Availability Analysis of Fusion Power Plants

C.W. Maynard and Z. Musicki

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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C.W. Maynard and Z. Musicki

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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C.W. Maynard

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Abstract

The authors are in the process of developing the techniques for analyzing the availability of fusion power plants. A computer code employing some of the ideas and utilizing the Monte Carlo approach is being developed and tested. Some preliminary results for the WITAMIR-I and TASKA mirror reactors have been compiled and they suggest a low availability of these plants.

1. INTRODUCTION

This work has been undertaken in order to assess the expected availability of future fusion power plants. These plants use many components and systems that have not been tested or built full scale. The sheer complexity and numbers of these engineering systems may represent reliability problems when these plants are built in the future. Various kinds of plants can be compared as to their availabilities, using the methodology developed in this work (e.g., comparison of tokamak vs. mirror concepts). Changes can be suggested in the plant layout that might improve overall system availability. For instance, weak links (i.e., unreliable subsystems impacting most on the overall unavailability) can be identified. Then, depending on the cost of each option, increased maintenance, redundancy, quality assurance or different design may be suggested.

In order to accomplish this task, a fusion power plant of a given kind is broken up into its functional subsystems. A logic diagram of the plant is produced, which shows the interconnection of the subsystems and the logic gates (AND and OR). A computer program was developed to simulate the failures of various subsystems using the Monte Carlo approach. Given the logic diagram of the plant, the computer program will predict the behavior (i.e., the availability) of the whole system either in the steady state mode or as a time dependent quantity. The same computer program can also be used to predict the reliability of a given subsystem, given the necessary data on its constituent components and their logic interconnections. The computer code can at this time take into account such features as redundancy, overdesign and repair. In the future, time dependent failure rates can be incorporated into the program, as well as preventive maintenance strategies.

The lack of hard data presents a problem. One has to rely on experience with similar systems, or ask experts in the field to quantify their "gut feelings" as to the reliability of various subsystems (i.e., their failure rates and repair rates). This introduces uncertainties that have to be dealt with. Suggestions can be made as to which data need improvement.

Reliability of an engineering system has been receiving increasing attention in recent years (especially with NASA systems). Safety of nuclear power plants has been studied using similar probabilistic methods. However, in safety work, large error bounds in the final answer are tolerable; this is not the case with the availability analysis. This work is one of the few attempts to deal with the problem at such an early stage of design. It is hoped that improvements can be suggested and costly mistakes avoided before these plants are built. Certainly, availability of such plants is one of the key elements that will determine their ultimate economic viability, and therefore acceptance.

2. THE FUNCTIONAL BREAKUP OF A TANDEM MIRROR PLANT

The main subsystems of a tandem mirror reactor plant are: plasma region itself (plugs, thermal barriers and the central cell), neutral beams, RF heating, direct convertor, vacuum pumping, cryogenic subsystem, magnets, fueling/tritium handling, blanket, shield, balance of plant (similar to BOP of conventional nuclear power plants), control and instrumentation subsystem. These subsystems will each be described and their functional and logic interconnections will be presented. The descriptions will be more or less taken from the WITAMIR-I reactor design, developed by the Fusion Engineering Program at the University of Wisconsin.

The reactor layout of the WITAMIR-I reactor is presented in Fig. 2-1. The plasma is contained within the device mainly by the three sets of cryogenic magnetic coils: the central cell coils, the barrier coils and the plug coils. Most fusion reactions between the deuterium and the tritium ions occur in the central cell. The plug regions each contain a magnetic mirror that prevents the ions from leaking through the ends of the reactor. The neutral beams and the RF are used to heat up the plasma. The neutral beams also contribute to fueling of the plasma since some of them inject the deuterium species; some neutral beams are employed to maintain the thermal barrier potential for more effective confinement purposes. The fusion energy of the D-T reaction is converted into electricity by virtue of the conversion into thermal energy of the blanket coolant and subsequent steam cycle conversion into electrical energy. A certain fraction of fusion power is directly converted into electric power via the direct convertor that traps the ions leaking out of the ends of the reactor. The blanket material is also a tritium breeding medium via capture of fusion neutrons. Other subsystems are self-explanatory.

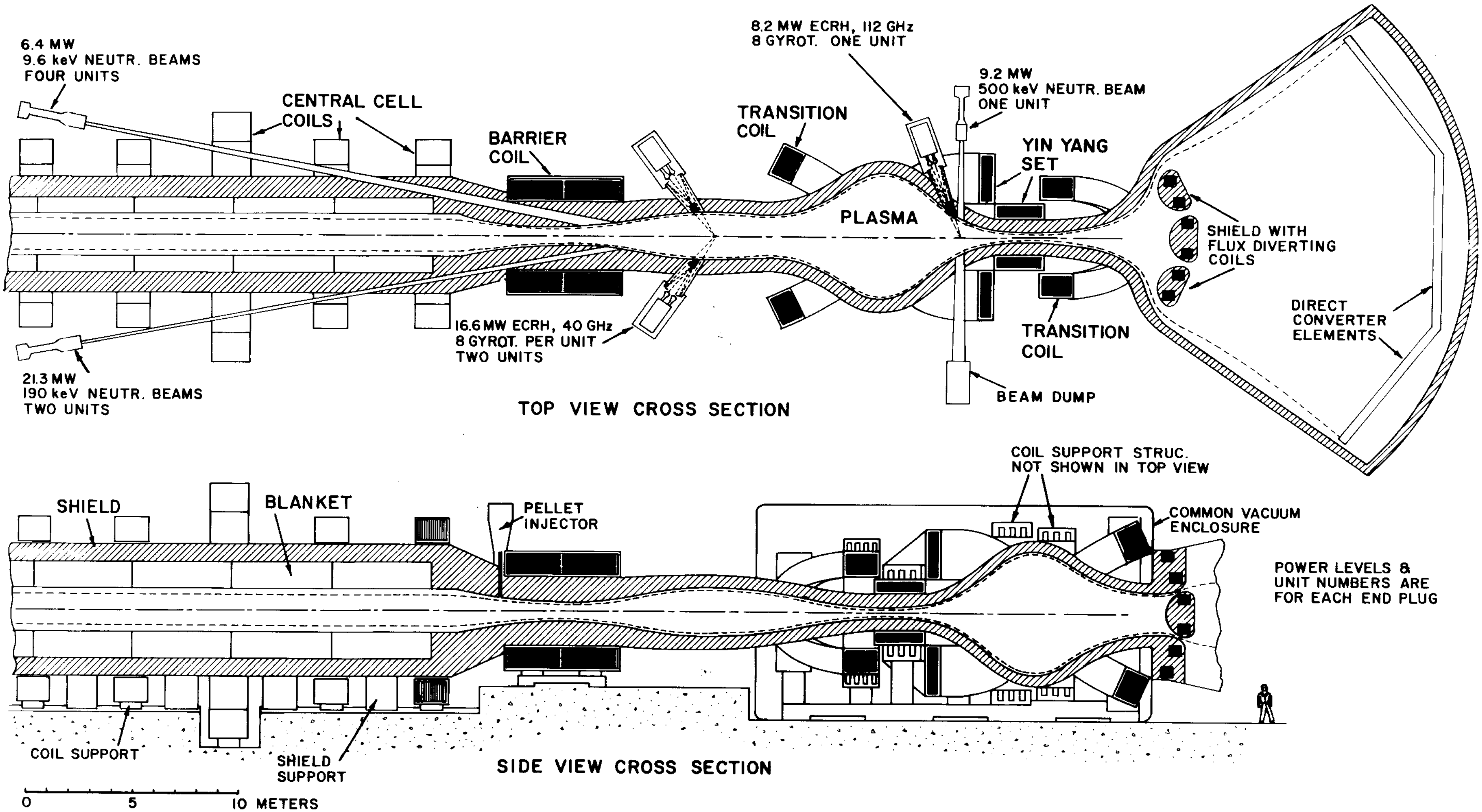
2.1 Neutral Beams

The neutral beam subsystem is used for heating the plasma and pumping the plug electrons in the thermal barriers. The energy is transferred to the plasma via a stream of high energy neutral particles, usually atoms of a hydrogen species (this means that a partial fueling of the plasma is also effected by this method). There are three kinds of beams in the WITAMIR-I design: the 9.6 keV low energy barrier pumping beams, the 190 keV high energy barrier pumping beams and the 500 keV plug beams.

Fig. 2-1

WITAMIR I

A WISCONSIN CONCEPTUAL TANDEM MIRROR FUSION REACTOR DESIGN



The engineering parameters of these beams are given in Table 2-1, and the layout with respect to the reactor in Fig. 2-1.

The 500 keV beams will have to use negative ion technology (explained below). The trapping fraction for the 500 keV beams is 0.128, necessitating the use of a 16 MW thermal dump, whereas the plug beams have essentially 100% trapping fraction.

An efficiency of 50% is expected for the 190 keV and 500 keV beams, whereas an 80% efficiency is expected for the low energy beams.

The low energy beams have a 3-out-of-4 operation, meaning that 4 beams are operating, while only three are needed for the successful operation of the reactor. There is no redundancy provided for the 190 keV beams, due to space limitations. A redundant beam can be provided for each 500 keV beam line (perpendicular to the plane of Fig. 2-1). This redundant beam is not shown in the original design of WITAMIR-I, but it will be assumed for the purposes of this study.

As far as availability of this technology at present is concerned, there should be no major problem for the 9.6 keV beams. 50 A-deuterium equivalent beam sources have been operated at 20 keV for 10 msec, and 30 A-equivalent deuterium at 120 keV have been operated for 1 sec. Hence, the main problem is increasing the pulse length for continuous operation. Continuous operation will likely decrease the life expectancy of the sources.

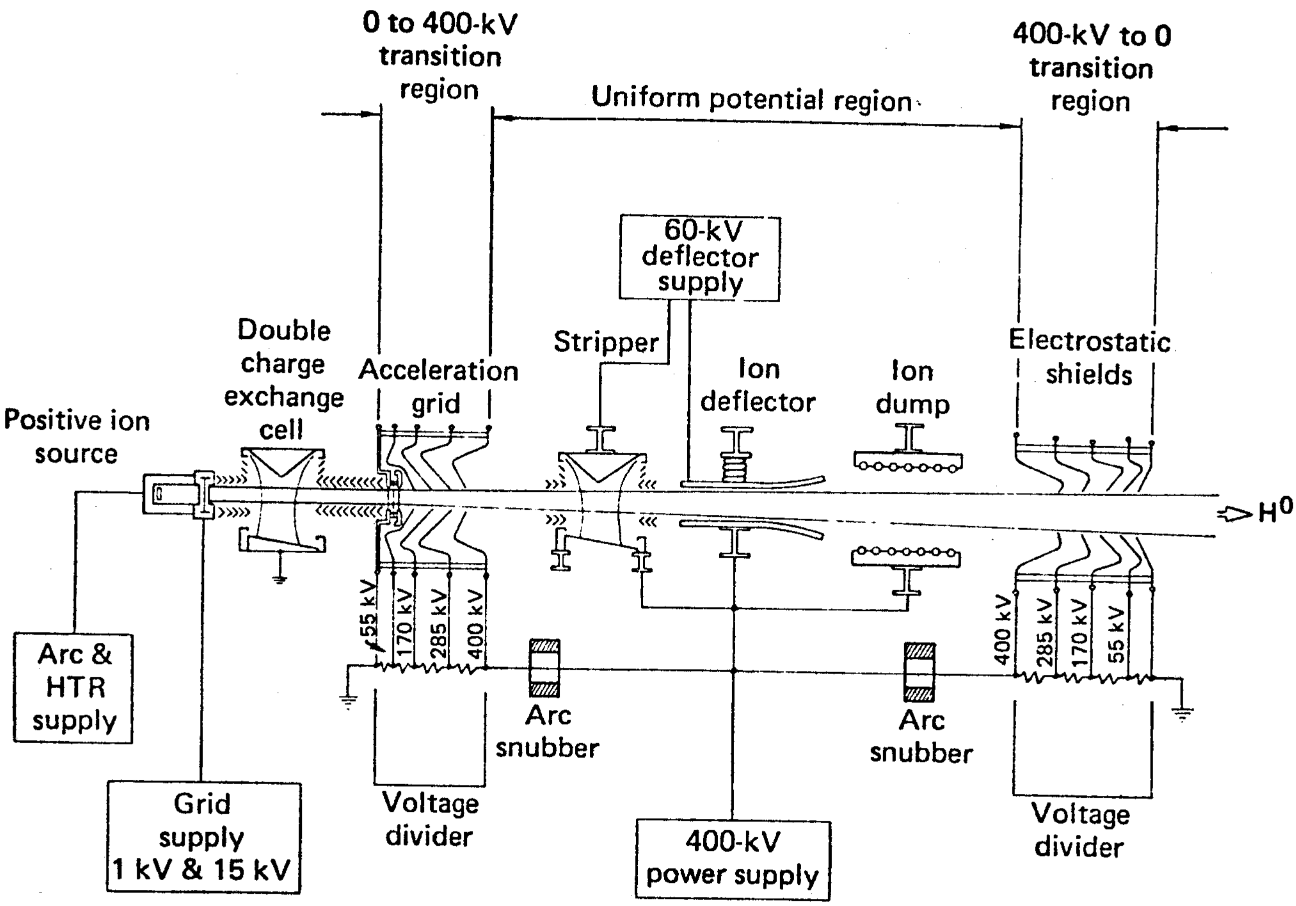
Both the 190 keV and the 500 keV neutral beams need negative ion technology, which requires considerable development at the present time.

The design for a negative ion, 400 keV neutral beam is shown in Fig. 2-2. This subsystem consists of a power supply, ion source, acceleration grid, double charge exchange cell, neutralizer cell (stripper), ion deflector and

Table 2-1. Neutral Beam Specifications

Beam	Power (both plugs) (MW)	Energy (keV)	Current (both plugs) (A)	Injection Angle	Species
Low energy barrier pump	12.7	9.6	1320	10°	d
High energy barrier pump	42.5	190	224	10°	d
Plug	18.4	500	36.8	90°	p

Fig. 2-2



Proposed design of a negative ion neutral beam subsystem.

ion removal sub-subsystems. Associated circuitry (mainly for arc suppression) and a cryogenic system are also necessary for operation of this subsystem. In the WITAMIR-I design, a thermal dump has to be operational for the 500 keV beams, due to the small trapping fraction in the plasma.

2.1.1 Ion Source

The critical component of the neutral beam subsystem is the ion source; we must assure its continuous, reliable and efficient operation for at least a year. To that end, we must increase cathode life, provide grid cooling and form beams that are 80-90% atomic ions.

For energies higher than 150 keV for deuterium and 75 keV for hydrogen, negative ion sources are required for efficient operation. The reason is that positive ions have a decreasing charge-exchange cross section with energy; this drastically reduces the efficiency of neutral production at high energies (see Fig. 2-3).

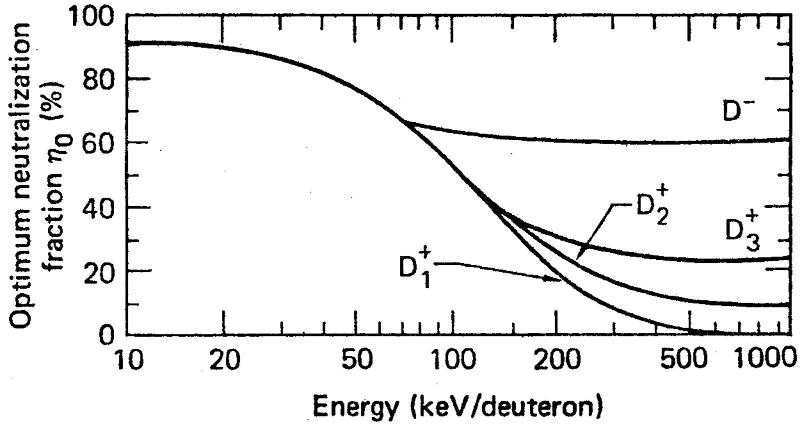
The ions must first be accelerated using an electric field, and then neutralized when the desired neutral beam energy is attained.

The critical component in the ion source is the cathode. The negative ion source needs more development than the positive ion source (which has already been used in several fusion devices). In the latest design proposals for the negative ion source concept, it is assumed that negative hydrogen ions can be formed directly; these are then accelerated to the desired energy and neutralized using the photodetachment technique.

2.1.2 The Accelerator Grid

This is another sensitive component of the NBI subsystem, and must be protected against voltage surges and arcing. Electrodes in this grid will

Fig. 2-3



Comparison of the charge-exchange cross section of the positive and negative deuterium ions.

have a certain lifetime. Other critical components may be insulators and the high voltage protective circuit (see Fig. 2-4).

2.1.3 The Photodetachment Cell

This is a relatively recent concept in ion neutralization, and replaces the old metal vapor neutralization cell (with its disadvantages of plasma contamination). Basically, it is proposed that the hydrogen ions be stripped of their excess electron by using finely tuned laser light.

2.1.4 The Beam Dump

Some method must be provided to dispose of the unneutralized ions (and also, later, of the uncaptured neutrals in the plasma). This is the purpose of the beam dump. The purpose can be accomplished via direct energy conversion or via thermal energy conversion. Thermal energy conversion, though less efficient, could be easier to implement at this time.

2.1.5 Vacuum Pumping

Due to the inefficiencies of the neutral beam subsystem, a tremendous volume of gas must be pumped relative to the neutral beam current. Hence, the vacuum subsystem must operate efficiently. The vacuum pumping is accomplished by employing cryopanels (Fig. 2-5) where any remaining gas molecules in the system are collected on the liquid helium surfaces.

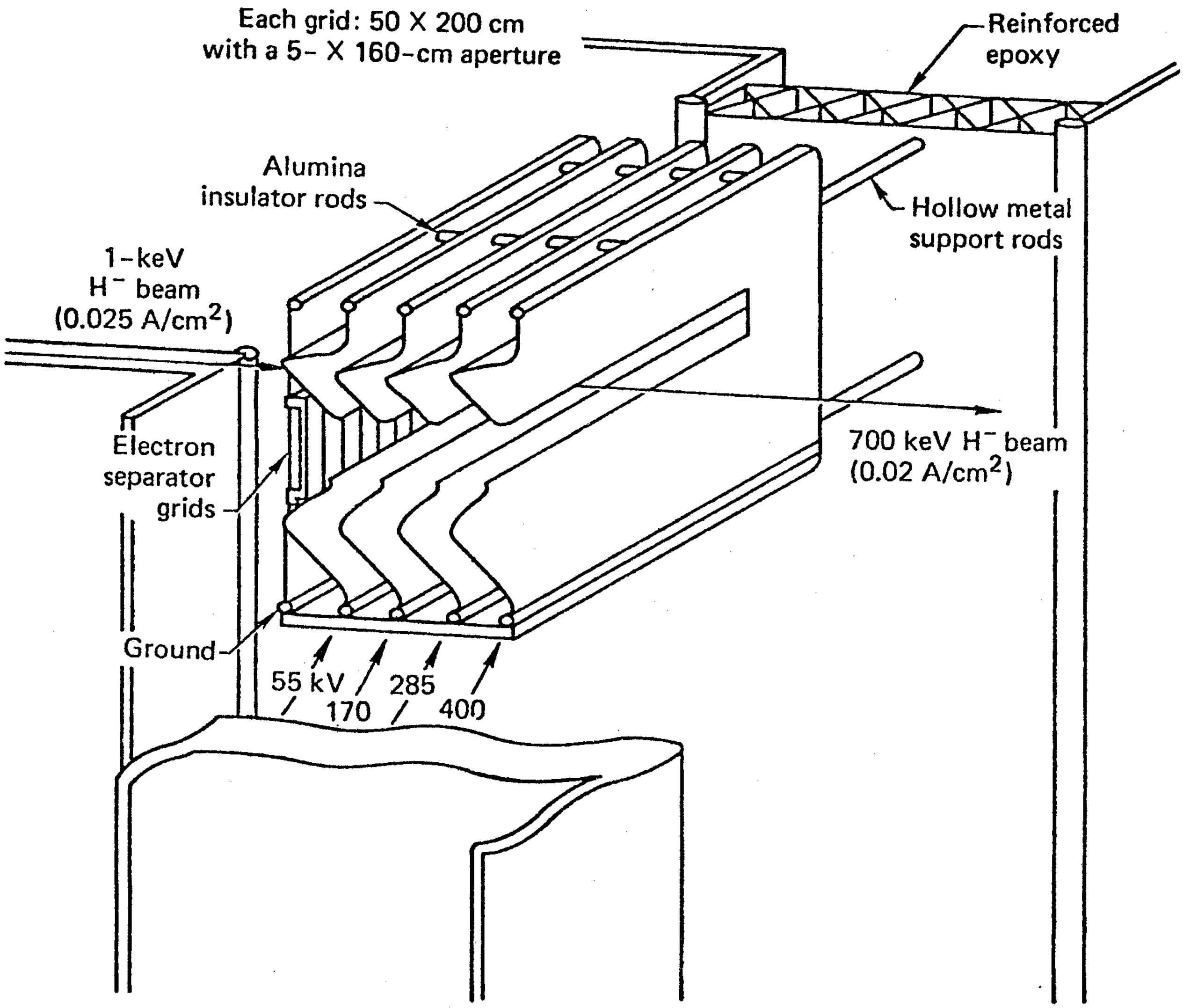
2.1.6 The Logic Diagram of the Neutral Beam Subsystem

The logic diagram of the neutral beam subsystem is presented in Fig. 2-6.

2.2 The ECRH Subsystem

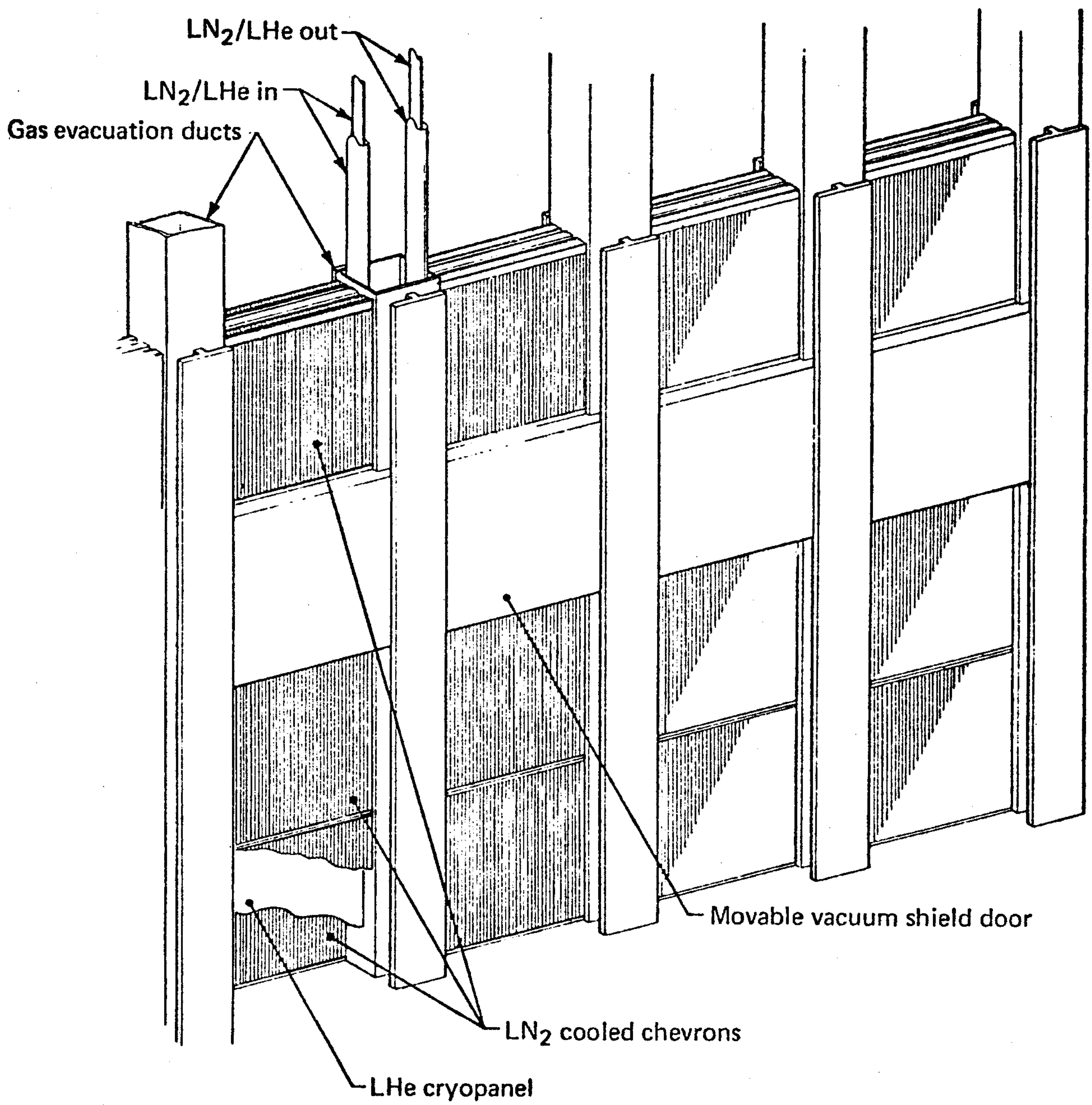
ECRH (electron cyclotron resonance heating) is another method used to heat the plasma in the WITAMIR-I design. Electromagnetic waves of certain frequencies are used to impart energy to the plasma electrons. In this

Fig. 2-4



Details of the 400-keV grid assembly.

Fig. 2-5



Cryopanels for continuous operation.

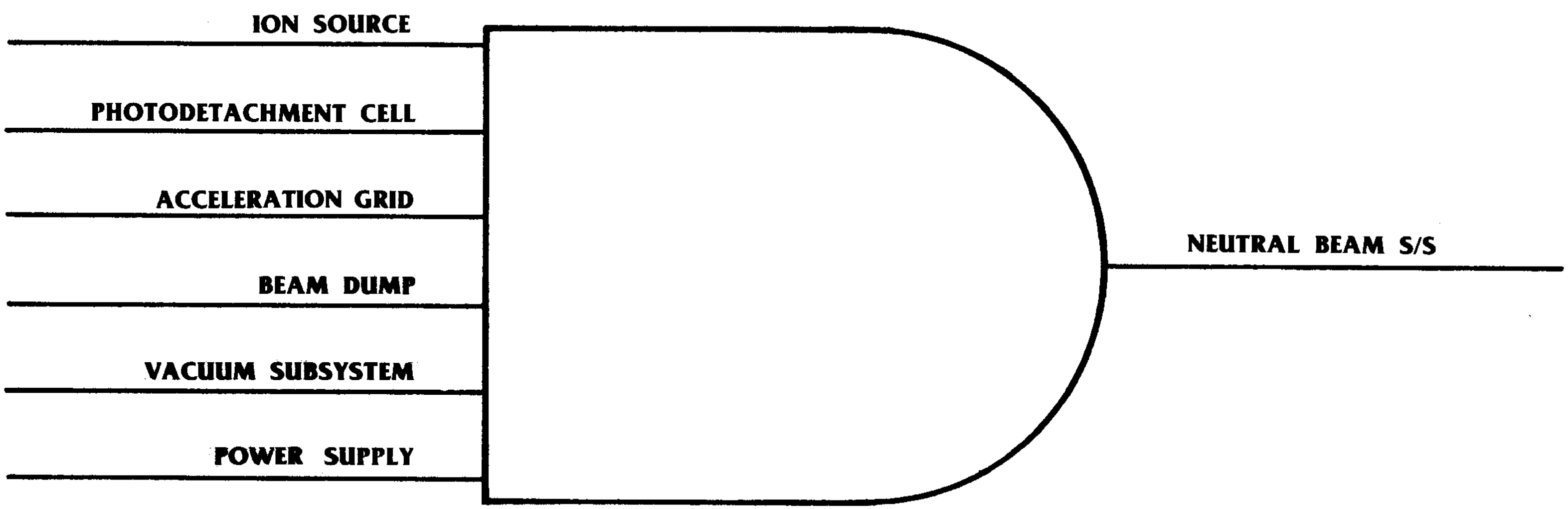


FIGURE 2-6 LOGIC DIAGRAM OF THE NBI SUBSYSTEM

designs, there is an 8.2 MW and two 16.6 MW subsystems, each with a standby (redundant) subsystem.

The main components of the WITAMIR ECRH subsystem (see Fig. 2-7) are: gyrotrons, parabolic and flat mirrors. Gyrotrons should be replaceable (like a TV tube) and they do burn out, possibly once a year. Mirrors may lose their reflectivity due to radiation damage.

The logic diagram of this subsystem is given in Fig. 2-8.

2.3 The Direct Convertor

The direct convertor is used to increase the efficiency of the machine and to capture the ions leaking out the ends of the reactor. It therefore converts the kinetic energy of the charged particles into the electric energy of d.c. current. The design of the WITAMIR-I reactor is set up so that the ions are preferentially lost through one end of the machine, hence only one direct convertor is provided (it may be possible to provide for another direct convertor at the other end as a backup in case of failure).

A temporary loss of the direct convertor can be tolerated (with a loss in the overall efficiency of the plant), but after a certain period of time a replacement must be provided or the plant shut down, because the ions will probably damage the walls of the reactor under prolonged exposure. Of course, this can be avoided by having a redundant direct convertor, as explained above, or providing special cooling for the reactor walls at the ends.

The direct convertor is another item that needs much development before it can be implemented. Several ideas for this concept have already been tested in various facilities at LBL and LLNL. A design proposed for the WITAMIR-I reactor is shown in Figs. 2-9 and 2-10.

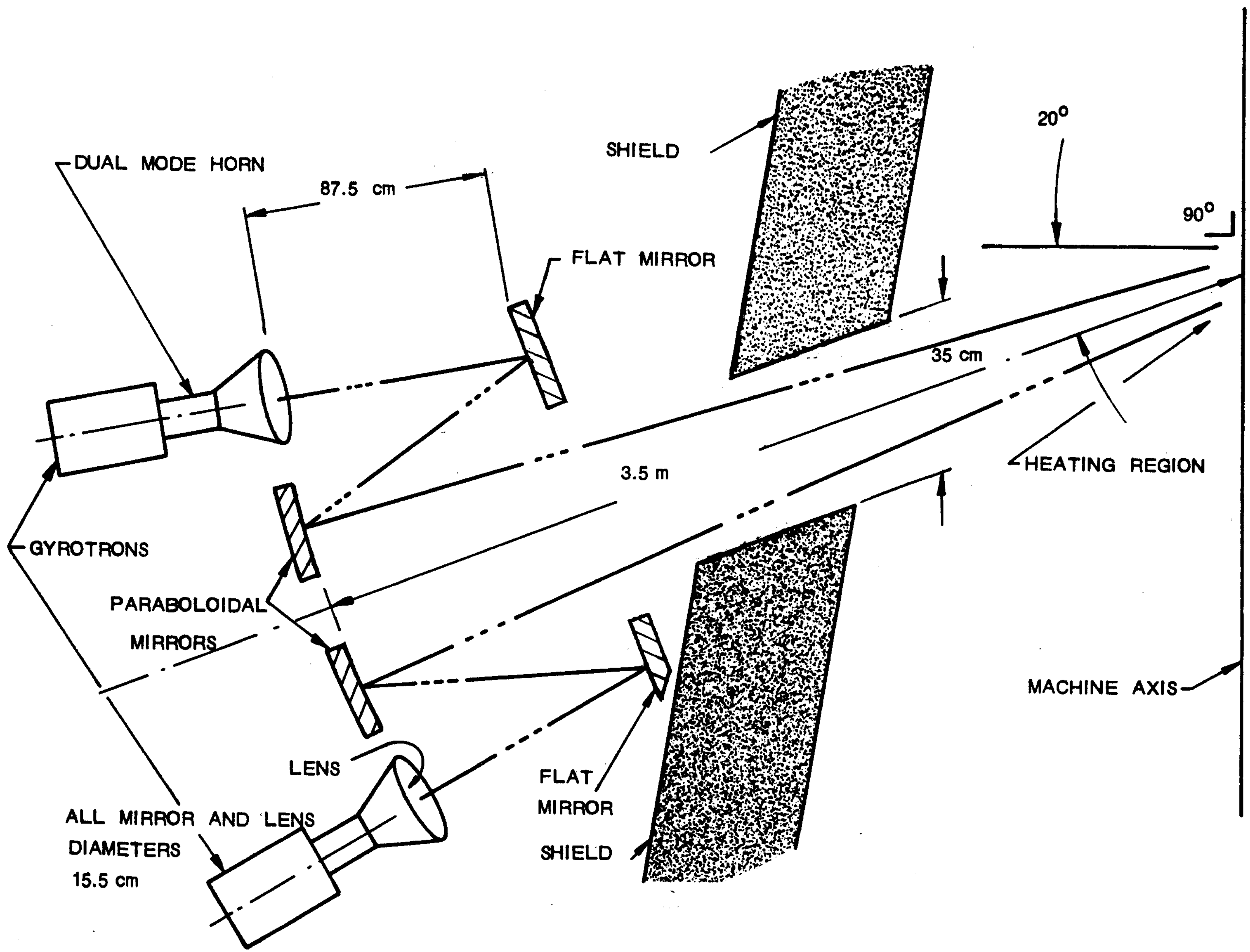


Fig. 2-7 **GYROTRON TRANSPORT SYSTEM**

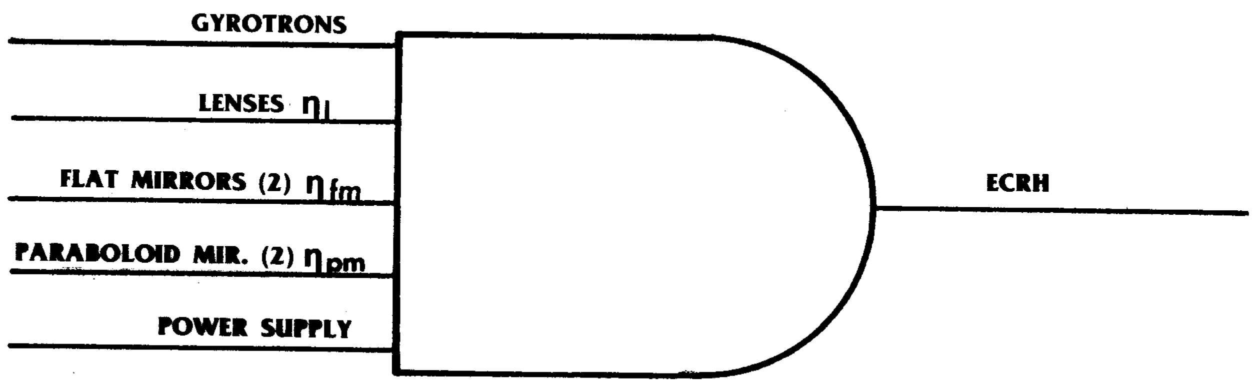
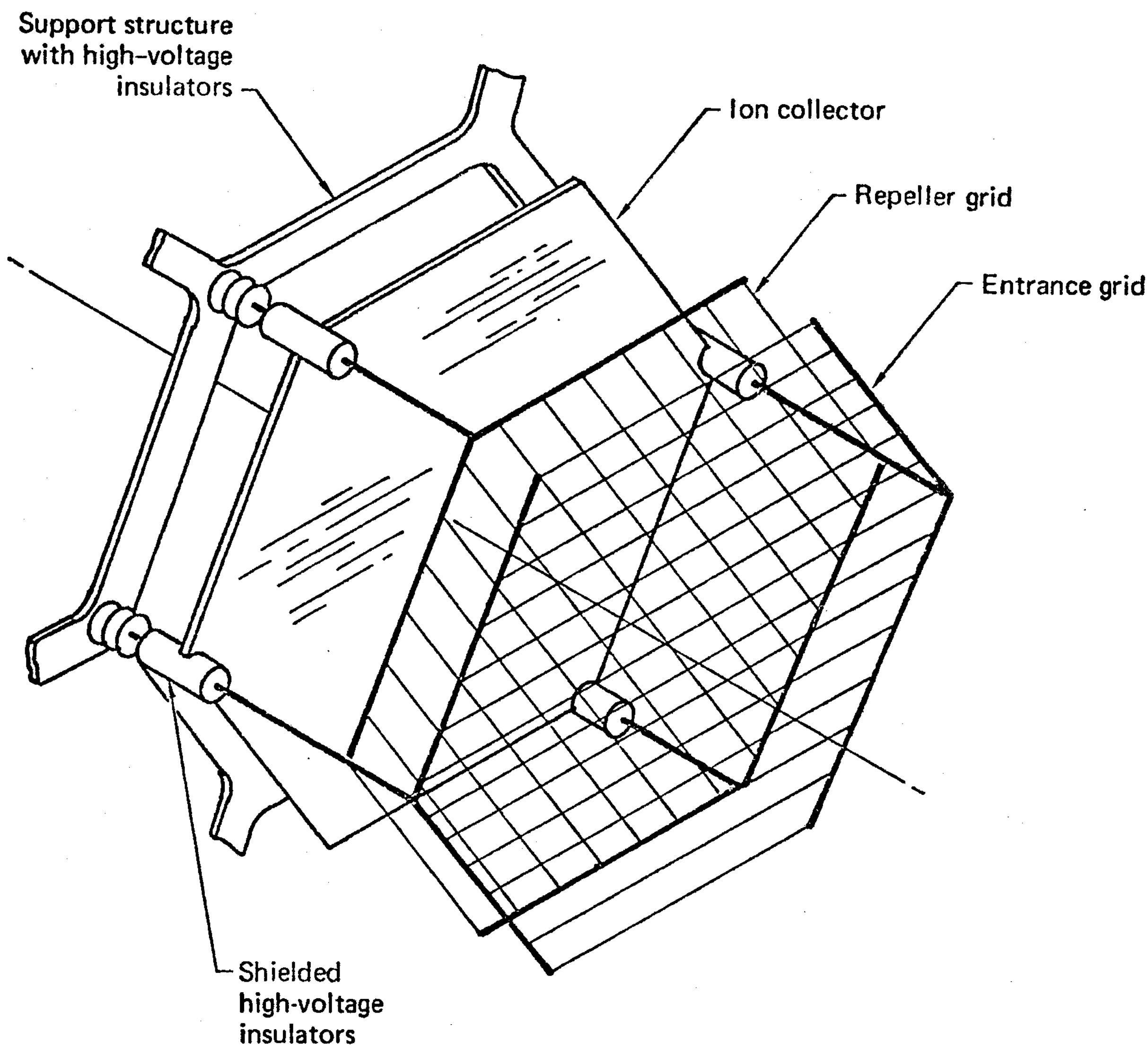


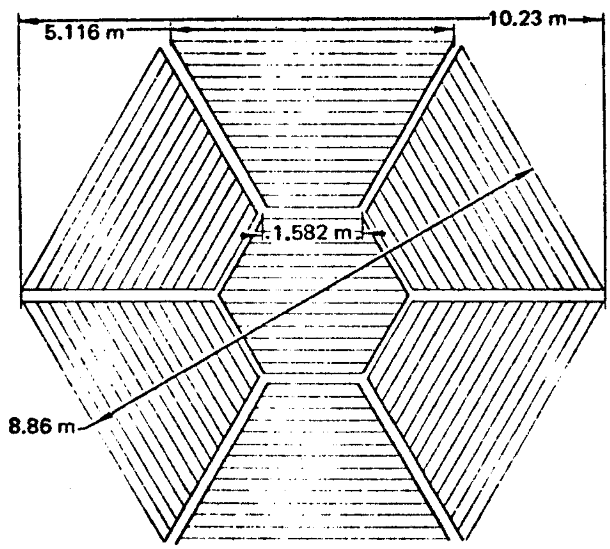
FIGURE 2-8 LOGIC DIAGRAM OF THE ECRH SUBSYSTEM

Fig. 2-9



Central module of plasma direct convertor.

Fig. 2-10



Seven sections of entrance grid.

The failure mode of this device will probably be radiation damage of the grid plates and the insulators. In addition, divertor magnet coils have to operate in order for the direct convertor to work. The logic diagram of the device is presented in Fig. 2-11.

2.4 The Vacuum Pumping Subsystem

Exceptional vacuum pumping requirements exist for a fusion reactor. On the one hand, the neutral beam and fueling subsystems inject a large number of atoms into the reactor; on the other hand, to prevent loss of ions, very low pressures within the vessel are required (on the order of 1.E-5 torr). In current experiments, the gas input into the plasma is 100 torr-liters/sec; future experiments will require an order of magnitude improvement over that figure, and reactor pumping requirements will be even more stringent.

The task will be accomplished by employing titanium gettering surfaces in the plasma chamber during the plasma buildup, by use of cryotrapping techniques (e.g., cryopanels in the neutral beam injection subystem) and by cryopumping. The cryopumps now being tested (see Fig. 2-12) work on the principle of condensation of gases on a surface cooled by liquid helium. Therefore, a supply of liquid helium and liquid nitrogen must be assured for this subsystem to work. Whether or not some type of mechanical failure can be a significant factor in failure rates of these pumps is not yet clear.

A simplified logic diagram of this subsystem is shown in Fig. 2-13.

2.5 The Cryogenic Subsystem

The cryogenic subsystem is a very important part of the overall system design, because so many other subsystems depend on its operation (magnets and confinement, neutral beams, vacuum pumping). This subsystem has conventional components (compressors, turbines, pumps, heat exchangers), so its design

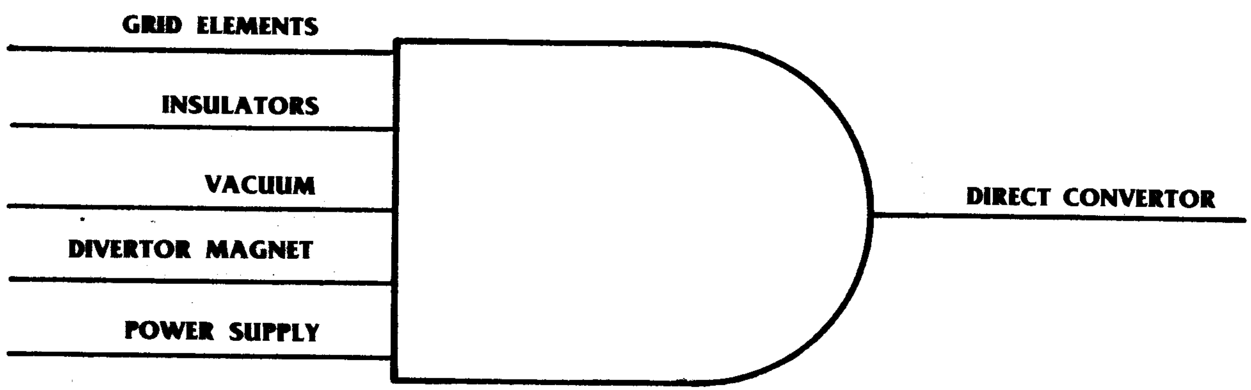
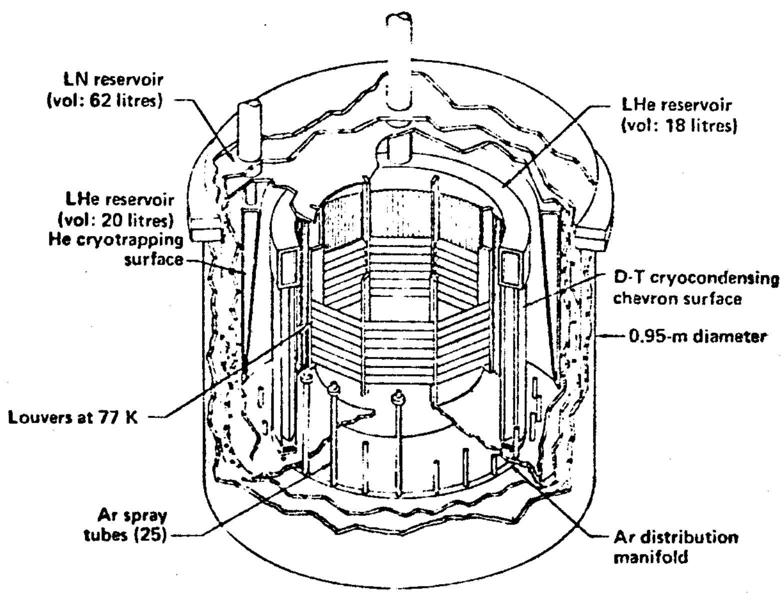


FIGURE 2-11 LOGIC DIAGRAM OF THE DIRECT CONVERTOR

Fig. 2-12



The compound cryopump for the Tritium System Test Assembly (TSTA) at LANL.

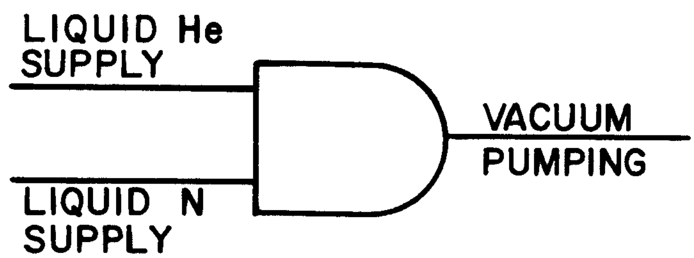


FIGURE 2-13 LOGIC DIAGRAM OF THE VACUUM SUBSYSTEM

should be a pretty straightforward extrapolation of the present technology, and failure rate data should not be hard to obtain. The cryogenic subsystem in the WITAMIR-I reactor supplies both the 4.5 K and the 1.8 K liquid helium to the magnets and other subsystems.

A schematic diagram of the cryogenic subsystem is given in Fig. 2-14.

2.6 The Magnets

The superconducting magnets are used to confine the plasma by providing the necessary variation of the magnetic field in the fusion reactors. Basically, in the tandem mirror reactor design there are three plasma regions, and therefore, three sets of magnets: the central cell, end plugs and the thermal barriers. The magnetic field profile looks as depicted in Fig. 2-15. The end plug, yin-yang magnets form magnetic mirrors which confine the hot ions in the central cell (see Fig. 2-1 for the reactor layout). Since the electrons escape from the plug region more quickly than the ions (due to higher velocity and collision rate), a positive potential is built up that traps the ions in the central cell region, where a bulk of the fusion power is produced. The ions in the central cell region are confined radially by the solenoid magnets there. The thermal barrier coils have been added in order to decrease the required plasma density in the end cells, thus lowering the demands on power consumption and technology. Thus, electrons in the end plugs can be heated independently, hence higher plug potential is reached.

Almost no redundancy is provided in the magnet coils of the WITAMIR-I reactor; in the central cell, 21 out of 22 magnet coils have to operate for successful confinement. If any other magnet should fail, the plant will have to be shut down.

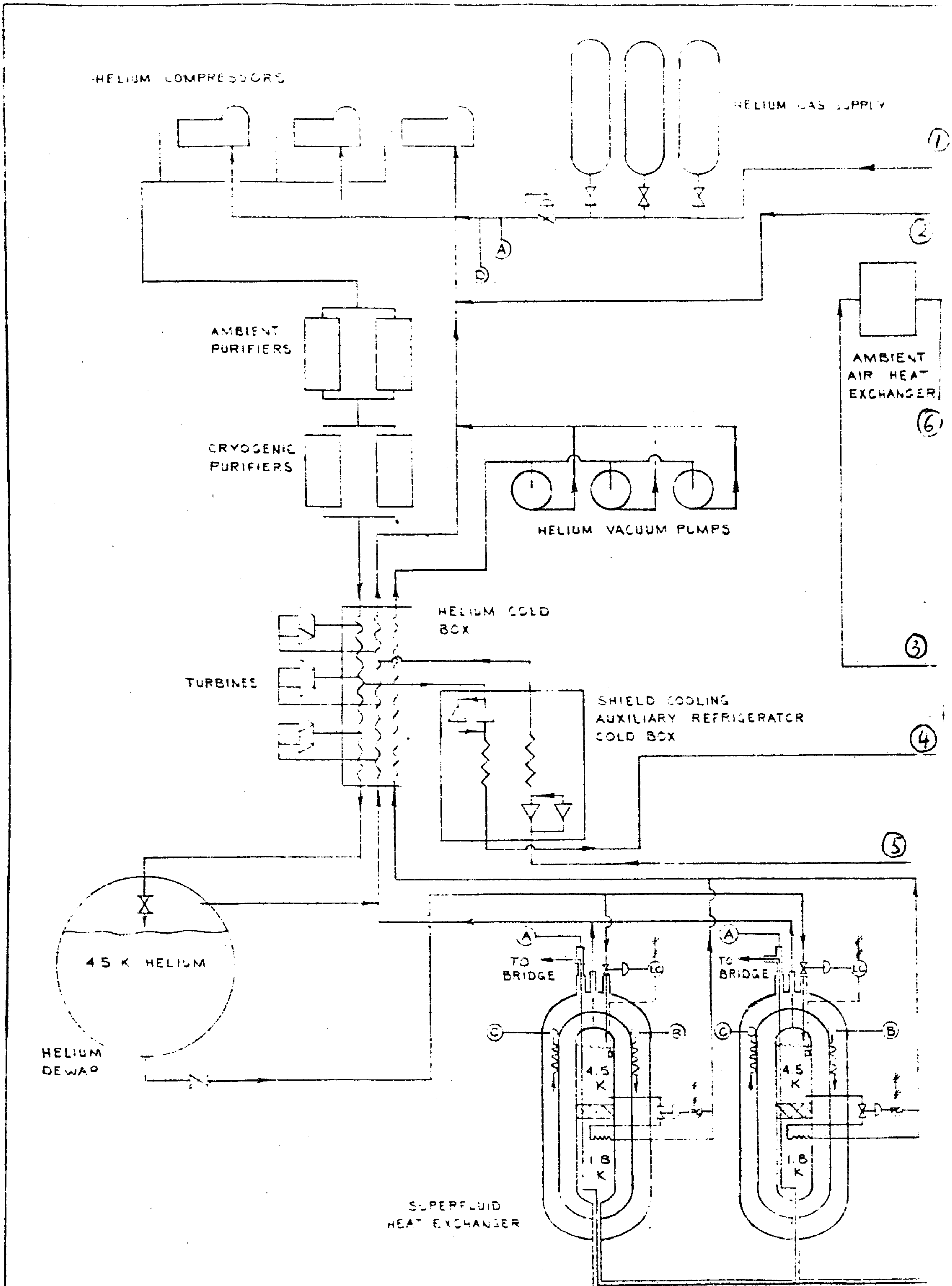
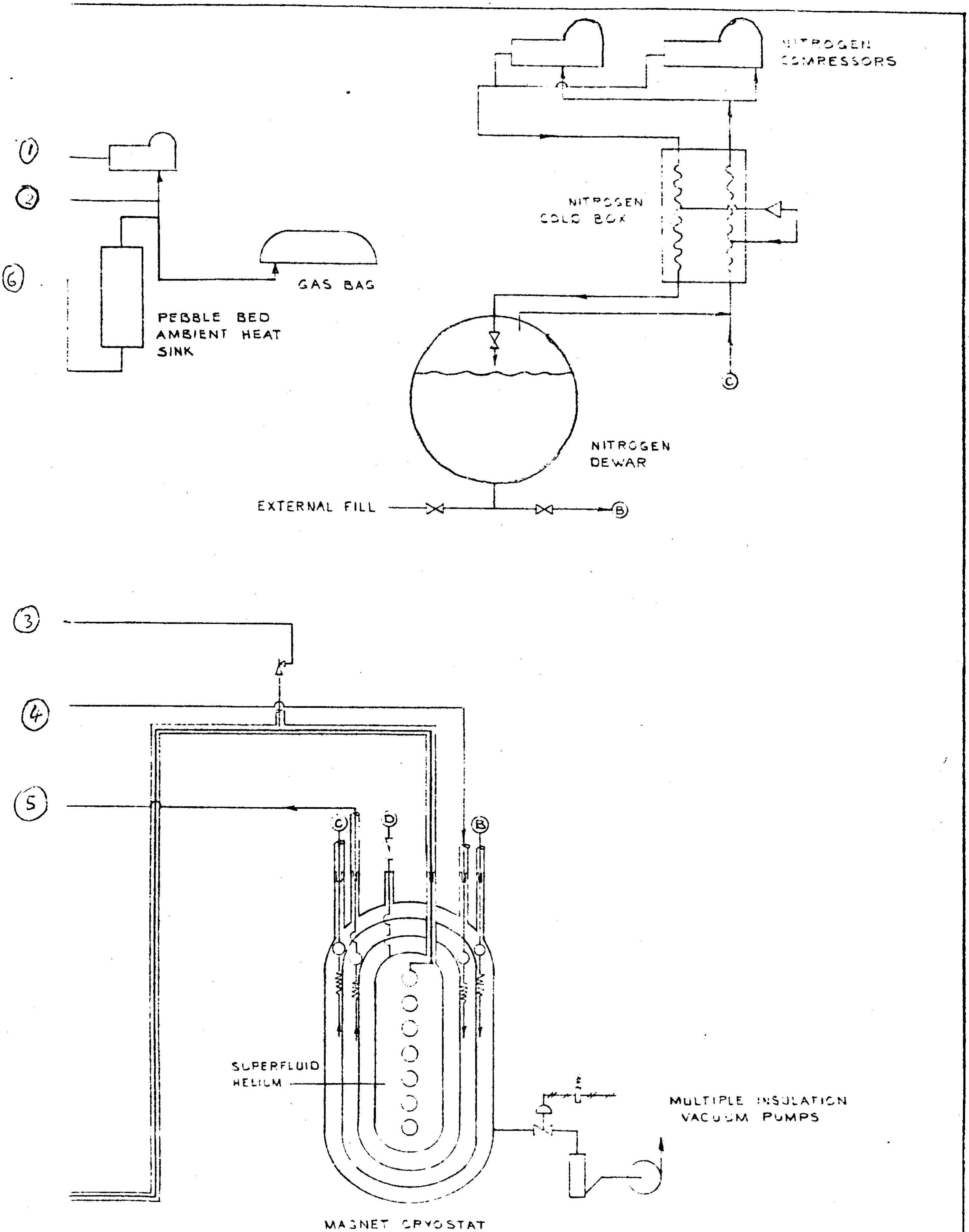


Fig. 2-14 Cryogenic Subsystem 1/2



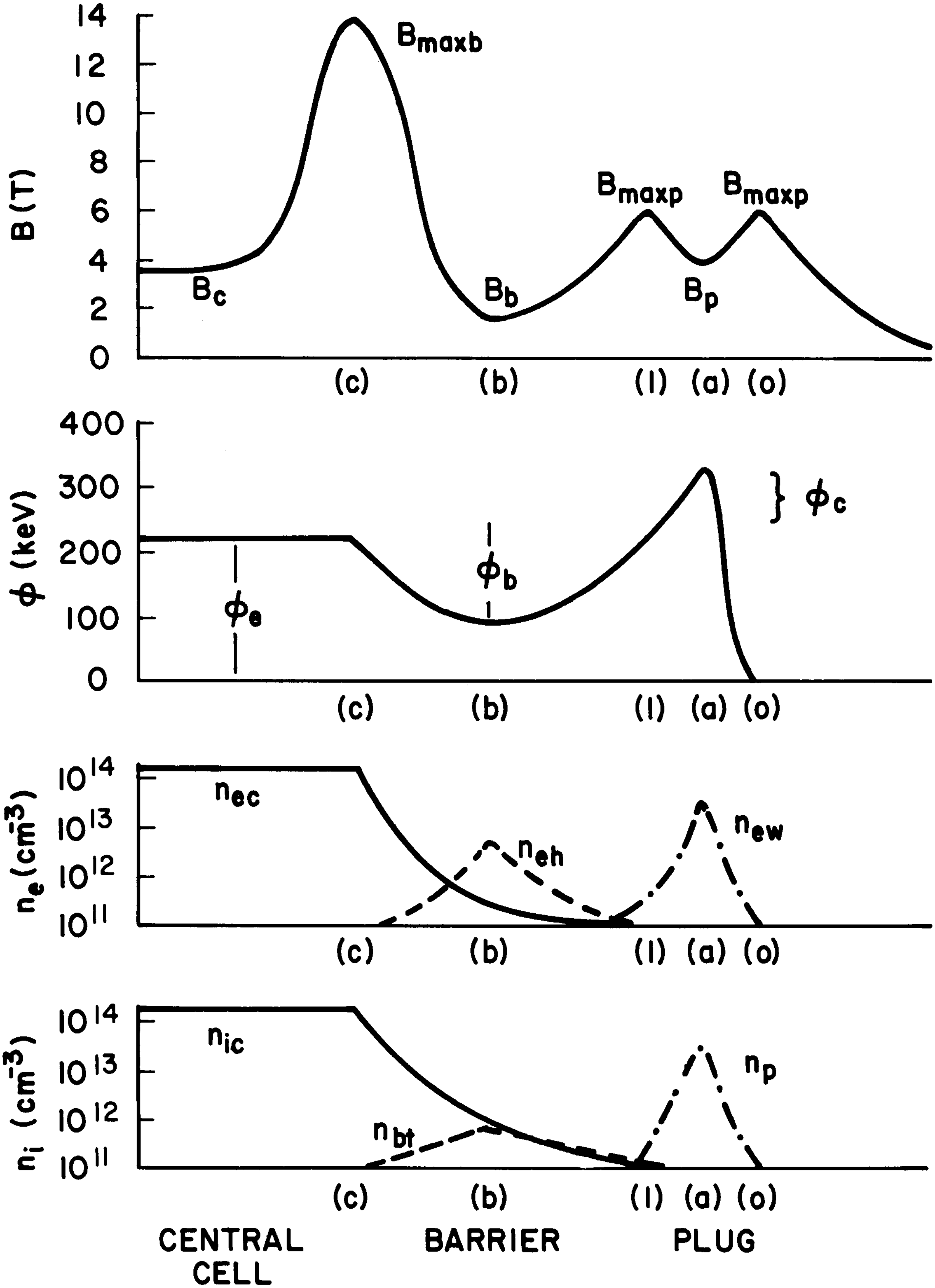
CRYOGENIC TECHNICAL SERVICES, INC.
BOULDER COLORADO

UNIVERSITY OF WISCONSIN
SUPERCONDUCTING MAGNET CRYOGENIC SYSTEM

BY: KEA | DATE: 8 8 80 | DWG: UW C 2

Figure 2-14, 2/2

Fig. 2-15



Magnetic field, electrostatic potential and densities in WITAMIR-I.

The major cause of magnet failure will probably be failures in the cryogenic subsystem (magnets are connected to the 4.5 K liquid helium supply; one coil of the thermal barrier magnet is connected to the 1.8 K supply). Other causes of magnet failure may be mechanical failure of the superconducting cable (due to mechanical or thermal stresses; the mirror magnets may be more reliable in this regard than the tokamak magnets, due to the steady state nature of the formers' magnetic field). Other sources of failure may be localized random loss of superconductivity (which can spread) or maladjustment of power supplies. A simplified logic diagram of the magnet subsystem is shown in Fig. 2-16.

2.7 Fueling/Tritium Separation

Hydrogen isotope pathways in the WITAMIR-I reactor are shown in Fig. 2-17. Tritium is bred by neutron absorption in Li-6 and Li-7 that circulate through the blanket as LiPb. This tritium is extracted using chemical separation techniques not yet sufficiently developed. Some deuterium (the other component of the necessary fuel mixture) and tritium are recovered from the plasma (i.e., direct convertor ion leakage) and from the neutral beams. Deuterium and tritium are separated using cryogenic separation columns. Pellets are made and injected into the reactor via pellet injector. For some of these sub-subsystems, data should be available from the chemical industry.

The logic diagram for this subsystem is shown in Fig. 2-18.

2.8 Blanket/Shield

This subsystem insures tritium breeding and transport of energy to the secondary heat transfer loop; it also protects other subsystems (e.g., magnets) from radiation damage. The tritium breeding medium and primary coolant, the LiPb eutectic, circulates through the blanket.

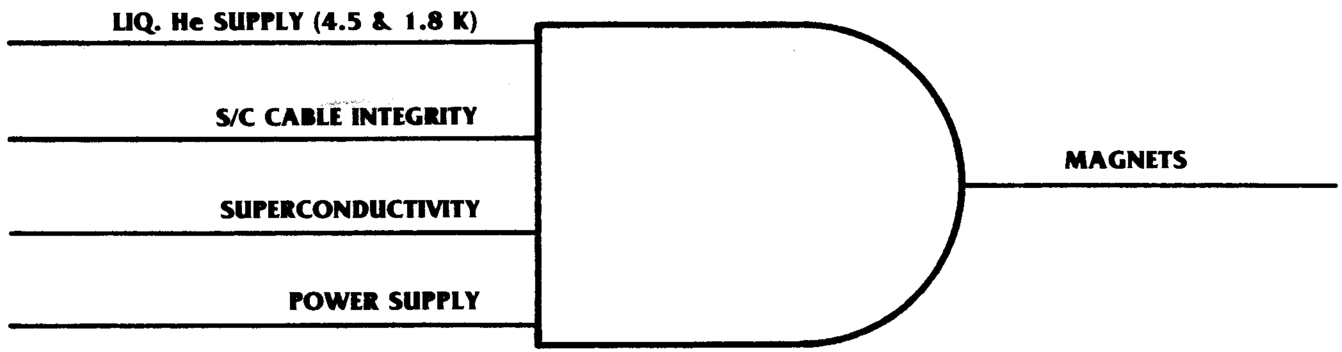
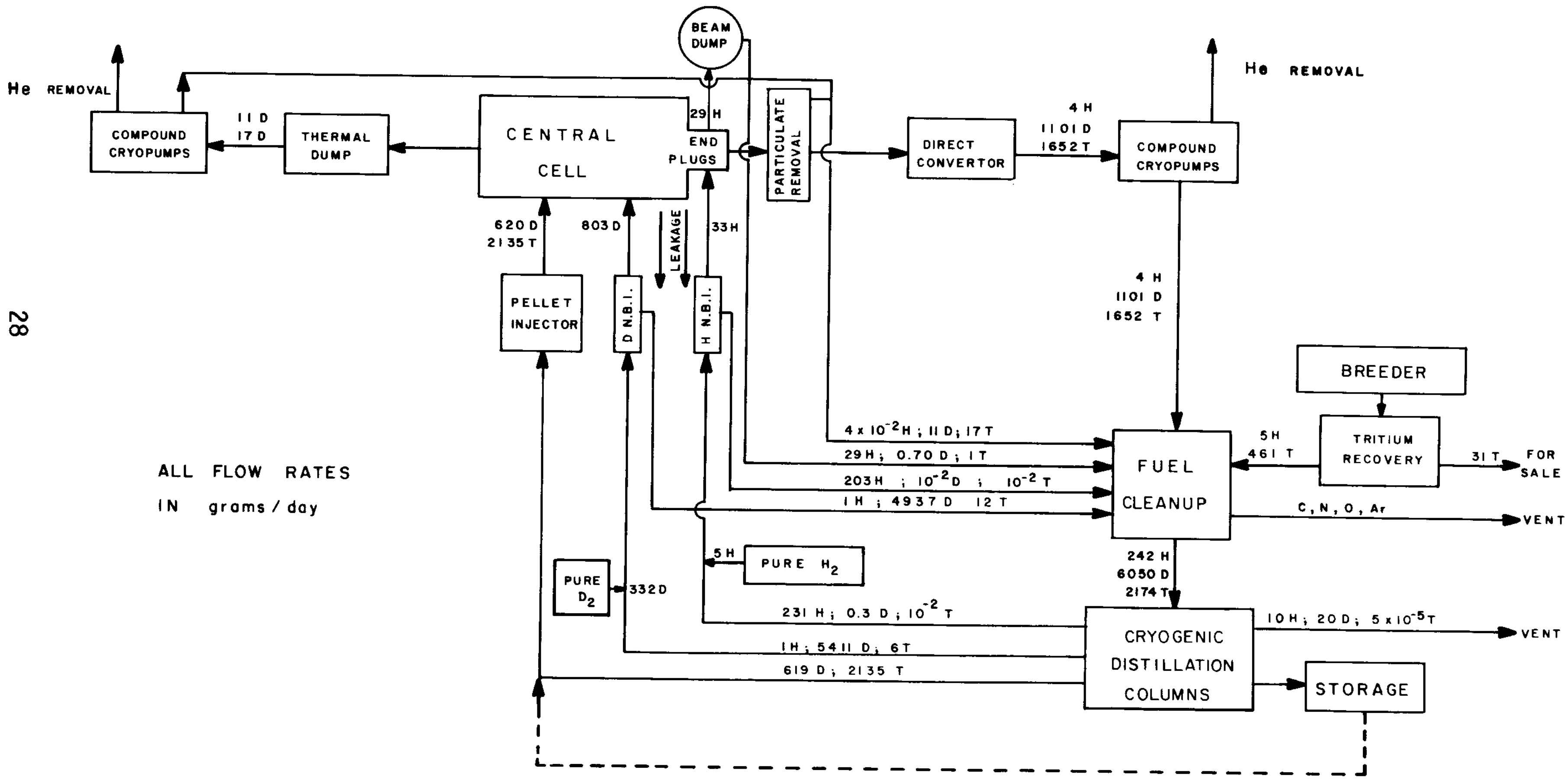


FIGURE 2-16 LOGIC DIAGRAM OF THE MAGNET SUBSYSTEM

Fig. 2-17

HYDROGEN ISOTOPE PATHWAYS IN WITAMIR-I



ALL FLOW RATES
IN grams / day

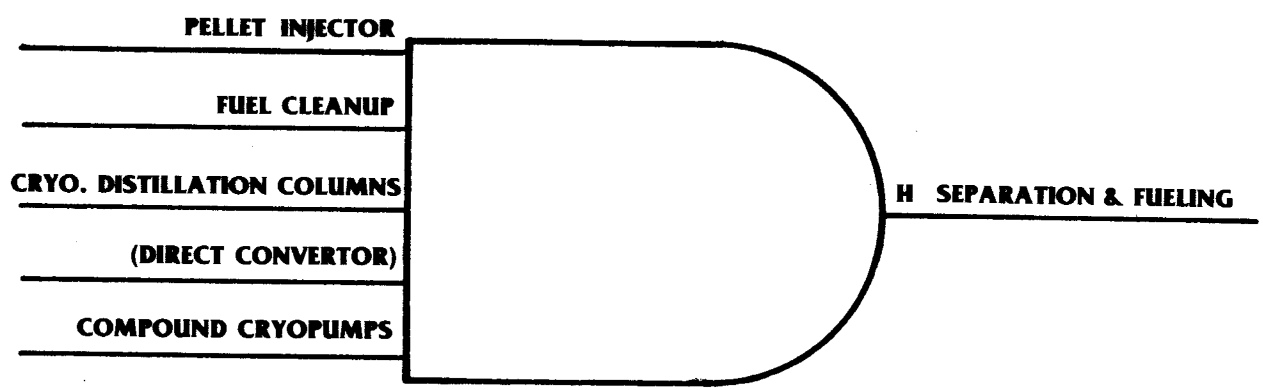


FIGURE 2-18 LOGIC DIAGRAM OF THE FUELING SUBSYSTEM

Causes of failure of this subsystem may be in the blanket modules, in the pumps or in the steam generator. The logic diagram of this subystem is given in Fig. 2-19.

2.9 Steam Generators/Balance of Plant

This subsystem is similar to a conventional plant, with a few exceptions (e.g., d.c. input from the direct convertor, liquid metal in the steam generators), so most conventional power plant data should be applicable, as to the most frequent modes of failure and failure rates.

2.10 Control and Instrumentation Subsystem

Not much is known about this subsystem for fusion power plants at the present time. It is proposed that, for now at least, data be used from the conventional nuclear power plants as to the frequency and consequences of this subsystem failure.

2.11 Preliminary Description of the Whole System

A functional diagram of the WITAMIR-I plant is given in Fig. 2-20. The corresponding logic diagram is shown in Fig. 2-21. Since a preliminary analysis has also been done for the TASKA reactor (tandem mirror materials testing facility), its simplified logic diagram is shown in Fig. 2-22. Tables 2-2 and 2-3 exhibit the necessary information used in the computer runs and in drawing the above figures.

3. MODEL FOR COMPUTING AVAILABILITY OF FUSION POWER PLANTS

The purpose of this computer model is to estimate the availability of a fusion power plant, knowing the failure and repair rates of components, their configuration in the plant, maintenance strategies, etc. Weak links can be identified and ways of improving their reliability can be suggested. Cost of each improvement option may be considered and the most cost-effective one

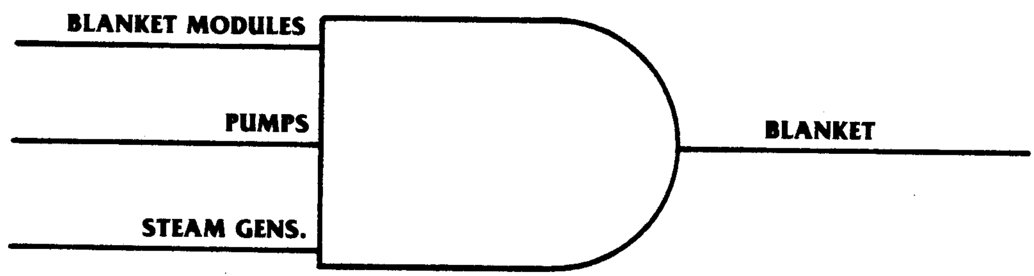


FIGURE 2-19 LOGIC DIAGRAM OF THE BLANKET SUBSYSTEM

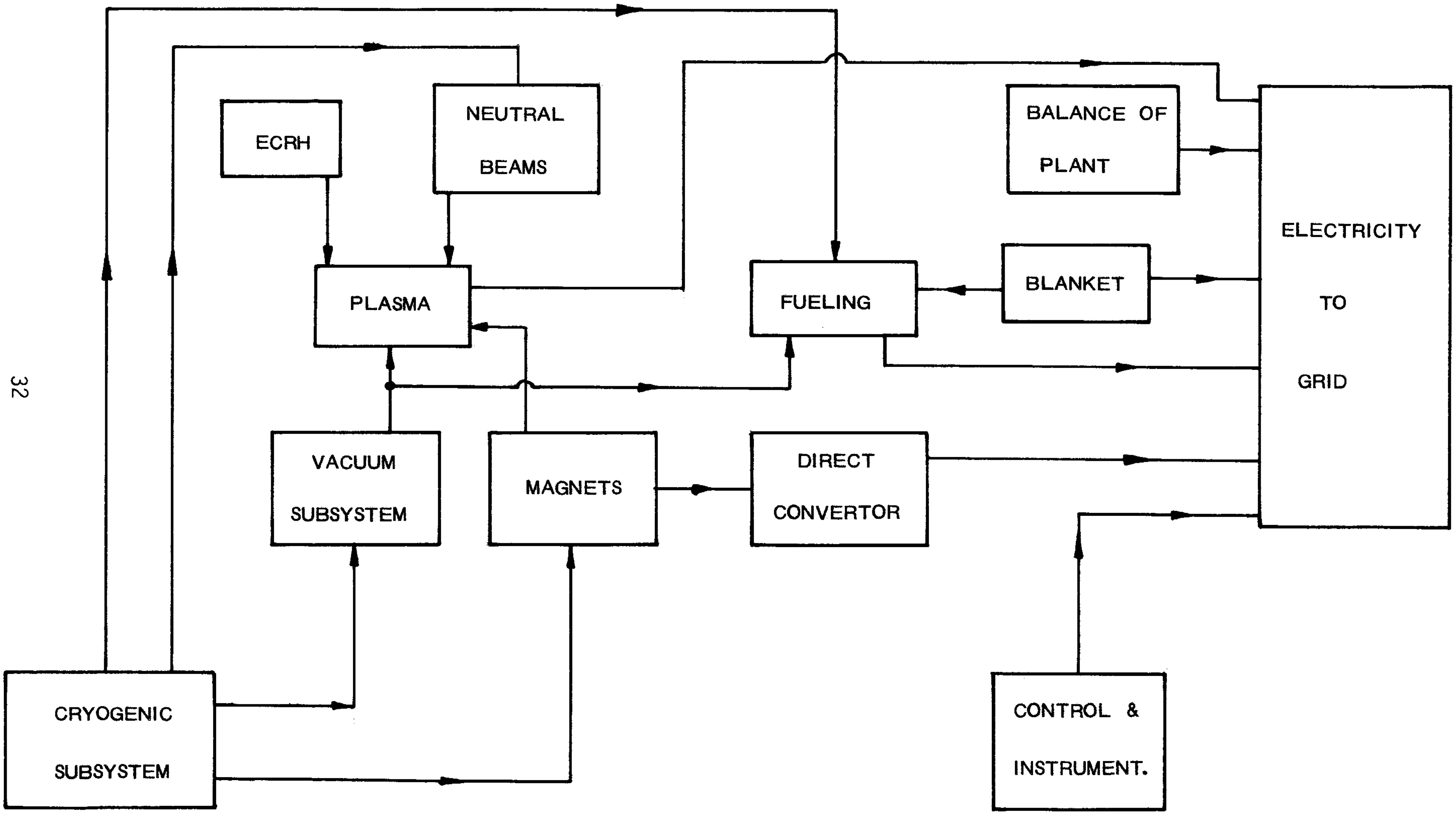


Fig. 2-20 FUNCTIONAL DIAGRAM OF WITAMIR - I

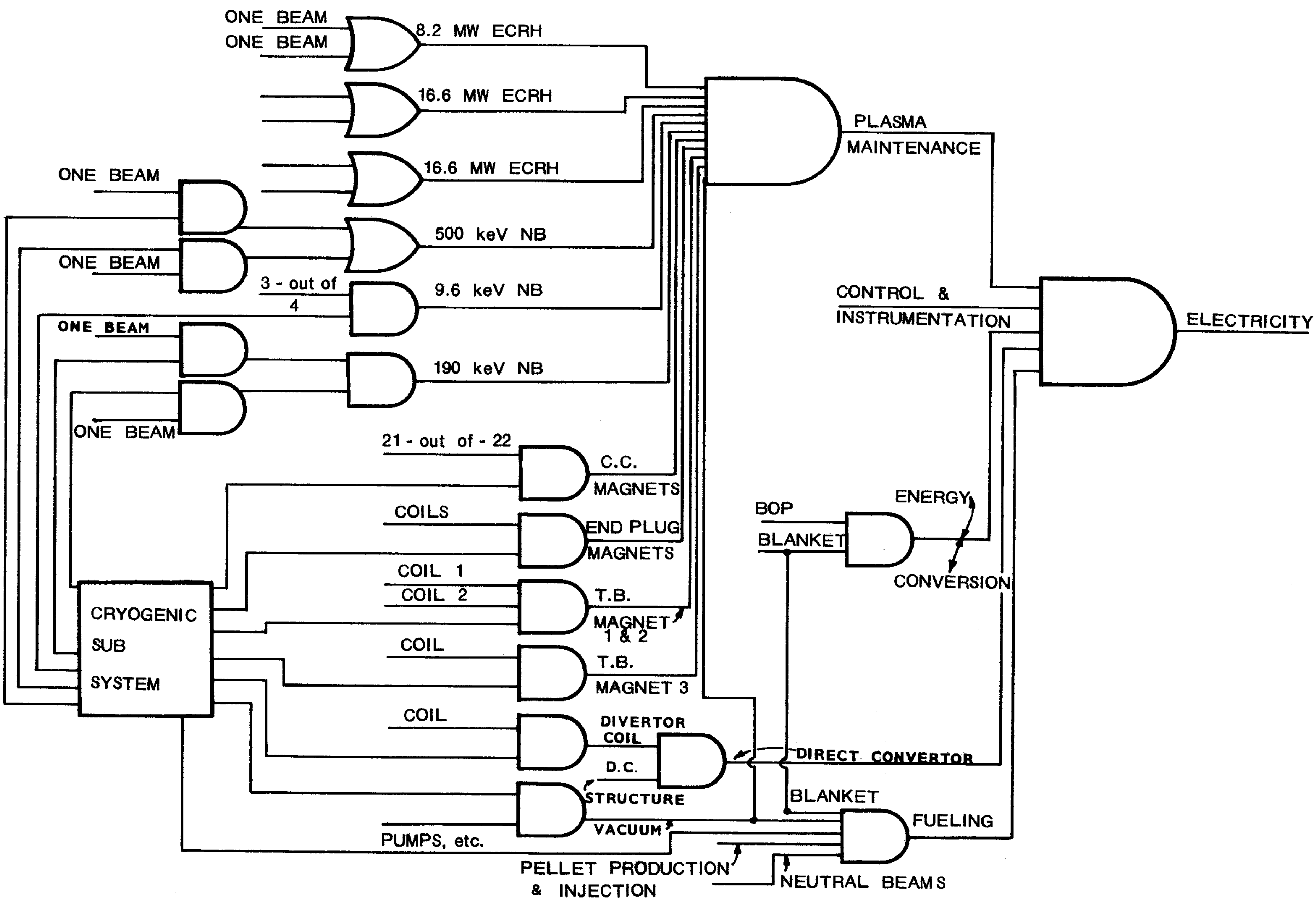


Fig. 2-21 LOGIC DIAGRAM OF THE WITAMIR - I POWER PLANT.

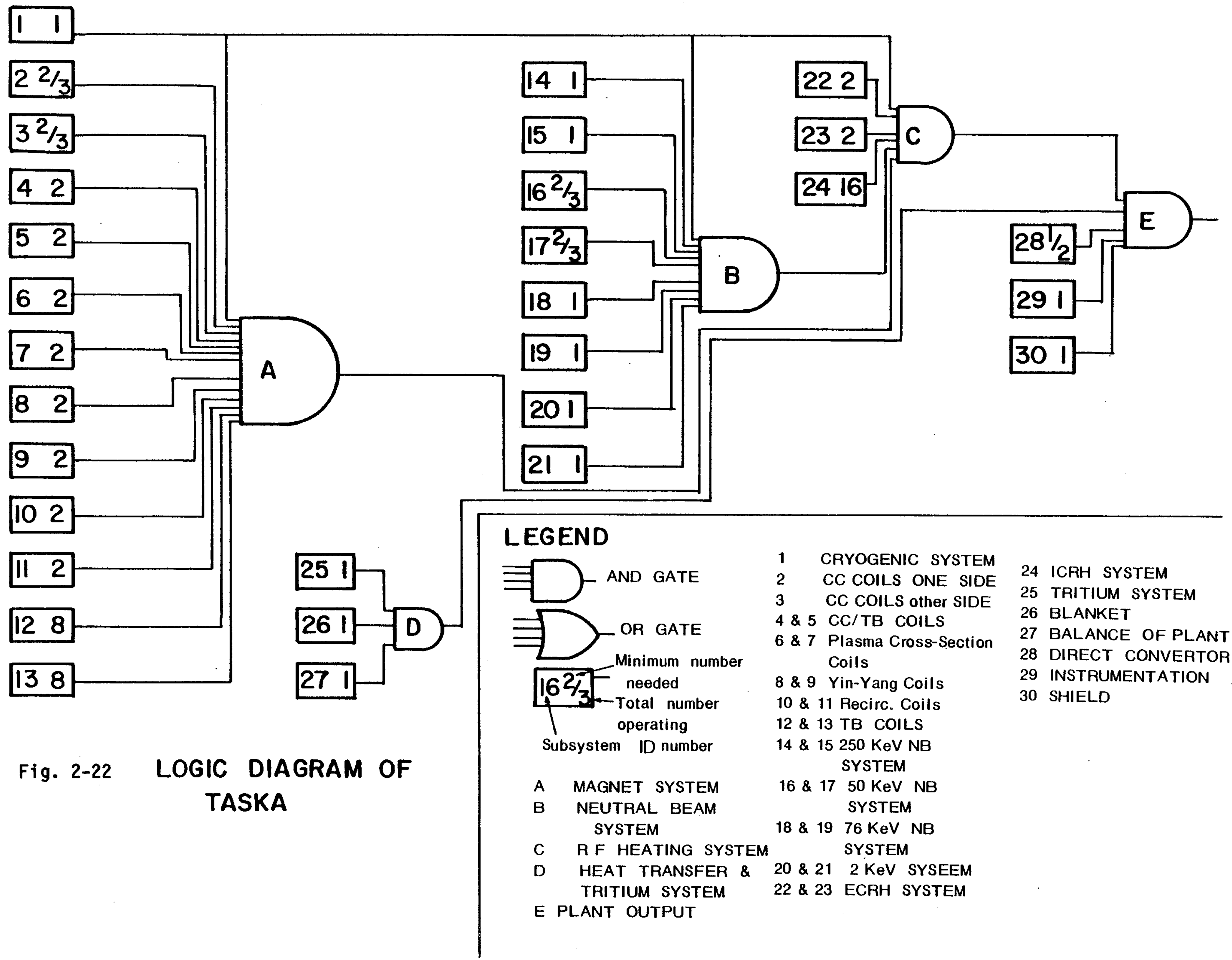


Fig. 2-22 **LOGIC DIAGRAM OF TASKA**

Table 2-2. Main Subsystems in WITAMIR-I

Subsystem	Number of Units	Redundancy	Min. No.
Cryogenic subsyst.	1	0	1
Solenoid coils	22	0	21
End plug coils	1/side	0	1
500 keV NB	2/side	0	1
8.2 MW ECRH	2/side	0	2
TB coils	3/side	0	3
9.6 keV NB	4/side	0	3
190 keV NB	2/side	0	2
16.6 MW ECRH	4/side	0	2
Divertor coils	1	0	1
Fueling	1	0	1
Direct convertor	1	0	1
Vacuum	1	0	1
Shield	1	0	1
Blanket	1	0	1
BOP	1	0	1
Instrumentation	1	0	1

Table 2-3. Main Subsystem in TASKA

Susbystem	Number of Units	Redundancy	Min. No.
Shield	1	0	1
Blanket	1	0	1
CC coils (1 side)	3	0	2
CC-TB coils	2	0	2
Plasma cross section coils	2	0	2
Yin-yang coils	2	0	2
Recirc. coils	2	0	2
TB coils	8	0	8
Cryosystem and vacuum	1	0	1
Neutral beams (1 side)			
250 keV	1	1	1
50 keV	1	0	1
76 keV	1	0	1
2 keV	1	0	0
ECRH (1 side)	2	0	2
ICRH	16	0	13
Direct convertor (1 side)	1	0	1 either side
Instrumentation	1	0	1
Balance of Plant	1	0	1
Tritium System	1	0	1

proposed. Similar analysis can be undertaken for each subsystem (e.g., neutral beams, ECRH, etc.).

The computer code proposed to model this system uses the Monte Carlo simulation method, whereby randomness of failure is simulated by generating random numbers and using them to determine if a component fails or normally operates. The states of all components are then combined in the logical diagram of the system, from which it is determined whether the system is up or down in this time step. The process is repeated for each time step, until the mission time expires. One can then compute the availability of the system, knowing the total mission time and the total system up time. To get better statistics on this average system availability, one would have to repeat the above procedure for a number of trials.

The advantage of the Monte Carlo approach over a deterministic model is that the former may be more straightforward to use for complicated systems and for analyzing time-dependent behavior. Another advantage is that uncertainties in input data can be handled employing the Monte Carlo method. Also, complex time variations of λ (see below) can be handled using this method.

3.1 Definitions

Availability of a system is defined as the fraction of the time that the system is up and capable of delivering 100% of its rated output, i.e.:

$$A = (\text{up-time})/(\text{up-time} + \text{down-time}) \quad .$$

If q(t) represents the time dependent instantaneous unavailability, then the average unavailability, $\hat{q}$, over a one year period is

$$\hat{q} = \frac{1}{T} \int_0^T q(t)\, dt$$

where T = one year.

Each component has a quantity known as the failure rate, λ, which is the probability that a failure will occur within a specified time interval.

The inverse of a failure rate is the mean time between failures, MTBF, which is the statistical mean of the time that the component operates between failures.

Similarly, the mean time to repair a component, MTTR, is the statistical mean of the time it takes to repair the specified component.

One can define the mean installation time in an analogous fashion.

Now, both the failure rate and the repair rate are often assumed to be constant in time. A constant failure rate means that the instantaneous reliability of a component is a falling exponential:

$$R(t) = \exp(-\lambda t)$$

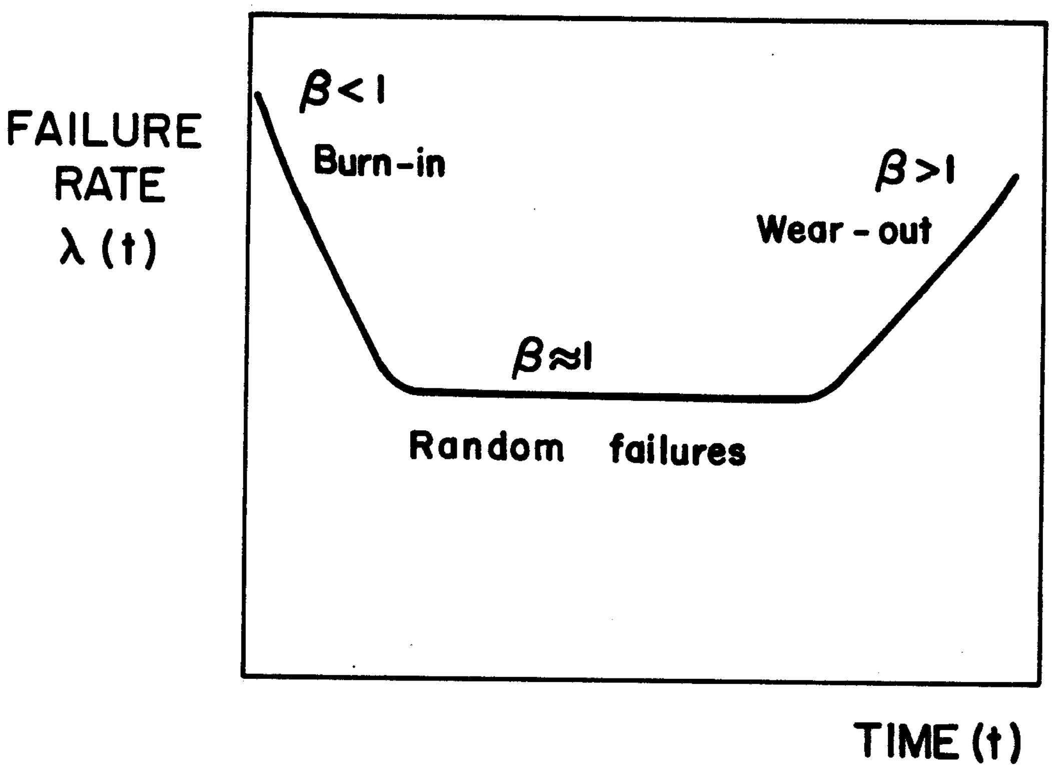
where R(t) is the probability that the component is working at time t.

However, in reality, components oftentimes have a time-dependent failure rate distribution. The most commonly used time-dependent failure rate distribution is the Weibull distribution:

$$\lambda(t) = \lambda_c \beta t^{\beta - 1} \qquad \lambda_c = \text{const.},\ \beta = \text{const.}$$

Failure rate distributions often resemble a bathtub curve (see Fig. 3-1).

Fig. 3-1.



FAILURE
RATE
λ (t)
β<1
Burn-in
β≈1
Random failures
β>1
Wear-out
TIME (t)

In the first (burn-in) period, the failure rate decreases with time, as the components are debugged, and defective ones discarded. Here, $\beta < 1$. The second period is characterized by an approximately constant failure rate, due to random failures, $\beta \approx 1$ in this period. In the third period, the failures occur with an increasing frequency. For this "wear-out" period, $\beta > 1$.

At present, we will model components using λ = const., due to lack of data on β.

If the system fails n times out of N trials, the average unavailability of the system is:

$$\hat{q} = n/N \quad .$$

The variance of $\hat{q}$ is:

$$\sigma_{\hat{q}}^2 = \frac{\hat{q}(1 - \hat{q})}{N}$$

(binomial distribution).

This can give us a clue as to how many trials are necessary in order to estimate $\hat{q}$ to a given percentage accuracy.

3.2 The Random Number Generator

The random number generator employs a congruential recursive method. This means that a random number is used for generation of the next random number. Random numbers generated are between 0. and 1.

First, the variables M, A, and X_0 are initialized. For our case, the best initial values are:

$$M = 2^{20}$$

$$A = 2^{10} + 3 \ .$$

For X_0, a different value will have to be used for each mission, otherwise the sequence of random numbers will be repeated. (A value of X_0 that worked well in the past is 566387.) Next, a variable X_n is calculated: $X_n = \mathrm{mod}_M(A.X_0)$.

X_n then becomes X_0 for the next random number; the nth random number itself is calculated as:

$$N_n = \mathrm{mod}_M(X_n \cdot A) \quad .$$

3.3 The Monte-Carlo Approach

In order to determine whether a certain component is up or down in a certain time interval, Δt, the instantaneous reliability of this component, is computed as:

$$R(t) = e^{-\lambda \Delta t} \quad .$$

Now a random number N_n between 0. and 1. is generated. If $N_n < R(t)$, no failure occurs in this time interval. If $N_n > R(t)$, failure of this component occurs in this time interval.

3.4 Repair

After a unit has undergone a failure, and the failure has been detected, the unit may go into the repair facility. The repair can be either immediate or deferred.

In immediate restoration, the repair of failed elements begins immediately upon failure. In deferred restoration, the repair of failed elements is deferred until the whole facility is shut down. This may be true of components that require the use of remote maintenance equipment (RME) to effect repairs.

Repair can also be parallel or serial. Parallel repair means that the repair facility has enough capacity to handle any and all components of the same type at the same time.

These options (immediate and deferred, parallel and serial repair) have not been employed in the computer code at this time.

At this stage, if a component failure is detected, and there are no readily available redundant or spare components of the same type, the execution of the main program is interrupted (this program keeps track of the total up time of the system) and subroutine REPAIR is entered. Within this subroutine, the component is not considered repaired until the elapsed time is equal to or greater than the component's mean time to repair (MTTR).

Should there be more than one type of component in the repair facility, the control is not returned to the main program until all of the components are "repaired". This effectively means that the system is shut down until all the vital components are operational.

If a redundant component fails, the main program is not interrupted. Instead, it just keeps track of the time that this redundant component has been down. When this time is greater than or equal to the MTTR of the component, it is considered repaired, and the number of available components of the given kind is updated by one.

Hence, in the present version of the computer code, the repair is immediate and parallel.

In order to include the deferred repair option, components will have to be identified that require the use of the RME. These components will be "flagged", such that if one of them fails, it would not be repaired concurrently with the system operation, but only after the system is shut down.

Serial repair can be included by somehow determining the maximum number of components of a given type that can be repaired simultaneously.

When the plant is shut down for repairs, that does not necessarily mean that all the unfailed subsystems have a zero probability of failure. Some subsystems will still be subjected to stresses that may be lower than during normal operation. The "idle" mode of operation is entered, whereby the failure rates of individual elements are adjusted, or multiplied by an off-line factor (OLF), between 0. and 1. Then the Monte Carlo procedure is repeated with these adjusted failure rates. At this point, it is unclear how the offline factors are to be obtained.

The scheduled maintenance is treated such that a 28-day period is set aside each year for this purpose. It is assumed, for now, that no residual failures occur when the plant is shut down.

3.5 Types of Components

We have considered, so far in this program, constant failure rate components that are continuously being monitored, with the probability of failure detection equal to unity.

The features incorporated to increase element reliability are redundancy, m-out-of-n operation and spares.

Redundant components are handled in such a way that a failure of one of them does not necessarily bring the system down. In other words, as explained above, the subroutine REPAIR is not called, unless all of the redundant components have failed. Instead, the component is "repaired" concurrently with the operation of the system, i.e. the "up-time clock" is updated as if nothing had happened.

m-out-of-n operation means that out of n components of a certain type that are on line, only m components are needed for the successful operation of the system. This means that first n-m failing components of this type are treated as redundant; failure of a greater number of components will bring the system down.

Spares. Some components will have spares on-site, due to excessive downtime required for repair. Spares usually require a certain installation time.

3.6 Improvements and Sophistication in the Type of Components Considered

Several improvements can be made in the code as it stands now. We can introduce the Weibull distribution in the failure rates of the components. This will also enable us to consider maintenance strategies, which would mean replacement of components in their wearout phase. One can also introduce periodic monitoring of redundant components, with a certain probability that the monitors will fail to detect a failure. Standby components can also be tested periodically, with probability that tests will themselves induce failures.

3.7 Gating

Individual components are represented by logic elements which are combined to form a system, using a collection of AND and OR gates. Each gate at its inputs can have individual logic elements and/or the outputs of other logic gates. The particular way in which components and gates are interconnected is read in as input to the computer program.

There are two ways to mathematically describe the logic gates, depending upon whether one is interested in the static or dynamic availability of the system.

For an AND gate, and for the static case, the availability at the output is equal to the product of availabilities at the input (see Fig. 3-2):

$$A = \prod_{i=1}^{N} a_i$$

where A is the output availability and a_i is the availability at the ith input.

For the dynamic case, the output of an AND gate is a "1" if and only if all of its inputs are "1", otherwise the output is a "0".

For an OR gate, and for the static case (Fig. 3-3):

$$A = 1 - \prod_{i=1}^{N} (1 - a_i) \quad .$$

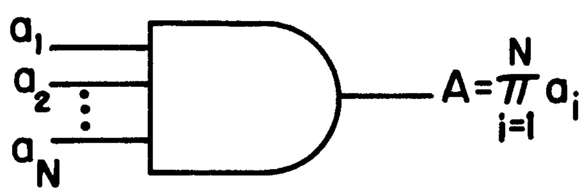
For the dynamic case, the output of an OR gate is a "0" if and only if all of its inputs are "0", otherwise the output is a "1".

The availability of the system is then equal to the availability at the output of the last logic gate in the schematic diagram of the system.

3.8 The Computer Code

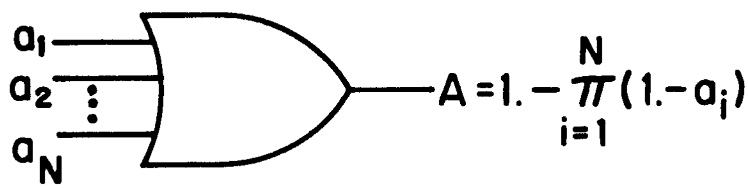
The flowchart of the computer code is presented in Fig. 3-4 and a sample input, output and the listing are appended to this chapter.

Fig. 3-2



AND GATE

Fig. 3-3



OR GATE

Sample Input

```
P 1000
25  10.  10000  4
1
21
1
1
1
1
1
1
4
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
4.0E-5  7.  0  1  0
4.6E-6  2.63E+4  0  1  0
4.6E-6  2.63E+4  0  1  0
2.55E-4  864.  0  1  0
4.57E-4  240.  0  1  0
4.6E-6  2.63E+4  0  1  0
4.6E-6  2.63E+4  0  1  0
4.6E-6  2.63E+4  0  1  0
2.55E-4  864.  0  1  1
2.55E-4  864.  0  1  0
4.57E-4  240.  0  1  0
4.6E-6  2.63E+4  0  1  0
1.14E-4  336.  0  1  0
2.30E-4  950.  1  1  0
5.71E-5  336.  0  1  0
2.28E-5  672.  0  1  0
1.71E-4  120.  0  1  0
1.1E-4  336.  0  1  0
2.55E-4  864.  0  1  0
4.57E-4  240.  0  1  0
2.55E-4  864.  0  1  0
4.57E-4  240.  0  1  0
4.57E-4  240.  0  1  0
4.57E-4  240.  0  1  0
5.7E-5  144.  0  1  0
26  4
```

```
2  0  0
2  0  0
2  0  0
2  0  0
2  0  0
0  2  0
0  0  2
0  0  2
0  0  2
0  0  2
0  2  0
0  2  0
2  0  0
2  0  0
3  0  0
2  0  0
2  0  0
2  0  0
0  2  0
0  2  0
0  2  0
1  1  0
0  11  0
3  0  0
3  1  0
1  4  0
1  4
1  21
1  10
1  19
1  9
3  4
1  1
2  2
3  3
4  4
5  5
6  6
1  2
1  3
1  6  7
1  8
1  12
1  15
14  14
15  15
16  16
14
17
7  8  9  10  11  12  13  19  20  21  18
16  17  18
13  1  17
18
25
23  24  25  22
2  0  0
2  0  0
2  0  0
0  2  0
5  22
11  20
23  24
2  1
*** TOP OF FILE ***
:
```

Sample Output

B@XQT REFUS.ABS
@ADD INPUT.
INPUT DATA

FLRT	MTTR	REDUN	IMRPR	MOFN
.4000-04	.7000+01	0	1	0
.4600-05	.2630+05	0	1	0
.4600-05	.2630+05	0	1	0
.2550-03	.8640+03	0	1	0
.4570-03	.2400+03	0	1	0
.4600-05	.2630+05	0	1	0
.4600-05	.2630+05	0	1	0
.4600-05	.2630+05	0	1	0
.2550-03	.8640+03	0	1	1
.2550-03	.8640+03	0	1	0
.4570-03	.2400+03	0	1	0
.4600-05	.2630+05	0	1	0
.1140-03	.3360+03	0	1	0
.2300-03	.9500+03	1	1	0
.5710-04	.3360+03	0	1	0
.2280-04	.6720+03	0	1	0
.1710-03	.1200+03	0	1	0
.1100-03	.3360+03	0	1	0
.2550-03	.8640+03	0	1	0
.4570-03	.2400+03	0	1	0
.2550-03	.8640+03	0	1	0
.4570-03	.2400+03	0	1	0
.4570-03	.2400+03	0	1	0
.4570-03	.2400+03	0	1	0
.5700-04	.1440+03	0	1	0

SYSTS	DELT	TOTAL NO. OF TIME STEPS	NUMBER OF HISTORIES
25	.1000+02	10000	4

SYSTEM ID NO.	NUMBER OF IDENTICAL COMPONENTS OF SAME KIND
1	1
2	21
3	1
4	1
5	1
6	1
7	1
8	1
9	4
10	1
11	1
12	1
13	1
14	1
15	1
16	1
17	1
18	1
19	1
20	1
21	1
22	1
23	1
24	1
25	1

NUMBER OF AND GATES = 26 NUMBER OF OR GATES = 4

SYSNO	TOTAL FAILURES	UP TIME	DN TIME	AVAILABILITY
1	.0000	.9999+05	.0000	.1000+01
2	.3000+01	.2924+05	.7075+05	.2924+00
3	.0000	.9999+05	.0000	.1000+01
4	.2000+01	.9825+05	.1740+04	.9826+00
5	.7000+01	.9831+05	.1680+04	.9832+00
6	.0000	.9999+05	.0000	.1000+01
7	.0000	.9999+05	.0000	.1000+01
8	.0000	.9999+05	.0000	.1000+01
9	.1100+02	.9825+05	.1740+04	.9826+00
10	.3000+01	.9738+05	.2610+04	.9739+00
11	.5000+01	.9879+05	.1200+04	.9880+00
12	.0000	.9999+05	.0000	.1000+01
13	.0000	.9999+05	.0000	.1000+01
14	.1000+01	.9999+05	.0000	.1000+01
15	.1000+01	.9965+05	.3400+03	.9966+00
16	.1000+01	.9931+05	.6800+03	.9932+00
17	.3000+01	.9963+05	.3600+03	.9964+00
18	.3000+01	.9897+05	.1020+04	.9898+00
19	.2000+01	.9825+05	.1740+04	.9826+00
20	.5000+01	.9879+05	.1200+04	.9880+00
21	.3000+01	.9738+05	.2610+04	.9739+00
22	.3000+01	.9927+05	.7200+03	.9928+00
23	.3000+01	.9927+05	.7200+03	.9928+00
24	.3000+01	.9927+05	.7200+03	.9928+00
25	.1000+01	.9984+05	.1500+03	.9985+00

AND GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9826+00	.9072+00
2	.9739+00	.8992+00
3	.9739+00	.8992+00
4	.9826+00	.9072+00
5	.9826+00	.9072+00
6	.9569+00	.8836+00
7	.9998+00	.9231+00
8	.9997+00	.9230+00
9	.9999+00	.9232+00
10	.9991+00	.9225+00
11	.9655+00	.8914+00
12	.9158+00	.8455+00
13	.2924+00	.2700+00
14	.1000+01	.9233+00
15	.1000+01	.9233+00
16	.1000+01	.9233+00
17	.1000+01	.9233+00
18	.9966+00	.9202+00
19	.1000+01	.9233+00
20	.1000+01	.9233+00
21	.1000+01	.9233+00
22	.1000+01	.9233+00
23	.2573+00	.2375+00
24	.9795+00	.9044+00
25	.9930+00	.9168+00
26	.2499+00	.2307+00

OR GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9999+00	.9232+00
2	.9999+00	.9232+00
3	.9999+00	.9233+00
4	.9995+00	.9229+00

SYSNO	TOTAL FAILURES	UP TIME	DN TIME	AVAILABILITY
1	.2000+01	.1001+06	.1000+02	.9999+00
2	.2000+01	.4749+05	.5260+05	.4745+00
3	.0000	.1001+06	.0000	.1000+01
4	.3000+01	.9748+05	.2610+04	.9739+00
5	.6000+01	.9865+05	.1440+04	.9856+00
6	.0000	.1001+06	.0000	.1000+01
7	.0000	.1001+06	.0000	.1000+01
8	.0000	.1001+06	.0000	.1000+01
9	[illegible]	.9661+05	.3480+04	.9652+00
10	.4000+01	.9661+05	.3480+04	.9652+00
11	.1100+02	.9745+05	.2640+04	.9736+00
12	.0000	.1001+06	.0000	.1000+01
13	.2000+01	.9941+05	.6800+03	.9932+00
14	.2000+01	.9957+05	.5200+03	.9948+00
15	.0000	.1001+06	.0000	.1000+01
16	.1000+01	.9941+05	.6800+03	.9932+00
17	.3000+01	.9973+05	.3600+03	.9964+00
18	.3000+01	.9907+05	.1020+04	.9898+00
19	.4000+01	.9661+05	.3480+04	.9652+00
20	.1200+02	.9721+05	.2880+04	.9712+00
21	.2000+01	.9835+05	.1740+04	.9826+00
22	.1000+02	.9769+05	.2400+04	.9760+00
23	.1100+02	.9745+05	.2640+04	.9736+00
24	.4000+01	.9913+05	.9600+03	.9904+00
25	.1000+01	.9994+05	.1500+03	.9985+00

AND GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9738+00	.8991+00
2	.9825+00	.9072+00
3	.9651+00	.8911+00
4	.9651+00	.8911+00
5	.9651+00	.8911+00
6	.9315+00	.8600+00
7	.9993+00	.9227+00
8	.9985+00	.9219+00
9	.9995+00	.9228+00
10	.9991+00	.9225+00
11	.9315+00	.8600+00
12	.8677+00	.8011+00
13	.4744+00	

		.4380+00
14	.9999+00	.9232+00
15	.9999+00	.9232+00
16	.9999+00	.9232+00
17	.9999+00	.9232+00
18	.9999+00	.9232+00
19	.9998+00	.9231+00
20	.9998+00	.9231+00
21	.9998+00	.9231+00
22	.9947+00	.9184+00
23	.3318+00	.3525+00
24	.9795+00	.9044+00
25	.9894+00	.9135+00
26	.3675+00	.3393+00

OR GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9997+00	.9230+00
2	.9992+00	.9226+00
3	.9997+00	.9231+00
4	.9995+00	.9229+00

SYSNO	TOTAL FAILURES	UP TIME	DN TIME	AVAILABILITY
1	.1000+01	.9998+05	.1000+02	.9999+00
2	.2000+01	.4739+05	.5260+05	.4739+00
3	.0000	.9999+05	.0000	.1000+01
4	.5000+01	.9531+05	.4180+04	.9582+00
5	.7000+01	.9831+05	.1680+04	.9832+00
6	.0000	.9999+05	.0000	.1000+01
7	.0000	.9999+05	.0000	.1000+01
8	.0000	.9999+05	.0000	.1000+01
9	.1900+02	.9668+05	.3310+04	.9669+00
10	.4000+01	.9651+05	.3480+04	.9652+00
11	.7000+01	.9831+05	.1680+04	.9832+00
12	.0000	.9999+05	.0000	.1000+01
13	.1000+01	.9965+05	.3400+03	.9966+00
14	.4000+01	.9895+05	.1040+04	.9896+00
15	.0000	.9999+05	.0000	.1000+01
16	.1000+01	.9931+05	.6800+03	.9932+00
17	.4000+01	.9951+05	.4800+03	.9952+00
18	.3000+01	.9897+05	.1020+04	.9898+00
19	.6000+01	.9477+05	.5220+04	.9478+00
20	.1000+02	.9759+05	.2400+04	.9760+00
21	.3000+01	.9738+05	.2610+04	.9739+00
22	.6000+01	.9855+05	.1440+04	.9856+00
23	.8000+01	.9807+05	.1920+04	.9808+00
24	.3000+01	.9927+05	.7200+03	.9928+00
25	.1000+01	.9984+05	.1500+03	.9985+00

AND GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9581+00	.8846+00
2	.9738+00	.8991+00
3	.9651+00	.8911+00
4	.9477+00	.8750+00
5	.9668+00	.8926+00
6	.9146+00	.8445+00
7	.9995+00	.9229+00
8	.9992+00	.9226+00
9	.9997+00	.9230+00
10	.9978+00	.9213+00
11	.9347+00	.8630+00
12	.8365+00	.7724+00
13	.4739+00	.4376+00
14	.9999+00	.9232+00
15	.9999+00	.9232+00
16	.9999+00	.9232+00
17	.9999+00	.9232+00
18	.9999+00	.9232+00
19	.9998+00	.9231+00
20	.9998+00	.9231+00
21	.9998+00	.9231+00
22	.9895+00	.9136+00
23	.3689+00	.3406+00
24	.9783+00	.9033+00
25	.9916+00	.9156+00
26	.3536+00	.3265+00

OR GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9998+00	.9231+00
2	.9996+00	.9229+00
3	.9999+00	.9232+00
4	.9989+00	.9223+00

SYSNO	TOTAL FAILURES	UP TIME	DN TIME	AVAILABILITY
1	.0000	.9999+05	.0000	.1000+01
2	.2000+01	.5370+05	.4629+05	.5371+00
3	.1000+01	.7369+05	.2630+05	.7370+00
4	.3000+01	.9738+05	.2610+04	.9739+00
5	.8000+01	.9807+05	.1920+04	.9808+00
6	.0000	.9999+05	.0000	.1000+01
7	.0000	.9999+05	.0000	.1000+01
8	.0000	.9999+05	.0000	.1000+01
9	.8000+01	.9999+05	.0000	.1000+01
10	.2000+01	.9825+05	.1740+04	.9826+00
11	.5000+01	.9879+05	.1200+04	.9880+00
12	.0000	.9999+05	.0000	.1000+01
13	.0000	.9999+05	.0000	.1000+01
14	.1000+01	.9999+05	.0000	.1000+01
15	.1000+01	.9965+05	.3400+03	.9966+00
16	.1000+01	.9931+05	.6800+03	.9932+00
17	.2000+01	.9975+05	.2400+03	.9976+00
18	.2000+01	.9931+05	.6800+03	.9932+00
19	.1000+01	.9912+05	.8700+03	.9913+00
20	.4000+01	.9903+05	.9600+03	.9904+00
21	.3000+01	.9738+05	.2610+04	.9739+00
22	.5000+01	.9879+05	.1200+04	.9880+00
23	.4000+01	.9903+05	.9600+03	.9904+00
24	.2000+01	.9951+05	.4800+03	.9952+00
25	.0000	.9999+05	.0000	.1000+01

AND GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9739+00	.8992+00
2	.9739+00	.8992+00
3	.9826+00	.9072+00
4	.9913+00	.9153+00
5	.1000+01	.9233+00
6	.9740+00	.8993+00
7	.9995+00	.9229+00
8	.9998+00	.9231+00
9	.9999+00	.9232+00
10	.9986+00	.9220+00
11	.1000+01	.9233+00
12	.9488+00	.8760+00
13	.5371+00	.4959+00
14	.7370+00	.6804+00
15	.1000+01	.9233+00
16	.1000+01	.9233+00
17	.1000+01	.9233+00
18	.9966+00	.9202+00
19	.5431+00	.5015+00
20	.1000+01	.9233+00
21	.1000+01	.9233+00
22	.1000+01	.9233+00
23	.2752+00	.2541+00
24	.9841+00	.9086+00
25	.9942+00	.9180+00
26	.2693+00	.2486+00

OR GATE NUMBER	W/O SCEDULED MAINTENANCE AVAILABILITY	W/SCHEDULED MAINTENANCE AVAILABILITY
1	.9998+00	.9231+00
2	.9999+00	.9232+00
3	.1000+01	.9233+00
4	.9993+00	.9227+00

Computer Code Listing

```
?RT,S REFUS.MAIN

?17616611*REFUS(1).MAIN(12)
      C     SUBROUTINE MAIN READS THE INTERCONNECTION BETWEEN THE VARIOUS SUBSYSTEMS
      C     AND LOGIC GATES AND CALCULATED THE AVAILABILITY AT THE OUTPUT OF EACH LOGIC
      C     GATE
              DIMENSION IAN(100,3),IOR(100,3)
             DIMENSION CAND(100),COR(100),IASUB(100,20),IAAND(100,20),IAOR(100,
            *20),IOSUB(100,20),IOAND(100,20),IOOR(100,20)
             DIMENSION IFAIL(50),MTTR(50)
             DIMENSION REDUN(50,3),MOFN(50),IMRPR(50),FLRT(50)
                DIMENSION AVAIL(50)
              DIMENSION CAVM(100),COVM(100)
              COMMON/BXY/TIMTRL,MTTR,IFAIL
              COMMON/CCC/MMNNYY,A,XO
              COMMON/AXY/SYSTS,DELT
             COMMON/XY/TRIALS,REDUN,MOFN,IMRPR,FLRT
              COMMON/XY/AVAIL
              COMMON/XY/NUMB(50)
             INTEGER SYSTS,TIMTRL,TRIALS,REDUN
              INTEGER A
              REAL MTTR
              REAL FLRT
              MMNNYY=2**20
              A=2**10+3
              XO=566387.
              READ,SYSTS,DELT,TIMTRL,TRIALS
              READ,(NUMB(J),J=1,SYSTS)
             READ(5,-) (FLRT(J),MTTR(J),REDUN(J,1),IMRPR(J),MOFN(J),J=1,SYSTS)
             WRITE(6,10)
             WRITE(6,20)(FLRT(J),MTTR(J),REDUN(J,1),IMRPR(J),MOFN(J),J=1,SYSTS)
             READ,NUMAND,NUMOR
             WRITE(6,53) SYSTS,DELT,TIMTRL,TRIALS
              WRITE(6,60)
             WRITE(6,65) (J,NUMB(J),J=1,SYSTS)
             WRITE(6,70) NUMAND,NUMOR
              IF(NUMAND .EQ. 0)GOTO 101
              READ,((IAN(I,J),J=1,3),I=1,NUMAND)
              DO 11     I=1,NUMAND
               LL=IAN(I,1)
              IF(LL .EQ. 0)GOTO 201
              READ,(IASUB(I,L),L=1,LL)
     201      MM=IAN(I,2)
```

```
          IF(MM .EQ. 0)GOTO 202
          READ,(IAAND(I,L),L=1,MM)
  202     NN=IAN(I,3)
          IF(NN .EQ. 0)GOTO 11
          READ,(IAOR(I,L),L=1,NN)
  11      CONTINUE
  101      IF(NUMOR .EQ. 0)GOTO 102
         READ,((IOR(I,J),J=1,3),I=1,NUMOR)
         DO 12   I=1,NUMOR
          LL=IOR(I,1)
          IF(LL .EQ. 0)GOTO 203
          READ,(IOSUB(I,L),L=1,LL)
  203     MM=IOR(I,2)
          IF(MM .EQ. 0)GOTO 204
          READ,(IOAND(I,L),L=1,MM)
  204      NN=IOR(I,3)
          IF(NN .EQ. 0)GOTO 12
          READ,(IOOR(I,L),L=1,NN)
  12      CONTINUE
  C
  C     DESCRIPTION OV VARIABLES
  C     SYSTS   NUMBER OF SUBSYSTEMS
  C     DELT   TIME STEP SIZE
  C     TIMTRL   MAXIMUM NUMBER OF TIME STEPS
  C     TRIAL   NUMBER OF TRIALS
  C     FLRT(J)   FAILURE RATE OF SUBSYSTEM J
  C     MTTR(J)    MEAN TIME TO REPSIR OF SUBSYSTEM J
  C     REDUN(J,1)   HOW MANY REDUNDANT SUBSYSTEMS FOR SUBSYSTEM J
  C     REDUN(J,2)   HOW MANY AVAILABLE REDUNDANT SUBSYSTEMS J
  C     IMRPR(J)   1   FOR IMMEDIATE REPAIR OF SUBSYSTEM J
  C     0   IF REPAIR NOT IMMEDIATE
  C     MOFN(J)   HOW MANY SUBSYSTEMS OF J KIND CAN GO DOWN WITHOUT IMPAIRING THE
  C     NG OPERATION OF THE POWER PLANT
  C     NUMAND   NUMBER OF AND GATES
  C     NUMOR   NUMBER OF OR GATES
  C     IAN(I,1)   NUMBER OF SUBSYSTEMS CONNECTED DIRECTLY TO AND GATE I
  C     IAN(I,2)   NUM BER OF AND GATES CONNECTED DIRECTLY TO AND GATE I
  C     IAN(I,3)   NUMBER OF OR GATES CONNECTED DIRECTLY TO AND GATE I
  C     CAND(I)    AVAILABILITY OF AND GATE I WITHOUT SCHEDULED MAONTENANCE
  C     CAVM(I)    AVAILABILITY OF AND GATE I WITH SCHEDULED MAINTENANCE
```

```
C     (4 WEEKS PER YEAR ON THE AVERAGE)
C     SIMILARLY COR(I) REFERS TO AVAILABILITY OF OR GATE I WITHOUT SCHEDULED
C     MAINTENANCE, AND COVM(I) IS AVAILABILITY OF OR GATE I WITH SCHEDULED
C     MAINTENANCE
C   SYSTEM AVAILABILITY PROGRAM
C     FOR EACH TIME TRIAL
102     DO 50    IT=1,TRIALS
          CALL MAIN2
C     INITIALIZE CAND AND COR
        IF(NUMAND .EQ. 0)GOTO 103
        DO 50101    I=1,NUMOR
50101   COR(I)=-1.
       DO 501     I=1,NUMAND
501    CAND(I)=-1.
1       DO 531    I=1,NUMAND
C     CAND(I) GE 0 MEANS THE STATE OF ITH GATE HAS ALREADY BEEN CALCULATED, SO SK
C     IP
         IF(CAND(I) .GE. 0.)GOTO 531
       MM=IAN(I,2)
        IF(MM .EQ. 0)GOTO 205
       DO 532    L=1,MM
C     IAAND(I,L) IS THE NUMBER OF THE AND GATE CONNECTED TO THE LTH INPUT OF THE
C     ITH AND GATE
       N=IAAND(I,L)
C     CAND(N) IS THEN THE STATE OF THAT GATE (1. OR 0. IF ALREADY CALCULATED;   -1
C      IF AND GATE NUMBER N HAS NOT BEEN CALCULATED)
        IF(CAND(N) .LT. 0.)GOTO 531
532    CONTINUE
205      NN=IAN(I,3)
        IF(NN .EQ. 0)GOTO 206
       DO 533    L=1,NN
C     HERE, N IS THE NUMBER OF THE OR GATE THAT IS DIRECTLY CONNECTED TO THE LTH
C     INPUT OF THE ITH AND GATE
       N=IAOR(I,L)
C     COR(N) IS ITS STATUS(1. OR 0. IF ALREADY CALCULATED; -1 OTHERWISE)
         IF(COR(N) .LT. 0.)GOTO 531
533    CONTINUE
206      JJ=IAN(I,1)
       CAND(I)=1.
        IF(JJ .EQ. 0)GOTO 207
C     CALCULATE THE STATUS OF THE ITH AND GATE TAKING INTO ACCOUNT THE STATES
C     OF ALL INPUTS (WHETER SUBSYSTEM , AND GATES OR OR GATES)
       DO 333    J=1,JJ
```

```
C     IASUB(I,J) IS THE NUMBER OF THE SUBSYSTEM THAT IS DIRECTLY CONNECTED TO THE
C     JTH INPUT OF THE ITH AND GATE
       N=IASUB(I,J)
333     CAND(I)=CAND(I)*AVAIL(N)
207       IF(MM .EQ. 0)GOTO 208
       DO 334   J=1,MM
       M=IAAND(I,J)
334    CAND(I)=CAND(I)*CAND(M)
208    IF(NN .EQ. 0)GOTO 531
       DO 335   J=1,NN
       N=IAOR(I,J)
335    CAND(I)=CAND(I)*COR(N)
531    CONTINUE
103     IF(NUMOR .EQ. 0)GOTO 54
       DO 502  I=1,NUMOR
502    COR(I)=-1.
C     THE SAME PROCEDURE IS NOW REPATED FOR EACH OR GATE
       DO 541   I=1,NUMOR
        IF(COR(I) .GT. 0.)GOTO 541
       MM=IOR(I,2)
        IF(MM .EQ. 0)GOTO 211
       DO 542    L=1,MM
       N=IOAND(I,L)
542     IF(CAND(N) .LT. 0.)GOTO 541
211     NN=IOR(I,3)
        IF(NN .EQ. 0)GOTO 212
       DO 543    L=1,NN
       N=IOOR(I,L)
        IF(COR(N) .LT. 0.)GOTO 541
543     CONTINUE
212     JJ=IOR(I,1)
        IF(JJ .EQ. 0)GOTO 213
       COR(I)=1.
       DO 343    J=1,JJ
       N=IOSUB(I,J)
        COR(I)=COR(I)*(1.-AVAIL(N))
343    CONTINUE
       GOTO 3436
213     IF(MM .EQ. 0)GOTO 214
3436   DO 344    J=1,MM
       M=IOAND(I,J)
344     COR(I)=COR(I)*(1.-CAND(M))
```

```
           GOTO 3446
     214   IF(NN .EQ. 0)GOTO 541
     3446  DO 345    J=1,NN
           N=IOOR(I,J)
     345    COR(I)=COR(I)*(1.-COR(N))
            COR(I)=1.-COR(I)
     541    CONTINUE
     54     ICNT1=0
            JCNT1=0
            IF(NUMAND .EQ. 0)GOTO 7071
            DO 707  I=1,NUMAND
     707    IF(CAND(I) .LT. 0.)ICNT1=1
     7071   IF(NUMOR .EQ. 0)GOTO 7271
            DO 727  J=1,NUMOR
     727    IF(COR(I) .LT. 0.)JCNT1=1
     7271   IF(ICNT1 .EQ. 1  .OR.  JCNT1 .EQ. 1)GOTO 1
            IF(NUMAND .EQ. 0)GOTO 511
            DO 7171  I=1,NUMAND
     7171   CAVM(I)=0.9233*CAND(I)/(1.077-0.153*CAND(I))
            WRITE(6,180)
            WRITE(6,80)
           DO 51      I=1,NUMAND
     51    WRITE(6,30)I,CAND(I),CAVM(I)
     511    IF(NUMOR .EQ. 0)GOTO 50
            DO 7373    I=1,NUMOR
     7373   COVM(I)=0.9233*COR(I)/(1.077-0.153*COR(I))
            WRITE(6,180)
            WRITE(6,90)
           DO 52    I=1,NUMOR
     52    WRITE(6,40) I,COR(I),COVM(I)
     50     CONTINUE
            STOP
       10  FORMAT(' ','INPUT DATA'//' ',T10,'FLRT',T30,'MTTR',T50,'REDUN',T70,
          *'IMRPR',T90,'MOFN')
     20    FORMAT(' ',T10,E10.4,T30,E10.4,T50,I3,T70,I3,T90,I3)
     30    FORMAT(' ',1X,I3,T25,E10.4,T55,E10.4)
     40    FORMAT(' ',1X,I3,T25,E10.4,T55,E10.4)
     53    FORMAT(' ','SYSTS',T20,'DELT',T40,'TOTAL NO. OF TIME STEPS',T70,'N
          *UMBER OF HISTORIES'/' ',I3,T20,E10.4,T40,I7,T70,I3)
     60    FORMAT(' ','SYSTEM ID NO.',T20,'NUMBER OF IDENTICAL COMPONENTS OF
          *SAME KIND')
     65     FORMAT(' ',I3,T20,I3)
     70    FORMAT(' ','NUMBER OF AND GATES =',I3,3X,'NUMBER OF OR GATES =',I3
          *)
     80     FORMAT(' ','AND GATE NUMBER',T25,'AVAILABILITY',T55,'AVAILABILITY')
```

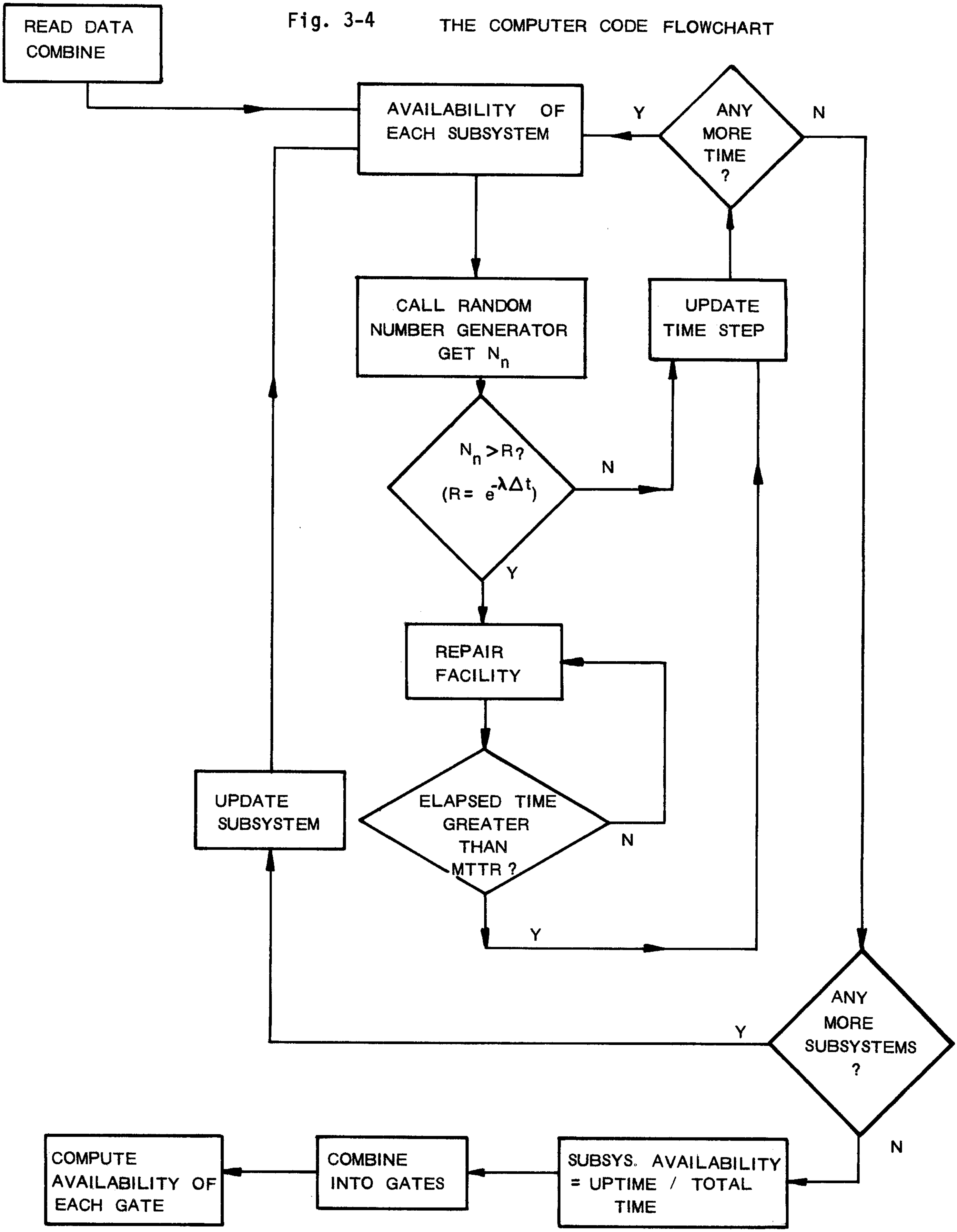
```
             *')
      90       FORMAT(' ','OR GATE NUMBER',T25,'AVAILABILITY',T55,'AVAILABILITY'
             *)
      180      FORMAT('0',T25,'W/O SCEDULED MAINTENANCE',T55,'W/SCHEDULED MAINTENANCE')
             *NANCE')
               END
---->EXIT PRT
RT,S REFUS.MAIN2

17616611*REFUS(1).MAIN2(17)
               SUBROUTINE MAIN2
                DIMENSION FLRT(50),AVAIL(50),SYSNO(5000),REL(50)
              DIMENSION REPTIM(50)
               DIMENSION REDUN(50,3)
              DIMENSION MOFN(50)
              DIMENSION IMRPR(50)
               COMMON/BBB/CLK(50,3),L,INDEX
              COMMON/BXY/TIMTRL,MTTR(50),IFAIL(50)
               COMMON/AXY/SYSTS,DELT
               COMMON/XY/TRLS,REDUN,MOFN,IMRPR,FLRT
               COMMON/XY/AVAIL
               COMMON/XY/NUMB(50)
              INTEGER SYSTS,TIMTRL
                INTEGER REDUN
               REAL MTTR
              WRITE(6,10)
      C INITIALIZE MATRICES
               DO 100     J=1,SYSTS
               REPTIM(J)=0.0
               AVAIL(J)=0.
      C      AVAIL(J)    AVAILABILITY OF SUBSYSTEM J
               REL(J)=1.
      C      REL(J)    RELIABILITY OF SUBSYSTEM J
               IFAIL(J)=0
      C      IFAIL(J)    IF 1    SUBSYSTEM J HAS FAILED
      C      IF 0 NO FAILURE
              REDUN(J,2)=MOFN(J)+REDUN(J,1)
      100      CONTINUE
               DO 150 J=1,SYSTS
```

```
      DO 150 I=1,3
C     CLK(J,1)   ELAPSED UP TIME
C     CLK(J,2)   TOTAL DOWN TIME
C     CLK(J,3)    NUMBER OF FAILURES SUBSYSTEM J HAS ENDURED DURING CURRENT TRIAL
  150 CLK(J,I)=0.0
      L=0
      INDEX=TIMTRL
      DO 400     I=1,INDEX
      L=L+1
      ICONT=0
      DO 300     J=1,SYSTS
C     CHECK FOR REDUNDANCY,IMMED. REPAIR,SPARES
      IF(REDUN(J,2) .EQ. (REDUN(J,1)+MOFN(J))) GOTO 340
      IF(IMRPR(J) .EQ. 0)GOTO 340
C   REPAIR OF REDUNDANT,SPARE SYSTEMS
      REPTIM(J)=REPTIM(J)+DELT
      IF(REPTIM(J) .LT. MTTR(J))GOTO 340
      REDUN(J,2)=REDUN(J,2)+1
       REPTIM(J)=0.
340   CLK(J,1)=CLK(J,1)+DELT
      IF(REDUN(J,2) .GE. MOFN(J))GOTO 7471
      MMMM=NUMB(J)-(MOFN(J)-REDUN(J,2))
      GOTO 881
7471  MMMM=NUMB(J)
881   DO 300    K=1,MMMM
C  ASSOCIATE RANDOM NUMBER WITH SYSTEMS
       CALL RANDNO(ANO)
      SYSNO(J)=ANO
C     RELIABILITY OF SUBSYSTEM J
      REL(J)   =EXP(-FLRT(J)*DELT)
C     TOSS THE COIN TO DETERMINE IF SUSSYTEM J IS UP OR DOWN
      IF(REL(J)    .LT. SYSNO(J))GOTO 350
      GOTO 300
350   CLK(J,3)=CLK(J,3)+1.
C     IN THIS CASE SUBSYSTEM J IS DOWN
       IF(REDUN(J,2) .NE. 0)GOTO 351
C     ARE THERE ANY REDUNDANT  AVAILABLE J SUBSYSTEMS
      REL(J)=0.
      IFAIL(J)=1
C     IFAIL(J)=1 SIGNIFIES SUBSYSTEM J IN FAILED STATE
      ICONT=1
```

```
C     ICONT=1 AT LEAST ONE SUSSYSTEM HAS FAILED
            GOTO 300
351     REDUN(J,2)=REDUN(J,2)-1
C     DECREASE THE AVAILABILITY OF REDUNDANT J SUBSYSTEMS (USED ONE UP DUE TO FAI
C     LURE)
300     CONTINUE
        IF(ICONT .EQ. 0)GOTO 400
C     ICONT=0 NO REPAIR NECESSARY
        CALL REPAIR(M)
        L=L+M
        IF(L .GE. INDEX)GOTO 401
400     CONTINUE
401     DO 75 J=1,SYSTS
C   CALCULATE SYSTEM AVAILABILITY
        AVAIL(J)=CLK(J,1)/(CLK(J,1)+CLK(J,2))
C     FOR EACH SUBSYSTEM, CALCULATE ITS AVAILABILITY IN THIS TIME TRIAL
75     WRITE(6,20) J,CLK(J,3),CLK(J,1),CLK(J,2),AVAIL(J)
         RETURN
10     FORMAT(' ','SYSNO',T10,'TOTAL FAILURES',T30,'UP TIME',T50,'DN TIME
      *',T70,'AVAILABILITY')
20     FORMAT(' ',I3,T10,E10.4,T30,E10.4,T50,E10.4,T70,E10.4)
        END


--->EXIT PRT
T,S REFUS.RANDNO

7616611*REFUS(1).RANDNO(2)
        SUBROUTINE RANDNO(ANO)
C     SUBROUTINE RANDNO  CALCULATESZ RANDOM NUMBERS BETWEEN 0 AND 1 BY USING
C     RECURSIVE CONGRUENTIAL METHOD
         COMMON/CCC/M,A,XO
         INTEGER A
        XN=XO*A-M*IFIX(XO*A/M)
C     XN OF THE CURRENT RANDOM NUMBER IS USED AS THE STARTING STEP FOR GENERATION
C     OF THE NEXT RANDOM NUMBER
        XO=XN
        ANO=(XN/M*A)-IFIX(XN/M*A)
        RETURN
        END
--->EXIT PRT
```

```
@PRT,S REFUS.REPAIR

3917616611*REFUS(1).REPAIR(16)
                 SUBROUTINE REPAIR(M)
        C     SUBROUTIME REPAIR CHECKS EACH SUBSYSTEM TO SEE IF IT NEEDS REPAIR;   IF IT
        C      DOES, IT MARKS THE TIME UNTIL THE ELAPSED REPAIR TIME IS GREATER THAN THE
        C     SUBSYSTEM J REPAIR TIME
               DIMENSION IFAIL(50),MTTR(50)
                DIMENSION CLK(50,3)
                DIMENSION RPRTIM(50)
                COMMON/AXY/SYSTS,DELT
                COMMON/BXY/TIMTRL,MTTR,IFAIL
                COMMON/BBB/CLK,LL,INDEX
                REAL MTTR
                INTEGER SYSTS,TIMTRL
                DO 600    I=1,SYSTS
        600     RPRTIM(I)=0.
                MMM=LL
                DO 900     L=1,INDEX
                M=L
                MMM=MMM+1
                IF(MMM .GE. INDEX)GOTO 801
                DO 800      J=1,SYSTS
                IF (IFAIL(J) .EQ. 0)GOTO 850
                RPRTIM(J)=RPRTIM(J)+DELT
                CLK(J,2)=CLK(J,2)+DELT
                IFC=1
                IF(RPRTIM(J) .GE. MTTR(J))GOTO 750
                GOTO 800
        850     CLK(J,1)=CLK(J,1)+DELT
                GOTO 800
        750     IFC=0
                IFAIL(J)=0
        800     CONTINUE
                IF(IFC .EQ. 0)GOTO 801
        900     CONTINUE
        801    RETURN
                END
------>EXIT PRT
```

Fig. 3-4 THE COMPUTER CODE FLOWCHART



The input consists of:

- Number of components; time interval; number of time intervals one wants to look at; number of trials (or histories of the whole system);
- number of identical components of each kind;
- for each component: failure rate; MTTR; number of redundant components; immediate repair (1-yes, 0-no); m-of-n, i.e. how many components of the given kind are operating above the necessary minimum number;
- number of AND gates; number of OR gates;
- for each AND gate: number of individual components at inputs; number of AND gates at input; number of OR gates at input;
- for each OR gate: number of individual components at inputs; number of AND gates at inputs; number of OR gates at inputs;
- for each AND gate: ID number of each component at its inputs; ID number of each AND gate at its inputs; ID number of each OR gate at its inputs;
- for each OR gate: ID number of each component at its inputs; ID number of each AND gate at its inputs; ID number of each OR gate at its inputs.

4. DATA

This chapter will present the techniques and the sources that we employed to garner the data for the analysis to be undertaken. We will also show how the data may be manipulated to obtain more useful information.

4.1 Types of Data Needed

The data needed are the mean times to repair and the failure rates of components. This data is obviously needed as input because we are using the exponential failure probability distribution; mean time to repair is used in the REPAIR subroutine. The above data is very hard to come by, especially for components that have never been built, so sometimes, rough estimates will be used. In order to evaluate the impact of not having "hard" data, we have asked our sources to estimate the confidence level that they have in the numbers they have supplied.

4.2 Sources of Data

Acquisition of good failure data is often the most important and frustrating part of reliability analysis. Most of the data sources give only the average constant hazard rate, rather than time dependent values. Reliability and availability analysis is a relatively recent branch of engineering analysis, and for many components and systems, data simply have not been compiled. Other systems or components for this study are relatively new, or in the research/development stage, so no appreciable operating experience really exists.

In order to obtain failure rate data, many failures of a given type of component have to be observed; also the total population size must be known; some of these records are difficult to keep track of. In addition, the reliability of a component is a function of its design and quality of manufacture as well as the operating environment (temperature, pressure, electrical and mechanical stresses, cycling-of-operation, etc.).

In order to judge the effect of environmental factors and the quality and frequency of maintenance, other information must be associated with failure data:

1. modes of failure experienced (e.g., "fails open", "fails closed", "fails under load", etc.)
2. sample size
3. environmental or special working conditions

4. the number of successful functions in relation to the failures, particularly in the case of equipment subject to an intermittent cycle of operation
5. true running time during the survey period, particularly for equipment which is run for standby or backup purposes at random times during the survey period
6. repair time
7. time intervals between failure
8. frequency of, or intervals between, periodic inspection of proof tests.

Number 2, sample size, is important because for many components only a very limited number of failure data exists. This is especially true of high-cost devices, because fewer tests have been performed on them.

4.3 Sources of Failure Data

Collecting failure data for a variety of devices is an enormous task. Up until a few years ago, most of the data was of a specialized nature, pertaining to military, aeronautical and space applications.

As a part of the Reactor Safety Study, a data base was compiled (and is still being expanded by the Nuclear Regulatory Commission) using sources such as incident reports at nuclear facilities, Edison Electric Institute failure data, and military sources.

Other sources include:

- IEEE STD-500-1977 gives reliability figures for electronics, electric and sensing components in nuclear power plants. Similar data are compiled in MIL-HDBK-217B for military electronic components. For non-electronic components in military hardware, one can go to the Non-electronic Parts

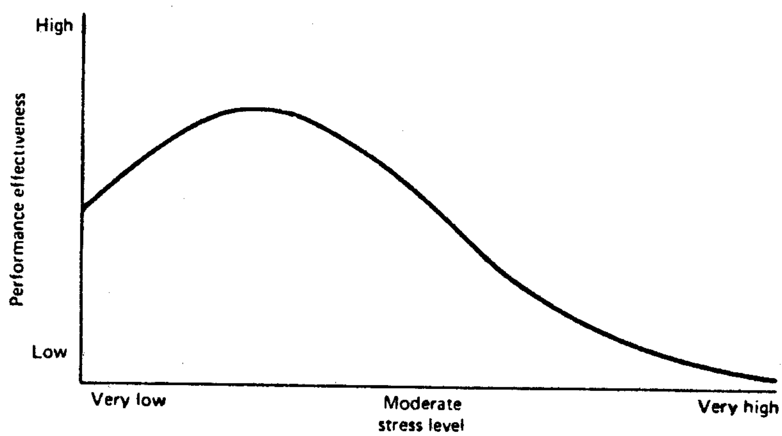
Reliability Databook (NPRD), put out by the Rome Air Development Center of the Air Force.

- Another possibility is the Government-Industry Data Exchange Program (GIDEP) operated by the Navy. This is a cooperative program between the government and the industry, where maintainability-reliability data and alert reports on potential problems can be found. Much of the data is not processed into an immediately useful form, such as failure rates.
- As for the human factor, some research has been done, indicating that the human operator error rate is dependent on the level of stress in a particular situation (see Fig. 4-1). For high stress situations such as a Loss of Coolant Accident in a nuclear power plant, a rough error rate estimate is 0.2 to 0.3. It is possible that this can be decreased with increased training.

Some representative failure rates and human error rates are given in Table 4-1. Data used in the TASKA analysis is shown in Table 4-2. However, for many of the components to be used in a fusion power plant, there are no published data available, nor has there been any operating experience with a full size model.

In this case, one can possibly use data for existing analogous equipment; for example, one could use data on accelerator failure for certain components of the neutral beam system. Another approach, which will be used to a great extent, will be to talk to people in the field, who are expert in the particular subsystem of interest (e.g., neutral beams, ECRH, cryogenics, etc.) and ask them what they feel would be reasonably achievable reliability figures for that particular subsystem.

Fig. 4-1



Hypothetical relationship between human performance and stress.

Table 4-1. Hazard Rates, Failure Probabilities and Error Rates for Mechanical and Electrical Equipment and Human Operators

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_s	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/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_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/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_s	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/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_s (severe)	$1 \times 10^{-7} - 1 \times 10^{-6}$/hr	3×10^{-7}/hr	3
	Rupture λ_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/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_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/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_s	$1 \times 10^{-9} - 1 \times 10^{-7}$/hr	1×10^{-8}/hr	10
8. *Pipes*				
a. Pipe ≤ 7.5 cm diam per section	Rupture/plug λ_s, 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_s, 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 4-1. (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_0	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_0 (normal environment)	3×10^{-6}–3×10^{-5}/hr	1×10^{-5}/hr	3
	Failure to run, given start λ_0 (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_0	1×10^{-7}–1×10^{-6}/hr	3×10^{-7}/hr	3
	Failure of NC contacts by opening, given not energized λ_0	3×10^{-8}–3×10^{-7}/hr	1×10^{-7}/hr	3
	Short across NO/NC contact λ_0	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
	Coil open λ_0	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Coil short to power λ_0	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_0	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_0	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Failure of NC by opening, given no switch operation λ_0	3×10^{-9}–3×10^{-7}/hr	3×10^{-8}/hr	10
	Short across NO/NC contact λ_0	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
7. Battery power systems (wet cell)	Failure to provide proper output λ_0	1×10^{-6}–1×10^{-5}/hr	3×10^{-6}/hr	3
8. Transformers	Open circuit primary or secondary λ_0	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
	Short primary to secondary λ_0	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_0	3×10^{-7}–3×10^{-5}/hr	3×10^{-6}/hr	10
	Fails shorted λ_0	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
b. Solid state devices, low power applications	Fails to function λ_0	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_0	3×10^{-4}–3×10^{-2}/hr	3×10^{-3}/hr	10
b. Diesels (engine only)	Failure to run, emergency conditions, given start λ_0	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_0	1×10^{-7}–1×10^{-5}/hr	1×10^{-6}/hr	10
	Shift in calibration λ_0	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_0	3×10^{-7}–3×10^{-6}/hr	1×10^{-6}/hr	3
13. Wires (typical circuits, several joints)	Open circuit λ_0	1×10^{-6}–1×10^{-5}/hr	3×10^{-6}/hr	3
	Short, to ground λ_0	3×10^{-8}–3×10^{-6}/hr	3×10^{-7}/hr	10
	Short to power λ_0	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10
14. Terminal boards	Open connection λ_0	1×10^{-8}–1×10^{-6}/hr	1×10^{-7}/hr	10
	Short to adjacent circuit λ_0	1×10^{-9}–1×10^{-7}/hr	1×10^{-8}/hr	10

Table 4-1. (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.

Table 4-2. Failure Rates and Mean Times to Repair for Various Subsystems in TASKA

Subsystem	λ (hr^{-1})	MTTR (hr)
Shield	2.3E-5, 1.9E-5, 5.7E-6	24., 240.
Blanket	1.7E-4, 1.1E-4, 1.9E-5	120., 240.
All Coils	3.8E-5, 4.6E-6, 2.9E-6	1056., 3600., 26298.
Cryosystem (Vacuum)	5.7E-5, 4.1E-5, 2.3E-5	24., 432., 4824.
All Neutral Beams	1.4E-3, 2.3E-4, 5.7E-5	24., 240., 864.
All ECRH	1.0E-3, 4.6E-4, 1.1E-5	240., 480.
ICRH	1.1E-4, 5.7E-5	240.
All Direct Convertors	2.3E-4, 1.1E-4, 2.3E-5	950.
Instrumentation	5.7E-5, 2.3E-5	144.
Balance of Plant	1.1E-4, 5.7E-5	240.
Tritium System	2.3E-5	60.

We have broken down each subsystem into its main components, and asked our sources to evaluate the mean time between failure (MTBF), the mean time to repair (MTTR) and the confidence level they have in these numbers. These numbers will then be used in the computer code.

A sample fill-out form is shown in Fig. 4-2.

4.4 Data Manipulation

In order to obtain useful numbers out of this analysis, we have to manipulate the raw data from the sources, because there are confidence levels attached to it. In some instances, an interval estimate (i.e., high and low value) rather than a point estimate of failure rates is given or a sample size from which the data is drawn may be too small.

When we have a small sample, the cumulative probability of failure of components in the sample is given in Table 4-3. This information can be used to fit the data to a specified distribution of cumulative failure probability, thus obtaining the parameters of the distribution (e.g., failure rate).

For example, ten identical devices are tested with failures occurring at 1.7, 3.5, 5.0, 6.5, 8.0, 9.6, 11., 13., 18., and 22. (*100) hr. It is believed that the data may be fitted with a Weibull distribution.

For the Weibull distribution, we will plot accumulated probability of failure on the ordinate using a log log scale, vs. time to failure on the abscissa, using a log scale. This is because the cumulative failure probability for a Weibull distribution is given by:

$$F(t) = 1 - \exp\left\{-(t/\beta)^{\alpha}\right\}$$

so

$$\ln \ln [1 - F(t)]^{-1} = -\alpha \ln \beta + \alpha \ln t$$

Fig. 4-2

ECRH

COMPONENT	TIME TO FAILURE	CONFIDENCE* LEVEL	TIME TO REPAIR	CONFIDENCE* LEVEL
GYROTRON				
MIRRORS				
POWER SUPPLY				

*Confidence levels: > 95%, 80-95%, 60-80%, 40-60%, < 40%

Sample data solicitation form.

Table 4-3. Cumulative Probabilities for a Small Sample

Table of Median Ranks r for Different Sample Sizes n

	Sample size *n*									
r	1	2	3	4	5	6	7	8	9	10
1	0.5000	0.2929	0.2063	0.1591	0.1294	0.1091	0.0943	0.0830	0.0741	0.0670
2		0.7071	0.5000	0.3864	0.3147	0.2655	0.2295	0.2021	0.1806	0.1632
3			0.7937	0.6136	0.5000	0.4218	0.3648	0.3213	0.2871	0.2594
4				0.8409	0.6853	0.5782	0.5000	0.4404	0.3935	0.3557
5					0.8706	0.7345	0.6352	0.5596	0.5000	0.4519
6						0.8909	0.7705	0.6787	0.6065	0.5481
7							0.9057	0.7979	0.7129	0.6443
8								0.9170	0.8194	0.7406
9									0.9259	0.8368
10										0.9330

	Sample size *n*									
r	11	12	13	14	15	16	17	18	19	20
1	0.0611	0.0561	0.0519	0.0483	0.0452	0.0424	0.0400	0.0378	0.0358	0.0341
2	0.1489	0.1368	0.1266	0.1178	0.1101	0.1034	0.0975	0.0922	0.0874	0.0831
3	0.2366	0.2175	0.2013	0.1873	0.1751	0.1644	0.1550	0.1465	0.1390	0.1322
4	0.3244	0.2982	0.2760	0.2568	0.2401	0.2254	0.2125	0.2009	0.1905	0.1812
5	0.4122	0.3789	0.3506	0.3263	0.3051	0.2865	0.2700	0.2553	0.2421	0.2302
6	0.5000	0.4596	0.4253	0.3958	0.3700	0.3475	0.3275	0.3097	0.2937	0.2793
7	0.5878	0.5404	0.5000	0.4653	0.4350	0.4085	0.3850	0.3641	0.3453	0.3283
8	0.6756	0.6211	0.5747	0.5347	0.5000	0.4695	0.4425	0.4184	0.3968	0.3774
9	0.7634	0.7018	0.6494	0.6042	0.5650	0.5305	0.5000	0.4728	0.4484	0.4264
10	0.8511	0.7825	0.7240	0.6737	0.6300	0.5915	0.5575	0.5272	0.5000	0.4755
11	0.9389	0.8632	0.7987	0.7432	0.6949	0.6525	0.6150	0.5816	0.5516	0.5245
12		0.9439	0.8734	0.8127	0.7599	0.7135	0.6725	0.6359	0.6032	0.5736
13			0.9481	0.8822	0.8249	0.7746	0.7300	0.6903	0.6547	0.6226
14				0.9517	0.8899	0.8356	0.7875	0.7447	0.7063	0.6717
15					0.9548	0.8966	0.8450	0.7991	0.7579	0.7207
16						0.9576	0.9025	0.8535	0.8095	0.7698
17							0.9600	0.9078	0.8610	0.8188
18								0.9622	0.9126	0.8678
19									0.9642	0.9169
20										0.9659

Table 4-3. (Continued)

Sample size *n*

r	21	22	23	24	25	26	27	28	29	30
1	0.0330	0.0315	0.0301	0.0288	0.0277	0.0266	0.0256	0.0247	0.0239	0.0231
2	0.0797	0.0761	0.0728	0.0698	0.0670	0.0645	0.0621	0.0599	0.0579	0.0559
3	0.1264	0.1207	0.1155	0.1108	0.1064	0.1023	0.0986	0.0951	0.0919	0.0888
4	0.1731	0.1653	0.1582	0.1517	0.1457	0.1402	0.1351	0.1303	0.1259	0.1217
5	0.2198	0.2099	0.2009	0.1927	0.1851	0.1781	0.1716	0.1655	0.1599	0.1546
6	0.2665	0.2545	0.2437	0.2337	0.2245	0.2159	0.2081	0.2007	0.1939	0.1875
7	0.3132	0.2992	0.2864	0.2746	0.2638	0.2538	0.2445	0.2359	0.2279	0.2204
8	0.3599	0.3438	0.3291	0.3156	0.3032	0.2917	0.2810	0.2711	0.2619	0.2533
9	0.4066	0.3884	0.3718	0.3566	0.3425	0.3295	0.3175	0.3063	0.2959	0.2862
10	0.4533	0.4330	0.4145	0.3975	0.3819	0.3674	0.3540	0.3415	0.3299	0.3191
11	0.5000	0.4776	0.4572	0.4385	0.4212	0.4053	0.3905	0.3767	0.3639	0.3519
12	0.5466	0.5223	0.5000	0.4795	0.4606	0.4431	0.4270	0.4119	0.3979	0.3848
13	0.5933	0.5669	0.5427	0.5204	0.5000	0.4810	0.4635	0.4471	0.4319	0.4177
14	0.6400	0.6115	0.5854	0.5614	0.5393	0.5189	0.5000	0.4823	0.4659	0.4506
15	0.6867	0.6561	0.6281	0.6024	0.5787	0.5568	0.5364	0.5176	0.5000	0.4835
16	0.7334	0.7007	0.6708	0.6433	0.6180	0.5946	0.5729	0.5528	0.5340	0.5164
17	0.7801	0.7454	0.7135	0.6843	0.6574	0.6325	0.6094	0.5880	0.5680	0.5493
18	0.8268	0.7900	0.7562	0.7253	0.6967	0.6704	0.6459	0.6232	0.6020	0.5822
19	0.8735	0.8346	0.7990	0.7662	0.7361	0.7082	0.6824	0.6584	0.6360	0.6151
20	0.9202	0.8792	0.8417	0.8072	0.7754	0.7461	0.7189	0.6936	0.6700	0.6480
21	0.9669	0.9238	0.8844	0.8482	0.8148	0.7840	0.7554	0.7288	0.7040	0.6808
22		0.9684	0.9271	0.8891	0.8542	0.8218	0.7918	0.7640	0.7380	0.7137
23			0.9698	0.9301	0.8935	0.8597	0.8283	0.7992	0.7720	0.7466
24				0.9711	0.9329	0.8976	0.8648	0.8344	0.8060	0.7795
25					0.9722	0.9354	0.9013	0.8696	0.8400	0.8124
26						0.9733	0.9378	0.9048	0.8740	0.8453
27							0.9743	0.9400	0.9080	0.8782
28								0.9752	0.9420	0.9111
29									0.9760	0.9440
30										0.9768

which is the equation of a straight line when the above mentioned scales are used.

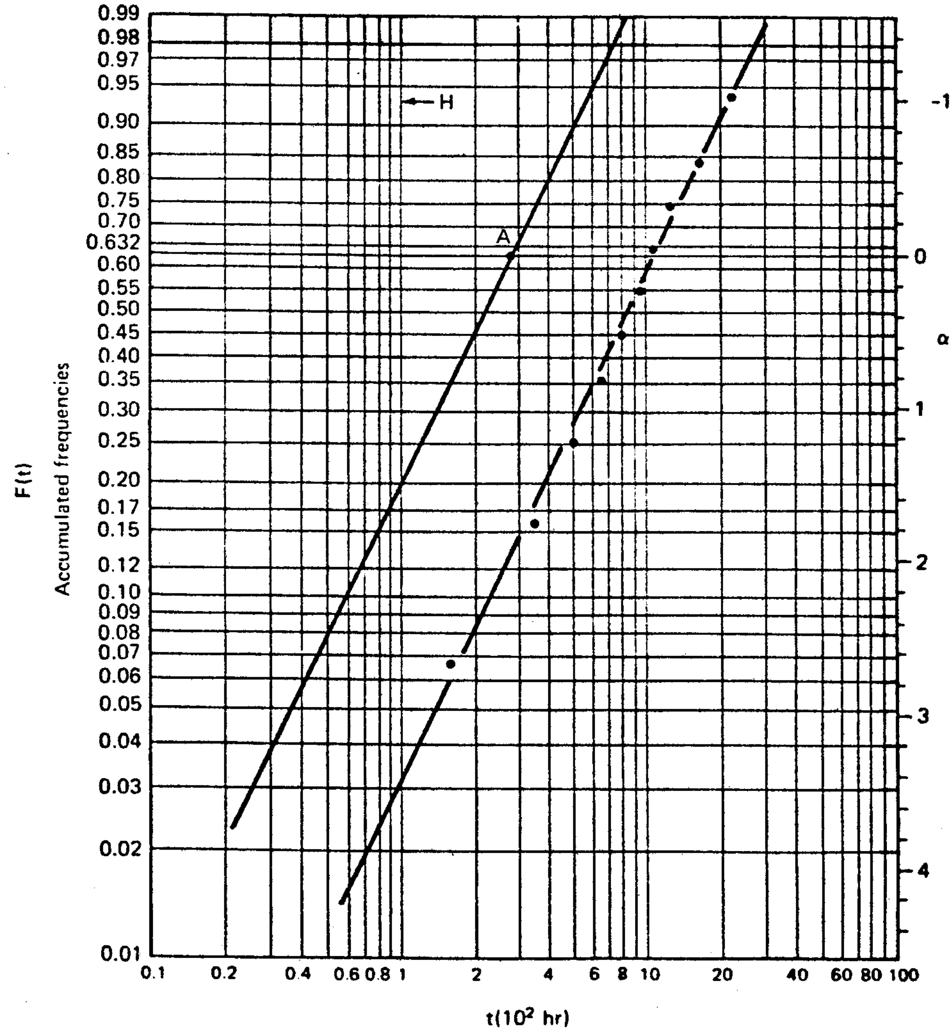
The ordinates corresponding to the given times to failure are found from Table 4-3 under sample size 10, to be: 0.0670, 0.1632, 0.2594, 0.3557, 0.4519, 0.5481, 0.6443, 0.7406, 0.8368, 0.9330.

Now, we draw a best straight line through the data (see Fig. 4-3). The value of β is equal to the value of t corresponding to $F(t) = 1. - e^{-1} = 0.632$. Hence, β = 1100 hr. To obtain α, a line parallel to that through data is drawn through the point A with coordinates (2.718, 0.632). The intercept of the line through A with the vertical line H, passing through abscissa 1., will give the value of α, read off the scale on the right hand side of the graph. In this case, $\alpha = 1.5$.

A similar technique can be used for estimating λ in the exponential distribution.

It is not clear at this time how the confidence levels are going to be incorporated into the analysis. One might, for example, take the statement: "40% confidence level that the average failure rate is $\overline{X}$" to mean the following: 40% of the the population of failure rates will fall within, say, 10% of either side of $\overline{X}$, and then, assuming a Gaussian distribution, one can estimate σ, the standard deviation. One can then look at $\overline{X} - \sigma$ as the lower limit, and $\overline{X} + \sigma$ as the upper limit of the failure rate of this device, and input these two values in the computer program; otherwise, some kind of sampling technique of the Gaussian failure rate distribution can be used.

Fig. 4-3



Fitting the data to the Weibull distribution.

5. PRELIMINARY RESULTS

For WITAMIR-I:

- It was found that the steady state availability for WITAMIR-I was around 20% when no redundancy in major subsystems was assumed. Data used were those employed for the analysis of the ETF facility, which represent an average between the pessimistic and the optimistic data. Assuming redundancy increases the availability markedly.
- The availability drivers were magnets (due to long repair time) and the neutral beam subsystem.

For TASKA:

- The results for the steady state availability under the above assumptions and assuming a 28-day scheduled annual shutdown period, are as follows:
  24-30% for the most pessimistic set of data;
  40-48% for the most reasonable set of data;
  74% for the most optimistic set of data.
  Due to the simplifying assumptions employed, the true values may be lower.
- The availability drivers are magnets, because there are so many of them and because their MTTR is relatively long (~ 40 days), due to the long time for warm-up and cool-down required for these cryogenic components. In order to improve the overall availability, the quality of magnets must be increased. The same holds true to a smaller extent for the neutral beam and the RF heating subsystems.

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