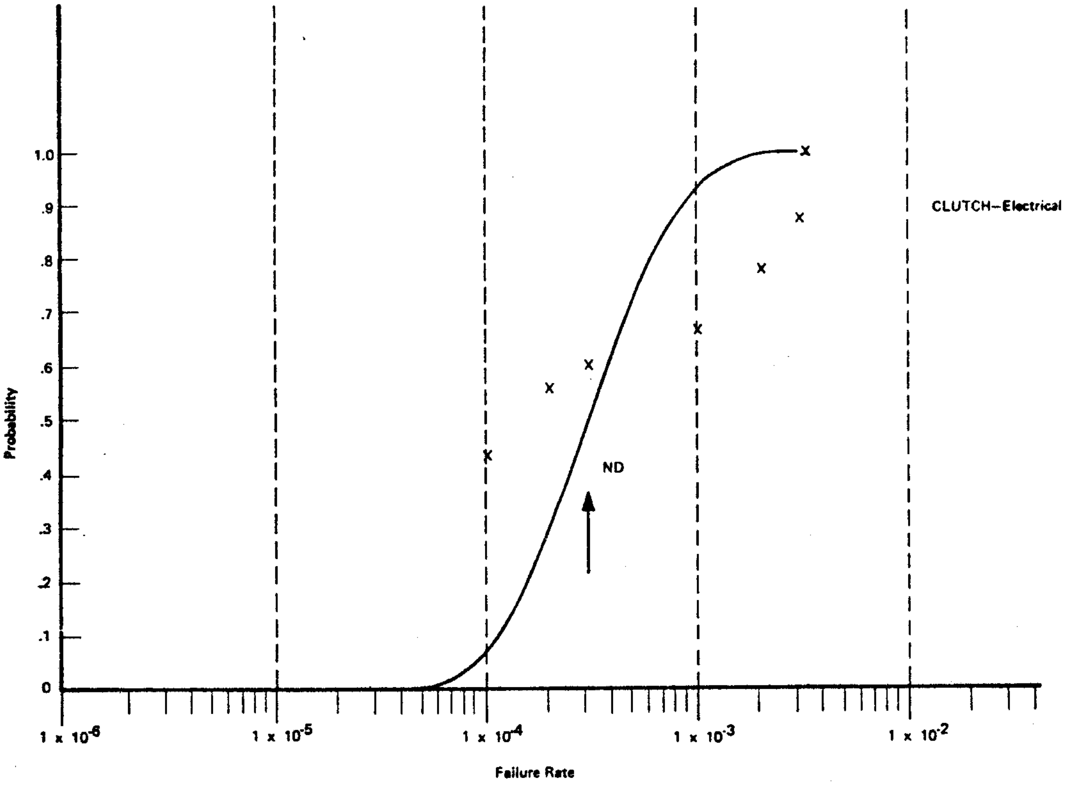


Log-Normal Distribution - Pumps



Log-Normal Distribution - Valves

Fig. 4. Repair time distributions, observed and predicted, from the Reactor Safety Study



Log-Normal Distribution - Clutch - Electrical

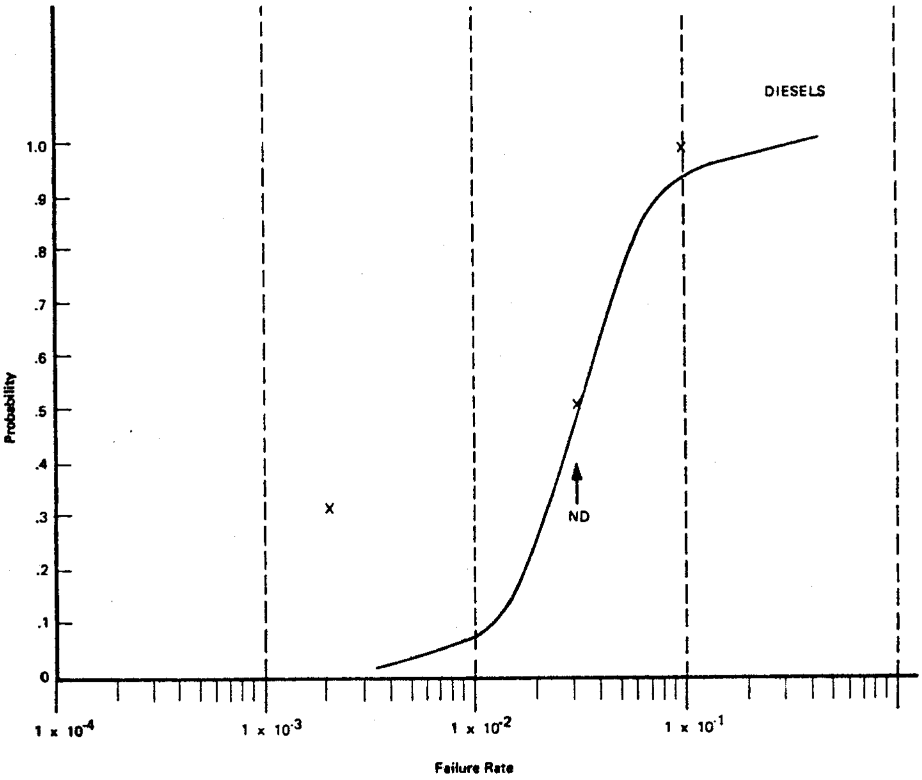


Fig. 4. Continued.

Log-Normal Distribution - Diesels

6.2 Fusion Reports and Design Studies

It has been realized recently that availability analysis will be an important part of fusion power plant design, so some thought has already been given to it and the data that may be required. Almost all design studies (WITAMIR-I,(11) STARFIRE,(12) EBT,(13) MARS,(14)) have a chapter on maintenance and the steps needed to accomplish it for major components. Some maintenance timelines have been developed (blanket in MARS and EBT, some magnets(15)) and failure rates and repair times have been estimated or apportioned (ETF report, STARFIRE, MARS).

Most design studies also pay much attention to the capital, operating and maintenance costs. Economics will have to eventually be coupled to the availability analysis, because availability has a price. Scaling laws and cost data are known much better than is the case for the failure rate data.

6.2.1 Preliminary Availability Assessment and Apportionment of the Engineering Test Facility(16)

The Engineering Test Facility was a test tokamak reactor designed for the DOE with a minimum availability of 50%. Thus, an effort has been made to include an availablity study in the design of this reactor. This ETF report consists of two parts: the assessed reliability data for individual components and the apportioned data that would have to be satisfied in order to achieve the minimum availability. Each data section consists of the data for hydrogen operation and for tritium operation. The table consists of the system description (i.e., number of units required and installed, redundancy, type of repair; mean time to failure, failure rate, mean time to repair, repair rate, offline factor (multiplying failure rate for offline configuration) and unit availability (see Table 11). A summary of reliability data is given in Table 12.

6.2.2 Isabelle Refrigeration System Availability Report(17)

This report estimates the failure data for specific components of the Isabelle accelerator cryogenic system. See Table 13 for data.

6.2.3 Double Wall Steam Generator Data(18)

This study has been done to generate the double wall steam generator fault tree, to estimate the failure event rates and repair times and calculate the steam generator failure rates and unavailabilities. This data can be applicable in the fusion availability studies, since fusion power plants may require a double wall steam generator (to limit tritium contamination and increase safety).

The MARS reactor concept utilizes 4 double wall steam generators to transfer part of the heat from the reactor to steam cycle (a helium loop is utilized for the other part). The LiPb coolant flows through the inner tube, steam through the outer tube and the He gas in the gap, to sweep away any water vapor and thus help detect a leak.

In the study to evaluate the reliability of the double wall steam generators (which may also be used in the LMFBRs), several failure modes are considered: water side leak event, small water to sodium leak and large water to sodium leak. These are caused by the component failures such as water weld leaks, sodium weld leaks, water tube leaks, sodium tube leaks, failure of the leak detection system, failure to locate leaks once they are detected. Some failures may be dependent on another failure.

The design of the particular steam generator may be a little different than the one employed at a fusion power plant, but the figures are indicative

Table 11. Format for the ETF Apportioned Failure Data (Only Part of Data Shown)

								*** HYDROGEN PHASE ***			*** TRITIUM PHASE ***		
NOMENCLATURE	REQ/ INST	REDUN- DANCY	RESTOR- ATION	REPAIR	MTBF	FAILURE RATE (E -6)	OFF LINE FACT	MTTR	REPAIR RATE (E -4)	AVAIL- BILITY	MTTR	REPAIR RATE (E -4)	AVAILA- BILITY
AC PWR/ENERGY STG	01/01	NONE								0.9985			0.9985
AC POWER	01/01	NONE								0.9986			0.9986
UNSPECIFIED EQ	01/01	NONE			2.0Y	57.1	1	1.0D	416.7	0.9986	1.0D	416.7	0.9986
STANDBY POWER	01/02	ACTIVE	IMEDIATE	PARALLEL						0.9999			0.9999
DIESEL GENERATOR	01/01	NONE			3.0Y	38.1	1	3.0D	138.9	0.9973	3.0D	139.0	0.9973
UNSPECIFIED EQ	01/01	NONE			20.0Y	5.7	1	1.0D	416.7	0.9999	1.0D	416.7	0.9999
ENERGY STORAGE	02/03	ACTIVE	IMEDIATE	PARALLEL						0.9999			0.9999
MGF SET	01/01	NONE			10.0Y	11.4	1	2.0W	29.8	0.9962	2.0W	29.8	0.9962
UNSPECIFIED EQ	01/01	NONE			10.0Y	11.4	1	1.0D	416.7	0.9997	1.0D	416.7	0.9997
NEUTRAL BEAM	01/01	NONE								0.9810			0.9420
NB INJECTION	01/01	NONE								0.9904			0.9489
SOURCES/BEAMLINES	01/01	NONE			9.0M	152.2	0	3.0D	138.9	0.9904	3.0W	19.8	0.9489
NB PWR SUPPLY	01/01	NONE								0.9904			0.9924
UNSPECIFIED EQ	01/01	NONE			6.0M	228.3	0	2.0D	208.3	0.9904	2.0D	208.3	0.9924
RF HEATING	01/01	NONE								0.9889			0.9869
RF INJECTION	01/01	NONE								0.9984			0.9944
OSCILLATORS	04/05	ACTIVE	IMEDIATE	PARALLEL	25.0Y	4.6	0	1.5D	277.8	0.9999	1.5D	277.8	0.9999
AMPLIFIERS	04/05	ACTIVE	IMEDIATE	PARALLEL	6.3Y	18.1	0	1.5D	277.8	0.9994	1.5D	277.8	0.9995
WAVEGUIDES	05/05	NONE			4.0Y	28.5	0	1.5D	277.8	0.9991	1.5W	39.7	0.9950
RF PWR SUPPLY	01/01	NONE								0.9904			0.9924
UNSPECIFIED EQ	01/01	NONE			6.0M	228.3	0	2.0D	208.3	0.9904	2.0D	208.3	0.9924
TRITIUM SYSTEMS	01/01	NONE								0.9963			0.9830
PELLET INJECTION	01/01	NONE								0.9988			0.9933
PELLET INJECTORS	01/02	ACTIVE	DEFERRED	PARALLEL	3.0Y	38.1	0	1.5D	277.8	0.9988	1.5W	39.7	0.9933
FUEL STG/DLVY	01/01	NONE								0.9976			0.9962
UNSPECIFIED EQ	01/01	NONE			2.0Y	57.1	0	2.0D	208.3	0.9976	4.0D	104.2	0.9962
TRITIUM CLEANUP	01/01	NONE								0.9999			0.9933
UNSPECIFIED EQ	01/01	NONE			2.0Y	57.1	0	1.0H	9999.9	0.9999	1.0W	59.5	0.9933
ICDH	01/01	NONE								0.9882			0.9837
INSTRUMENTATION	01/01	NONE								0.9991			0.9946
UNSPECIFIED EQ	01/01	NONE			6.0M	228.3	1	4.0H	2500.0	0.9991	1.0D	416.7	0.9946
PROCESS CONTROL	01/01	NONE								0.9946			0.9946
UNSPECIFIED EQ	01/01	NONE			2.0M	684.9	1	8.0H	1250.0	0.9946	8.0H	1250.0	0.9946
DATA HANDLING	01/01	NONE								0.9946			0.9946
UNSPECIFIED EQ	01/01	NONE			1.0M	1370.0	1	4.0H	2500.0	0.9946	4.0H	2500.0	0.9946
TORUS	01/01	NONE								0.9895			0.9440
TORUS PLASMA CHAMBER	01/01	NONE								0.9924			0.9592
SECTORS	16/16	NONE			4.0Y	28.5	0	4.0D	104.2	0.9976	4.0W	14.9	0.9868
LIMITERS	02/02	NONE			2.0Y	57.1	0	4.0D	104.2	0.9952	4.0W	14.9	0.9739
TEST MODULES	20/20	NONE			6.0Y	19.0	0	1.0D	416.7	0.9996	1.0W	59.5	0.9978
TORUS DUCTING	05/05	NONE								0.9970			0.9835

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Table 12. ETF Failure Data Summary

EQUIPMENT (QUANTITY)	MTBF (1)		MTTR (2)	
	ASSESSED, YR	APPORTIONED, YR	ASSESSED	APPORTIONED
DIESEL GENERATOR (1)	3.0	3.0	3.0 DAYS	3.0 DAYS
MGF SET (1)	10.0	10.0	2.0 WEEKS	2.0 WEEKS
SOURCES/BEAMLINES (ALL) (3)	0.25	0.75	5.0 WEEKS	3.0 WEEKS
RF OSCILLATOR (1)	2.0	2.0	2.0 DAYS	2.0 DAYS
RF AMPLIFIER (1)	1.0	1.0	3.0 DAYS	3.0 DAYS
RF WAVEGUIDE (1)	10.0	20.0	2.0 WEEKS	1.5 WEEKS
PELLET INJECTOR (1)	1.0	2.0	2.0 WEEKS	1.0 WEEK
SECTORS (16)	1.5	4.0	1.5 MO.	4.0 WEEKS
LIMITERS (2)	1.0	2.0	1.5 MO.	4.0 WEEKS
TEST MODULES (ALL)	2.0	6.0	1.0 WEEK	1.0 WEEK
DUCT (1)	3.0	10.0	2.0 WEEKS	1.0 WEEK
HARD VALVE (1)	5.0	10.0	1.0 WEEK	1.0 WEEK
CERAMIC JOINT (1)	20.0	20.0	1.0 WEEK	1.0 WEEK
CRYOPUMP ASSEMBLY (1)	2.0	5.0	2.0 WEEKS	2.0 WEEKS
LITHIUM PUMP (1)	2.0	3.0	3.0 WEEKS	2.0 WEEKS
LITHIUM/WATER HX (1)	10.0	10.0	2.0 WEEKS	1.0 WEEK
DIVERTOR COIL (1)	8.0	12.0	1.5 MO.	1.0 MO.
EXPANDER COIL (1)	50.0	100.0	3.0 WEEKS	2.0 WEEKS
DIVERTOR SHIELD (1)	3.0	3.0	4.0 WEEKS	2.0 WEEKS
TF COIL (1)	300.0	360.0	3.0 YR	1.5 YR
OH COILS (ALL)	25.0	60.0	1.0 YR	6.0 MO.
EF COILS (ALL)	10.0	30.0	1.0 YR	6.0 MO.

(1) MEAN TIME BETWEEN FAILURES

(2) MEAN TIME TO REPAIR (ACTIVE REPAIR TIME IN THE TRITIUM PHASE)

(3) SOURCES WERE ASSUMED TO HAVE A USEFUL LIFE OF 6 MONTHS IN THE ASSESSMENT, AND 10-12 MONTHS IN THE APPORTIONMENT.

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Table 13. Isabelle Refrigeration System Failure Data

MASTER DATA LIST RELIABILITY & MAINTAINABILITY

ITEM	HP85	GENERIC DESCRIPTION	FAIL RATE	SOURCE	MTTR	SOURCE	M_s	USE
Turbo-Expander	A&B	N/A	40.0	1 p9.4				
			19.0	3 p7-10	5	3 p7-10		
			80.9	2				
					6	11 T C-2		
Adsorber/Tank	C	N/A	11.11	3	4	9	24	
Adsorber/Filter	D	Filter, Gas (GRF)	1.2	8 p46	4	9	4	
					8	11 T C-1		
Heat Exchanger	E	N/A	19.0	3 p7-10	108	3		
					16	9	1	
		Heat Exchanger (GRF-Mil)	.9	8 p55				
		" " (Comm)	5.3	8 p55				
		Heat Exchanger #1	1.3	10 p5-15	128	10 p5-15		
Venturi Element & Transmitter	F	Same - Rosemount	126.6	4 p414	1	9	1	
		Fluid Flow Xducer	194.8	8 p102				
Hand Valve	G	Valve, Needle (GRF)	1.4	8 p109				
		(Butterfly - Cryo)			3	11 T C.1		
		Valve, Ball	.65	8 p105				
Pressure Relief Valve	H	Valve, Relief (Comm)	9.2	8 p111				
		Valve, Relief (Mil)	.9	8 p111				
Cryo Valve - Manual	I	N/A	3.2	6				
Cryo Valve - Auto	J	Cryo Valve - Manual 3.2	4.8	6				
		Valve-Solenoid 1.6		8				
Compressor - Cold & Circulator Drive	K	Electro-Mechanical Drive						
		Motor (5 - 20 HP) 5.9		8 p166	12	12 p26		
		Gear Ass'y 51.9	62.7	8 p 59				
		Coupling 5.3						

Table 13. Continued

MASTER DATA LIST RELIABILITY & MAINTAINABILITY

ITEM	HP-85	GENERIC DESCRIPTION	FAIL RATE	SOURCE	MTTR	SOURCE	M_s	USE
Liquid Level	L	Indicator, Liquid Level	11.9	8 p154	24.		1	
Temperature Sens	M	Sensor, Temperature(Rose)	18.8	4 p433	1	9	1	
		Transducer, Temp (Mil)	2.4	8 p105				
		Transducer, Temp (Comm)	21.9	8 p 105				
Pressure Xducer	N	N/A	189.9	HPS	1	9	1	
		Transducer, Press. (Mil)	6.8	8 p 104				
		Transducer, Press. (Com)	54.1	8 p104				
		Pressure Sensor			4	11		
Diff Press Trans	O	N/A	444	HPS	1	9	1	
		Transducer, Press (MIL)	6.8	8 p104				
		Transducer, Press (Com)	54.1	8 p 104				
Elec/Pneu Transducer	P	N/A (see N above)	368	HPS	1	9	1	
Speed Indicator	Q	N/A	238.1	HPS	1	9	1	
		Transducer, Tach-Gen	54.3	8 p104				
Speed Transducer	S	N/A (see Q above)	224.7	HPS	1	9	1	
Speed Controller	T	N/A	113.6	HPS	2	9	1	
Hi Speed Alarm	U	N/A	74.1	HPS	1	9	1	
Vibration Transducer	V	N/A	303	HPS	1	9	1	
		Transducer, Motional	3.9	8 p103				
Hi Vibrational Alarm	W	N/A	74.	HPS	1	9	1	

of what might be expected. Assuming a failure rate, λ_D, of the leak detection system, λ_D = 0.02/leak, the failure rates and repair times arrived at are shown in Table 14.

6.2.4 STARFIRE Design Study(13)

The STARFIRE tokamak reactor is assumed to be capable of reaching a 75% availability in this study. There are estimates of failure data for each subsystem; failure modes, failure rates and downtimes are given as well as scheduled maintenance requirements and maintenance equipment needed for repair.

6.2.5 The MARS Study Availability Data(19)

The Mirror Advanced Reactor Study project generated some reliability data, because an attempt was made to assess the availability of the plant and to determine what needs to be done to improve it. This data consists of assessed failure rates and repair times (including detailed maintenance procedures for some components), as well as scheduled maintenance requirements, and any redundancy provisions.

The data was obtained almost exclusively by expert judgement; persons responsible for designing a certain part of the system were asked to supply their estimate of the appropriate failure data. Each person was asked to fill in a form specifying the following data:

1) System descriptive data (system name and function; description of system elements; redundancy provisions and maintenance requirements).
2) Failure modes (failure mode description for each system element, mean time to failure for that mode and comments/basis for the estimate).
3) Element repair/replacement description (repair time for each failure mode and comments/basis).

Table 14. Double Wall Steam Generator Failure Data

Failure Rate (/hr)	Repair Time
$\lambda_{SG,A} = 8.3 * 10^{-9} N$	1 week
$\lambda_{SG,B} = ((1.5 * 10^{-10} + 1.014 * 10^{-14} N) + 5.78 * 10^{-9} \beta)N$	6 weeks
$\lambda_{SG,C} = (5.69 * 10^{-12} + 9.93 * 10^{-17} N)N$	11 months

where N = number of tubes

β = fraction of leaks detected but not located

$\lambda_{SG,A}$ = water side leak event rate

$\lambda_{SG,B}$ = small water to Na leak event rate

$\lambda_{SG,C}$ = large water to Na leak event rate

The results of an availability analysis indicate an acceptable MARS performance with these data; an avialability of 72% is achieved with a 28 day annual plant outage time.

Generally speaking, the failure rate estimates are much softer than the repair time estimates, because some thought has been given to disassembling of certain equipment (e.g., the blanket, some magnet coils, etc.). The failure rate data also contains the predominant failure modes. These data are shown in Table 15.

As an example of how a repair time was arrived at, see Table 16 and Fig. 5 for the MARS blanket maintenance timeline(20) and Table 17 for the choke coil maintenance timeline.

Scheduled maintenance data have also been included in this effort, see Table 18.

6.3 Data Compiled from Expert Opinion

As a part of the ongoing fusion availability study at the University of Wisconsin, we have solicited failure data from experts around the United States. We have sent them our data solicitation form (see Table 19 for a sample) in which we have asked them to give us their best estimate of a component's mean time to failure (MTTF), mean time to repair (MTTR) and the confidence they have in the supplied values. A similar approach, but more exhaustive (Delphi procedure) was used in IEEE Std-500-1977, for some components. Following is a compilation of data we have for different subsystems (Table 20).

As can be seen, sometimes there is a wide variation in estimates. The ones that seem reasonable and produce acceptable results have been employed. Magnet data can be further refined to make the magnet failure rate proportion-

Table 15. MARS System Failure Data

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
22.01.01.01	blanket	LiPb leak	3 yr*	12 days	Reactor outage during changeout
22.01.01.02	reflector	H_2O leak	15 yr*	40 days	Conservative design, simple structure
	bellows	vacuum leak	5 yr*	10 days	based upon bubble chamber experience
22.01.01.03	service station closure	vacuum leak at cover	5 yr	0.5 day	reactor can operate until scheduled downtime
		vacuum leak in wall	20 yr	7 days	" " " "
	service station cover	vacuum leak at penetration	2 yr	6 days	" " " "
	removable reflector/ shield	vacuum leak at interface	5 yr	7 days	" " " "
		water leak in service station	10 yr*	7 days	reactor shutdown required
	turbo-molecular pump	fails to start	10 yr	4 days	no steady-state impact
		bearing failure	5 yr	4 days	reactor can operate until scheduled downtime
		failure of vacuum valve	5 yr	4 days	" " " "
22.01.01.04	omega bellows	LiPb leak	20 yr*	5 days	based on bubble chamber experience. Reactor operation permitted until normal shutdown.

Table 15. (Continued)

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
	lower seal	vacuum leak	4 yr*	5 days	" " " "
	upper bellows	"	"	"	" " " "
	lower bellows	"	"	"	" " " "
	upper seal	"	"	"	" " " "
	clamp drive, clamp mechanical	inoperable	30 yr	"	secondary impact; important only during a maintenance activity
	solenoid	normally open, stuck open	5 yr	1 day	replace at scheduled downtime; may have manual override
	cooling/ heating lines	large He leak	10 yr*	5 days	reactor shutdown required
		small He leak	5 yr*	5 days	reactor operation may continue until scheduled shutdown
22.01.02.01	central cell shield	water leak	25 yr*	40 days	shutdown required
22.01.02.02	choke coil shield	water leak	30 yr	20 days	" " " "
22.01.02.03	transition coil shield	water leak	30 yr	20 days	" " " "
22.01.02.04	anchor coil shield	water leak	30 yr	20 days	" " " "
22.01.02.05	plug coil shield	water leak	30 yr	20 days	" " " "
22.01.02.06	recircularizer coil shield	water leak	30 yr	20 days	" " " "

Table 15. (Continued)

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
22.01.03.01	central cell magnets	conductor layer-to-layer or turn-to-turn short	~ 100 yr	30 days	estimate of MTBF. Assume no failure intensity during lifetime of 30 yrs.
		insulator deteriation	~ 50 yr	30 days	radiation-induced damage or defective materials. Materials selection, shielding selected result in neglectable failure intensity during lifetime.
		vapor-cooled leads burnup	> 100 yr	30 days	related to loss of He gas. Neglect due to interlocks.
		collector leads collapse		30 days	detectable during acceptance test. No failure intensity during reactor lifetime.
22.01.03.02.01	superconducting choke coils	Availability Data Similar to C.C. Magnets			
22.01.03.02.02	normal choke coils	coolant leakage at joint	10 yr	10 days	leakage must be of sufficient magnitude to warrant shutdown
		broken/ damaged insulation	---	10 days	defective materials detectable during acceptance testing. Radiation damage controlled through shield design; replacement at scheduled downtime acceptable.
		insufficient cooling	---	10 days	preventable through interlocks
22.01.03.03	transition coils	Availability Data Similar to C.C. Magnets			

Table 15. (Continued)

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
22.01.03.04	anchor coils	Availability Data Similar to C.C. Magnets			
22.01.03.05	plug coils	Availability Data Similar to C.C. Magnets			
22.01.03.06.01	c-shape recirc. coils	Availability Data Similar to C.C. Magnets			
22.01.03.06.02	recircularizing solenoid	Availability Data Similar to C.C. Magnets			
22.01.04.01	sloshing ion beam	gun filament failure	> 400 hr	4 hr	other components neglected; filament is clear weak link
22.01.04.02	thermal barrier ECRH	Similar Availability Data to Above			active redundancy of gyrotrons provided to permit on-line changeout
22.01.04.03	potential peak ECRH	" " " "			" " " "
22.01.04.04	anchor ICRH	" " " "			same comment as sloshing ion beam
22.01.04.05	startup ICRH	Not Considered in Steady-State Assessment			
22.01.07.01	supplemental htg. power supply	Non-specific; Availability of Comparable D.C. Transmission Power Supply = 0.4985			
22.01.07.02	magnet power supplies	shorted thyristor	10 yr	2 day	estimate for failure for water-cooled, solid-state device. Replacement item.
		shorted transformer	> 25 yr	2 day	replacement item
		controls	---	---	high availability, arbitrarily redundant
22.01.07.03	startup ICRH power supply	See 22.01.04.05 -- No Impact			

Table 15. (Continued)

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
22.01.08	drift pump coils & power supplies	Availability Data Similar to Normal Choke Coils			
22.01.09	direct convertor	channel burn-through -- collectors & halo scrapers	20 yr	3 days	reactor down; repair is sector replacement
22.02.01	heat transfer -- LiPb coolant	pump failure	7 yr	< 14 days	treat as nonrepairable but interchangeable during reactor operation. Redundancy provided. Heat exchangers, piping assumed not to fail.
22.02.02	heat transfer -- reflector H_2O	pump failure	7 yr	< 14 days	" " " "
22.02.03	heat transfer -- end tank	pump failure	7 yr	< 14 days	" " " "
22.03.01	auxiliary cooling cryogenics	compressor bearing failure or loss of lubrication	3 yr	52 hr	some redundancy and overcapacity provided
		turbo-expander engine failure	3 yr	52 hr	" " " "
		dewar & gas storage failure	> 30 yr	8 hr	very low failure probability
		structural failure of turbine or vacuum jacket	> 30	8 hr	" " " "

Table 15. (Continued)

Code of Accounts Designation	System/ Subsystem	Failure Mode	MTTF	MTTR	Comment
22.05.01	fuel handling & storage -- tritium extraction	cover seal leak	20 yr	24 hr	neglect nozzle & vacuum pump failures; arbitrary redundancy
22.05.02	fuel handling & storage -- fuel preparation	valve sticks, plugs, etc.	10 yr	2 hr	fully redundant; neglect sensor failure. Operation continues during repair.
22.05.03	fuel handling & storage -- fuel purification	plugged or leaking lines	~ 10 yr	16 hr	no impact on availability. Fully redundant components allow operation for ~ 2 days during which failed units can be repaired.
22.05.04	fuel handling & storage -- storage	valve or piping failure	~ 10 yr	~ 8 hr	full redundancy installed, low frequency of occurrence. Negligible impact (spare tankage also provided). Tank failure unlikely.
22.05.05	fuel handling & storage -- fuel injection	gas puffer valves stick	10 yr	8 hr	fully redundant hardware
		pellet fabricator malfunction	5 yr	8 hr	" " " "
		rail-gun electrical failure	5 yr	16 hr	" " " "
22.05.06	fuel handling & storage -- air detritiation	Highly Redundant System - No Direct Availability Impact			
Accounts 23	turbine plant	non-specific	---	---	use historic data for nuclear systems

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* "Whole reactor" specification

Table 16

Table 16. MARS Blanket Scheduled Maintenance Timeline

TIME ESTIMATE FOR MAJOR OPERATIONS IN MAPS REACTOR BLANKET REPLACEMENT

		Time
1.	Reactor Shutdown & Staging	2.3 days
2.	Setup Workstand & Remove Approach Header	1.5 hours
3.	Unbolt Headers at Header/Service Station Cover Interface. Bag Bolts & Mark for Reassembly	3.0 hours
4.	Unbolt Service Station Cover	1.0 hour
5.	Position Crane, Attach Sling & Load Cell. Remove Cover To Floor Area	2.0 hours
6.	Erect Work Platform & Temporary Shielding. Disconnect Main Coolant Header, Upper and Lower.	3.0 hours
7.	Disconnect Additional Service Lines To Reflector.	PARALLEL OPERATION
8.	Unbolt Reflector/Shield Structure Position Overhead Crane, Attach Sling and Load Cell.	4.0 hours
9.	Clear Work Platforms, Clean Up, Evacuate Reactor Compartment	1.0 hours
10.	Remove Reflector From Reactor Remotely With Crane Monitoring Load Remotely, Place Reflector In Staging Position	1.5 hours
11.	Using Manipulator System, Retrieve Sling or Lift Fixture From Staging Area. Atach Sling to Crane, Position Crane Over Blanket #0 And Remotely Attach Sling.	5.0 hours
12.	Lift Blanket #0 From Reactor & Place In Cart or Pool For Removal To Hot Cell. Disconnect Sling, Remove Sling From Crane	3.0 hours

Table 16. Continued

		TIME
13.	Using Manipulator and Crane, Retrieve Blanket Module Translating Machine From Staging Area, Lift Machine Into Reactor and Install	8.0 hours
14.	Actuate Machine and Engage Blanket #1 Right. Retrieve #1 Into Service Bay	1.0 hours
15.	Using Manipulator and Crane Attach Slings to #1 And Remove From Reactor	8.0 hours
16.	Remove Blanket #2 Right As in Step14, 15	9.0 hours
17.	Remove Blanket # 3 Right As in Step 14, 15.	9.0 hours
18.	Attach Crane & Sling To New Module. Lift Module Into Service Bay. Actuate Translating Machine and Position Module #3 Right.	9.0 hours
19.	Repeat Step 18 For Module #2 Right	9.0 hours
20.	Repeat Step 18 For Module #1 Right	9.0 hours
21.	Using Manipulator and Crane, Remove and Turn The Module Translating Machine For Left Side Modules. Reinstall.	8.0 hours
22.	Remove Blanket #1 Left As IN Step 14, 15	9.0 hours
23.	Remove Blanket #2 Left As In Step 14, 15.	9.0 hours
24.	Remove Blanket #3 Left As In Step 14, 15	9.0 hours
25.	Attach Crane & Sling To New Module Lift Module Into Service Bay. Actuate Translating Machine and Position Module #3 Left.	9.0 hours
26.	Repeat Step 25 For Module #2 Left	9.0 hours
27.	Repeat Step 25 For Module #1 Left	9.0 hours
28.	Using Manipulator and Crane Attach To New Module #0 And Install In Service Bay	8.0 hours
29.	Remotely Install Reflector Shield Into Reactor Service Bay	8.0 hours

Table 16. Continued

		TIME
30.	Enter Cell, Health Physics Servey, Decontaminate	8.0 hours
31.	Erect Service Platforms Bolt Reflector/Shield Into Place	4.0 hours
32.	Install All Headers On Reflector Leak Check Joints, Prepare Upper Seal For Cover Installation	8.0 hours
33.	Position Cover Seal. Lift Cover Into Position. Bolt Cover Into Place Attach Headers To Cover. Leak Check Cover At all Joints.	8.0 hours
34.	Install Approach Header	1.5 hours
35.	Service Equipment Cleanup and Removal	4.0 hours
	TOTAL HOURS	198.5 hours

Table 17

Table 17. Choke Coil Maintenance Timeline (Removal and Replacement)

	Hours
Choke Coil Assembly Preparation	
• Disconnect Bus Connection	1
• Disconnect Cryogenic Lines N_2, He_2, He	2
• Close Vacuum Valve and Remove Vacuum Duct	2
Insert Magnet Preparation	
• Disconnect Bus Connection	1
• Drain and Disconnect Water Cooling Lines	1
Structural Disassembly	
• Position Transhaulers to Support Choke Section	1
• Retract Reflector End Vacuum Seal	-
• Retract Structural Assembly Jack	2
• Removal Shield Segments (Start of Remote Operation	4
Removal Operations	
• Move Coil Axially With Transhauler	1
• Rotate Transhauler 90°	0.5
• Move Coil Assembly Laterally From the Machine	1
Insert Removal	
• Remove All Insert Fastners	1.5
• Attach To and Remove Coil Insert	1

Table 17. Continued

	Hours
Insert Assembly	
• Position and Align Insert in Magnet	3
• Reinstall All Fasteners	2
Installation Operations	
• Move Coil Laterally Into Machine	1
• Rotate Transhauler 90°	0.5
• Move Coil Axially Into Seal Recess	1
Structural Assembly	
• Position and Assemble Shield Segments	5
• Actuate Structural Assembly Jacks (Start of Manual Operations)	3
• Dielectric Test	
• Test Buckhead End Seal	1
• Actuate Reflector End Seal and Test	1
• Remove Transhaulers	0.5
Insert Magnet Attachment	
• Assemble and Test Bus Connection	2
• Attach Waterlines and Hydrotest System	2
Choke Coil Attachment	
• Attach Vacuum Ducts and Leak Check	2
• Connect Cryogenic Lines and Test	2
• Attach Bus Connections and Test	2

Table 18. MARS System Scheduled Outage Data

Code of Accounts Designation	System/ Subsystem	Activity	Comments
22.01.01.01	blanket	replacement of 20% each year	20% replacement internally tied to module lifetime of 4 full power years @ 80% availability. No maintenance requirement other than replacement.
22.01.01.02	reflector	---	no specified maintenance activity
22.01.01.03	service station	---	no maintenance requirement save those stations at which module replacement occurs
22.01.01.04	piping & joints	routine inspection, continuous monitoring during operation	inspection & some test required at annual shutdown. Continuous monitoring during operation.
22.01.02	shields	---	no anticipated maintenance on regular basis
22.01.03	magnets		
22.01.03.01	central magnets	no requirements	no annealing requirement; designed for 24 full power years
22.01.03.02.01	superconducting choke coil	removal every other year for access to normal insert	routine inspection during removal. Designed for 24 full years without anneal.
22.01.03.02.02	normal choke coil	replacement every other year at scheduled outage	replacement item. Roughly 2 day replacement time, each end -- may be done in parallel
22.01.03.03	transition	anneal (warmup)	required anneal about every five full power years. Can be accommodated within 30 day anticipated shutdown.
22.01.03.04	anchor coils	" "	" " " " "

Table 18. (Continued)

Code of Accounts Designation	System/ Subsystem	Activity	Comments
22.01.03.05	plug coils	" "	" " " " "
22.01.03.06.01	c-shape recircularizing coil	" "	" " " " "
22.01.03.06.02	recircularizing solenoid	" "	number of anneals < above, but not specified
22.01.04	supplemental heating	gyrotron/ filament replacement	provision made for changeout in < 4 hr on continuous basis as hedge against short lifetimes. Inspection and maintenance on other components as required at annual shutdown or during other reactor shutdowns, access permitting.
22.01.07.01	supplemental heating power supplies	inspection, calibration	accomplished at annual shutdown. Monitored during operation.
22.01.07.02	magnet power supplies	calibration/ inspection of quench detector & breaker driver circuitry	no downtime requirement during annual shutdown or reactor operation (spares provided). 6 month interval recommended.
22.01.07.03	startup ICRH power supply	calibration/ adjustment	done while startup system not on line
22.01.08	drift pump coils & power supplies	roughly annual replacement	designed for reasonably straightforward removal/insertion. Done at annual shutdown.
22.01.09	direct convertor	inspection/ replacement as required	do on annual basis at routine shutdown as required. Inner halo scraper is minimum lifetime component -- rated at twelve full power years.

Table 18. (Continued)

Code of Accounts Designation	System/ Subsystem	Activity	Comments
22.02.01	heat transfer -- LiPb coolant	pump inspection replacement	failures during reactor operation are valved off and replaced at annual shutdown. All units inspected and maintained as required at this time.
	heat exchangers	inspection/ replacement/ repair	while no failures are considered in this assessment, it is anticipated that at annual shutdown appropriate maintenance of these devices will be accomplished on an as-needed basis within the annual shutdown period
22.02.02 22.02.03	heat transfer (reflector H_2O & end tank)	Similar to 22.02.01	
22.03.01	auxiliary cooling -- cryogenics	service compressors, expansion engines, removal of "aircicles," replace adsorbers	performed on line, drawing down on reservoirs or exploiting installed redundancy. All equipment inspected at annual shutdown as well.
22.05	fuel handling & storage	nozzle replacement, redundant valves, sensors	done at annual shutdown or on-line as permitted
	fuel injection	service pellet fabricators, rail-gun	done at annual shutdown or during forced outages, as allowed
Accounts 23	turbine plant & electric plant equipment	inspection/ replacement/ refurbishment	most equipments to be serviced on annual basis, with opportunity outages during year providing for additional times

Table 19. Sample Data Solicitation Form

CRYOGENIC SYSTEM

COMPONENT	TIME TO FAILURE	CONFIDENCE* LEVEL	TIME TO REPAIR	CONFIDENCE* LEVEL
He SUPPLY				
COMPRESSORS				
AMBIENT PURIFIER				
CRYOGENIC PURIFIER				
TURBINE				
He COLDBOX				
He DEWAR				
SUPERFLUID HEAT EXCHANGER				
S/C MAGNETS				
N_2 DEWAR				
N_2 COLDBOX				
N_2 COMPRESSOR				

*Confidence Levels
> 95%, 80-95%, 60-80%, 40-60%, < 40%

Table 20. Compilation of Expert Opinion

Component	MTTF	Confidence	MTTR	Confidence
MAGNETS				
Power supply	5 yr	< 40%	6 mo	< 40%
Cryogenics	5 yr	< 40%	6 mo	< 40%
Coils	25 yr	< 40%	3 yr	< 40%
DIRECT CONVERTOR				
Grids	6 yr		950 h	
Power supply	6 mo		2 d	
CRYOGENIC SUBSYSTEM, SOURCE 1				
Compressors	5 yr	< 40%	1 mo	60-80%
Turbine	5 yr	< 40%	1 mo	60-80%
He dewar	25 yr	< 40%	6 mo	60-80%
Superfluid				
Heat exchangers	25 yr	< 40%	3 mo	60-80%
CRYOGENIC SUBSYSTEM, SOURCE 2				
Compressor	1.8 yr		1 d	
Turbine	2.8 yr		7 h	
He dewar	5 yr		4 wk	
ECRH, SOURCE 1				
Power supply	1000 h	80-95%		
Gyrotron & assoc. eqt.	1000 h	80-95%		
(This was a 8-16 MW system)				
ECRH, SOURCE 2				
Power supply	6 mo		48 h	
Triggering circuit	2 yr		3 d	
Waveguide	10 yr		2 wk	
NEUTRAL BEAM, SOURCE 1				
Ion source	3mo	< 40%	1 wk	60-80%
Cryopanels	2 yr	80-95%	2 wk	60-80%
Cooling beam dumps	3 yr	80-95%	2 wk	60-80%
Deflecting magnets	5 yr	>95%	2 wk	80-95%

Table 20. (Continued)

NEUTRAL BEAM, SOURCE 2				
Power supply	6 mo		2 d	
Ion source	2 yr		1 wk	
Cryopanels	2 yr		2 wk	
Beamline (mag. to dump)	3 yr		4 wk	
NEUTRAL BEAM, SOURCE 3				
Ion source	1 mo			
TRITIUM SYSTEM AND FUELING				
Cryopumps	2 yr		2 wk	
Fuel cleanup	1 yr		1 wk	
Pellet injection	1 yr		2 wk	
BLANKET	2 yr	40-60%	5 d	40-60%

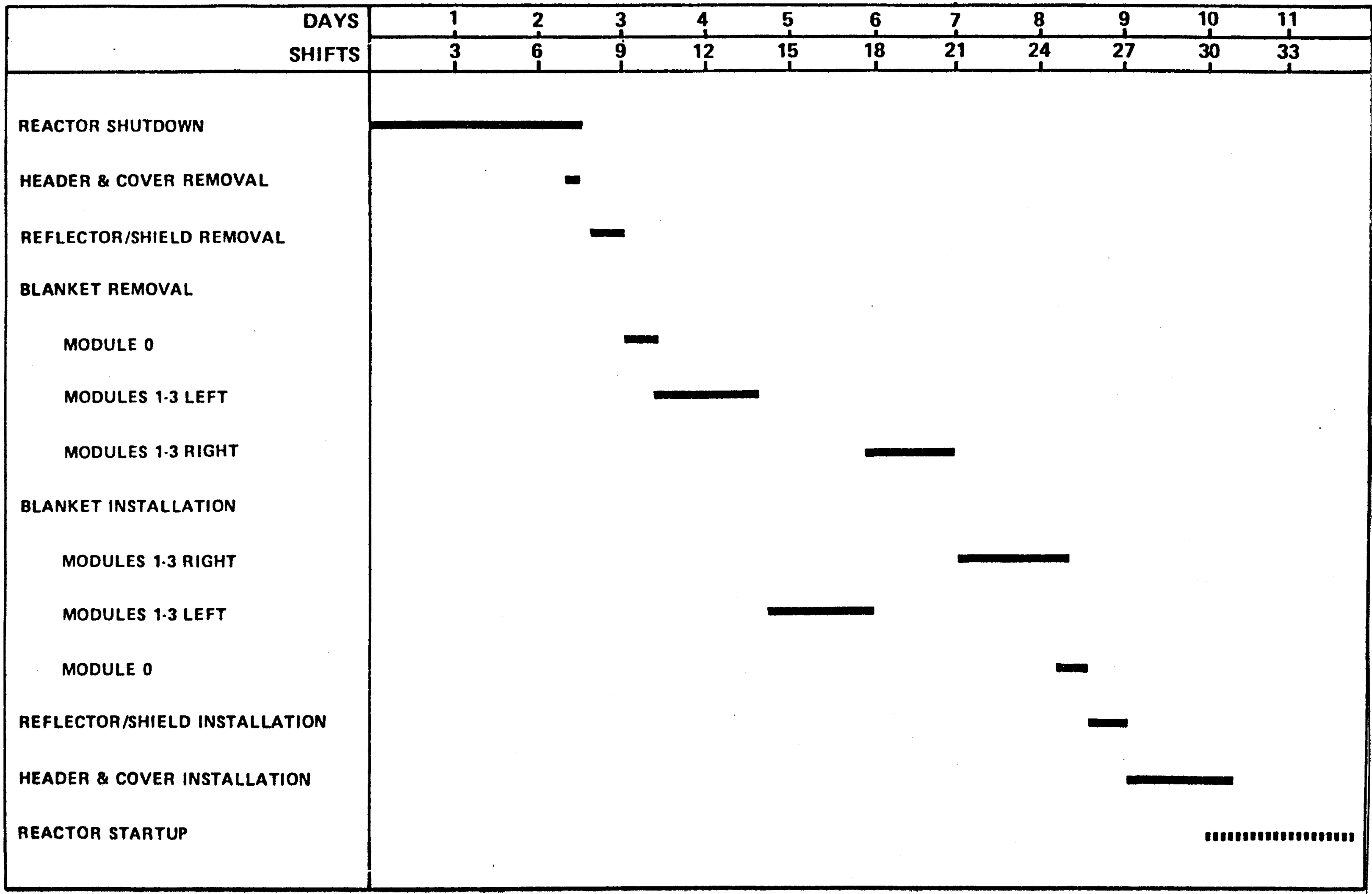

Fig. 5. MARS Blanket Module Replacement Time Estimate.

al to the coil mass (see UWFDM-531), since the failure rate may depend on the conductor length.

7. Recent Data Employed in This Study

The data compiled from different sources sometimes have a range of values associated with them (see also Ref. 2 for a tabulation of failure data ranges for some subsystems). Some of this data will produce unacceptable availability results. Hence, either redundancy must then be employed if feasible, or failure data has to be changed in order to achieve reasonable results. This new failure data then represents a design constraint that has to be met by a certain component or a subsystem. Arriving at failure data may involve a trial and error procedure including interaction with the experts.

Failure data are actually pretty flexible. Past experience indicates that quality assurance and better design can cut the failure rate of certain subsystems by orders of magnitude.(21)

Table 21 is a compilation of data recently employed in studying MARS availability. These are not recommended values, but reasonable ones to use that give us acceptable availability results.

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Table 21. Recent Mars Data

Subsystem	Failure Rate (/hr)	mttr(hr)*
CC magnet coil	4.5E-6	720.
Choke magnet, superconducting	4.5E-6	720.
Choke magnet, normal	1.1E-5	240.
Transition magnet	4.5e-6	720.
Anchor magnet	4.5E-6	720.
Plug magnet	4.5E-6	720.
Recircularizing magnet	4.5E-6	720.
Recir. magnet C coils	4.5E-6	720.
Drift pump magnet	4.5E-6	720.
Direct convertor	5.7E-6	72.
ICRH	2.5E-3	4.
ECRH, low power	2.5E-3	4.
ECRH, high power, 2 launchers/side	2.5E-3	4.
Neutral beams	2.5E-3	4.
Vacuum pumps	4.6E-5	96.
Shield	2.4E-5	168.
Blanket, LiPb leak	3.8E-5	288.
Blanket, He leak	1.1E-5	120.
Reflector	7.6E-6	960.
Bellows seal	2.3E-5	240.
Service station	1.1E-5	168.
LiPb pump	1.6E-5	336.
Reflector water pump	1.6E-5	336.
End tank H_2O pump	1.6E-5	336.
Balance of plant	2.5E-4	240.
Control and instrumentation	2.0E-4	48.
Fueling - rail gun	2.3E-5	16.
Fuel: T_2 extraction	5.7E-6	24.
Fuel: preparation	1.1E-5	2.
Fuel: pellet fabrication	2.3E-5	8.

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*mttr = mean time to repair

Table 21. (Continued)

Cryogenic system, compressors	3.8E-5	52.
Cryogenic system, turboexpanders	3.8E-5	52.
Power supply, SCR	1.1E-5	48.
Power supply, transformer	4.6E-6	48.

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