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Fusion Energy Division

AVAILABILITY PROGRAM: PHASE I REPORT

S. L. Thomson
Bechtel National, Inc.

A. Dabiri
Science Applications International Corporation

D. C. Keeton
Tennessee Valley Authority/Electric Power Research Institute

B. W. Riemer
Grumman Aerospace Corporation

L. M. Waganer
McDonnell Douglas Astronautics Company

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
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1. INTRODUCTION AND SUMMARY

1.1 BACKGROUND

An Availability Working Group was formed within the Office of Fusion Energy in March 1984 to consider the establishment of an availability program for magnetic fusion. The scope of this program is defined to include the development of (1) a comprehensive data base, (2) empirical correlations, and (3) analytical methods for application to fusion facilities and devices. The long-term goal of the availability program is to develop a validated, integrated methodology that will provide (1) projections of plant availability and (2) input to design decisions on maintainability and system reliability requirements.

The Phase I Study Group was commissioned to assess the status of work in progress that is relevant to the availability program. The scope of phase I included surveys of existing data and data collection programs at operating fusion research facilities, the assessment of existing computer models to calculate system availability, and the review of methods to predict and correlate data on component failure and maintenance. The results of these investigations are reported to the Availability Working Group in this document.

1.2 SCOPE

The long-term objectives of the availability program are related to the demonstration of the economics of fusion power, so the scope of the phase I investigations can be presented in terms of the information that will be required to assess the availability of a commercial fusion power plant. As the task flow diagram of Fig. 1 shows, an availability assessment requires a complete description of the plant, including possible failure modes and consequences. This description is used to construct a model for the plant operation, which is in turn used to calculate the plant availability for given operating options and for given data on failure rates, repair times, and scheduled maintenance.

The availability calculation models reviewed during phase I are described in Sect. 2. There are two distinct approaches to availability modeling: the deterministic and the stochastic. Either type of model can be used to calculate system availability, but their different input data requirements and capabilities make the selection of one over another dependent on the specific application. To further explore the capabilities and limitations of the models, example calculations were performed using both a deterministic and a stochastic model. These calculations are reported in Appendix A.

The essential input data to any of the models are the failure rates and repair or replacement times for the plant components and systems. The best source of these data is clearly the operation of identical equipment under similar conditions. This is available for those elements of the fusion balance of plant (BOP) that are adopted from existing power plants. For fusion-specific components, data must be predicted or extrapolated from current experience. In the long run, a comprehensive data base must be developed from near-term experimental projects.

Section 3 is an assessment of the ability to correlate or predict failure and repair data for the fusion components. The data required to permit correlation of data with causative factors are described in Sect. 3.1. Various maintenance approaches can be evaluated

Fig. 1. Task flow diagram for assessment of commercial fusion power plant availability. BOP = balance of plant, TTF = time to failure, TTR = time to repair.

through existing network analysis codes, and the simulation of the actual mechanical motion requirements is being developed through computer-aided design (CAD) system programs. These are discussed in Sect. 3.2. Finally, the estimation of future failure and repair rates through formal interrogation of experts is discussed in Sect. 3.3.

The status and prospects for obtaining data from existing or near-term fusion experimental facilities were reviewed primarily through discussions with the operators of those devices. Section 4 reports the results of these discussions, including the procedures used and recommended to collect data and the availability of data. Existing fusion programs relevant to the availability program and general attitudes toward the formation of a comprehensive data collection system are also discussed.

1.3 CONCLUSIONS AND RECOMMENDATIONS

The review of existing availability calculation models shows that they are sufficient to meet the needs of the fusion program. The models are not used to their potential because the quality of the input data for fusion systems does not warrant sophisticated availability analyses. In the near term, the best source of reliability input data is expected to be expert opinion, and the best source of repair data is expected to be maintenance simulation. In the long term, the development of a comprehensive and validated reliability, availability, and maintainability (RAM) data base will be essential to the fusion program, but the value of data from existing experimental devices is arguable. It is recommended that selective collection of experimental project data be initiated as a test of the timeliness and current value of a comprehensive data base. Detailed conclusions and recommendations follow.

1.3.1 Availability Models

Existing availability calculation models are sufficient to meet the needs of the fusion program. The deterministic model developed by the Electric Power Research Institute (EPRI) for advanced power system applications, UNIRAM, is recommended for rapid assessment of the effect of changes in design and input data on the overall system availability. Two stochastic codes developed specifically for fusion systems, the University of Wisconsin (UW) and the Fusion Engineering Design Center (FEDC) models, are recommended for more detailed systems analysis. These stochastic codes can assess more complex operating and maintenance scenarios, and they provide a more realistic model of the plant than the deterministic code does. Both the UW and FEDC codes are in development, and neither has reached the limits of the stochastic model capability. It is recommended that use and development of both continue so that the codes' progress can be reviewed by sample case comparisons.

1.3.2 Data Requirements

Availability models are not routinely used in design studies, and they are not used to their full potential. The reason is that the models are already well advanced compared with the availability and quality of the input data. Effective use of the models requires detailed design definition and realistic inputs for failure rates and repair times. Essential elements

of the design definition are the complete definition of systems and components, the identification of failure modes and consequences, and the specification of the maintenance approach. The degree of definition in most preconceptual design studies does not warrant the use of a sophisticated availability model. The fusion component failure and repair inputs to the model are estimates based largely on the experience of people familiar with the development of similar components. These data are useful for rough estimates of plant availability or, as is more commonly the case, for apportionments of the availability of each component to achieve the plant target availability.

No systematic method was discovered to formalize the correlation of RAM data so that data for analogous systems could be derived. The development of such a method would require the collection of historical information on the operation of a component and of the system of which it was a part. No formal work on data correlation is recommended until a comprehensive data base is developed.

1.3.3 Data Prediction

In the near term, the best source of reliability data is expected to be expert opinion, and the best source of repair data is expected to be maintenance simulation. Currently, maintenance assessment involves a visualization of all the tasks to be performed to repair or replace a component of the system being analyzed. Network analysis codes can be developed to speed this process, allow more variations, and form a record for future studies. It is recommended that projections of mean time to repair or replace (MTTR) make use of such codes. Network analysis is not expected to provide good estimates of the absolute value of repair times or to be useful unless the user has a good understanding of the maintenance operations required in the expected environment. Repair and replacement times are strong functions of the system design and operation, and experience on experimental devices is not necessarily relevant. Simulation of mechanical motions by CAD kinematics software may become the best source for maintenance data in the future. This capability would allow assessment of new designs without physical mock-ups and could be conveniently connected to designs in progress in the CAD system. It is recommended that software be acquired for the Computervision CAD systems (or other available systems) to assess the potential of maintenance simulation.

As stated in Sect. 1.3.2, no systematic method of data correlation was found. However, data are informally correlated and related to causative factors by fusion personnel. These correlations can be discovered and estimates of future performance obtained through formal interrogation of these personnel. It is recommended that Bayesian interrogation of experts be selectively applied to obtain essential data in the near term. This approach is not validated, but it is seen as the only method of obtaining projected failure rates for fusion components until a formal system of data collection is adopted.

1.3.4 Data Base Assessment

The key issue in the data base assessment is whether it is worthwhile to collect data from existing experimental devices. The value of these data is arguable, but these data, if properly used, are better than no data. Data should be collected only to the extent that, and in a manner such that, the data will be useful. Potential users of RAM data are those

engaged in the conceptual design of next-generation devices and the operators of existing devices.

The operating logs and other records kept for existing devices are used selectively and individually by experimental projects to identify downtime drivers. Although these devices do not have high availability as a goal, the projects are judged by the experiment time accomplished. The need for centralization of the device RAM data is questionable because device-specific problems are perceived as more important than generic problems and because generic problems are identified through professional exchanges. Comprehensive collection of RAM data is justified if the cost of collecting the data is less than the value of the data to the experimental project or if one objective of the project is to provide RAM data for future applications. The first condition is met by projects that are so large, expensive, and controlled that a quality assurance and control program is implemented. This is true of the Tokamak Fusion Test Reactor (TFTR) and will be true of the Tandem Mirror Fusion Test Facility (MFTF-B). The second condition is met by the technology development programs, such as the Tritium Systems Test Assembly (TSTA) and the Large Coil Program (LCP).

The goal of the fusion program is to provide the information required for the private sector to invest in fusion. A key element of this information will be the projection of plant availability. Availability analysis and projection should become as much a part of reactor design studies as cost analysis and projection. Historically, availability analysis has been used to improve the performance of existing or fully characterized systems. It is ambitious for the fusion program to intend to confidently predict the availability of a power plant before a full prototype has been operated. However, the capital investment required for a fusion plant mandates this projection. The long-term objectives of the availability program, to project fusion plant availability and to guide designs, require the development of a comprehensive data base. In the long run, the existence of a comprehensive and validated RAM data base will be of high value to the fusion program.

It is recommended that selective collection of experimental project data be initiated as a trial. Procedures for collection should be developed by the operators of TFTR, TSTA, LCP, and MFTF-B in cooperation with the future users of these data. Software should be developed to analyze the data and report the results to the projects. A key test of the timeliness of data collection would be a demonstration of the value of the reports to the projects in reducing downtime, predicting the effect of design changes, or identifying components that should be subject to quality assurance and control programs.

2. AVAILABILITY MODELS

One of the ingredients of an availability program is the analytical techniques through which the reliability, availability, and maintainability (RAM) of a system can be quantified as a function of its components' reliability and maintainability. This section discusses two widely used methods for performing RAM calculations. Several existing computer codes and procedures for performing RAM calculations are evaluated based on a literature survey, and a preliminary recommendation is made on two computer codes for use in the fusion reactor program. Results of a simple case run with the two codes are presented in Appendix A.

The deterministic method of performing RAM calculations algebraically combines the component reliability data into values for system and plant reliability, according to the configuration of components within the plant. This calculation is performed on a once-through basis with all plant parameters fixed. The result is a snapshot of plant availability based on the single-input values. If different or time-dependent results are desired, the calculation must be repeated with new input data applied for each new configuration or time step. The formulas used to calculate availability with this method are well known and relatively simple. When programmed for a computer, the resulting calculation is fast. Using this method, several calculations can easily be performed with various input parameters to determine the effect of modifying the plant configuration or component reliability.

The stochastic method can simulate time-dependent operation of a plant with statistical methods employing Monte Carlo techniques, in which failure of equipment and systems is a random process within a distribution function in time. Operation of the plant over a period of time (mission) may be simulated in a single calculation by this method. Because operation of the plant is followed through a mission, time-dependent processes may be included in the calculation. These may include the effect of various maintenance strategies, such as deferred maintenance, stocking levels of different spares, or irregular length of maintenance outages. Time-dependent failure rates or repair times may also be included in this method. The major disadvantage of the stochastic method is that the computation time is relatively long, even for very fast computers, if results with a high level of confidence are to be obtained on a plant with a reasonable number of components.

The literature was searched to determine whether available RAM calculational models could be used in the fusion program. Numerous models are described in the literature, but only a few have features that were considered appropriate for fusion reactor plants. Three deterministic models were chosen for evaluation: the Grumman ETF availability model,¹ the GO methodology,² and UNIRAM.³ Two stochastic or Monte Carlo models were chosen: the UW model⁴ and the FEDC model.⁵ The following sections describe these models. Table 1 compares the features of the models.

2.1 DETERMINISTIC MODELS

2.1.1 ETF Availability Model

The ETF availability model, developed by Grumman Aerospace Corporation for the Engineering Test Facility (ETF), is a Markovian process, which is a discrete-state, continuous-time process. The purposes of this model were to identify the ETF availability

Table 1. Comparison of availability models

	ETF	GO	UNIRAM	UW	FEDC
Limitations					
Maximum number of different component types		8,000	1,575	100	400
Maximum number of systems plus components		8,000	1,660	2,000 ^a	2,000
Maximum number of trials (or histories)				10,000 ^b	999 ^c
Maximum number of time steps per history				1,000	
Maximum number of gates				100	
Features in a single calculation					
Allows deferred maintenance	Yes ^d	No	No	Yes	Yes
Allows choice of serial/parallel repair	Yes ^d	No	No	No	No
Allows equipment failures and repair while plant is scheduled down	No	No	No	No	Yes
Treats standby (or on-demand) failure	Yes ^d	Yes	No	Yes ^e	No
Treats online redundant equipment	Yes ^d	Yes	Yes	Yes	Yes
Treats time-dependent failure rate	No	No	No	No	No
Allows major/minor repair option	No	No	No	No	Yes
Calculates plant availability uncertainty based on uncertainty in equipment failure rate	No	Yes	Yes	No	No
Calculates sensitivity of plant availability to individual equipment availability	No	Yes	Yes	No	No
Ranks components according to effect on plant availability		Yes	Yes	No	No
Calculates standard deviation of plant availability				Yes	Yes ^f
Available on National Magnetic Fusion Energy Computing Network	No ^g	No	No ^h	Yes	Yes

^aMaximum of 20 identical components per component type.

^bEach history represents a mission and may contain up to 1000 time steps.

^cEach trial represents a plant mission, typically 30-40 years.

^dUsing an equivalent failure rate and repair time for input to the problem.

^eIf equipment has dormant failure rate in standby, this rate is used during operation in the UW model.

^fOnly for overall plant availability.

^gIs not encoded.

^hImplementation is under way.

drivers, provide a preliminary assessment of ETF availability, and provide a preliminary apportionment of ETF availability so that the target availability could be achieved.

This model distinguishes between active and standby redundancies, immediate and deferred restoration of redundancies, and serial and parallel repair. Scheduled maintenance and level of support were considered parametrically.

The three levels of input to the model are the equipment level, the subsystem level, and the system level. The main inputs to the model are:

- the baseline configuration,
- the mean time between failures (MTBF) of equipment,
- the mean time to repair equipment, and
- the number of identical equipment/subsystems/systems installed and required, redundancy classification, immediate/deferred restoration, and parallel/serial repair (maintenance strategies).

No computer program is available to perform these calculations on an arbitrary plant configuration.

2.1.2 GO Model

The GO methodology is a success-oriented analysis technique used to evaluate the reliability and availability of systems. The method can also provide details about the dominant contributors to unreliability or unavailability. This methodology has been used extensively in the defense and aerospace industries. In recent years, EPRI has sponsored research and application programs to foster the use of GO in the utility industry because of its unique features. A study of the availability of the Sequoyah Nuclear Power Plant⁶ was done to demonstrate the applicability of the methodology. The method can perform the following types of evaluations:

- Determination of system reliability and/or availability for use in probabilistic risk assessments.
- Identification and ranking of the importance of critical components, which helps to develop a maintenance policy.
- Identification of component failure combinations that can lead to system failure.
- Identification of potential system success states, which could help to develop an operating and maintenance procedure.

The success orientation of the GO method permits a straightforward approach to system analysis, since it closely resembles the standard engineering approach to system analysis. A system is analyzed by constructing a GO model and evaluating it using the GO computer code. A GO model consists of an arrangement of GO symbols, called "operators," which are essentially substituted for engineering drawing symbols representing system components. This results in a one-to-one correspondence between the engineering elements and the operators in the GO model. Since a GO model often closely resembles the schematic drawing of the system being analyzed and system interactions and dependencies

are explicitly modeled, it enhances the review process as compared with other techniques. In addition, the model can represent both success and failure states of a system.

In addition to representing hardware interactions, GO can be applied to other events that affect system operation. Human actions can be modeled explicitly to account for time-dependent operations or for the status of the system when an operator action occurs. The ability to model the effect of external events (i.e., seismic phenomena and environmental effects of system operation) is now being incorporated into GO.

The current version of GO can handle as many as 8000 operators that represent components and the associated success logic. The GO computer code includes various options for addressing a number of reliability/availability problems. In addition to 12 basic GO modules, other modules can be used in reliability analysis. One major option relevant to availability analysis is the Effect Evaluation Sequence. This sequence provides three optional measures of uncertainty in the final system results relative to variations in the input data.

- The improbability option indicates the change in the final system probability as a result of assuming that a particular component operates perfectly, with no failure.
- The sensitivity option indicates the change in the final system result of an incremental change in the component failure data.
- The statistical confidence bounds option determines the statistical confidence bounds on the final system that result from using two statistical parameters for the components' reliability—mean and standard deviation.

2.1.3 UNIRAM Model

The UNIRAM model was developed by EPRI to perform RAM analyses of advanced power generation systems. The model is based on the creation of an availability block diagram, which divides the system into basic manageable subsystems, and of fault trees to adequately represent each subsystem. The UNIRAM package consists of three major elements: the RAM modeling methodology, a preprocessor program, and the UNIRAM program. Figure 2 is a typical scenario for the system that shows these three elements.

There are many approaches to preparing a RAM model of a system. Although most approaches are fundamentally equivalent, they often are superficially quite different from one another. The main features of the UNIRAM approach are as follows.

- The methodology was developed through applications to existing systems.
- The methodology was developed specifically for advanced power system applications.
- The methodology is associated with generalized computer system software that evaluates the model and automatically performs various analyses of it.

Fig. 2. Typical scenario for use of the UNIRAM system.

Application of this methodology to a system design generates a model that can be analyzed by the UNIRAM software. The model elements used as input to the program are

- a basic subsystem diagram, which partitions the system into groups of equipment;
- a nested subsystem diagram, which illustrates how basic subsystems are connected in series or in parallel to form the plant;
- fault trees, which represent each basic subsystem failure, singly or in combination; and
- component-level MTBF and MTTR data, which can be input as single values or as ranges of values if there is uncertainty about the data.

It is rather simple to become familiar enough with this methodology to prepare a RAM model for a system with a design and mode of operation that are well known and understood.

The preprocessor program is a FORTRAN-based computer program designed to help the user in preparing, displaying, checking, and changing data input files. It offers the user four modes of operation.

1. Create mode helps with the creation of a new data input file.
2. Display mode displays all or part of a data input file in readable, tabular format.

3. Change mode helps the user in changing a data input file to correct errors, to represent a different configuration, or to reflect different component data.
4. Check mode performs 50 different error checks to ensure proper format, consistency, and legitimacy of values and informs the user of any errors found.

The UNIRAM program is a FORTRAN-based computer program that can perform various analyses of system for which a RAM model has been prepared. The major evaluation options and their output are as follows.

1. The baseline run gives
 - system availability,
 - system equivalent availability,
 - system forced outage rate (FOR),
 - system equivalent forced outage rate (EFOR),
 - subsystem RAM measures,
 - approximate mean time to unplanned outage, and
 - system mean unplanned outage duration.
2. The component ranking run ranks the system's components according to any of three criteria:
 - sensitivity of system EFOR to an incremental change in each component's failure rate,
 - sensitivity of system EFOR to change in each component's forced outage rate, or
 - decrease in system EFOR as each component is made perfectly available.
3. The data uncertainty run uses a Monte Carlo approach to estimating the resultant composite uncertainty in the system's RAM measures; on this run the user must specify at least two items of component RAM data as ranges of values rather than single values.
4. The data variation run allows the user temporarily to change the MTBF/MTTR data for as many as 20 components and to assess the impact on baseline run results without changing the input file.
5. The subsystem sensitivity run varies the availability of the basic subsystems, one at a time, and tabulates the resultant system EFOR. When plotted, the curve with the steepest slope corresponds to the subsystem for which a given change in the subsystem's availability would most change the system EFOR.

2.2 STOCHASTIC MODELS

2.2.1 UW Model

The UW model uses a Monte Carlo approach, where randomness of failure is simulated by generating random numbers, which are used to determine if a component has failed or is operating. The status of all components in each time step is then combined

according to the logic diagram of the system, from which it is determined whether the system is up or down in the time step. This process is repeated for each subsequent time step, up to the predetermined mission. The availability of the system is the ratio of system uptime to the system mission lifetime. This procedure is repeated many times to calculate a statistically sound average availability. This model has been programmed in modular fashion to facilitate future additions. The program can take into account the following options: multiple units of subsystem, per-demand and per-hour failure rates, redundancy in any subsystem, deferred repair option for any subsystem, and a specified scheduled maintenance period for the plant.

The main inputs to this model are

- the configuration of the equipment, including component interconnections and logic gates;
- the MTBF of equipment (constant failure rates);
- the MTTR of equipment; and
- maintenance strategies.

Output from this model includes the calculated MTBF and MTTR for each subsystem; total failures, uptime, downtime, and availability for each subsystem; number of failures, downtime, and plant availability for each time step (typically one week); and standard deviation for the total plant availability.

This model has been tested, and some preliminary results for the Mirror Advanced Reactor Study (MARS) have been compiled. The computer program is available on the National Magnetic Fusion Energy Computing Network (MFEnet).

2.2.2 FEDC Model

The FEDC model uses a Monte Carlo-based simulation technique that is similar to the UW model. The model consists of three main sections. The first, data input and initialization, read input data on component configuration, failure rate, and repair time. The second (main) section simulates plant operating history. This section steps through the time history of plant operation using variable time steps calculated from the next plant event: next component failure, end of a repair, plant scheduled shutdown or startup, or end of mission. Time to the next failure of each component is chosen by the Monte Carlo technique. The number of failures and the cumulative downtime for each component and system and for the plant are recorded. This process continues until the required number of plant missions, or trials, has been satisfied. The third section of the model processes data generated by the simulation. The record of total failures and cumulative downtime is used to calculate the component, system, and plant failure rates, MTTR, and availability. The standard deviation from the calculated plant availability is also derived.

Input to the program consists of three data files (in addition to interactive input supplied at the beginning of each run). These are

1. the equipment data file, which consists of failure rates, repair times, and maintenance strategy for each component or subsystem that is not developed further;
2. the system data file, which contains only two items of essential information about each system: whether it is a series or parallel system and, if it is parallel, the number of elements that must function for system success; and

3. the common data file, which contains three essential items of information about each element in the plant: its level in the plant hierarchy (or block diagram), whether it is a component or a system, and its component or system identification number, corresponding to data assigned in the equipment data file.

Output from the program consists of

- a summary of input data used in the calculation;
- a table of the total number of failures and cumulative downtime for each component and system;
- a summary of calculated failure rate, MTTR, and availability for each component and system; and
- calculated plant availability and the corresponding standard deviation.

The program will also calculate the probability of achieving an availability equal to or greater than a value provided as input.

2.3 ASSESSMENT OF MODELS

2.3.1 Comparison of Deterministic and Stochastic Approaches

Although both deterministic and stochastic techniques are capable of predicting a system's availability, it appears that each has a specific application. The advantages and disadvantages of each approach are summarized in Table 2. The application of each approach is evident from this table. A deterministic approach is preferred for studying the availability of a system in various stages of design and for rapidly analyzing the impact of design changes on system performance. In this approach, many design scenarios can be studied with a small amount of computer time and relatively good accuracy. A simulation or stochastic approach may be useful once the design is reasonably fixed. In this approach, the absolute value of system availability is of more interest and could be obtained through many simulation trials. The stochastic approach may also be used to obtain a realistic system availability with real-life failure rates that are time dependent. In addition, various

Table 2. Comparison of deterministic and stochastic (Monte Carlo) models

Deterministic	Monte Carlo
<ul style="list-style-type: none"> • Easier to use for simple systems • Can rank the critical components in a more straightforward manner • No ability to simulate actual plant operating and maintenance schemes 	<ul style="list-style-type: none"> • More straightforward for complicated systems • Can handle the uncertainties in input data • Can handle complex time variations of failure rates • Large amount of computer time needed for a reasonable level of confidence (if the plant has many components) • Can handle complex and dependent relations between the failure, repair, and maintenance processes

maintenance strategies may be evaluated with this method. Table 1 is a more detailed comparison of the important features of each model included in this assessment.

2.3.2 Comparison of GO and UNIRAM Models

Although both GO and UNIRAM use primarily a deterministic approach to RAM analyses, there are some differences that make each one more suitable for certain applications. The major differences are as follows.

- UNIRAM is more straightforward and easier to use for rather simple systems. The GO model is more efficient in its use of the analyst's time for complex systems.
- UNIRAM requires a lower level of modeling expertise than the GO method.
- UNIRAM has a preprocessor program, which makes the method user-friendly and minimizes the effort lost as a result of input errors.
- UNIRAM cannot easily be used for detailed reliability analyses; the GO method is primarily designed for reliability analyses and probabilistic risk assessment.
- UNIRAM cannot handle complex system success criteria, for which the GO method is designed.

The UNIRAM model appears to be better suited to performing availability analyses of fusion reactors, which is the primary objective of the availability program. It could be a starting point for constructing an availability model for fusion reactors or experimental machines.

2.4 CONCLUSIONS AND RECOMMENDATIONS

Based on the study of some existing reliability/availability models and on the objectives of the availability program, the following conclusions and recommendations are made.

- There are sufficient availability models (tools to obtain the availability of fusion reactors, given a data base) in the literature that development of a new model for fusion reactors is not warranted at present.
- A rather small effort is needed to bring the existing models to the level required for a reasonable model of fusion reactor availability.
- Both deterministic and stochastic techniques should be pursued since they have different but equally important applications.
- The UNIRAM model could be a starting point for the deterministic approach. Either the FEDC or the UW model could be chosen as a basis for improvements in the stochastic approach.

3. CORRELATION AND PREDICTION

The ability to successfully predict availability is dependent upon having accurate reliability and maintainability data. For new systems, these data will be based on historical data, much of which may be for different environments and design conditions. Correlation is the ability to transfer this knowledge into a useful data base for new systems. The goal is the ability to predict the availability of a power plant early in the conceptual design stages, based on data for existing equipment. If the existing equipment were identical to that in the proposed power plant and if a complete history of reliability and maintainability in equivalent environments were available, these data could be directly input into the models with no manipulation and would yield results with high confidence. However, this is not the real-world case. Existing data are sparse, with limited applicability to a fusion reactor. Very little reactor plant equipment experience is directly applicable, and most equipment is prototypical, experimental, or nonexistent. Even worse, most of the equipment has not been operated in the envisioned system configuration, at the expected design conditions, in the anticipated environments, or with remote maintenance. Thus, it is clear that existing data must be extrapolated to fusion conditions in order to predict the reliability and maintainability of proposed conceptual designs.

3.1 DATA CORRELATION

The correlation of reliability and maintainability data is necessary to translate the data on existing hardware and software into the data needed to evaluate the proposed fusion systems. For reliability data, a failure rate at the subsystem level probably masks too many component-level causes to be useful. Data at the component level (e.g., pumps, distillation columns, or magnetic coils) will probably be most useful. Fusion reliability data at the system level probably cannot be obtained from current fission systems due to the dissimilarity of the systems. Maintainability data (MTTR) will be necessary at the lowest level of repairable or replaceable items. A pump would constitute the replaceable item even though the actual repair was replacement of a gasket. A decision on what is to be repaired or replaced is required before appropriate data can be gathered.

Data can be collected and correlated in a general sense, without applying them to any specific reactor designs. This is useful because these data can guide system designers in preparing the conceptual, preliminary, and final designs to meet the system reliability and maintainability specifications, but each piece of data entering this data base carries along its own historical information. At best, this information for failure rates would consist of detailed design specifications, specific material composition, quality control during fabrication, qualification testing, handling and shipping environments, installation procedures, operational and idle environments, operational performance history (time at percent of design conditions), and any operational anomalies. The desired data for the MTTR for each component consist of the cause for replacement or repair; scheduled or unscheduled action; remote or hands-on maintenance; maintenance equipment required; required preparatory time (logistics delay, removal or placement of equipment, analysis, or training); accessibility; size and weight of component; number of electrical, instrumentation and control (I&C), mechanical, and fluid connections; unusual circumstances causing short or long repair/replacement times; and requirements for verification of system operational

status. These data requirements are very detailed and probably would not be available for existing components; however, if past history is to be used to predict the behavior of components and systems in the future, then such detailed data will eventually be required. Correlation involves using these data to predict reliability and maintainability over a range of performance, environmental conditions, and maintenance equipment, some of which are not included in the component operating data base and would constitute an extrapolation of the data base.

A key factor in this process is that application of the MTBF and MTTR data must take place in the context of a specific design for which the availability is desired. One cannot estimate the availability of a fusion power plant without specifically defining that power plant. Component designs, interfaces, environments, and operating scenarios must all be set out. After the power plant is defined, data can be drawn from the MTBF and MTTR data bank to enable prediction of the plant availability.

The system definition has a profound effect on the reliability and maintainability of the plant. A given component may have a poor failure rate history. This effect can be mitigated or nullified by incorporating redundancy in the design or by adjusting the operating environment or scenario. Certain failure modes can be tolerated if the reactor can be operated in a degraded mode (lower power output) until the next available maintenance period. On the other hand, some failures will cause a chain of events that have a detrimental effect on many systems. The plant design definition also significantly influences the maintenance times. The component's design must be compatible with the maintenance system employed. Schedules for maintenance periods must consider the replacement of life-limited components and preventive maintenance of other components. Each reactor will have design-specific shutdown and startup sequences, which add to the maintenance timelines. Even the inventory of spare parts will influence the maintenance times.

At present, no "system" of data collection and data correlation exists to take raw reliability (failure) and maintainability data and transform them into a useful set of algorithms. Some correlation of reliability data for electronic components with more significant failure factors, such as power level and environmental factors, has been carried out.⁷ A program sponsored by EPRI correlated power plant failures with the global parameters of power level, steam-generator type, and number of system components.⁸ Although no system of data correlation now exists for a fusion application, similar techniques have been used in other disciplines. For example, parametric costing uses correlations to prepare cost estimates of proposed concepts based on historical data. As the concept evolves and more data become available for correlation, the accuracy of the estimates improves. Techniques employed by these disciplines are directly applicable to reliability and maintainability analysis.

3.2 MAINTENANCE SIMULATION

As stated in Sect. 3.1, one element of the data needed for the availability analysis is the MTTR for all the major components of the plant or at least of the reactor island. Generation of these data will involve combining data and the design features of components, interfacing systems, maintenance systems, facilities, and operational procedures. These factors will be evaluated and assessed in analytical models or simulations.

The use of analytical models or simulations will be required because there is no similar plant from which to draw historical data. The cost of physical mock-ups or demonstration plants to obtain data becomes excessive, especially over a range of performance or design options. What is needed is a set of tools to emulate the operation and maintenance of fusion power plants over a spectrum of design and maintenance options. These tools can be used to inexpensively explore these options. The more promising options can then be validated with physical mock-ups and demonstration plants.

The creation or generation of realistic MTTR data applicable to a spectrum of future designs is a formidable task. A major element is visualizing the sequence of maintenance tasks to be performed. This visualization includes the definition of the configuration of the reactor, building, and maintenance systems; the sequencing of events and actions; and the verification procedures. This assessment is a manual procedure involving consideration of all plausible permutations of equipment, failures, and maintenance actions. Only a few such permutations can be fully evaluated and probably only one, the "final" design, can be examined in detail. To consider more options, computer simulations can be used to describe the equipment, facilities, maintenance equipment failures, and maintenance actions. The computer can explore and evaluate the consequences of these perturbations, providing answers obtained relatively quickly at nominal cost. Changes in input parameters are easily accomplished, and the simulation can keep track of the current design configuration, the as-built configuration, or the proposed configuration.

Current computers have the necessary computing power to adequately model the physical envelopes and properties, functional requirements, operating performance, and maintenance requirements for all of the reactor and maintenance equipment. It is anticipated that as simulation models become more sophisticated, the capabilities of computers will be expanded to adequately handle the requirements.

The maintenance actions previously discussed generally fall into two categories, scheduled maintenance and unscheduled maintenance. Scheduled actions involve all preventive maintenance to extend the lifetime of the components, replacement of components that have achieved their lifetime goals, and replacement of redundant or noncritical components that have failed since the last scheduled maintenance action. Unscheduled maintenance actions are principally to replace or repair critical components, the failure of which requires immediate reactor shutdown. Other noncritical components may be repaired or replaced during an unscheduled maintenance on a nonconflicting basis. It is assumed that a general-purpose maintenance simulation computer code could be constructed to evaluate both of these types of maintenance actions, since only the specific tasks, unique maintenance equipment, and timelines are different. The time to accomplish each task would be established by the maintenance simulator and then integrated into a network analysis program to optimize all necessary actions based on available resources (manpower, time, equipment, and space).

Several administrative actions that require a finite amount of time need not be simulated but must be accounted for in assessment of maintenance time:

1. Failure detection and assessment.
2. Decision to repair or replace.

3. Determination of actions required to permit access for maintenance.
 - Shut down reactor
 - Power down related systems
 - Modify environment (radioactive decay, breathable air)
 - Remove any obstructing subsystem/components
 - Check availability of all tools, equipment, and personnel
4. After the repair, performance verification before removal of maintenance equipment.
5. Verification of full operational status.

The computer maintenance simulation should be able to generate these specific data:

1. Required resources.
 - Spare components and bulk materials
 - Maintenance equipment and tools
 - Personnel
 - Support systems
2. Sequence of actions.
3. Physical access and working envelopes.
4. Time required to accomplish action.

The specific maintenance actions that could be evaluated are included in the following:

1. Reactor/component powerdown, disassembly, and removal.
2. In-situ repair of disabled components or replacement of removable components.
3. Replacement and reactivation of removed systems/components.

The variables that influence these items, sequences, actions, and resources will probably include some of the following:

- type of failure,
- location of failure,
- environment,
- repair requirements,
- repair verification,
- replaceable component's physical description (weight, size, shape, alignment, number of connectors),
- available spares.

It is envisioned that the computer maintenance simulation could be used to establish a library of times to repair or replace for each anticipated fusion reactor component over the parameter range. Also, when a specific set of design conditions is known, a simulation can be accomplished with parametric variations from the base cases. These MTTR data form the basis for the network analysis of the scheduled and unscheduled maintenance actions.

No computer codes to accomplish such a detailed evaluation now exist. However, there are codes that could form the framework for such a code. Some of those with the necessary attributes are:

1. PLACE [McDonnell Douglas Automation Company (McAuto)]. Robot positioner and cell evaluator. Creates and optimizes robot programming. Has three-dimensional (3-D) color simulation of robot operations. Determines time to accomplish tasks. Has library of robots. Determines interferences and reach limits. Calibrates program to actual installation. Is being purchased and used by General Motors (GM) and Ford, among others. Future developments include artificial intelligence for collision avoidance.
2. GEOMOD [General Electric (GE) CAE International]. Solid modeler with free-form, sculptured surfaces. Can assemble individual components into computer mock-ups. Has kinematic capability and interference checks. Formed the basis for ROBOSYM, Calma's (GE's) entry into the robotics field.
3. RoboTeach (GM Research Laboratories). Integrates robotics programming and solid modeling into simulation package. Defines robot motion with geometric representation of environmental components in correct spatial relationships to anticipate collisions. Allows task definitions and selection of robots. Is a proprietary GM program.

These codes are representative of the basis for constructing a geometric maintenance simulation code. The maintenance code could represent the maintenance equipment, the reactor components, the building environment, the articles to be transported, and the maintenance actions. Eventually, a simulation code can be run in near-real time to evaluate and plan the maintenance actions of an operating fusion reactor.

The network analysis technique should be applied to the scheduled and unscheduled outages in order to plan activities and manage resources. Data from the failure predictions will establish the maintenance frequency and the requirements of the scheduled outages. This is illustrated in Fig. 3 for maintenance on an imaginary system. The maintenance simulator will also produce data on the equipment required and the time needed for each part of the repair/replacement. Managing the resources and sequencing the activities are major undertakings. Several codes that are now in existence can accomplish these functions; two of these are the MISTER (on the Lawrence Livermore National Laboratory defense computer network) and MSCS (McAuto). They are mainly oriented toward scheduling and cost management, but redefining the resources will make them suitable for this application. MSCS has been used for fusion maintenance network analysis.⁹ Specialized versions of these codes may be used to plan scheduled and unscheduled maintenance actions in near-real time on future fusion reactors.

3.3 RELIABILITY AND MAINTAINABILITY ESTIMATION TECHNIQUES

As discussed in Sect. 3.1, applicable data on fusion components of interest generally do not exist. The only data are related to experimental, prototypical, or developmental components; components that are smaller in size; or components used in dissimilar applications. Knowledge of how these components will function in specific fusion applications and environments can be determined with surety only through extensive test programs.

REPAIR ACTIVITIES

COMPONENT 1
COMPONENT 2
COMPONENT 3
COMPONENT 4
COMPONENT 5

RESOURCE REQUIREMENTS

MAINT. MACHINE "A"

MAINT. MACHINE "B"

CRANE

PERSONNEL

Fig. 3. Network analysis.

In lieu of expensive and time-consuming test programs, an analytical approach can be employed in the near term. This approach, a data collection technique used to obtain, quantify, and normalize subjective information, is called "Bayesian interrogation."¹⁰ A description of the methodology is given in Appendix B; it is summarized below.

A face-to-face interview is conducted with a technical expert, who is asked for his/her judgment as to the expected future performance of a component when it is subjected to new performance specifications, materials, environments, and system configurations. The technical ground rules must be very specific so that definitive data comparable to data obtained from other sources can be obtained. It is recommended that several experts be interviewed to ensure data consistency. Discrepancies are usually traced to a lack of specificity in the ground rules. If this is not the problem, then there is an inherent difference of technical judgment regarding the component. This can be resolved, or it can remain and be expressed as a range of uncertainty attached to the associated data.

No one can ever foretell the exact performance of a component. However, via Bayesian interrogation, the method of data collection can be tailored to obtain the expert's judgment of success as a probability function. He/she will be asked whether there is a 50%

chance of success at meeting a technical specification, such as failure rate or time to repair. Then, the odds are changed (e.g., 25% success, 75% failure), and a new data point is obtained. This process is repeated until a complete probability distribution for this one parameter is obtained. Obtaining the initial distribution from an expert is a lengthy process, but as the expert becomes acquainted with the procedures, the process can be done quickly. Data on the same component from different sources can be resolved into individual composite data probability functions. These data can be used in a stochastic availability model. This process has been applied in forecasting technical success¹⁰ and assessment of technical risk.¹¹ It is recommended that this process be employed *in the near term* to forecast technical data in lieu of testing. These data could then be used in the availability models to ascertain which equipment, systems, processes, and materials hold the most promise for application in the fusion field. Then, efforts can be directed toward development and validation of those more promising systems. Data from these developments and validations can be returned to improve the data base.

4. DATA BASE ASSESSMENT

4.1 DATA REQUIREMENTS

The minimum parameters of interest for availability assessment are the MTBF and MTTR. All of the availability models being considered for use by the availability program require these parameters. The accuracy of availability analyses is a function of the applicability of the data to the device being modeled; the precision is limited by the level of data available. Suggested levels for hierarchical structure¹² are:

- system,
- subsystem,
- equipment,
- component,
- module, and
- part or component part.

When performing an availability analysis, the analyst chooses a format for breakdown of the device. At some time it will be beneficial for the fusion program to establish a standard format or set of guidelines for device breakdown. This would facilitate data classification and produce more comparable results from different analyses. The system currently used for cost accounting may also be useful for the availability data program. An example cost account is shown in Appendix C (reactor plant equipment only). The cost accounting system may be too limited in depth for availability analysis, and it is presented here primarily to give some perspective on this subject. Another approach suggested was the use of IEEE standards for equipment identification.¹³ However, these standards have not yet been developed in detail for fusion equipment.

The simulation models require some data elements in addition to MTBF and MTTR, such as dormant failure rates for components in standby redundancy (failure rate = $1/\text{MTBF}$) and for minor repairs, major repairs, and overhauls. These parameters would be supplied by the analyst.

Careful judgment is needed in using data values as input to models. The applicability of specific values to the modeling process should be examined in terms of the origin of the values and the way in which they were obtained. Were they derived from "informed qualitative judgments" based on generic-part handbook data or similar-part handbook data, from frequency data of similar parts in similar applications, from identical parts in identical applications, etc.⁷ (This concept is further explored in ref. 12.) Some supporting information or means of contacting someone familiar with the data's origin is needed to identify the source of data adequately for the analyst to make these judgments. Enough specific information should be available to describe the part, component, equipment, or subsystem and its design application, environment, operational history, etc., so that the value's applicability to the model can be best assessed by the analyst.

4.2 SOURCES OF DATA

Data sources examined so far include existing documented reports and experience from U.S. fusion projects. Documented sources include various fission nuclear power reports, industrial standards, and military reliability handbooks.¹⁴⁻¹⁸

Failure rates for most conventional equipment can be obtained from these and other documented sources. Care must be taken, when values from such sources are selected and applied, to choose values obtained from experiences as similar as possible to the application and environment of the component being modeled.

Data (MTBFs and MTTRs) for equipment specific to fusion are not readily available. The fusion projects listed in Table 3 were investigated to assess the types of data that could be obtained from their experiences. In addition, the University of Wisconsin, Madison, was visited to review work on fusion availability, and EG&G Idaho, Idaho Falls, was visited to review their work on the Fusion Safety Data Base, which contains some failure rate data. A further objective of the laboratory visits was to identify experts for Bayesian interrogation, as discussed in Sect. 3.

4.3 LABORATORY PROGRAMS

The objectives of each project investigation or visit specifically included determining (1) what failure and repair records are available and to what level of detail; (2) what logs of machine operating time and downtime are available; (3) what methodology is used for data collection and data processing; and (4) how the data are being used. In addition, it was desired to obtain inputs on the availability program, to assess the receptiveness to a centralized fusion availability data base, and to identify key personnel as contacts for obtaining data in the future.

Note that MFTF-B is not yet complete, and TSTA and the Large Coil Test Facility (LCTF) have just recently begun operations. None of the projects collects data for the

Table 3. Fusion research projects investigated as data sources

Site	Projects
Princeton Plasma Physics Laboratory	Tokamak Fusion Test Reactor, Princeton Large Torus, Poloidal Divertor Experiment
Oak Ridge National Laboratory	Large Coil Test Facility, Impurity Study Experiment, ELMO Bumpy Torus
Lawrence Livermore National Laboratory	Tandem Mirror Experimental Upgrade, Tandem Mirror Fusion Test Facility
Los Alamos National Laboratory GA Technologies	Tritium Systems Test Assembly Doublet III

explicit purpose of determining reliability (or maintainability) parameters. Though the procedures employed differ somewhat at each project, logs of operations, interruptions, and problems with equipment are kept (on a computer for some projects). Qualitative information can be derived from these regarding failure modes and their relative frequency, but generally at a high subsystem level. The logs from TFTR and the Impurity Study Experiment (ISX) are regularly used to produce summaries of machine unavailability, broken down by major subsystems; this is done occasionally on some other projects. In some cases, subsystem managers keep logs of their equipment problems that can provide a greater level of detail; however, these logs are also not maintained with the intent of deriving failure rates.

4.3.1 Laboratory Data Collection

Some of the major findings from each project site are summarized below (names of contacts identified appear in Appendix D).

Princeton Plasma Physics Laboratory

In addition to log books of problems kept by subsystem managers, TFTR employs Trouble Reports (TRs) and Nonconformance Reports (NCRs). Log books are used on the Princeton Large Torus (PLT) and the Poloidal Divertor Experiment (PDX) only for recording problems. The TRs originate in the operations control room only when a problem causes a significant interruption of scheduled operations (approximately 5 min). This system provides for failure documentation and identification of downtime drivers by major subsystem, and it is used for preparing the monthly unavailability summaries. The NCRs are issued primarily by the construction quality assurance and control group as a means of tracking discrepancies of installations and equipment not matching design specification. A few of these are issued because of failures. Only the NCR system is tracked with a computer. What is collected by the TR system is primarily of value in a qualitative sense; it does not fulfill the requirements of a data collection system from which to derive quantitative reliability and maintainability parameters.

Oak Ridge National Laboratory

Log books of problems with ISX date back through 1981. It is estimated that 90% of the problems that occurred during operations were recorded. Problems considered significant (recurring or hazardous) or time-consuming (approximately 2 h or more to repair) are written up. The log identifies the problem, the fix employed, and the corrective action initiated (if any) to prevent further occurrences. Summaries are produced for each subsystem in categories of number of incidents and total downtime attributed. The logs are kept in a computer file as a text base, and it is not intended to derive availability parameters.

The LCTF has recently begun testing with magnets installed. Because it is a test program, records on magnet failures will be kept in detail. The facility itself has accumulated some data from use prior to installation of magnets, particularly on the cryogenics and vacuum system. The log book includes identification of failures and Maintenance Work

Requests (MWRs) written for maintenance personnel to correct them. The MWRs are tracked on a computer for purposes of job control and man-hour accounting (not elapsed maintenance time) and are kept on computer file for six months after being closed out.

Lawrence Livermore National Laboratory

Logs are kept in computer text files for the following Tandem Mirror Experiment (TMX) subsystems: neutral beams, titanium gettering, gas fueling, magnets and magnet power, vacuum (including external), gettering and fueling, potential control, electron cyclotron resonance heating, ion cyclotron resonance heating, computer system, and some diagnostics. Again, these logs are kept for tracking purposes and not for deriving MTBFs or MTTRs. They have been used on occasion to produce machine unavailability by subsystem plots.

Though no work has been done on the task as yet, these are plans for a computerized system of tracking failures and repairs on MFTF-B when it becomes operational.

Los Alamos National Laboratory

The TSTA facility at Los Alamos, which has recently begun operations with tritium, was investigated. Currently, there are two levels of data collecting. Corrective Maintenance Reports (CMRs) are prepared each time a component or equipment fails or needs major adjustment to continue operation; they will be used for determining failure rates. The CMR form does not record the time for the repair activity (needed for determining MTTRs), but it may be changed in the future to incorporate this. An NCR is completed in addition to CMRs if a component or equipment fails before its expected lifetime under normal operating conditions. It is more detailed and comprehensive than the CMR, and it initiates an investigation that requires some significant action by management and/or engineering. As TSTA gets more operational experience, it will become an excellent source of reliability and maintainability data for tritium processing and handling systems.

GA Technologies

The Doublet-III machine at GA Technologies has records on equipment dating back to 1978; since 1980 these have been kept in a computer text data base. The data gathered are broken down into six major subsystems: power supplies, vacuum system, computer system, neutral beams, diagnostics, and others.

4.3.2 Related Programs

A Preliminary Fusion Availability Data Base has been compiled at the University of Wisconsin to support studies in fusion availability there. The data were compiled primarily from the opinions of various experts in the fusion community using an approach called the Delphi procedure (which is not as rigorous as Bayesian interrogation). Though the data base has been useful for the studies that have been conducted, confidence in the values compiled is admittedly low. The need for a more comprehensive data base with a greater confidence level was emphasized not only for reactor plant studies, but for next-generation devices as well.

The Fusion Safety Data Base developed by EG&G Idaho will soon be available to users of the MFEnet. It is a user-friendly data base system with powerful software that can provide information on fusion in nine different categories, including component failure rates (no repair rate data are included). The failure rate base is not complete, though updating of the entire base will occur continually. Sources for this section are mostly from analogous fission equipment. The possibility of increasing the scope of the data base to incorporate failure rates and repair rates for availability purposes was discussed.

Problems of obtaining data from fusion projects were also discussed, specifically the conflict of trying to collect data in the easiest and most elementary way while still providing specific information on failures for some data users, such as the safety program. One approach might be the two-level approach such as used by the TSTA staff. (TSTA is considering shortening the CMR form to a size roughly that of a computer punch card.) To be successful, a data collection system should provide some direct benefit to the projects that collect and supply the data.

4.3.3 Laboratory Recommendations/Comments

The general objectives of the availability program were supported by project personnel; however, there was some objection to centralized data collection. There was skepticism about the data's usefulness, objection to the expense of time and money for the data collection, and concern that a specific project's data would be unfairly compared to other projects without sufficient information about the circumstances under which the data were generated. There were no objections to supplying what data they could now and in the future.

Objections came primarily from operations personnel, while the most enthusiastic support came from quality assurance personnel, who felt that the overall program and the data collection would reinforce their own program objectives. The need for quantifying RAM parameters becomes stronger as fusion devices become bigger, more complex, and more expensive, and monitoring and improving machine availability becomes a more important aspect of operations management. The need for failure rate data for safety studies is growing as well.

4.4 CONCLUSIONS

All of the fusion projects investigated record failures as a regular part of their everyday business, but the ground rules for documenting events vary. Individual projects have specific needs, and determining reliability and maintainability parameters is not an objective at any, except TSTA, where only failure rates are documented. A failure that is significant at one project may not be at another. One could attempt to obtain failure rates for subsystems from these records (it does not appear feasible to obtain repair rate data from these records). This would take a substantial amount of work and involve significant interpretation and uncertainty, and confidence in the results would be questionable. Fortunately, numerous contacts were identified who could estimate current RAM parameters on their respective projects and predict what they believe to be achievable values in the future. The people contacted were generally confident that they could accurately give the

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failure rates of major subsystems to roughly an order-of-magnitude approximation. Confidence in predictions, though, would be difficult to assess.

The applicability of data derived from current project records to future reactor studies is a debatable subject. Employing data from devices that are primarily experimental in nature is not clearly valid, since the emphasis of operations is not to operate at high availability, and the range of operating and design parameters can differ significantly in some subsystems from what is expected. However, it is believed that some project data can be applied directly or extrapolated in a reasonable fashion, which would be better than no data at all. Quantifying current equipment reliability would also supply some perspective on the accuracy of previous allocations of availability and would point to areas in which further improvements are required to meet availability objectives. It would provide the maximum learning potential from existing fusion experiments and a greater confidence level in future projections. The level of effort of developing a fusion availability data base needs to be put in perspective with availability tasks that should or could be accomplished in the near and distant future.

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Appendix A

SAMPLE CALCULATIONS WITH UNIRAM AND FEDC MODELS

A simple fusion reactor configuration was run on the UNIRAM and FEDC models to gain familiarity with each model; to assess salient features of the models, such as ease of input; and to compare calculational results.

The difficulty of preparing the plant model and encoding the input appears to be about the same for each program. The FEDC code requires that the plant be modeled in block diagram form, as shown in Fig. A.1. This modeling is straightforward and requires no special techniques. On the other hand, UNIRAM requires that plant equipment be combined into subsystems and nested subsystems, encompassing progressively larger parts of the plant until the entire plant is finally one subsystem. The structure of these subsystems must be chosen carefully by the user according to rules provided with the program instructions. A block diagram of the plant model that was analyzed is shown in Fig. A.1, which also shows the basic reliability data used as input to the calculation by both computer programs.

A summary of the results of the availability calculations is shown in Table A.1. For this simple case and with identical input data, UNIRAM and the FEDC model provide almost identical results.

Figures A.2 and A.3 and Table A.2 show sample input data for the FEDC model, and Fig. A.4 summarizes the results of a calculation using 30 trials or missions of 40 years each.

Figure A.5 shows sample input data for the UNIRAM code, and Figs. A.6 through A.9 show the results of a UNIRAM calculation using the same data as in the FEDC model. Figures A.6 and A.7 are a baseline run to calculate plant availability based on base input data. Figures A.8 and A.9 show examples of other calculations that may be performed by UNIRAM during a single session. Figure A.8 is a ranking of components by two different criteria: (1) failure rate, where the criterion for ranking is the change in plant forced outage rate per percentage change in component failure rate, and (2) criticality, where the criterion for ranking is the change in plant availability as the component is made perfectly reliable. Figure A.9 shows a subsystem sensitivity calculation that varies the availability of each subsystem from 0.8 to 1.0, one at a time, and tabulates the resulting plant availability. When these data are plotted, the curve with the steepest slope corresponds to the subsystem for which a given change in the subsystem's availability would most change the plant availability.

Fig. A.1 Fusion plant block diagram used for comparison of availability models.

Table A.1. Results of UNIRAM and FEDC models on a fusion reactor plant model

Scheduled outage duration (weeks)	Calculated plant availability (%)	
	UNIRAM	FEDC model
1	73.07	73.2
2	71.73	71.8
6	66.43	66.4

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id	component name	rate	df	kspare	mttr0	mttr1	mttr2	fmaj	kdef	kpm
1	electric plant	1.0e-04	1.00	0	90.	70.	0.	0.100	0	0
3	plant services	6.0e-06	1.00	0	170.	72.	0.	0.100	0	0
4	pellet injector	2.3e-04	1.00	1	240.	72.	0.	0.100	0	0
5	gas purging	1.0e-04	1.00	0	53.	0.	0.	0.100	0	0
9	coil support system	3.0e-07	1.00	0	5000.	1000.	0.	0.100	1	0
36	reactor instrumentation	1.0e-03	1.00	2	100.	3.	0.	0.100	0	0
51	cryogenic system	2.0e-04	1.00	2	500.	24.	0.	0.100	0	0
52	water cooling system	1.0e-06	1.00	2	100.	5.	0.	0.100	0	0
53	gas cooling system	1.0e-06	1.00	2	100.	5.	0.	0.100	0	0
54	tf coil power supply	1.0e-07	1.00	2	1000.	10.	0.	0.010	0	0
55	pf coil power supply	1.0e-07	1.00	2	1000.	10.	0.	0.010	0	0
57	plasma chamber vacuum system	5.7e-07	1.00	2	572.	6.	0.	0.100	0	0
58	ext.vacuum vessel vacuum syst.	5.7e-07	1.00	2	72.	6.	0.	0.100	0	0
59	secondary vacuum system	5.7e-07	1.00	2	72.	6.	0.	0.100	0	0
126	ef coil/oh coil, upper, ext.	4.6e-07	1.00	0	2560.	24.	0.	1.000	0	0
127	ef coil/oh coil lower, ext.	4.6e-07	1.00	0	3640.	24.	0.	1.000	0	0
128	ef coil lower inboard	5.7e-09	1.00	0	5064.	24.	0.	1.000	0	0
129	oh/eh coil in core	4.6e-07	1.00	0	2520.	24.	0.	1.000	0	0
133	rf heating system	1.6e-03	1.00	1	1000.	20.	0.	1.000	0	0
137	tf magnet system	1.2e-04	1.00	0	203.	0.	0.	0.000	0	0
139	plasma chamber segment	6.0e-06	1.00	2	430.	317.	0.	0.500	0	0
140	impurity control system	1.4e-04	1.00	0	251.	0.	0.	0.000	0	0
141	limiter cooling system	1.1e-05	1.00	0	136.	0.	0.	0.000	0	0
142	blanket cooling loop	2.4e-06	1.00	0	107.	0.	0.	0.000	0	0
143	turbine plant	6.6e-04	1.00	0	172.	0.	1344.	0.000	0	10
144	heat rejection system	9.0e-07	1.00	0	13.	0.	0.	0.000	0	0

Fig. A.2 Equipment data for FEDC model availability calculation.

```

4 8 137 tf magnet system
5 8 126 e:/oh coils, upper, external
5 8 127 ef/oh coils, lower, external
5 8 128 ef coils lower, inboard
5 8 129 ef coils in core
4 1 49 pf coil system
4 8 9 coil support structure
3 1 19 magnet system
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
5 8 139 plasma chamber segment
4 1 15 plasma chamber
4 8 140 impurity control system
3 1 46 reactor
4 8 57 plasma chamber vacuum system
4 8 58 external vacuum vessel vacuum system
4 8 59 secondary vacuum system
3 1 21 vacuum system
3 8 133 rf heating system
5 8 54 tf coil power system
5 8 55 pf coil power system
4 1 41 magnet power supplies
3 1 33 power conditioning system
4 8 141 limiter cooling loop
5 8 142 blanket cooling loop
5 8 142 blanket cooling loop
4 1 39 blanket cooling system
4 8 51 cryogenic system
5 8 52 water cooling system
5 8 53 gas cooling system
4 1 88 gas/water cooling system
3 1 37 heat transport system
3 8 36 reactor plant i&c
4 8 5 gas puffing system
5 8 4 pellet injector
5 8 4 pellet injector
4 1 51 pellet injection system
3 1 16 fuelling system
2 1 30 fusion reactor plant
3 8 143 turbine plant
3 8 1 electric plant
3 8 3 plant services
3 8 144 heat rejection system
2 1 87 balance of plant
1 1 10 fusion power plant

```

Fig. A.3 Common data file for FEDC model.

Table A.2. Explanation of data in Fig. A.2

Data	Explanation
id	Equipment identification number
frate	Failure rate (h^{-1})
df	Dormancy factor (fraction of failure rate effective when plant is down)
kspare	0 for no spares on hand; 1 for spares on hand; 2 for major/minor failure option
mttr0	Repair time with no spares on hand or for major failure
mttr1	Repair time with spares on hand or for minor failure
mttr2	Scheduled major overhaul time, effective every (kpm)th scheduled plant outage
fmajor	Fraction of major failures (used with kspare = 2)
kdef	1 for deferred maintenance, 0 for immediate maintenance
kpm	Major overhaul frequency (see mttr2)

summary results

id	nomenclature	lvl	eq/sys	failure rate	attr	availability	unavail.
1	tf magnet system	4	eq	1.6e-04	2.78e+02	9.59e-01	4.18e-02
2	of coil/oh coil, upper, ext.	5	eq	8.8e-07	2.36e+03	9.98e-01	1.88e-03
3	of coil/oh coil lower, ext.	5	eq	6.6e-07	3.42e+03	9.98e-01	2.27e-03
4	of coil lower inboard	5	eq	8.	8.	1.88e+00	8.
5	oh/oh coil in core	5	eq	2.7e-07	2.35e+03	9.99e-01	6.25e-04
6	pf coil system	4	system	1.3e-06	2.76e+03	9.97e-01	3.43e-03
				1.7e-06			
7	coil support system	4	eq	2.7e-07	4.83e+03	9.99e-01	1.28e-03
8	magnet system	3	system	1.2e-04	3.85e+02	9.65e-01	3.58e-02
				1.6e-04			
9	plasma chamber segment	5	eq	8.2e-06	3.66e+02	9.97e-01	3.88e-03
10	plasma chamber segment	5	eq	7.8e-06	3.78e+02	9.97e-01	2.89e-03
11	plasma chamber segment	5	eq	7.6e-06	3.48e+02	9.97e-01	2.63e-03
12	plasma chamber segment	5	eq	9.8e-06	3.68e+02	9.97e-01	3.24e-03
13	plasma chamber segment	5	eq	9.7e-06	3.71e+02	9.96e-01	3.58e-03
14	plasma chamber segment	5	eq	7.7e-06	3.76e+02	9.97e-01	2.89e-03
15	plasma chamber segment	5	eq	9.2e-06	3.48e+02	9.97e-01	3.18e-03
16	plasma chamber segment	5	eq	7.3e-06	3.49e+02	9.97e-01	2.55e-03
17	plasma chamber segment	5	eq	7.7e-06	3.75e+02	9.97e-01	2.89e-03
18	plasma chamber segment	5	eq	7.3e-06	3.76e+02	9.97e-01	2.74e-03
19	plasma chamber segment	5	eq	7.2e-06	3.73e+02	9.97e-01	2.67e-03
20	plasma chamber segment	5	eq	9.4e-06	3.53e+02	9.97e-01	3.32e-03
21	plasma vacuum vessel	4	system	7.1e-05	3.68e+02	9.75e-01	2.53e-02
				9.6e-05			
22	impurity control system	4	eq	1.8e-04	2.41e+02	9.57e-01	4.25e-02
23	reactor	3	system	2.1e-04	2.88e+02	9.44e-01	5.63e-02
				2.7e-04			
24	plasma chamber vacuum system	4	eq	5.3e-07	6.88e+00	1.88e+00	3.19e-06
25	ext.vacuum vessel vacuum syst.	4	eq	9.3e-07	1.54e+01	1.88e+00	1.44e-05
26	secondary vacuum system	4	eq	1.2e-06	1.33e+01	1.88e+00	1.59e-05
27	vacuum pumping system	3	system	2.1e-06	1.25e+01	1.88e+00	2.41e-05
				2.7e-06			
28	rf heating system	3	eq	2.2e-03	1.96e+01	9.59e-01	4.87e-02
29	tf coil power supply	5	eq	8.	8.	1.88e+00	8.
30	pf coil power supply	5	eq	1.3e-07	1.88e+01	1.88e+00	1.33e-06
31	magnet power supplies	4	system	1.3e-07	1.88e+01	1.88e+00	9.54e-07
				1.3e-07			
32	power conditioning system	3	system	1.3e-07	1.88e+01	1.88e+00	9.54e-07
				1.3e-07			
33	limiter cooling system	4	eq	1.6e-05	1.28e+02	9.98e-01	1.99e-03
34	blanket cooling loop	5	eq	3.9e-06	1.87e+02	1.88e+00	4.12e-04
35	blanket cooling loop	5	eq	3.6e-06	9.98e+01	1.88e+00	3.55e-04
36	blanket cooling system	4	system	5.4e-06	1.83e+02	9.99e-01	5.51e-04
				7.4e-06			
37	cryogenic system	4	eq	2.8e-04	7.47e+01	9.88e-01	2.81e-02
38	water cooling system	5	eq	1.1e-06	1.62e+01	1.88e+00	1.73e-05
39	gas cooling system	5	eq	1.2e-06	1.56e+01	1.88e+00	1.86e-05
40	gas/water cooling system	4	system	1.2e-06	1.59e+01	1.88e+00	2.58e-05
				2.3e-06			
41	heat transport system	3	system	2.2e-04	7.78e+01	9.83e-01	1.67e-02
				3.8e-04			
42	reactor instrumentation	3	eq	1.4e-03	1.22e+01	9.84e-01	1.64e-02
43	gas puffing	4	eq	1.3e-04	5.11e+01	9.93e-01	6.61e-03
44	pellet injector	5	eq	3.3e-04	6.94e+01	9.78e-01	2.21e-02
45	pellet injector	5	eq	3.1e-04	6.95e+01	9.79e-01	2.13e-02
46	pellet injection system	4	system	7.3e-06	3.45e+01	1.88e+00	2.68e-04
				1.1e-05			
47	fuelling system	3	system	1.8e-04	4.99e+01	9.95e-01	5.84e-03
				1.4e-04			
48	reactor plant	2	system	3.3e-03	5.38e+01	8.54e-01	1.46e-01
				3.8e-03			
49	turbine plant	3	eq	8.2e-04	1.88e+02	8.71e-01	1.29e-01
50	electric plant	3	eq	4.4e-04	8.65e+01	9.88e-01	1.16e-02
51	plant services	3	eq	8.1e-06	1.57e+02	9.99e-01	1.27e-03
52	heat rejection system	3	eq	9.3e-07	1.35e+01	1.88e+00	1.26e-05
53	balance of plant	2	system	7.7e-04	1.67e+02	8.85e-01	1.15e-01
				9.6e-04			
54	fusion power plant	1	system	4.8e-03	8.11e+01	7.56e-01	2.44e-01

mean availability=0.718 std deviation = 0.0115
p(e)>0.78)=0.936

Fig. A.4 Output from FEDC model availability calculation.

STARFIRE - 52 ELEMENT
 168. 0 1000.
 15
 BOP
 100 1 4 1
 -1 0
 HEAT REJ
 1 1 1.02E6 1 13.
 PLT SERV
 1 1 1.67E5 1 170.
 ELE PLT
 1 1 10000. 1 90.
 TURB PLT
 1 1 1515. 1 187.6
 I&C
 100 1 1 0
 INST & CONT
 0 1 1000. 1 12.7
 R-F HT
 100 1 1 0
 R-F HEAT
 0 1 625. 1 20.
 FUELING
 100 1 3 2
 -1 0
 +1 1
 PELLET INJTR1
 2 1 4348. 1 72.
 PELLET INJTR2
 2 1 4348. 1 72.
 GAS PUFFING
 1 1 10000. 1 53.
 GAS/H2O C
 100 1 2 1
 -1 0
 GAS COOLING
 1 1 1.E6 1 14.5
 WATER COOLING
 1 1 1.E6 1 14.5
 CRYO
 100 1 1 0
 CRYOGENIC
 0 1 5000. 1 71.6
 BLANKT COOL
 100 1 2 1
 -1 0
 BLANKET LOOP 1
 1 1 4.17E5 1 107.
 BLANKET LOOP 2
 1 1 4.17E5 1 107.
 LIMTR COOL
 100 1 1 0
 LIMITER COOLING
 0 1 9.09E4 1 136.
 COIL POWER
 100 1 2 1
 -1 0
 PF COIL POWER
 1 1 1.E7 1 19.9
 TF COIL POWER
 1 1 1.E7 1 19.9
 VACUUM
 100 1 3 1
 -1 0
 SEC VAC
 1 1 1.75E6 1 12.6
 EXT VAC VESSEL
 1 1 1.75E6 1 12.6
 PLASMA CH VAC
 1 1 1.75E6 1 62.6
 IMP CON
 100 1 1 0
 IMPURITY C
 0 1 7143. 1 251.
 PLASMA CH
 100 1 12 1
 -1 0
 PL CH SEG1
 1 1 1.67E5 1 377.5
 PL CH SEG2
 1 1 1.67E5 1 377.5
 PL CH SEG3
 1 1 1.67E5 1 377.5

PL CH SEG4
 1 1 1.67E5 1 377.5
 PL CH SEG5
 1 1 1.67E5 1 377.5
 PL CH SEG6
 1 1 1.67E5 1 377.5
 PL CH SEG7
 1 1 1.67E5 1 377.5
 PL CH SEG8
 1 1 1.67E5 1 377.5
 PL CH SEG9
 1 1 1.67E5 1 377.5
 PL CH SEG10
 1 1 1.67E5 1 377.5
 PL CH SEG11
 1 1 1.67E5 1 377.5
 PL CH SEG12
 1 1 1.67E5 1 377.5
 COIL SUPRT
 100 1 1 0
 COIL SUPPORT
 0 1 3.33E6 1 5000.
 PF COILS
 100 1 4 1
 -1 0
 EF COILS 1C
 1 1 2.17E6 1 2520.
 EF COILS LI
 1 1 1.75E6 1 5064.
 EF/CH COILS LE
 1 1 2.17E6 1 3648.
 EF/CH COILS UE
 1 1 2.17E6 1 2568.
 TF MAGNETS
 100 1 1 0
 TF MAG
 0 1 8330. 1 283.
 5
 HEAT TRAN
 4 4
 5 1
 6 1
 7 1
 8 1
 100 1 1 0
 TF MAG
 0 1 8330. 1 283.
 5
 HEAT TRAN
 4 4
 5 1
 6 1
 7 1
 8 1
 REACTOR
 4 2
 11 1
 12 1
 MAGNETS
 4 3
 13 1
 14 1
 15 1
 RX PLANT
 4 8
 2 1
 3 1
 4 1
 16 1
 9 1
 10 1
 17 1
 18 1
 PLANT
 4 2
 1 1
 19 1
 0

Fig. A.5 Input data for UNIRAM sample case.

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BASELINE RUN

FAULT TREE EVALUATION

SUBSYSTEM	MEAN TIME TO RESTORE (HOURS)	MEAN TIME BETWEEN FAILURES (HOURS)	AVAILABILITY
1 BOP	174.41	1303.72	0.8820
2 I&C	12.70	1000.00	0.9875
3 R-F HT	20.00	625.00	0.9690
4 FUELING	51.84	9313.46	0.9945
5 GAS/H2O C	14.31	500000.25	1.0000
6 CRYO	71.60	5000.00	0.9859
7 BLNKT COOL	106.99	208500.00	0.9995
8 LIMTR COOL	136.00	90900.00	0.9985
9 COIL POWER	19.07	5000001.00	1.0000
10 VACUUM	28.37	583333.62	1.0000
11 IMP CON	251.00	7143.00	0.9661
12 PLASMA CH	382.19	13916.69	0.9733
13 COIL SUPRT	5000.00	3330000.00	0.9985
14 PF COILS	2923.04	720355.87	0.9960
15 TF MAGNETS	283.00	6330.00	0.9671

Fig. A.6 Output from UNIRAM availability calculation (part I).

STATE DEFINITIONS WITH CORRESPONDING
OUTPUT CAPABILITIES

CURTAIL- MENT		STATE	STATE OUTPUT	STATE DEFINITIONS (SUBSYSTEM IDENTIFICATION NUMBERS AND CURTAILMENT LEVELS)							
SUBSYSTEM	LEVEL	AVAILABILITY (PERCENTAGE)	CAPACITY (PERCENTAGE)								
-----				-----							
16 HEAT TRAN				5	6	7	8				
-----				-----							
	0	98.3877	100.	0	0	0	0				
	1	1.6123	0.	*							
-----				-----							
17 REACTOR				11	12						
-----				-----							
	0	94.0232	100.	0	0						
	1	5.9768	0.	*							
-----				-----							
18 MAGNETS				13	14	15					
-----				-----							
	0	96.1791	100.	0	0	0					
	1	3.8209	0.	*							
-----				-----							
19 RX PLANT				2	3	4	16	9	10	17	18
-----				-----							
	0	84.6571	100.	0	0	0	0	0	0	0	0
	1	15.3429	0.	*							
-----				-----							
20 PLANT				1	19						
-----				-----							
	0	74.6682	100.	0	0						
	1	25.3318	0.	*							

NOTE: "*" INDICATES THAT NO SINGLE DEFINITION CAN
COMPLETELY DESCRIBE A GIVEN SUBSTATE.
SEE USER'S GUIDE FOR DETAILED EXPLANATION.

PLANT STATE	AVAILABILITY	OUTPUT CAPABILITY	DAYS / YEAR
1	74.67%	100.00%	242.1
2	25.33%	0.00%	38.9

PLANT RAM MEASURES

EFFECTIVENESS	FORCED OUTAGE RATE	EQUIVALENT FORCED OUTAGE RATE	EQUIVALENT AVAILABILITY	
			AVAILABILITY	AVAILABILITY
74.67%	25.33%	25.33%	71.80%	71.80%

Fig. A.7 Output from UNIRAM availability calculation (part 2).

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COMPONENT RANKING FOR FAILURE RATE				
SUBSYSTEM NUMBER	COMPONENT NUMBER	RANKING FACTOR	SUBSYSTEM	COMPONENT
1	4	0.0820	BOP	TURB PLT
11	1	0.0253	IMP CON	IMPURITY C
15	1	0.0246	TF MAGNETS	TF MAG
3	1	0.0231	R-F HT	R-F HEAT
6	1	0.0105	CRYO	CRYOGENIC
2	1	0.0094	I&C	INST & CONT
1	3	0.0066	BOP	ELE PLT
4	3	0.0040	FUELING	GAS PUFFING
12	1	0.0016	PLASMA CH	PL CH SEG1
12	2	0.0016	PLASMA CH	PL CH SEG2
12	3	0.0016	PLASMA CH	PL CH SEG3
12	4	0.0016	PLASMA CH	PL CH SEG4
12	5	0.0016	PLASMA CH	PL CH SEG5
12	6	0.0016	PLASMA CH	PL CH SEG6
12	7	0.0016	PLASMA CH	PL CH SEG7

COMPONENT RANKING FOR CRITICALITY				
SUBSYSTEM NUMBER	COMPONENT NUMBER	RANKING FACTOR	SUBSYSTEM	COMPONENT
1	4	9.2136	BOP	TURB PLT
11	1	2.6134	IMP CON	IMPURITY C
15	1	2.5264	TF MAGNETS	TF MAG
3	1	2.3793	R-F HT	R-F HEAT
6	1	1.0606	CRYO	CRYOGENIC
2	1	0.9397	I&C	INST & CONT
1	3	0.6638	BOP	ELE PLT
4	3	0.3878	FUELING	GAS PUFFING
12	8	0.1611	PLASMA CH	PL CH SEG8
12	9	0.1611	PLASMA CH	PL CH SEG9
12	10	0.1611	PLASMA CH	PL CH SEG10
12	11	0.1611	PLASMA CH	PL CH SEG11
12	12	0.1611	PLASMA CH	PL CH SEG12
12	1	0.1611	PLASMA CH	PL CH SEG1
12	2	0.1611	PLASMA CH	PL CH SEG2

Fig. A.8 UNIRAM component ranking calculation.

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SUBSYSTEM SENSITIVITY
EQUIVALENT FORCED OUTAGE RATE (PERCENTAGE)

SUBSYSTEM	I	AVAILABILITIES				
		0.80	0.85	0.90	0.95	1.00
1 BOP	I	32.27	28.04	23.81	19.58	15.34
2 I&C	I	39.57	35.79	32.01	28.24	24.46
3 R-F HT	I	38.42	34.57	30.72	26.87	23.02
4 FUELING	I	39.79	36.24	32.49	28.74	24.99
5 GAS/H2O C	I	40.32	36.59	32.86	29.13	25.40
6 CRYO	I	39.47	35.69	31.90	28.12	24.34
7 BLNKT COOL	I	40.29	36.56	32.83	29.10	25.37
8 LIMTR COOL	I	40.24	36.50	32.77	29.03	25.30
9 COIL POWER	I	40.32	36.60	32.87	29.14	25.41
10 VACUUM	I	40.32	36.59	32.86	29.13	25.40
11 IMP CON	I	38.23	34.37	30.51	26.65	22.79
12 PLASMA CH	I	38.69	34.85	31.02	27.19	23.36
13 COIL SUPRT	I	40.24	36.50	32.76	29.03	25.30
14 PF COILS	I	40.08	36.34	32.59	28.85	25.10
15 TF MAGNETS	I	38.30	34.44	30.58	26.73	22.87

Fig. A.9 UNIRAM subsystem sensitivity calculation.

ABSTRACT

An Availability Working Group was formed within the Office of Fusion Energy in March 1984 to consider the establishment of an availability program for magnetic fusion. The scope of this program is defined to include the development of (1) a comprehensive data base, (2) empirical correlations, and (3) analytical methods for application to fusion facilities and devices. The long-term goal of the availability program is to develop a validated, integrated methodology that will provide (1) projections of plant availability and (2) input to design decisions on maintainability and system reliability requirements.

The Phase I study group was commissioned to assess the status of work in progress that is relevant to the availability program. The scope of Phase I included surveys of existing data and data collection programs at operating fusion research facilities, the assessment of existing computer models to calculate system availability, and the review of methods to predict and correlate data on component failure and maintenance. The results of these investigations are reported to the Availability Working Group in this document.

Appendix B**METHODOLOGY FOR TECHNICAL RISK ASSESSMENT**

**Excerpt from *Assessment of Technical Risks and R&D Requirements
for a Magnetic Fusion Fuel Confinement System*,**

AP-3283, Electric Power Research

Institute, Palo Alto, Calif.,

November 1983

**D. A. DeFreece, L. M. Waganer, D. S. Zuckerman, J. R. Bartlit,
P. J. Dinner, and P. A. Finn**

The choice of what R&D work to fund in order to achieve a required set of goals most efficiently is a very difficult process. In this endeavor, the ability to forecast the expected future technical performance of various alternatives is a valuable asset. This section describes the methodology developed for the assessment of the technical risk of a fusion fuel system and is based on References 1 and 2. The methodology is general and may be applied to any engineering system for technical risk assessment. With appropriate modifications to the input parameters and simulation code, it may also be adopted to accomplish economic, safety and reliability assessments, thus making a complete risk assessment tool.

This methodology was devised at the beginning of the study and modified during the course of work as situations demanded. As such, it represents not only a blueprint for the Fuel System TRA, but a result in its own right. A formal description of the methodology is presented here to familiarize the reader with the technique and give him or her an overall perspective of the TRA. The details of the application to the Fuel System and the resulting conclusions and recommendations are presented in Sections 3 through 7.

The methodology for assessing the technical risk of an engineering system is comprised of a number of discrete steps, as outlined in Table 2-1. The methodology is described so as to apply to an assessment of either complete systems or sets of modular subsystems. These individual steps are examined and explained in more detail in the following subsections. The end result is the selection of a system option or a combination of subsystem options considered to have the highest probability of achieving (or least risk of failing to achieve) the desired technical performance requirements. Based on this result, an R&D strategy can be devised to meet these performance requirements.

Table 2-1

TECHNICAL RISK ASSESSMENT STEPS

1. Define system technical performance requirements and specifications.
2. Define system (subsystem) functions and options.
3. Determine key system (subsystem) technical performance parameters.
4. Acquire expected technical performance data.
5. Forecast future technical performance.
6. If performance forecasts were developed for subsystems rather than an entire system, simulate overall system performance.
7. Evaluate probability of achieving (risk of not achieving) system technical requirements and specifications.
8. Compare system (subsystem) options based on projected technical performance or risk.

2.1 DEFINE SYSTEM TECHNICAL PERFORMANCE REQUIREMENTS AND SPECIFICATIONS

The first task of the TRA methodology is to clearly and completely define the functional requirements or system specifications. If the requirements are to be time-phased (some applicable in the short term, others not until the distant future), they should be so defined. There are also interface requirements with other systems which must be characterized. If ranges on the specifications are acceptable or the specifications are not yet precise enough to be represented by a single number, ranges can be used in this methodology. The relative desirability of the range's lower limit as compared to its upper limit will be accommodated in Step 7 of the methodology.

As an example of these requirements, the fuel system specification includes acceptable chronic and accidental tritium loss, maximum tritium inventory, required D and T flow rates, etc. Interface requirements would include making sure that the output on one subsystem can be adequately handled by the next subsystem in line and that overall system inputs and output are properly matched to the requirements of the rest of the reactor (e.g., the DT fuel leaving the fuel system is in the proper form - pellets, gas, etc. - and has the required purity to be burned efficiently in the reactor plasma).

2.2 DEFINE SYSTEM (SUBSYSTEM) FUNCTIONS AND OPTIONS

This represents the system definition phase. Certain functions must be accomplished. Complete, unique system options may be defined to satisfy those functional requirements, or the system may be built up of multiple subsystems, each accomplishing a particular function (a more likely approach). Options can then be identified at a subsystem level to accomplish the function requirements. If these functional requirements are sufficiently independent, options can be evaluated as modular replacements, which simplifies the comparison process. Otherwise the complete system has to be reconfigured to accommodate the substitution of subsystem options. Both subsystem approaches were required in the Fuel System. For example, an argon cryotrapping pump can be substituted for a charcoal cryosorbing pump for plasma chamber evacuation without changing the overall system configuration. However, if a solid breeder is substituted for a liquid breeder, a completely different flow path is required since the liquid breeder acts as both a coolant and a tritium extraction medium while a solid breeder uses separate coolant and tritium extraction media.

In the beginning of the system definition step, all reasonable approaches and options should be considered for completeness. A set of screening criteria should be set up to reduce the number of subsystems and options considered to a manageable number if the study is of limited size. The actual screening criteria will vary from project to project but there are a few general guidelines to consider. Only the more important subsystems which have a significant impact on the system requirements need be evaluated. Ancillary subsystems, although required for completeness in the system definition, need not be included. Since the purpose of the methodology is to assess the technical risk of the system, subsystems with very low technical risk (mature, existing technologies) also need not be included. Subsystems which lack good technical definition and performance data or have poorly-defined requirements should not be included, as any assessment of their technical risk would be highly questionable. The development of such nebulous subsystems without further definition of their requirements would constitute a high risk effort. An example of this latter condition was encountered in the fuel system assessment. A goal was to determine the tritium inventory of the entire system to ± 100 Ci, but there is no technology presently identified which is capable of achieving this requirement.

Even after screening out the very low-risk and the poorly defined subsystems, the number of subsystems may still be too large to carefully examine since the TRA itself is an extremely time-consuming process. In such a case, the remaining

subsystems under consideration should be rank ordered, and the most important ones selected for examination. The number of options may also have to be limited, usually to a few of the more promising ones. Care must be exercised, however, so as not to eliminate any feasible option prior to a rigorous evaluation of its capabilities. In the Fuel System TRA all feasible subsystem options were defined and written up in Subsystem Design Descriptions in order to completely document their capabilities, limitations, and technical obstacles. These descriptions helped to accomplish the narrowing process.

The final result of this screening is a reduced set of subsystems and options which can be technically and quantitatively evaluated.

2.3 DETERMINE KEY SYSTEM (SUBSYSTEM) TECHNICAL PERFORMANCE PARAMETERS

Uncertainty about the future capabilities of a system or component creates risk regarding the possible achievement of technical performance requirements. These uncertainties arise from lack of knowledge or data, changing funding levels, unforeseen development difficulties and a variety of other reasons. In order to quantify the technical risk, the performance parameters against which the system or subsystem alternatives are to be judged must be identified.

It is easiest to first define those technical performance parameters applicable to the system as a whole. For example, tritium loss to the environment, tritium inventory and the purity of fuel being sent to the injectors are all performance parameters of the fuel system as a whole. Then, if individual subsystems are being examined, these system parameters can be applied to each one in turn. For instance, the fuel system impurity removal subsystem has impacts on all three of these overall system parameters and therefore, all three should be considered when evaluating the various impurity removal options. In addition, there may be other subsystem technical performance parameters which do not directly affect the overall system parameters but which do affect subsystem performance (e.g., cryopump regeneration time). These parameters will be useful for comparing options for a specific subsystem.

Once all of these parameters have been identified, it is possible to assess the expected performance of all of the system and subsystem options.

2.4 ACQUIRE EXPECTED TECHNICAL PERFORMANCE DATA

This is the data acquisition phase of the TRA. The subsystems and options have been selected and the apposite performance parameters chosen. The intent is to

solicit accurate past and current technical information regarding the performance of the various subsystem options as well as their expected future performance capabilities. This data is obtained from face-to-face interviews with subsystem experts. The method used for information gathering is a variant of the work pioneered by Dr. William J. Walsh of Argonne National Laboratory in "A Bayesian Approach to Forecasting Technical Success" (1). Technical experts are interviewed to obtain system and subsystem performance histories and projected future capabilities. The past or current application of the technology under scrutiny may not exactly coincide with the proposed application, and thus adjustment or normalization of the data may be required.

The central thesis of Bayesian Forecasting is that a person familiar with the past history of a system is the best predictor of its future performance. Thus the experts are interrogated as to their technical judgement of how well the system or subsystem might operate in the future. To assess the uncertainty of their predictions, a probability distribution of the expert's performance estimate is obtained for each time period considered. Several experts must be interviewed for each option and a composite distribution obtained. The results are similar to those shown in Figure 2-1 for some subsystem "x," option "y" and performance parameter "A." The past performance is shown as a particular value in the 1970 and 1980 time frames. However, since an uncertainty would likely exist in

Figure 2-1. Illustration of Technical Performance Forecast

expected performance in future time periods, performance is represented as a probability distribution. In actuality, the fuel system TRA required probability distributions for all historical as well as future times because none of the subsystems under investigation had ever been built for a fusion environment (many had never been built at all) and therefore there were no specific data points.

To obtain an indication of whether technical progress is influenced by funding constraints, estimates of future performance are solicited using two separate R&D scenarios. The first uses a future R&D funding level for the technology similar to what has existed previously; namely, funds are being shared by several approaches and only limited funds are available. This is termed a "constant funding" scenario. The second scenario adopts the philosophy that this technical approach had been selected as the principal technology in this area and funds are no longer a constraint. Progress is assumed to proceed as rapidly as possible, limited only by technological and schedule constraints. This is called the "sufficient funding" scenario. Anticipated technical performance using these two scenarios is plotted in Figure 2-1. The unconstrained funding scenario basically shows the technical limitations of the R&D, and eventually, the maximum possible expected performance of the technology itself. In general, the expected future performance using the technology-limited scenario will outstrip that expected using the constant funding scenario at any point in time. This illustrates the near-term performance benefits of increasing R&D funding. Eventually, of course, both scenarios will achieve the same results, with the time difference in achievement of the technology limit being a measure of the difference between current and maximum usable funding.

The people conducting the interviews must have technical backgrounds and be fully knowledgeable about the entire system. This is very important because any information obtained from the experts must be correctly interpreted. The interviewers must also be skilled in the interview process so that questions can be correctly formulated and a realistic representation of the experts' technical judgement obtained.

It is also very important to establish the technical basis for each subsystem prior to the interview. This can be accomplished during the formulation of the subsystem functions and options phase. Specific subsystem requirements, operating environments, and interface requirements (power, temperatures, fluid flows, radiation levels, etc.) must be defined. The most important facet is the clear definition of the performance parameters to be examined. These parameters must be

analyzed in an identical manner with each expert. If for any reason, new information is discovered during an interview, prior interviewees must be recontacted to ascertain if this new information would alter their responses.

Several experts should be selected for each subsystem option to allow formulation of a composite opinion. Three experts for each option was found to be the best number; two are not sufficient if differences of opinion between experts occur, and interviewing four or more escalates the magnitude of the TRA process. Prior to the interview, information should be sent to each expert regarding the purpose of the interview, the subsystem and option to be investigated, the pertinent technical background, and the performance parameters of interest. During the interview, each expert should be asked if there are any performance parameters which have not been included. If there are, prior interviewees must be questioned about these new parameters. The interview process should be a face-to-face meeting as opposed to a telephone interview. This will allow a more meaningful technical interchange and provide a better understanding of results. If several experts are co-located, a plenary meeting of all is recommended where an overview of the process is explained and demonstrated. Since the process of defining probability distributions is required from each expert, it was found that if the group witnessed a sample interrogation, the time spent with each expert was considerably shortened.

After the group meeting, each expert must be interviewed in private. This is imperative to insure independent results. It was also found to be beneficial to have two interviewers; one asks the questions and maintains a flow of information while the other records the results and general comments. Prior to any specific questions regarding the performance parameters, each expert is asked if he understands the purpose of the interview, the application of the subject technology, and if he feels that the performance parameters are the correct ones (or if any other parameters should be added). Then for each performance parameter, time period and funding level, the expert is asked the value of the performance parameter such that there is a 99% probability that the subsystem option can meet or exceed that value. Next the expert is asked the value of the performance parameter such that there is only a 1% chance that the option would surpass it. These two responses establish the approximate upper and lower bounds of performance. Additional questions determine the 25%, 50% and 75% fractiles of the probability distribution. Throughout the process, consistency checks are performed. As a final check, a histogram or a curve is drawn which reflects the final probability distributions and the expert is asked to verify that it is

reasonable. This process is described in detail in Section 4.

Developing the first probability distribution with each expert required approximately 30 minutes to one hour. Subsequent distributions could be accomplished in 10 minutes or less. In the fuel system TRA, there were two historical time periods plus three future time periods and two funding levels requiring up to eight distributions for each performance parameter. There were also usually three or more parameters per subsystem. Thus each interview on a single subsystem option required several hours. If the same expert is interviewed for several options, some time savings can be realized. Nevertheless, this process is very time consuming. The actual data gathering and compilation process for the 25 fuel system performance parameters presented in this report took several months.

2.5 FORECAST FUTURE TECHNICAL PERFORMANCE

After acquiring the expected subsystem performance data, the opinions of the various experts for each performance parameter and subsystem option must be compiled. If the data obtained from different experts was similar, the largest of the maximum values and the smallest of the minimum values obtained were kept to represent the extreme values of the composite data distribution. The intermediate values were averaged, and a beta function was fitted to the composite data, producing smooth curves. If the data from the experts showed discrepancies, the expert with the minority view was contacted and asked for further clarification of his or her reasoning. Usually the differing responses were caused by inconsistent assumptions or unclear instructions. If all parties used the same technical assumptions and groundrules, but none wished to adjust their data, then the discrepancy was assumed to be simply a difference of opinion and was so treated.

The technical forecast of the system or subsystem options is concluded by combining the individual forecasts by time period and funding level into a single forecast as shown in Figure 2-1.

2.6 SIMULATE OVERALL SYSTEM PERFORMANCE

If the experts had been asked the expected performance of an overall system, the prior step would have directly forecast the overall system performance and this step could be skipped. However, the more likely situation would be for the system to be comprised of several subsystems, each with options to be compared and evaluated. In the case of the Fuel System, five subsystems were evaluated which resulted in 25 total performance parameter forecasts for the various options.

This step in the TRA process simulates the overall system performance given a set of subsystem options operating as predicted in the technical performance forecasts.

The simulation is accomplished by constructing a computer code to model all pertinent aspects of the system, including both the subsystems being evaluated and those not being evaluated. The performances of the latter are represented either as constants or as a function of other system elements. All performance parameters are described by the performance probability functions obtained in the interviews. The computer code is designed to conduct a Monte Carlo analysis. The code simulates a given set of subsystem options thousands of times, sampling the performance distribution of each subsystem on every iteration in order to produce a statistically accurate analysis. The result is a set of probability distributions for the overall system performance parameters.

2.7 EVALUATE PROBABILITY OF ACHIEVING (RISK OF NOT ACHIEVING) SYSTEM TECHNICAL REQUIREMENTS AND SPECIFICATIONS

This next step utilizes the expected system performance as a function of time and funding and compares those results to the overall system requirements and specifications. This comparison can be accomplished directly with the data already obtained in prior steps. There are a number of specific requirements and the probability of achieving each of those can be determined. But the desirability of achieving, or conversely, the consequences of not achieving those requirements is not known. If these factors can be determined, a measure of the technical risk associated with each set of subsystem options can be obtained.

In order to measure the risk, a "utility" function is defined which measures the "desirability" of a technical performance parameter over its range of interest. Normal convention expresses the value from zero to one with zero being the most undesirable and one being the most desirable. Utility functions may be defined for all the system performance parameters. Details of how these utility functions were devised and applied to the fuel system can be found in Section 4. Then a figure-of-merit (sometimes called the "expected utility") can be defined to evaluate simultaneously the multiple attributes of the system. The figure-of-merit (FOM) can be represented by

$$FOM = \sum_{i=1}^n W(x_i) \int p(x_i) U(x_i) dx_i$$

where n is the number of system performance parameters, W_i is a relative weighting value for the i th performance parameter (x_i), p_i is the probability function for the i th performance parameter (calculated by the simulation code) and U_i is the utility function for the i th performance parameter. The product of the utility function and the probability function is integrated for each parameter and all parameters are summed. This can be accomplished for each unique set of subsystem option combinations. Combinations with high FOM values have a high probability of achieving the more desirable and worthwhile requirements and thus have a low risk.

2.8 COMPARE SYSTEM (SUBSYSTEM) OPTIONS

Section 2.7 outlined a technique to compare system options or combinations of subsystem options. Each unique system or combination of subsystems can be represented by a single FOM value. When evaluating system options there may only be a few values to compare for each time period and funding level. But in the case of sets of discrete subsystems, the number of unique combinations can be substantial. The Fuel System, with five subsystems considered and two to three options each, yielded 192 unique combinations. Figures-of-merit can be calculated for each of these combinations for each time period and funding level ($192 \times 8 = 1536$ FOM's).

Solely on the basis of technical risk, the options with the highest FOMs should be selected to be fully developed. R&D funds should be redirected toward that end, excluding all other options save a few back-ups. However, there are several other factors to consider (economics, safety, reliability and integration with other subsystem and system elements) which will also influence the choice for development.

An alternative course of action is to see which subsystem options are most influential in the technical risk assessment and rank order these for consideration for development. These subsystem options can be determined by examining the FOM's for all combinations. If all high-scoring combinations always utilize a certain subsystem option, that subsystem is the most influential. This process can be continued until the better options cannot be identified for the remaining subsystems. Table 4-2 in Section 4.8 shows the application of this technique to the fuel system.

2.9 SUMMARY OF TECHNICAL RISK ASSESSMENT

These eight steps constitute a methodology for conducting a technical risk assessment. With some modification in specifications or requirements it can be extended to be a complete risk assessment.

The methodology was developed to allow visibility of the intermediate results (subsystem options and technical forecasts) as well as to predict preferred technical R&D strategies. The interviewing method eliminates most of the biases held by the various experts and is thus dependent only on the experts' availability and cooperation.

In the following sections, the first application of such a technique to fusion is documented. The data resulting from this project is extensive but not all-encompassing and care must therefore be taken by the reader to examine these results in the context of the method used to obtain them. In particular, these results are strictly the result of a technical analysis and do not incorporate economic or safety aspects.

Appendix C**EXAMPLE COST ACCOUNT**

- 22. Reactor Plant Equipment
 - 221. Reactor
 - 221.1 First Wall
 - 221.1.1 Plasma Chambers
 - 221.1.2 Wall Modifiers
 - 221.1.3 Impurity Control
 - 221.2 Blanket
 - 221.2.1 Blanket Structure
 - 221.2.2 Breeder
 - 221.2.3 Reflector
 - 221.2.4 Multiplier
 - 221.3 Shield
 - 221.3.1 Bulk Shield
 - 221.3.2 Penetration Shielding
 - 221.3.2 Localized Shielding
 - 221.4 Reactor Structure
 - 221.4.1 Reactor Support Structures
 - 221.4.2 External Vacuum Vessel
 - 221.4.3 Magnet Structural Support
 - 221.4.4 Equipment Support Structures
 - 222. Magnets
 - 222.1 (Specify separate account for each type of magnet)
 - 222.1.1 Magnet
 - 222.1.2 Individual Vacuum Dewar
 - 223. Power Injection
 - 223.1 ECRH System
 - 223.1.1 RF Power Source
 - 223.1.2 Power Distribution System
 - 223.1.3 Launcher
 - 223.2 ECRH System
 - 223.2.1 RF Power Source
 - 223.2.2 Distribution System
 - 223.2.3 Launcher
 - 223.3 LHRH System
 - 223.3.1 RF Power Source
 - 223.3.2 Power Distribution System
 - 223.3.3 Launcher
 - 223.4 Neutral Beam Injection
 - 223.5 Drift Pump System
 - 223.6 Direct Energy Convertor
 - 223.6.1 Collector
 - 223.6.2 Grid

- 224. Vacuum Systems
 - 224.1 Plasma Chamber
 - 224.2 External Vacuum Vessel
 - 224.3 Secondary Vacuum Systems
- 225. Power Conditioning
 - 225.1 Magnet Power Supplies
 - 225.2 Power Injection
 - 225.2.1 ECRH Power Supplies
 - 225.2.2 ICRH Power Supplies
 - 225.2.3 LHRH Power Supplies
 - 225.2.4 NBI Power Supplies
 - 225.2.5 Drift Pump Power Supply
 - 225.2.6 Direct Energy Convertor Inverter
 - 225.3 Impurity Control Systems
 - 225.4 Energy Storage
- 226. Heat Transport
 - 226.1 Blanket Heat Transport System
 - 226.2 Shield Heat Transport System
 - 226.3 Cryogenic Cooling Systems
 - 226.4 Water Cooling Systems
 - 226.5 Gas Cooling Systems
- 227. Fuel Handling
 - 227.1 Fuel Injection Systems
 - 227.2 Fuel Processing and Purification
 - 227.3 Storage and Receiving
 - 227.4 Atmospheric Recovery Systems
 - 227.5 Coolant Recovery Systems
- 228. Instrumentation and Control
 - 228.1 Process Instrumentation and Control
 - 228.2 Safety Instrumentation
 - 228.3 Diagnostics
 - 228.4 Data Processing
- 229. Maintenance Equipment
 - 229.1 Manipulator Systems
 - 229.2 Transport Systems
 - 229.3 Inspection, Viewing and Test Systems
 - 229.4 Remote Cutting, Welding, and Machine Tool Systems
 - 229.5 Mockup Equipment
 - 229.6 Miscellaneous Tools
 - 229.7 Decontamination Equipment
 - 229.8 Radwaste Treatment and Disposal

Appendix D

FUSION PROJECT PERSONNEL CONTACTED

Site	Project	Contacts
Princeton Plasma Physics Laboratory	TITR PLT, PDX, SI	Harry Howard, Ray Camp, Judy Malsbury, Dick Reny, Tom Triolo, Frank Ferraro Ken Wakefield, Ken Young, Gordon Rappe, Jim Sinnis, Dale Meade, Rich Hawryluk, Joel Hosea, Kees Bol
Oak Ridge National Laboratory	LCTF ISX EBT	John May, Paul Haubenreich, Jack Rider (QA), John Sheffield Dwaine Coppenger (QA), Phil Edmonds Robert Livesey
Los Alamos National Laboratory	TSTA	Lyle Kerstein (QA), John Anderson, John Bartlit
Lawrence Livermore National Laboratory	TMX MFTF-B	Bill Turner, Tony Chargin, Jim Doggett Ted Kozman
GA Technologies	Doublet III	Richard Callis, R. Hager, F. Puhn, A. Gootgeld, D. Doll, C. Ward, P. Anderson
University of Wisconsin		Charles W. Maynard, Zoran Musicki
EG&G Idaho		Jim Crocker, Doug Holland, Tom Laats, Milan Stewart, Cindy Gentillion, Steve Piet

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52. M. A. Abdou, School of Engineering and Applied Science, 6288 Boelter Hall, University of California, Los Angeles, CA 90024
53. J. L. Anderson, CMB-3, Mail Stop 348, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
54. C. C. Baker, FPP/208, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
55. M. Barrett, Duke Power Company, P.O. Box 33189, Charlotte, NC 28242
56. J. Bartlit, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
57. S. E. Berk, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
58. R. Beuligmann, General Dynamics Convair Division, P.O. Box 85377, San Diego, CA 92138
59. R. Botwin, C47-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
60. W. B. Briggs, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166

61. R. Bunde, NET Team, Max-Planck-Institut fur Plasmaphysik, D-8046 Garching bei Munchen, Federal Republic of Germany
62. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
63. R. Callis, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
64. A. K. Chargin, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
65. D. R. Cohn, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
66. R. W. Conn, School of Chemical, Nuclear, and Thermal Engineering, Boelter Hall, University of California, Los Angeles, CA 90024
67. J. G. Crocker, EG&G Idaho, P.O. Box 1625, Idaho Falls, ID 83401
68. D. P. Dautovich, Ontario Hydro, 620 University Avenue, Toronto, Ontario M5G1X6, Canada
69. R. C. Davidson, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
70. N. A. Davies, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
71. S. O. Dean, Director, Fusion Energy Development, Science Applications, International Corporation, 2 Professional Drive, Suite 249, Gaithersburg, MD 20760
72. J. F. Decker, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
73. D. DeFreece, E451, Building 81/1/B7, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
74. D. Dobrott, Science Applications International Corporation. P.O. Box 2351, La Jolla, CA 92038
75. J. N. Doggett, L-441, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
76. R. J. Dowling, Office of Fusion Energy, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
77. W. R. Ellis, Office of Fusion Energy, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
78. J. Erickson, Grumman Aerospace Corporation, 1803 Research Boulevard, Rockville, MD 20850
79. F. Farfaletti-Casali, Engineering Division, Joint Research Center, Ispra Establishment, 21020 Ispra (Varese), Italy
80. A. Favale, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
81. H. K. Forsen, Bechtel Group, Inc., Research & Engineering, P.O. Box 3965, San Francisco, CA 94119
82. J. S. Foster, Jr., Building R4-2004, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
83. T. K. Fowler, Associate Director for MFE, L-436, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
84. J. W. French, EBASCO Services, Inc., Forrestal Campus, CN-59, Princeton University, Princeton, NJ 08544

85. H. P. Furth, Director, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
86. J. G. Gavin, Jr., President, A01-11, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
87. G. Gibson, Westinghouse Electric Corporation, Advanced Energy Systems Division, P.O. Box 158, Madison, PA 15663
88. J. R. Gilleland, Manager, Fusion Project, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
89. M. Y. Gohar, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
90. S. Golan, Bechtel Group, Inc., P.O. Box 3965, San Francisco, CA 94119
91. A. Gootgeld, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
92. J. Gordon, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
93. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91109
94. M. W. Griffin, Department E236, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
95. E. R. Hager, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
96. C. R. Head, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
97. C. D. Henning, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
98. R. Herberman, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
99. D. F. Holland, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401
100. J. J. Holmes, Westinghouse-Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
101. H. Howard, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
102. D. Hwang, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
103. B. K. Jensen, PSE&G Research Corporation, 80 Park Place, Newark, NJ 07101
104. J. B. Joyce, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
105. L. Kerstein, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
106. R. A. Krakowski, CTR-12, Mail Stop 641, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
107. G. L. Kulcinski, University of Wisconsin, Department of Nuclear Engineering, Engineering Research Building, Room 439, 1500 Johnson Drive, Madison, WI 53706
108. D. L. Kummer, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166

109. J. D. Lee, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
110. B. G. Logan, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
111. B. W. Logan, Duke Power Company, P.O. Box 33189, Charlotte, NC 28242
112. C. W. Maynard, University of Wisconsin, Madison, WI 53706
113. D. G. McAlees, Exxon Nuclear Company, Inc., 2101 Horn Rapids Road, Richland, WA 99352
114. W. Marton, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
115. L. G. Masson, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401
116. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
117. A. T. Mense, Building 107, Post B2, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
118. R. W. Moir, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
119. D. B. Montgomery, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
120. D. Moyer, Grumman Aerospace Corporation, 1803 Research Boulevard, Rockville, MD 20850
121. A. E. Munier, Grumman Aerospace Company, P.O. Box 31, Bethpage, NY 11714
122. G. R. Nardella, Office of Fusion Energy, Mail Stop G-256, U.S. Department of Energy, Washington, DC 20545
123. R. E. Nygren, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
124. T. Ohkawa, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
125. A. L. Opdenaker, Office of Fusion Energy, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
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