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Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems

Main Report

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Volume II

MAIN REPORT

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Abstract

This study examines the interaction of the electromagnetic pulse from a high altitude nuclear burst with commercial nuclear power plant systems. The potential vulnerability of systems required for safe shutdown of a specific nuclear power plant are explored. EMP signal coupling, induced plant response and component damage thresholds are established using techniques developed over several decades under Defense Nuclear Agency sponsorship. A limited test program was conducted to verify the coupling analysis technique as applied to a nuclear power plant. The results are extended, insofar as possible to other nuclear plants. Based upon the analysis, it was concluded that: (1) Diffuse fields inside Seismic Class I buildings are negligible; (2) EMP signal entry points are identifiable; (3) Interior signal attenuation can be reasonably modeled; (4) Damage thresholds, even for equipment containing solid state components are high; (5) EMP induced signals at the critical equipment in the example plant are much less than nominal operating levels, but plant topology and cabling practice have a strong influence on responses; (6) The likelihood that individual components examined will fail is small; therefore, it is unlikely that an EMP event would fail sufficient equipment so as to prevent safe shutdown.

CONTENTS

CONTENTS (Continued)

Chapter Page

CONTENTS (Continued)

APPENDICES

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

TABLES

Acknowledgments

The authors are indebted to the Tennessee Valley Authority for their cooperation and assistance during the conduct of this study. Special appreciation goes to Mr. Charles Gilliland of the Office of Engineering Design and Construction for his aid in obtaining plant drawings, equipment specifications and other engineering data, and to Mr. James Vineyard of the Watts Bar Nuclear Plant for his aid in defining equipment interfaces and operating procedures during the on-site portions of this study. Mr. Vineyard's knowledge of plant details saved many hours of effort. Our thanks also go to Mr. James Gallacher, Mr. Steve Wilmet, and Mr. Bruce Harlacher of IRT Corporation for their efforts in conducting the verification measurements.

1.0 Introduction

1.1 Background

It has been recognized for many years that the detonation of a nuclear weapon at high altitude (≥ 40 kM) leads to the creation of an intense electromagnetic field of very short duration, the electromagnetic pulse (EMP). The EMP from a single detonation at the proper altitude could induce large currents and voltages in electrical equipment over the entire continental United States. As a result, the U.S. Defense Department has devoted substantial resources to understanding EMP effects on military systems. Based upon these studies, some weapons systems and defense communications systems have been "hardened" against EMP by radio frequency shielding or by installation of protective devices.

At the present time, commercial nuclear power plants are not required to have protection against EMP. The Nuclear Regulatory Commission (NRC) Regulations (10 CFR 50.13) state that license applicants are, "not required to provide for design features or other measures for the specific purpose of protection against the effects of (a) attacks and destructive acts including sabotage, directed at the facility by an enemy of the United States, whether a foreign government or other person, or (b) use or deployment of weapons incident to U. S. defense activities." Therefore, no protection against EMP has been required in nuclear power plant design. Given this situation, the present study was undertaken to address the question: "Could the effects of an EMP due to high altitude nuclear weapon detonation (which produces no significant radiation or physical damage at ground level) adversely affect the safe shutdown capability of commercial nuclear power plants?" A sustained inability to shut down such plants could lead to significant public health effects or impair our national recovery capability in event of an actual nuclear attack. Therefore, the overall objective of this study is to provide the NRC with a basis for considering the need to amend the regulations to include design requirements for the protection of nuclear power plants against the effects of EMP.

The effects of EMP on a nuclear power plant were considered in earlier studies by the Oak Ridge National Laboratory.[1,2] The purpose of the work described in Reference 2 was to determine if EMP is a serious problem for nuclear power plants and, if necessary, recommend means of protecting these plants from potentially unsafe conditions. This was a limited scope study and as a result, zero or first-order estimates were used to define EMP induced transients and their probable effects on the plant. In the Oak Ridge study the emphasis was upon the EMP signal which could be induced directly on plant cabling, given very conservative assumptions on shielding effectiveness. Less effort was directed toward EMP-induced signals induced on cabling penetrating into the plant because for the plant considered all underground ducting had metal conduit over the entire length. Although the study drew upon design information for several plant types, no single plant was subjected to a detailed analyses. The Oak Ridge study concluded that,

> "The most probable effect of EMP on a modern nuclear power plant is an unscheduled shutdown. EMP may also cause an extended shutdown by the unnecessary activation of some safety related systems. In general, EMP would be a nuisance to nuclear plants, but it is not considered a serious threat to plant safety."

Because the Oak Ridge study did not attempt to analyze any particular plant in depth, some questions persist as to the applicability of the conclusions, and as to whether or not nuclear plants can be safely shutdown subsequent to an EMP interaction. Also, some of the newer operating plants and plants under construction use more electronic devices (semiconductors, transistors, integrated circuits, etc.) considered to be particularly susceptible to the currents and voltages which can be induced by an EMP interaction than do the older plants. Because of the resultant uncertainty about EMP effects on commercial nuclear power plant shutdown capability, this study was undertaken.

The vulnerability of nuclear power plants to sabotage or terrorist acts employing land-based generators which are capable of producing EMP-like effects was also considered early in the study. It was concluded that a serious threat of this type did not exist. This is discussed further in Section 2.4.

1.2 Objectives

This program was established as a scoping study with the following objectives:

1. Determine the vulnerability of systems required for safe shutdown of a specific nuclear plant to the effects of EMP.
2. Establish how any safe shutdown systems vulnerable to EMP may best be hardened against it.
3. Characterize to the extent possible, the effects of EMP on nuclear plants in general based upon the results for systems in the example plant.

An alternate expression of the objectives is that this study assesses the EMP sensitivity of essential features of selected safe shutdown systems on nuclear power plants in order to identify any points which may be unduly exposed or sensitive. Then, where appropriate, proposes remedies for such sensitivity.

1.3 Study Approach

To accomplish these objectives, the program was structured as shown on Figure 1.1. First the systems of concern were identified and defined. Then estimates were made of the currents and voltages which might exist at key points (systems of concern) if the plant

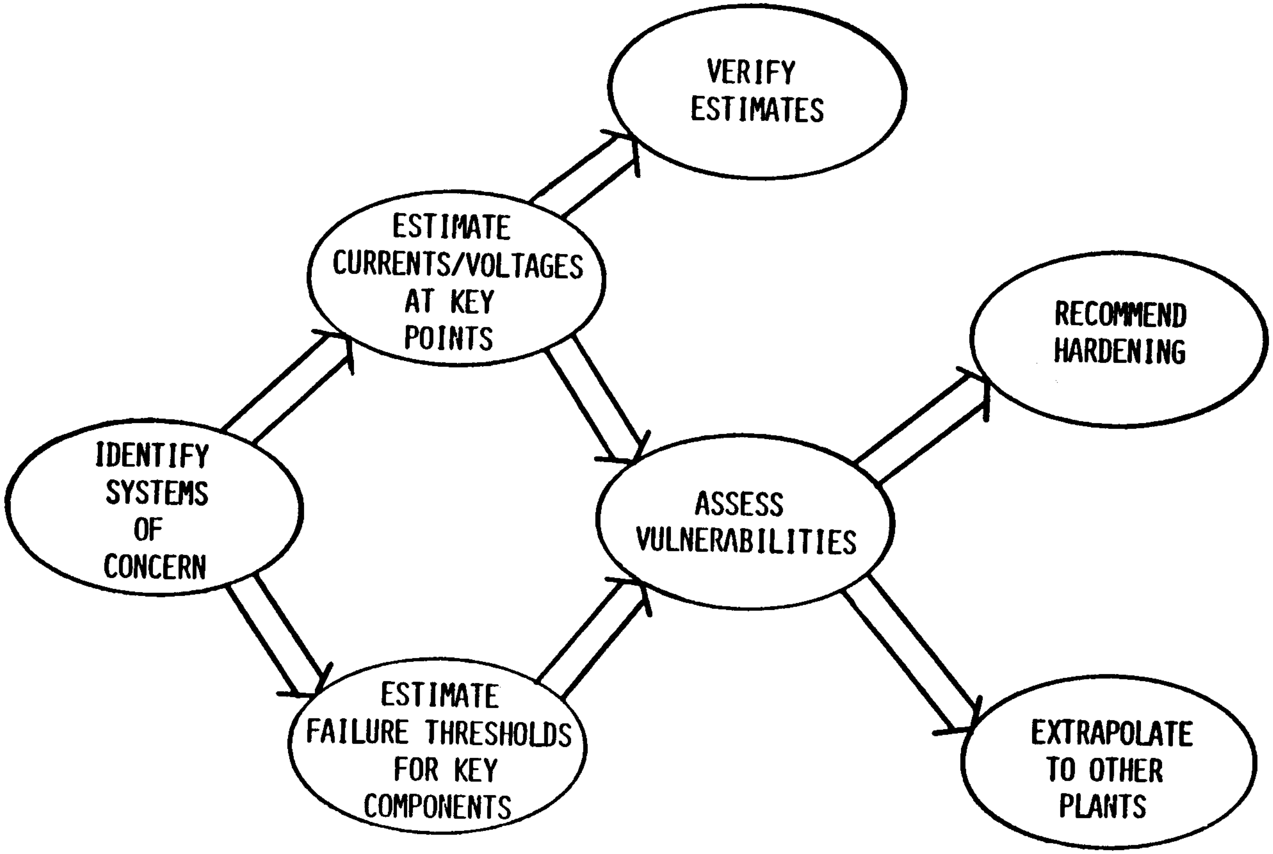


Figure 1.1. Study Approach for EMP Interaction with Nuclear Power Plants.

should be subjected to an EMP. This involves examining the plant in light of the potential interaction mechanisms, and based upon the configuration of the plant systems (that is, what loads are active, what circuits are open, where are cables routed, etc.) analyzing how signals could be induced and distributed. Concurrently, component damage thresholds were estimated. The components of the systems of concern were examined, and based upon circuit configurations and piecepart characteristics, estimates made of the signal levels at the component interconnections which could cause failure of the component. These two sets of estimates were then compared to assess the vulnerability of the selected components. Because nuclear plants, like many military systems, are very complex, a modest experimental program was conducted to provide some verification of the estimated induced signal levels. These measurements were not intended to establish whether the example facility is or is not hard to EMP. Rather they serve to verify (or reject) conclusions reached about signal distribution and attenuation. If vulnerabilities are predicted, recommendations are made for eliminating or reducing them; that is, recommendations are made for hardening. Finally, the results are extrapolated to other nuclear plants. This report describes the study and reports the results and conclusions.

1.4 Study Organization

Any investigation of the potential effects of EMP on commercial nuclear power plants requires a broad range of expertise in nuclear plant systems and nuclear weapons effects. For this reason, a number of government and industry organizations are involved as shown in Figure 1.2. Overall program direction is the responsibility of the NRC Office of Nuclear Reactor Regulation. The program technical monitor is supported by other members of the NRC staff and a Research Review Panel comprised of nationally known authorities on nuclear systems and nuclear weapon effects. The Defense Nuclear Agency (DNA) of the Department of Defense (DOD) participated in the planning of the program and is represented on the review panel. The day-to-day technical management has been handled by Sandia National Laboratories. In this capacity, Sandia provided the necessary nuclear systems analyses and the interfaces between the subcontractors conducting specific portions of the study. The EMP response and vulnerability analyses were prepared by Boeing Aerospace Co. using the techniques and expertise developed over a number of years in various programs done for the DOD. The verification measurements were made by IRT Corporation, again using techniques, equipment, and expertise developed in various DOD programs. The damage threshold estimates were developed by Booz-Allen & Hamilton. Although similar work has been sponsored by the DOD, the equipment used in nuclear power plants contains components which are not included in current damage threshold data bases. This required Booz-Allen to do some extrapolation.

Subsequent sections of this report outline the boundary assumptions and constraints, the implementation of the approach, described above, and the results of the study.

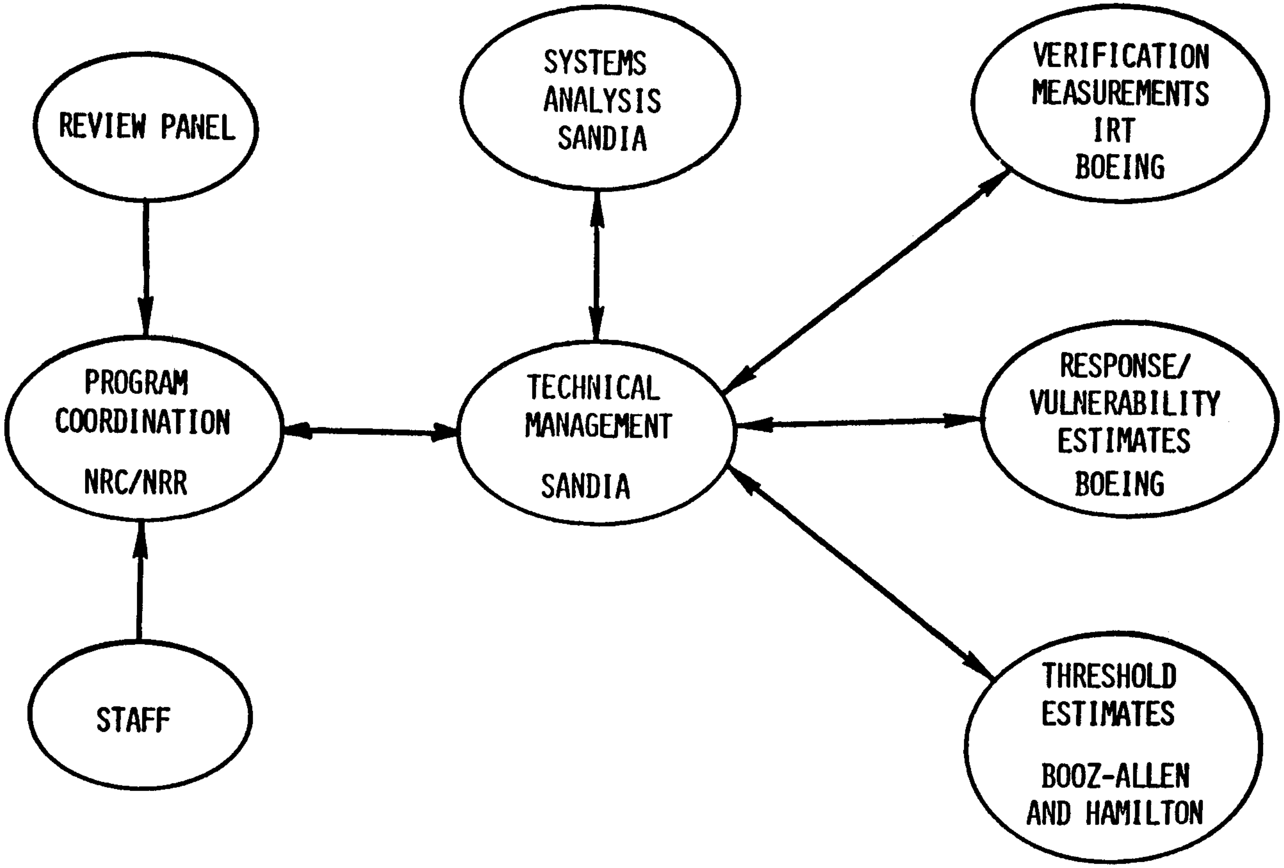


Figure 1.2. EMP Study Organization.

1.5 Study Constraints and Assumptions

Certain constraints and assumptions were adopted early in the work to keep the problem tractable. These bounding conditions are discussed in more detail where they appear in the report. However, they are assembled here because they effect the conduct of the study and the conclusions drawn, and so that they may be more readily identified by the reader.

1. The study is limited to those systems required for safe shutdown of the nuclear plant. It is focused on particular systems and on components representative of classes of equipment used in plant systems so that a detailed analysis provides insight into potential vulnerabilities.

2. The study is based on a "worst case" EMP threat situation. That is, it was assumed that the incident EMP threat embodied a bounding peak field intensity and an orientation relative to the plant system such as to optimally excite every point of interaction.

3. The magnetohydrodynamic (MHD) EMP was not considered extensively in the study for reasons cited in Section 2.3.

4. Permanent damage failure is the criterion used to assess system vulnerability. That is, signal upset effects were not considered in the study.

5. No attempt was made to estimate damage thresholds for cables, power and distribution transformers and rotating machinery. This was not deemed necessary because of considerations cited in Section 7.1, however, estimates of such thresholds based upon available data are used in Section 8.0.

6. The damage threshold calculations were analytical only, i.e., no supporting component test program was conducted as is traditionally done by the EMP effects research community. However, the data base used included experimental data from previous programs, published threshold data, and data derived using empirical models and published device electrical parameters.

7. Because semiconductor devices generally have been shown to be more susceptible to EMP induced failure than passive components, the failure threshold analysis focused upon those devices and excluded the passive components.

8. The failure threshold analysis was conducted at 1 MHz, chosen as a median value for the predicted dominant responses. Coupling data subsequently developed (Figure 6.11) indicates that this was a reasonable choice.

9. Internal interfaces within individual modules or equipment cabinets were not included in the damage threshold analysis. That is, on equipment items analyzed, only those pins that serve as interfaces to the "outside world" were considered. More specifically, the threat parameter (voltage or current) is traced from its source in the external circuitry to the module interface pin, the individual component damage threshold parameter is reflected back from the component through the module circuitry to the same interface pin, and the parameter valves are then compared.

2.0 EMP Phenomena of Interest

2.1 High-Altitude EMP

When a nuclear weapon is detonated at very high altitudes ($\geq$40 kM), the prompt radiation travels substantial distances before significant interactions occur in the upper atmosphere. Eventually, however, the energy in the form of gamma radiation that is radiated toward the earth begins to interact with air molecules, primarily through Compton scattering. Because the gamma energies are high there is a net "forward" motion of the Compton electrons. That is, a net movement of charge in the same direction as the gamma photons. However, because the negatively charged electrons are moving in the geomagnetic field, they are turned. The acceleration associated with this turning produces radiation which is propagated earthward. Because the gamma photons travel at light speed and the electrons travel in the same direction, the radiation from the turning interferes constructively, with the net result that a large radio frequency signal is generated. This is the high-altitude electromagnetic pulse (HEMP). A more complete technical descrption of this phenomena may be found in a review article by Longmire.[3]

The EMP signal generated by the interaction described above is characterized by intense electric fields with peak values approaching 10-50 kilovolts per meter. The pulse has a very short rise time, on the order of 5-10 nanoseconds with a duration of 0.5-1 microsecond. The peak power density is high, approaching several megawatts per square meter. However, because of the very short pulse duration and because only a very small fraction of the total weapon energy is converted to EMP, the total energy density is modest, on the order of a few tenths of a joule per square meter (see Table 2.1).

Table 2.1.

Typical EMP Values

Peak Electric Fields	~10-50 kV/ M
Pulse Rise Time	~ 5-10 nsec
Pulse Duration	~ 0.5-1 μsec
Peak Power Density	~ 1-5 MW/m^2
Total Energy Density	~ 0.1-0.9 J/m^2

With weapon burst heights of 100 kilometers the area covered by the pulse is very large. In fact, a single megaton size detonation can cover most of the North American Continent with fields of tens of kilovolts per meter as illustrated in Figure 2.1. The field strengths near the outer limit of coverage will be about half that of the maximum which occurs in the vicinity of surface zero in Figure 2.2.

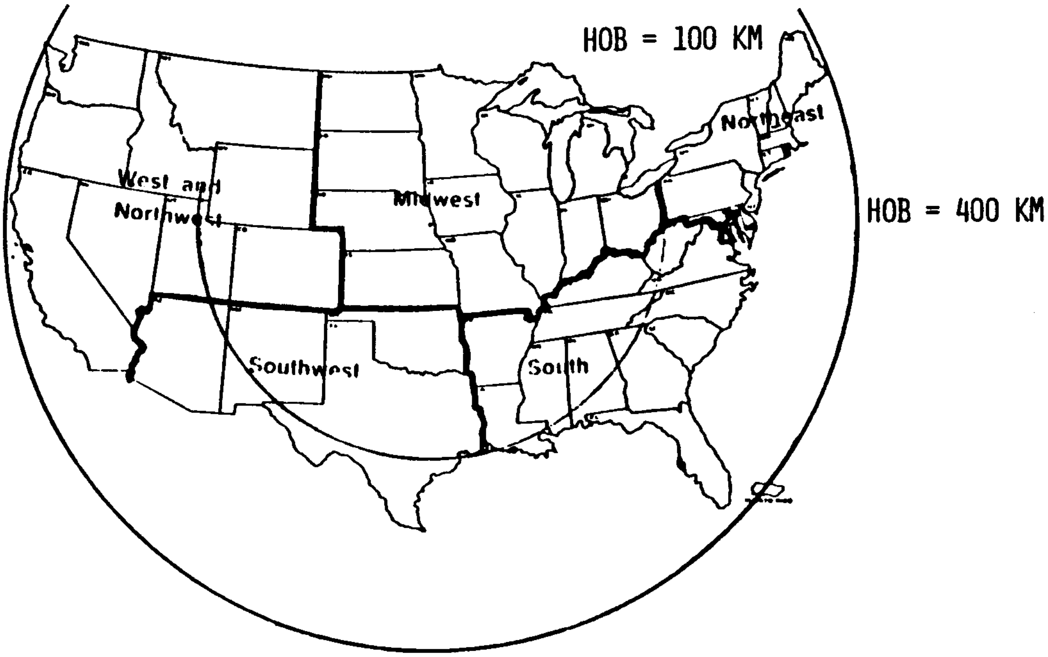


Figure 2.1. Tangent Radius (Surface Area Covered by EMP) for Two Burst Heights.

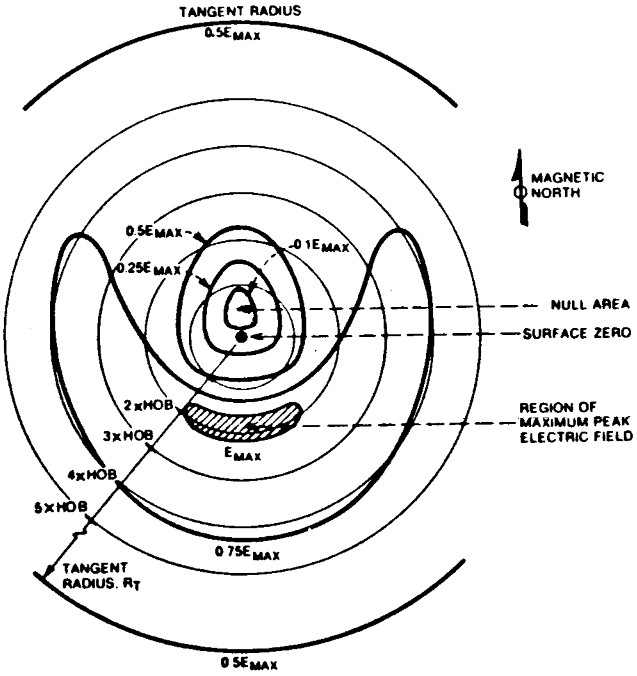


Figure 2.2. Variations in High Altitude EMP Peak Electric Field on Surface of Continental United States (Reference 4).

2.2 EMP Interactions

The HEMP, being a broad-band radio frequency signal, can interact with a variety of electrical networks which are specifically designed as antennas or which act as an antenna when subjected to such a signal. For land-based facilities, such as nuclear power plants, we can identify three potential interaction paths. The EMP signal may penetrate directly into the plant interior, the so-called diffused field, and then couple with interior plant cabling to induce currents on those cables. The EMP can interact with the external power grid to which the plant is connected, and currents induced on the external distribution system in close proximity to the plant could penetrate into the plant on power lines feeding plant systems. Finally, the EMP might induce currents on power and instrumentation lines which interconnect various plant buildings and systems. All of these potential mechanisms are addressed in this study.

2.3 EMP Threat

In any vulnerability study one of the first questions of concern is, what is the threat? Because defining an EMP threat to the continental U.S. involves many factors and transcends problems associated with just the nuclear power industry, the decision was made that this study would look at a "worst case" situation. That is, it was assumed that the threat is such as to optimally excite each and every potential point of interaction. Clearly, in any actual scenario, no single weapon could be so targeted as to do that, therefore the results establish an upper bound to the threat to the plant.

The actual EMP threat waveform used later in the coupling analyses is the commonly recognized double exponential, high altitude EMP waveform[4] characterized by an electrical field time history of:

$$E(t) = E_o(e^{-\alpha t} - e^{-\beta t})$$

where

$$E_o = 5.25 \times 10^4 \text{ V/m}$$
$$\alpha = 4.0 \times 10^6 \text{ sec}^{-1}$$
$$\beta = 4.76 \times 10^8 \text{ sec}^{-1}$$

The frequency spectrum of this pulse can be obtained by taking the Fourier transform of the time domain wave form. The significant frequencies extend out to about 150 MHz with the bulk of the energy (99.9 percent) below about 100 MHz.[4]

Because EMP susceptibility questions are of particular concern to the DOD, there is continuing research and investigation designed to better define the EMP environment. In the early stages of this study there was some discussion between the study team and the Defense Nuclear Agency as to the appropriate threat waveform. When some of the newer formulations were compared to the standard double exponential cited above, it was observed that in the frequency domain the double exponential threat bounds all other threats. Likewise, none of the other suggested threats had peak field intensities (E_O) greater than the 5.00×10^4 V/M cited. Therefore, because there was no compelling reason to change, the double exponential waveform was used.

It is known that a magnetohydrodynamic (MHD) pulse, persisting for tens to hundreds of seconds, follows the early time HEMP. A typical normalized waveform derived from atmospheric nuclear test data is shown in Figure 2.3. The MHD-EMP waveform can have peak electric field intensities of 10 to 100 V/km over large areas. In order to be a threat to nuclear plant equipment, two conditions must be present:

1. Transmission lines must be sufficiently long to allow for large potential differences to exist between end points.

2. A low impedance dc ground must exist at both ends of the transmission line to allow dc currents to flow.

These two conditions are typically present in the bulk distribution system of electric power systems. In particular, wye-connected transformers or auto-transformers are usually used at this level of distribution which allows for the required dc earth connection.

At Watts Bar the 24 kV/500 kV transformers are delta-wye connected with the wye connection on the 500 kV distribution side. This seems to be true for most plants. Thus MHD-EMP currents induced on the 500 kV transmission lines can be expected to flow to earth ground via the 500 kV secondary windings of the transformers. Due to the inherent dc isolation of the delta-connected transformer primaries, dc currents will be blocked at the transformer and not coupled further into the plant. The major consideration, then, is the reaction of the main power tranformers to dc biasing currents on the outputs.

Electric utilities in norther latitudes have been concerned about solar-induced currents and their effect on bulk power distribution for many years. For solar-induced currents of less magnitude than may be expected from MHD-EMP, some of the following effects have been observed:[5,6]

1. The crest of the transformer magnetizing flux rises above the saturation level resulting in increased magnetizing current.

2. Reactive power increases.

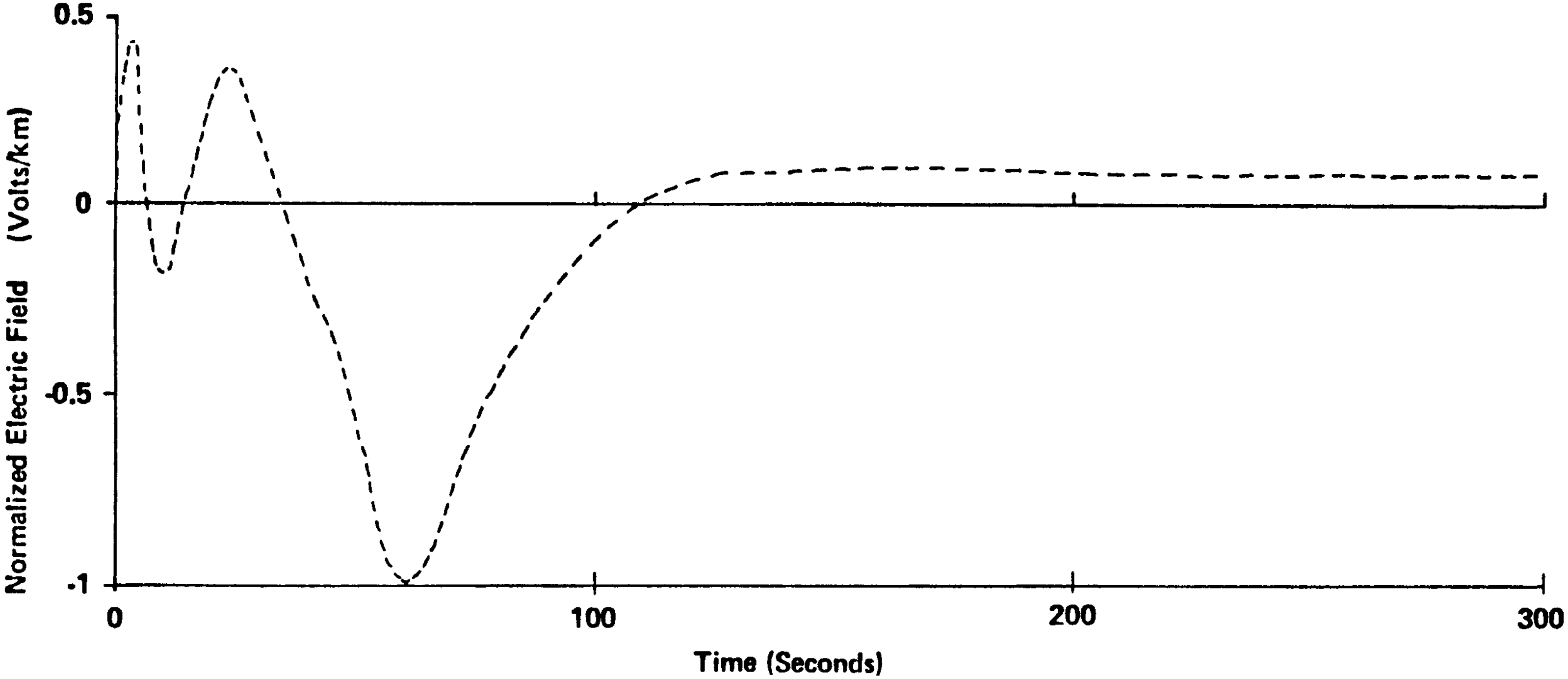


Figure 2.3. Magneto-hydrodynamic EMP Waveform.

3. Significant levels of 60 Hz harmonics are generated.
4. Heating may occur.
5. Protection circuitry may be initiated by the unusally large magnitude of the exciting current.

The MHD-EMP threat, then, is expected to be confined to the main output transformers. The most drastic response of the power system to MHD-EMP would likely be a disconnection of the transformer from the transmission grid as a result of either damage to the transformer itself by thermal effects or initiation of the transformer protective circuitry. Neither of these occurrences would affect the ability of safety systems to shutdown the plant. The Department of Energy and the DOD intend to address the MHD-EMP effect on power system equipment in a program currently being conducted.[7] That program will likely provide better estimates of MHD-EMP effects on transformers.

2.4 EMP Generators

Land based generators capable of being transported by truck have been developed in connection with EMP vulnerability testing of military systems. These generators are capable of producing localized EMP-like effects. Concerns have been expressed regarding the vulnerability of commercial nuclear power plants to sabotage or terrorist acts employing such generators. This type of EMP threat was considered early in the study by the government and industry participants involved, including the Research Review Panel established to monitor the study and provide peer review of its results. It was concluded that a threat did not exist because of the difficulty of deploying and operating such equipment in the vicinity of a plant without being detected, and because the effects of this type of equipment are low level and highly localized. Therefore, no further analysis of this type of EMP threat was included in this study.

3.0 Example Plant Description

3.1 General

The Watts Bar Nuclear Plant of the Tennessee Valley Authority was selected as the example plant for this study. This selection was predicated upon several factors. This plant was used in an earlier study on systems interactions in nuclear power plants,[8] therefore a significant amount of information was already available in the form of system descriptions and system fault trees. In addition, the design and construction of the plant had progressed to the point where final configurations were known, but at the same time it was "open enough" so that details of system arrangements could be observed visually.

The Watts Bar Nuclear Plant is a two-unit Westinghouse, pressurized water reactor plant located on the Tennessee River, approximately midway between Knoxville and Chattanooga. Each unit is rated at 1177 MWe (3425 MWt). Located in close proximity to the nuclear plant are the Watts Bar coal-fired Steam Plant and the Watts Bar Hydroelectric Dam. Figure 3.1 is a plan view of the area around the plant and Figure 3.2 provides two photographic views.

Offsite electrical power is supplied to the common station service transformers at the nuclear plant from two 161 kV feeders from the switchyard adjacent to the dam powerhouse. This 161 kV feed is required to power both reactor startup and shutdown systems. On-line operational power is derived from the 24 kV output of the nuclear plant turbine generators through the unit station service transformers. The plant main transformers supply 500 kV to the TVA transmission grid from the same 24 kV turbine outputs. Figure 3.3 is a plot plan of the nuclear plant showing the location of the various transformers and identifying the buildings and structures associated with the operation of the plant.

The plot plan shows the locations of the various plant buildings, the routing of conduit duct banks, and a partial layout of earth grounding cables. Only a rough layout of grounding is included to show the magnitude of the grounding arrangement. The extensive network of buried mechanical piping is not shown on the plot plan due to its complexity. Because this is an "integrated" two unit plant, there are a number of shared facilities. The auxiliary and control buildings, the diesel generator building and the intake pumping station house systems for both units. However, separation is maintained between units and between redundant safety trains for each unit.

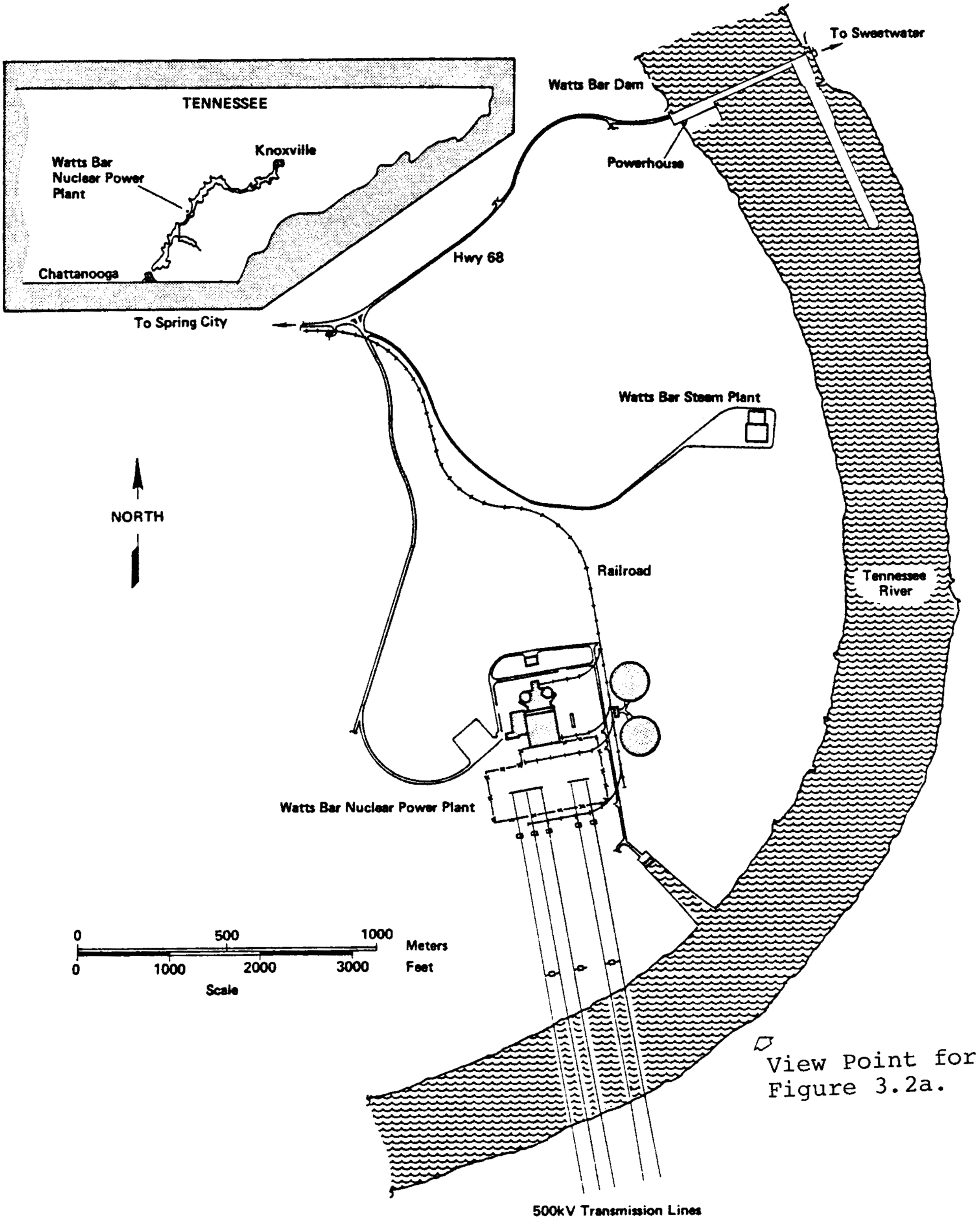
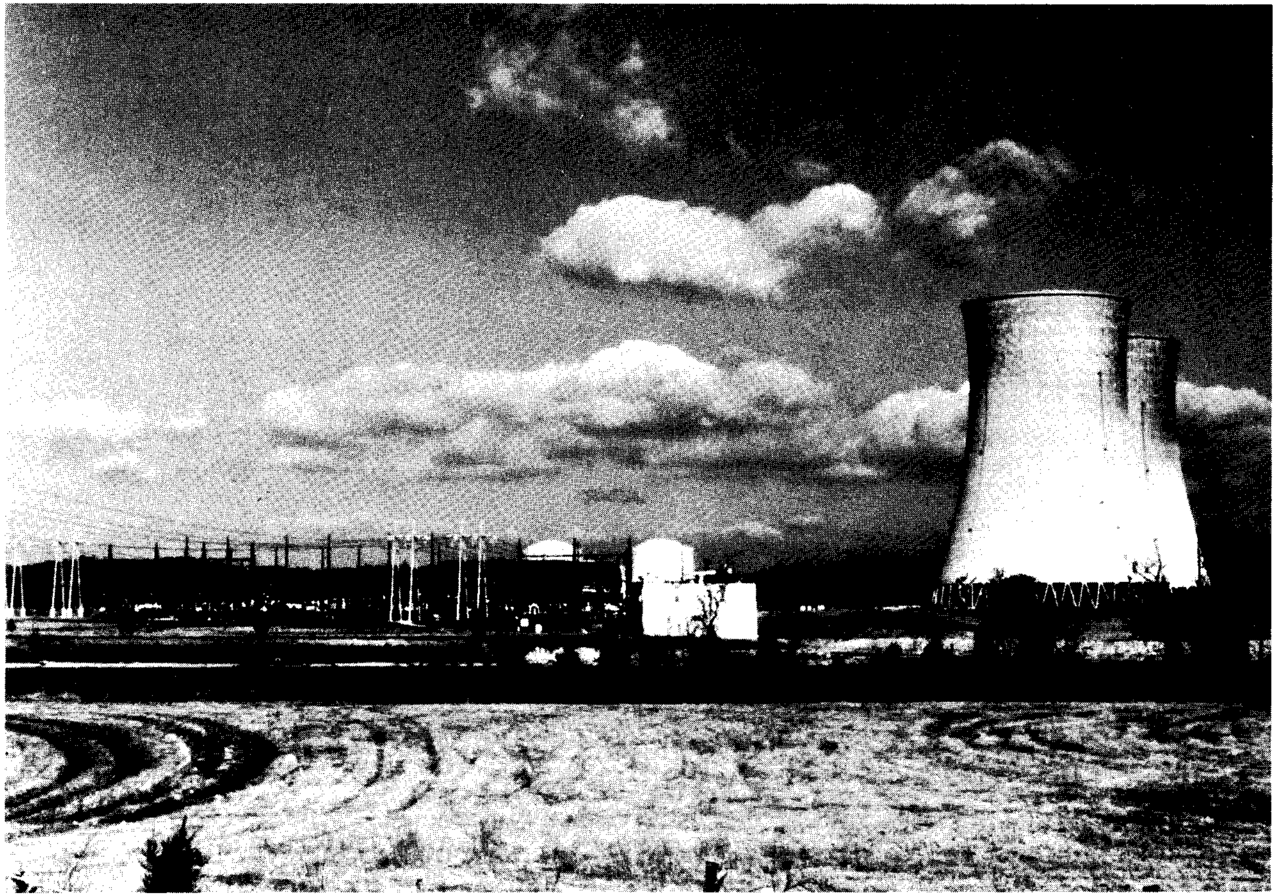
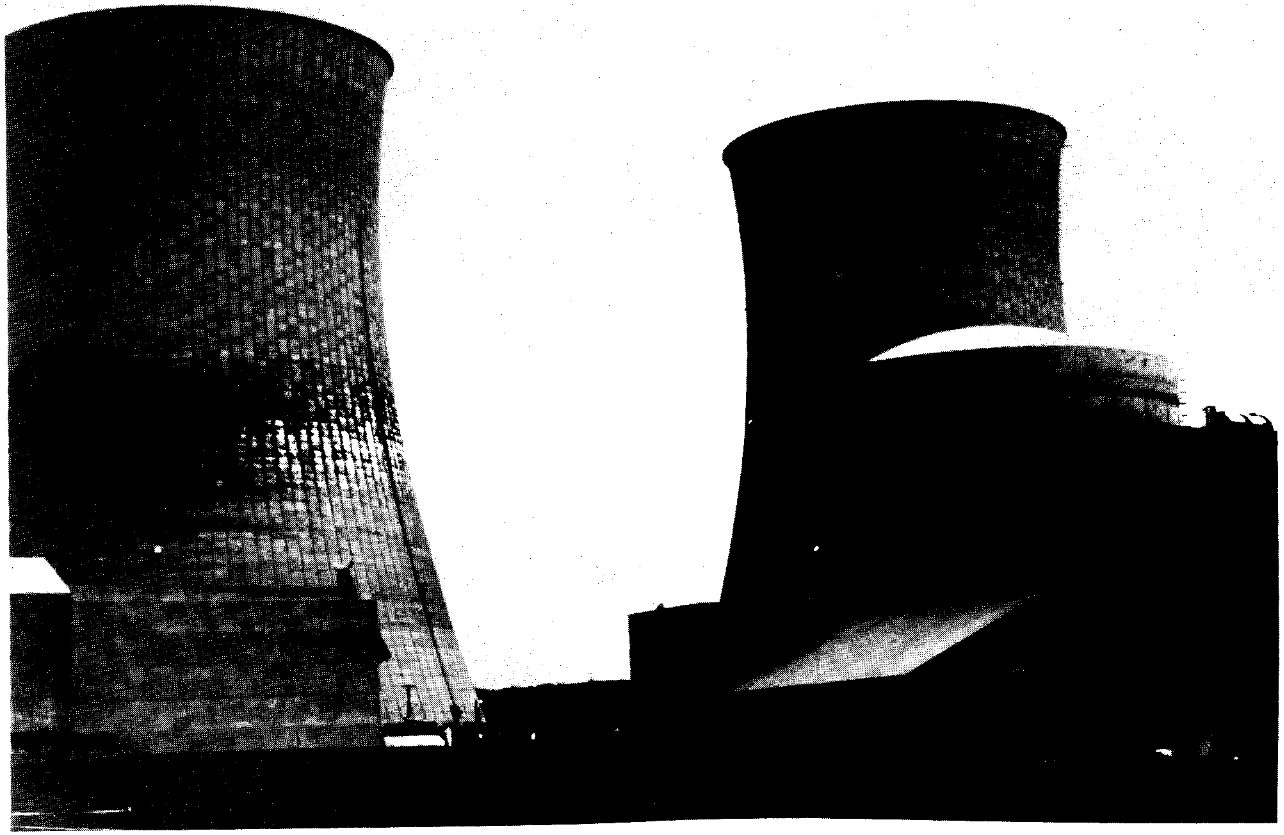


Figure 3.1. Watts Bar Nuclear Plant and Environs.



(See Area Plan in Figure 3.1 for
Photograph Orientation.)

Figure 3.2a. Photographic View of Watts Bar Nuclear Plant (Looking Northwest).



(See Site Plan in Figure 3.3 for Photograph Orientation.)

Figure 3.2b. Photographic View of Watts Bar Nuclear Plant (Looking Southeast).

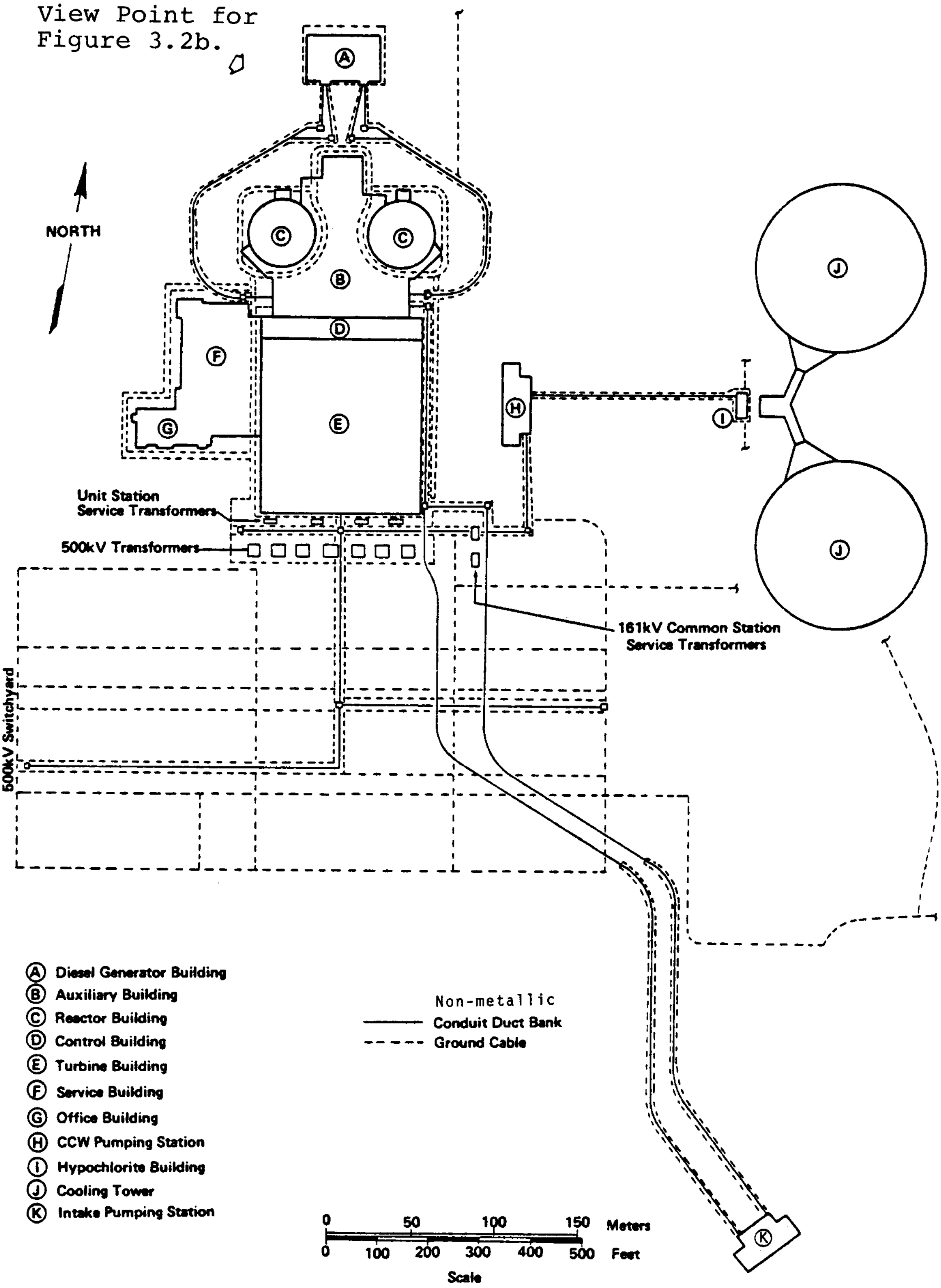


Figure 3.3. Plot Plan Watts Bar Nuclear Plant.

All buildings housing safety-related equipment are constructed to seismic Category I specifications. The walls of the Auxiliary Building, for example, are approximately 2 feet thick with a double course of reinforcing bars. Other Category I structures include the Diesel Generator, Control, and Intake Pumping Station Buildings. The reactor building is even more massive because of its containment function. Figure 3.4 shows some of the plant construction features in a cross sectional view of the Auxiliary, Control, and Turbine Buildings. The Turbine Building, because it does not house safety-related equipment, is not constructed to Category I specifications but is built of structural steel beams with a sheet steel and glass outer shell.

3.2 Design Features of Special Interest

Conduit duct banks (see Figure 3.3) interconnect plant buildings and provide seismic Category 1 protection for power, control, and signal cables that connect to various plant systems. A detail of a duct bank section that connects the Auxiliary Building to the Intake Pumping Structure is shown on Figure 3.5. The duct bank consists of an array of plastic conduits encased in concrete. Steel conduits are used instead of plastic from the final manhole to the actual penetration of a building, but this represents a short distance compared to the overall length of the duct bank.

Cables are pulled into the conduits in functional groupings based on power levels. In general, the high-voltage, high-power cables are routed along the top ducts of the bank and the low voltage, low-power cables are routed along the bottom. The duct banks are buried as deeply as 20 feet and, in general, slope to a depth of 5 to 10 feet at the building penetrations. Ground cables are run parallel to the duct banks in order to provide lightning protection.

Within the buildings, cables typically run on ladder and ventilated louver-type cable trays. As with the conduit duct banks, cables are separated on trays as to functional type based on voltage and power levels. When a variety of cable types share a coincident routing, the trays are arranged into levels as shown in Figure 3.6. The high-voltage, high-power cables are physically at the top of the stack and the low-voltage, low-power cables are at the bottom. Physical separations of about 1 foot are typicaly maintained between levels.

With the exception of certain low-level signal and control cables, most cabling within and between buildings is unshielded. High-voltage, three-phase 6.9 kV power cables consist of an individual cable per phase, each wrapped with an overlapping helical foil shield which is locally grounded at each point of distribution or termination. All 480 V cables are unshielded and consist of both three-phase-per cable and individual-cable-per-phase cable types. Medium-level signal and control cables are usually unshielded-twisted pair or multiconductor cables.

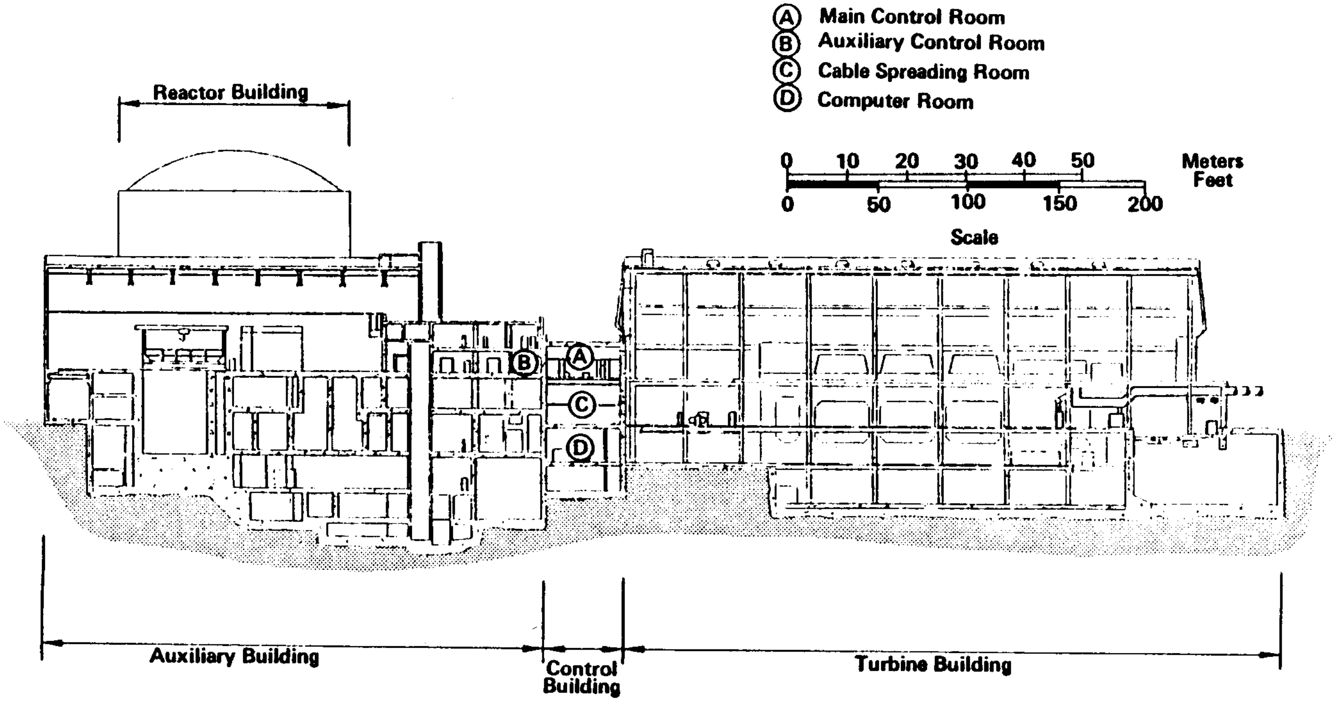


Figure 3.4. Cross-sectional View Watts Bar Nuclear Plant.

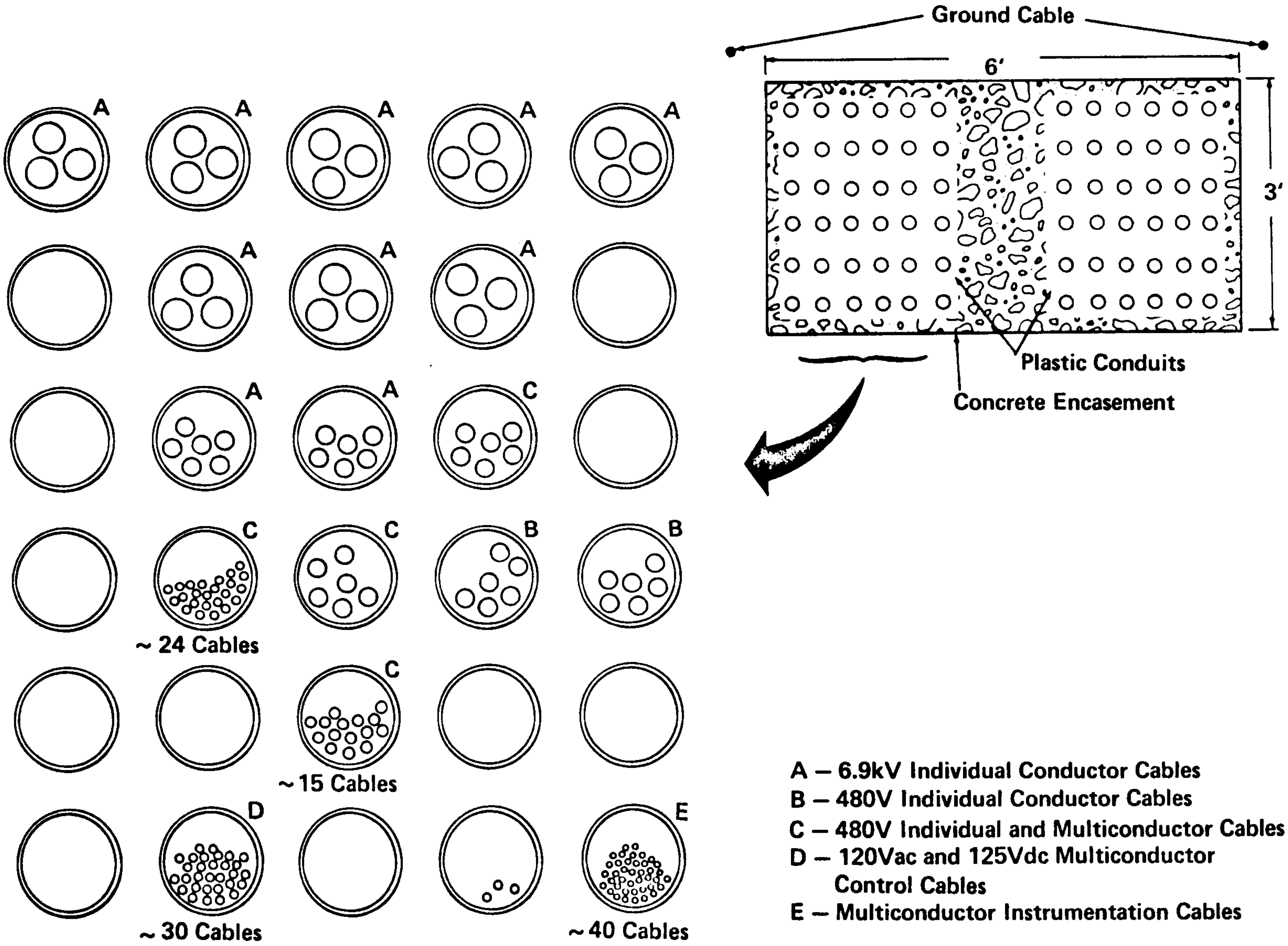


Figure 3.5. Conduit Duct Bank Details.

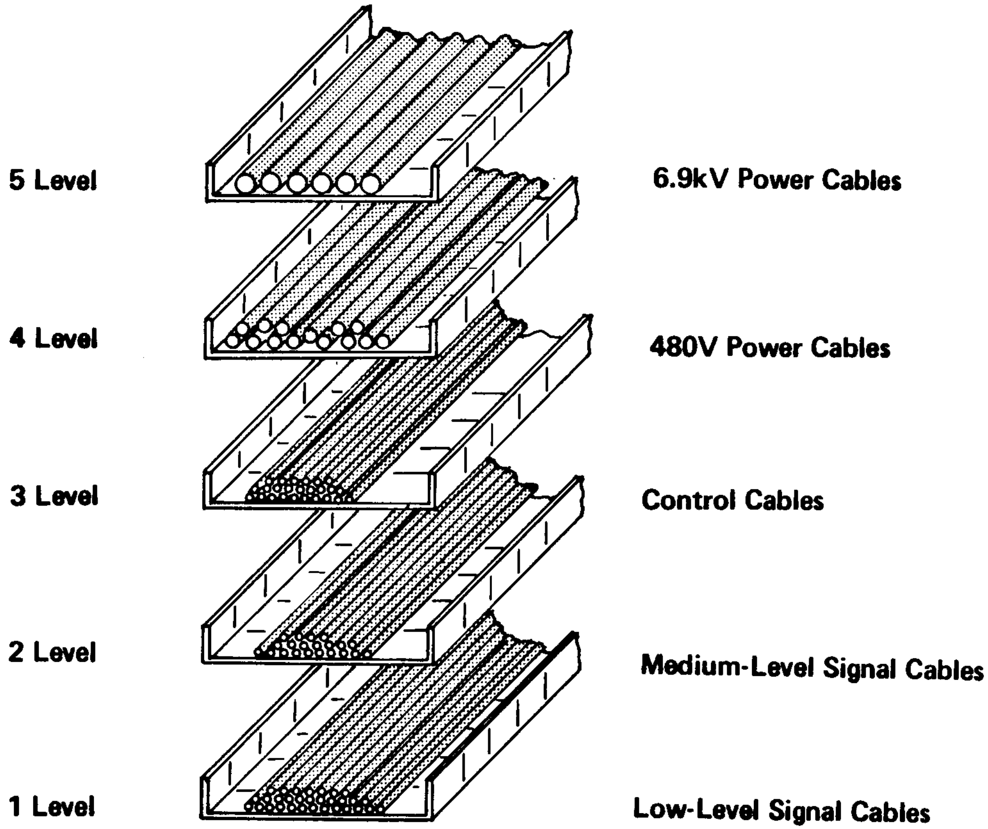


Figure 3.6. Cable Tray Details.

4.0 Nuclear Systems Analysis

4.1 Critical Systems

This investigation is limited to selected systems required for safe shutdown of a nuclear power plant, therefore the systems of interest must be defined. Three essential functions must be accomplished to safely shut down a nuclear plant.

> The fission process must be terminated, i.e., the reactor must be shutdown.
>
> The coolant inventory must be maintained so that the core remains covered.
>
> The heat generated from the radioactive decay of fission products must be removed.

Given the functions which must be carried out, it is a relatively straightforward task to define the systems of interest. In fact, this is normally done by each licensee in the Safety Analysis Report. For the example plant, the systems required for safe shutdown include:

> The reactor protection system (at least a manual scram capability).
>
> The ac/dc emergency power systems (required for power, control, and instrumentation).
>
> The auxiliary feedwater system (first path for decay heat removal if the main condenser is not available and there is no major loss of coolant).
>
> The residual heat removal system (required for primary system cooling to take plant to cold shutdown).
>
> Chemical and volume control system (necessary to make up coolant loss from seal leakage, volume shrink on cooling, etc.).
>
> Component cooling water system (the intermediate loop between equipment being cooled and the ultimate heat sink).
>
> Essential raw cooling water system (the ultimate heat sink for a wide range of support systems).
>
> Portions of the heating, ventilating and air conditioning system.
>
> Instrument air (for instrumentation and in some instances valve control).

These systems may carry other titles in other plants but similar functions will be performed.

Based upon other studies conducted by Sandia there are several observations which can be made about this list. First, not every system is required at the instant of shutdown. And, in fact, some systems may not be needed until many hours after shutdown is initiated. This can have an important bearing on the effects of a system failure. Second, as shown below, there is a "common denominator" present and that is the dependence upon emergency electrical power. For example, in most instances, even the steam turbine powered auxiliary feedwater system requires dc power for control purposes.

4.2 Initial Analyses of Safe Shutdown Systems

As indicated above, a number of system level fault trees were prepared previously for the Watts Bar Plant. Because the Auxiliary Feedwater System can be extremely important for decay heat removal, this system was analyzed first. The fault trees prepared under the Systems Interaction Methodology Applications Program[8] were used as the starting point for the EMP analysis. However to adequately treat the questions of EMP susceptibility, it was necessary to further develop the fault trees. Because there is widespread interest in the methods and techniques of probabilistic risk assessment, there is active research in the area of fault tree development. In fact, standardized procedures are being developed to provide consistency in the fault trees generated. These standardized techniques[9] were used here. An example of the results follows.

The Auxiliary Feedwater Systems are typically designed so that even if failures occur in the emergency electrical power system, feedwater can be provided by means of a steam turbine driven pump. However, if the motor operated valve (MOV) in the steam supply line fails to open to supply steam to the turbine then that system is inoperative. Figure 4.1 shows the development of the event, MOV 1 Fails Closed, using the IREP procedures.[9] The valve fails closed if there is no electrical power, which can result if circuit breakers fail open, if cables fail or if there is a loss of power on the bus. This latter loss of power can be further defined as indicated in the subsequent development of the tree. The obvious conclusion is that the emergency electrical power systems are indeed crucial to the operation of the auxiliary feedwater systems. It was quickly apparent from a brief review of other systems that this was indeed the "common denominator" throughout the safe shutdown systems. Therefore, the subsequent analyses focused on the ac/dc emergency power systems and control and instrumentation systems for the critical systems.

4.3 Electrical Distribution System

A simplified one line diagram for the internal electrical power systems is shown in Figure 4.2. The Station Service Transformers provide 6.9 kV power to the Unit Boards which in turn feed the 6.9 kV Shutdown Boards and also some non-safety loads through

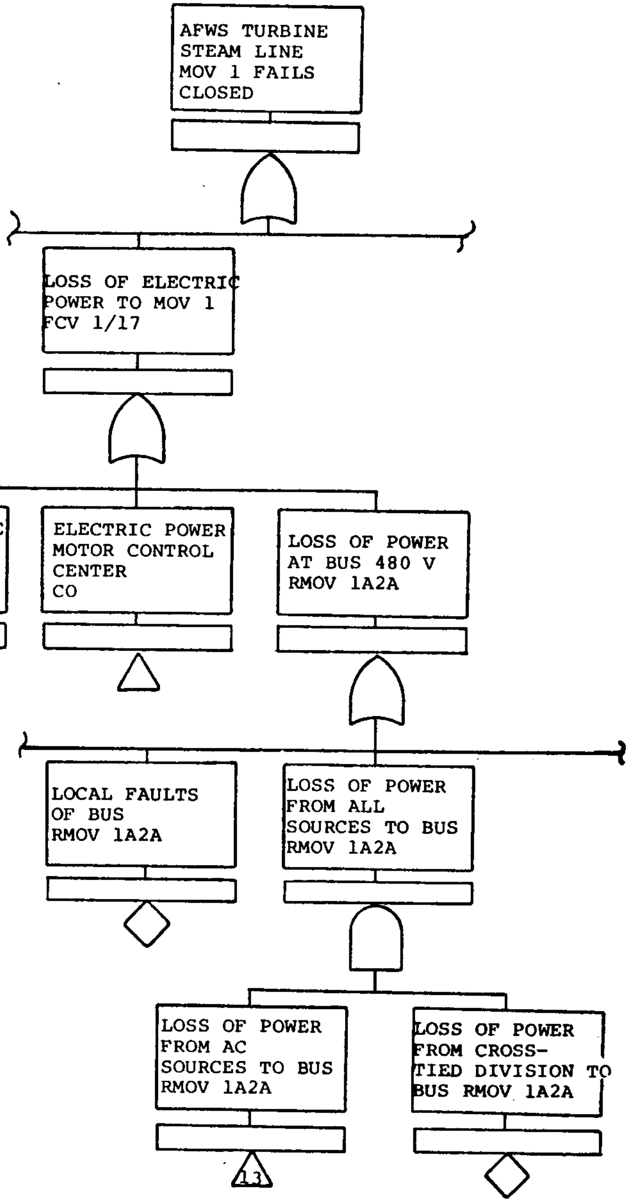


Figure 4.1. Portion of AFWS Fault Tree.

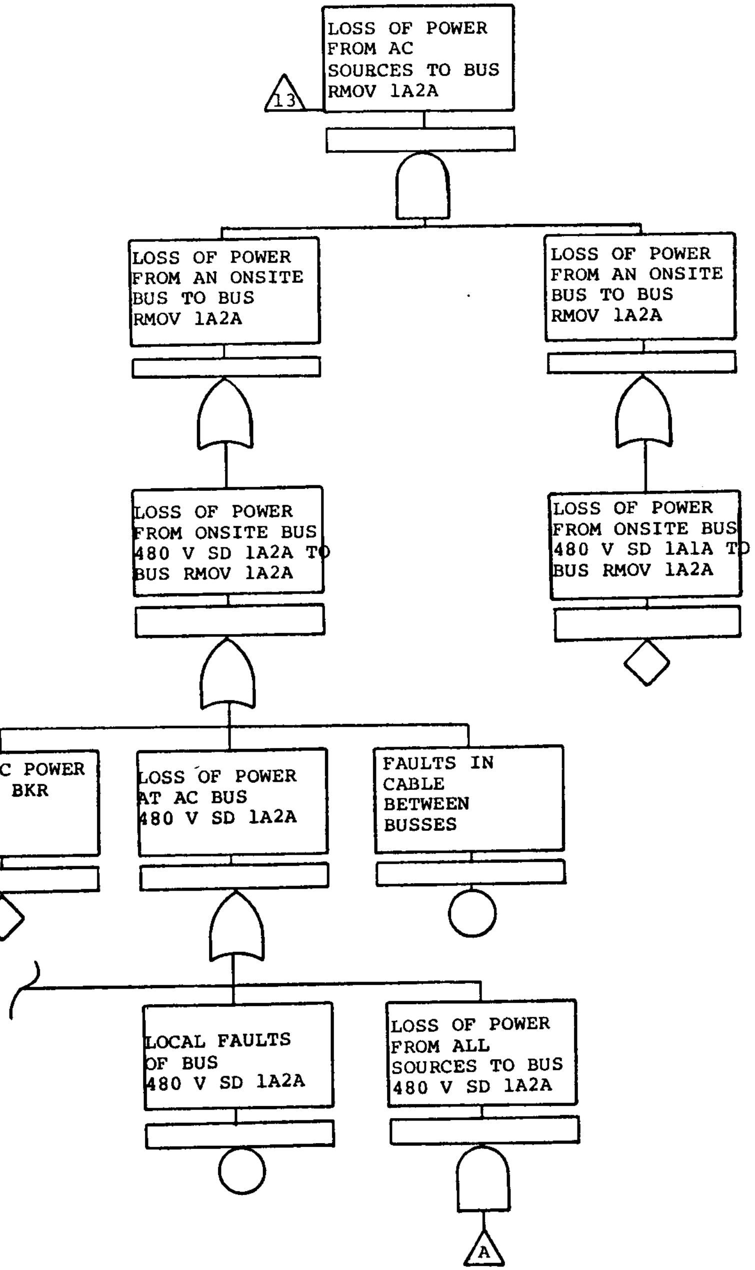


Figure 4.1. Portion of AFWS Fault Tree (Continued).

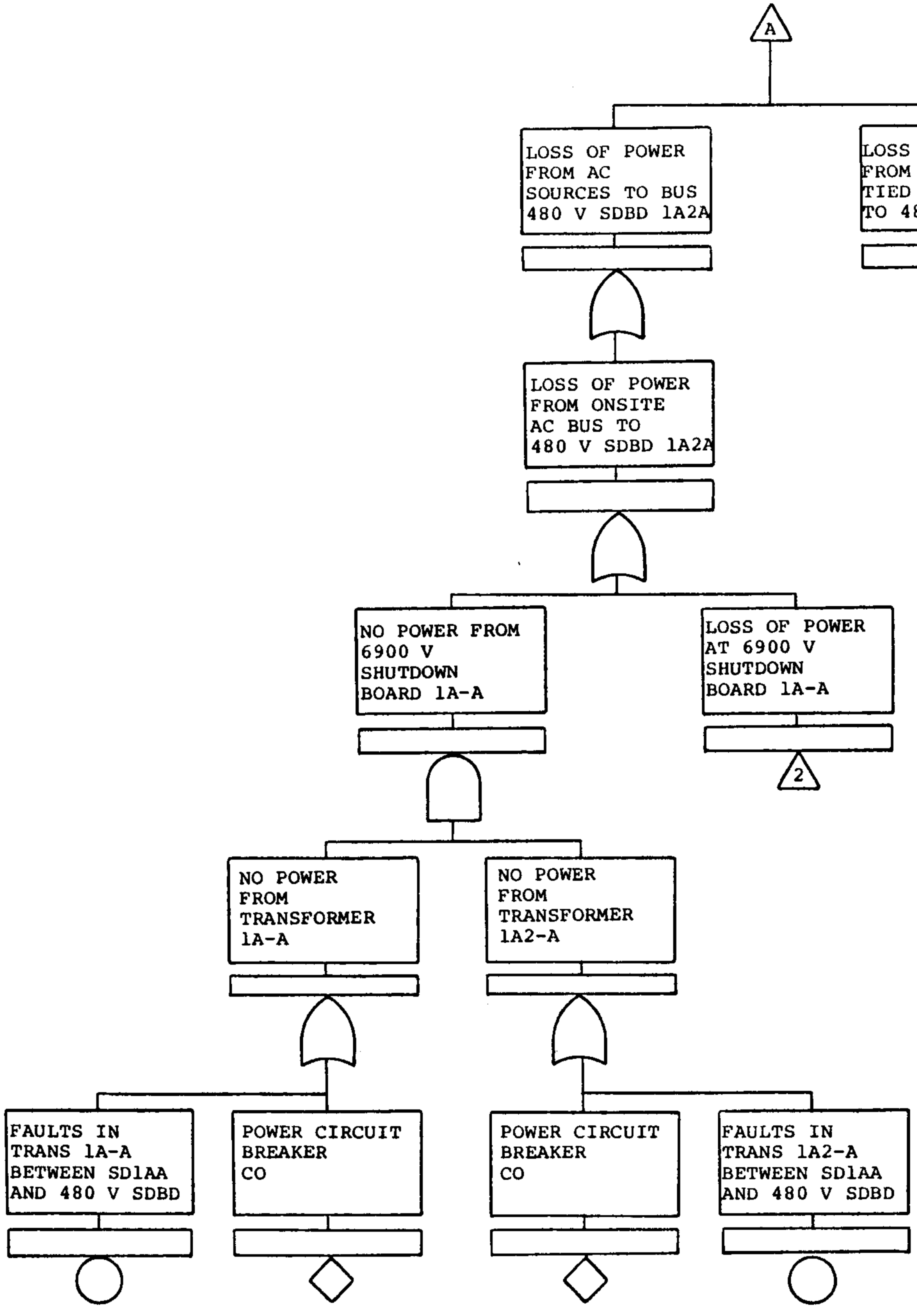


Figure 4.1. Portion of AFWS Fault Tree (Continued).

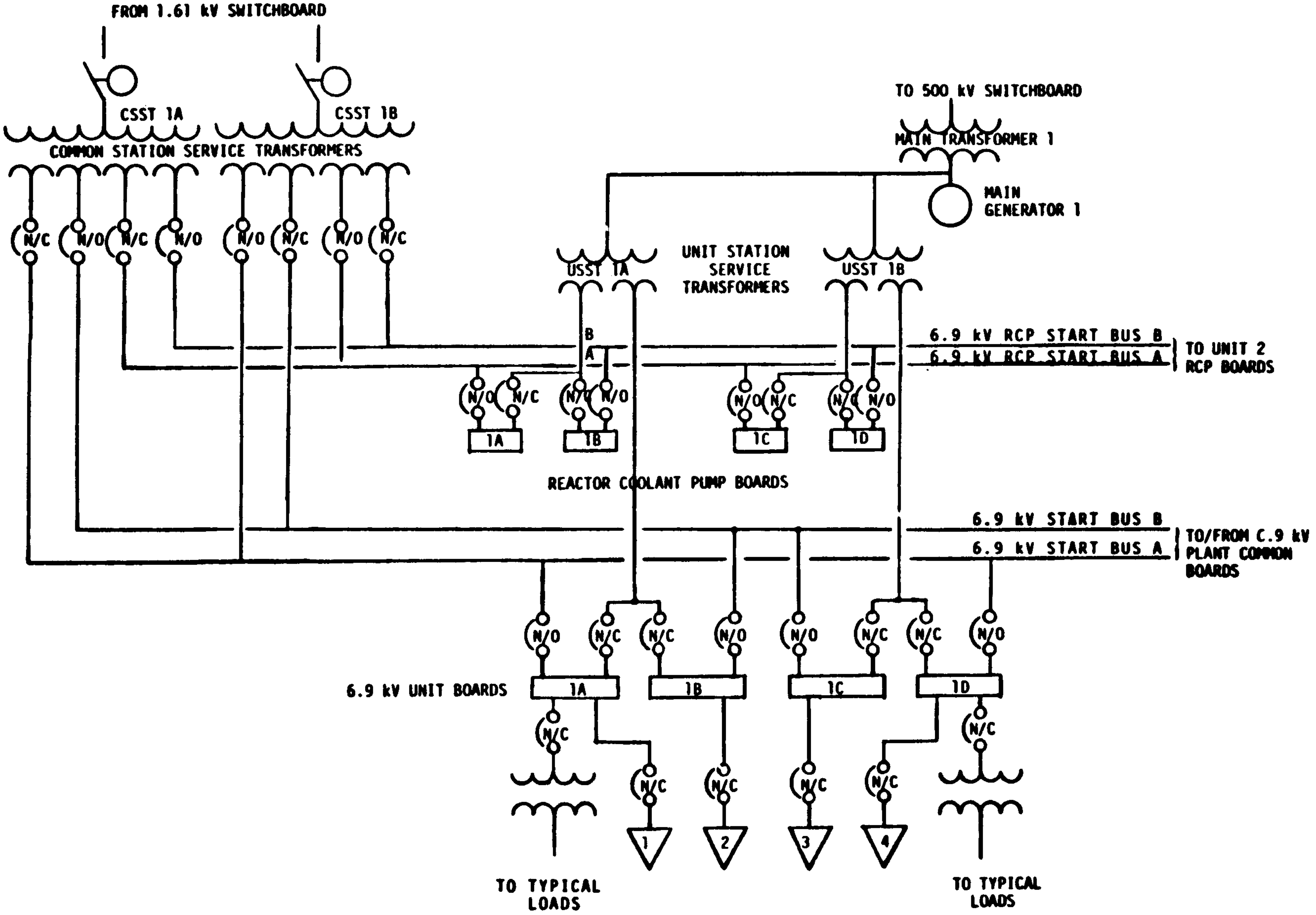


Figure 4.2. Simplified One-Line Diagram Watts Bar Nuclear Plant Electrical Power System.

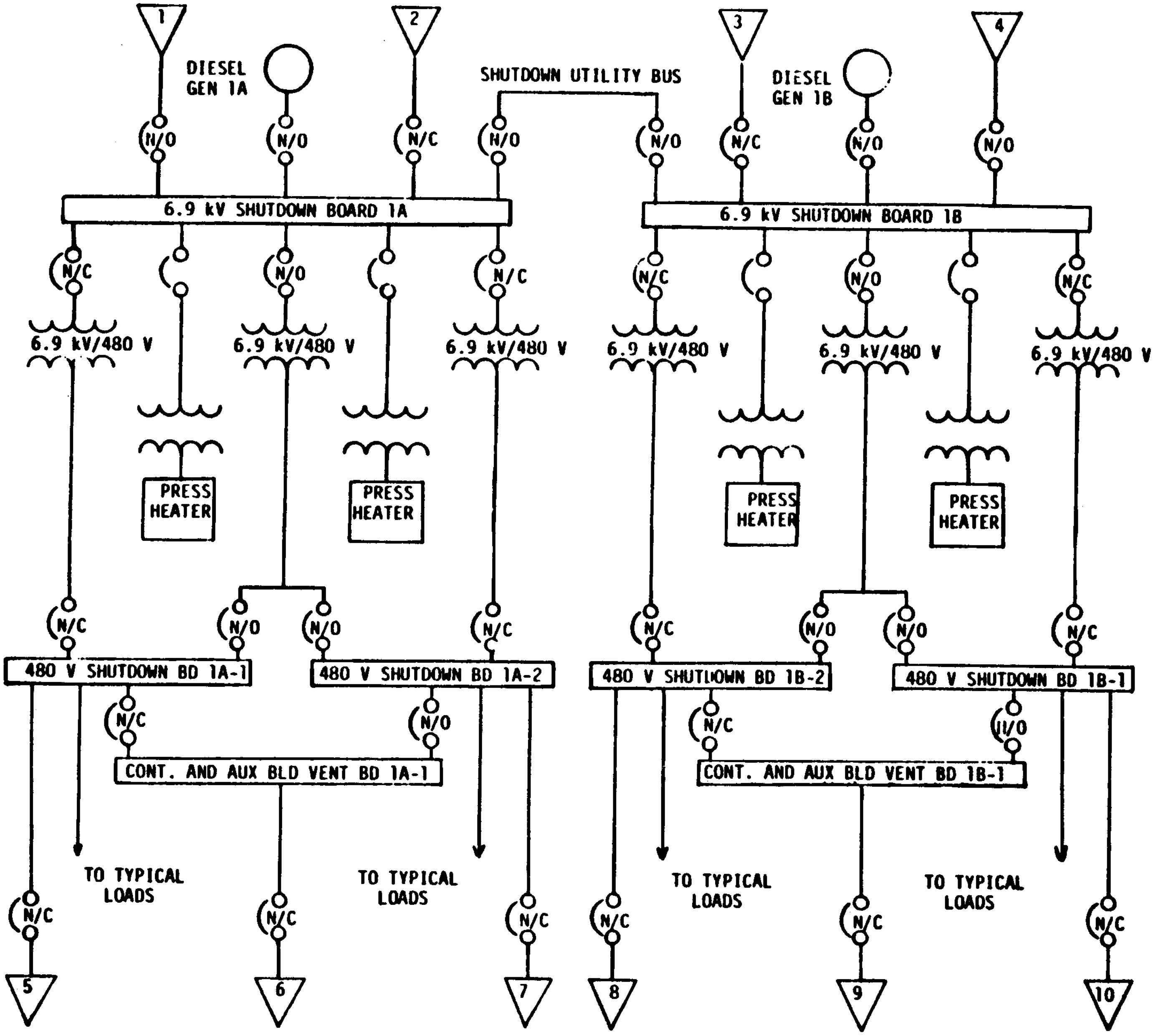
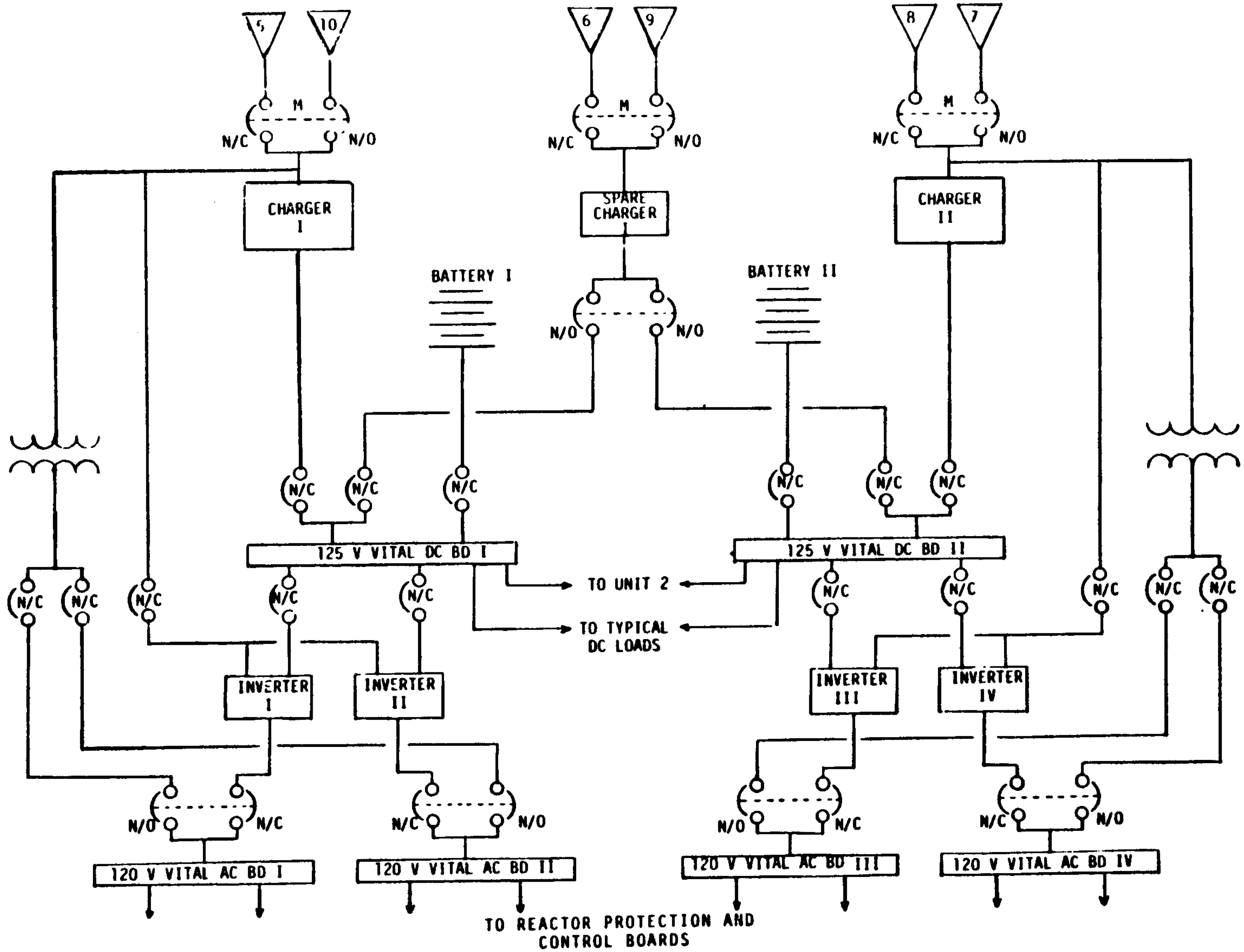


Figure 4.2. Simplified One-Line Diagram Watts Bar Nuclear Plant Electrical Power System (Continued).



NOTE: 125 V BATTERY CHARGERS III & IV AND THEIR RESPECTIVE INVERTERS ARE SUPPLIED BY UNIT 2 480 V SHUTDOWN BOARDS.

Figure 4.2. Simplified One-Line Diagram Watts Bar Nuclear Plant Electrical Power System (Continued).

6.9 kV/480 V transformers and provide 6.9 kV power. The 6.9 kV Shutdown Boards may also be supplied from the Standby Diesel Generators. Power is passed to the 480 V Shutdown Boards via 6.9 kV/480 V transformers. The 480 V power is then fed to a number of motor control centers (e.g., the Containment and Auxiliary Building Ventilation Board). The 480 V Shutdown Boards also provide power to the battery chargers and inverters and thus to the vital dc and ac boards.

The actual loads associated with each of the shutdown boards and subsequent load centers were established by a detailed examination of the one-lines for each board. Such a one-line is shown in Figure 4.3. This permitted us to define the loads, the control systems (ac or dc), the location of switches (control room, motor control center, local). This information was combined with estimates of the length of cable runs interconnecting the load and the bus, a decision as to load status assuming the plant was at normal full power operation (normally energized, normally open, etc.), a decision as to load criticality, and tabulated as shown in Table 4.1. These tables were then used by the analysts to establish the points in the system at which predictions of EMP-induced signals were to be made. The typical prediction points are summarized in Table 4.2.

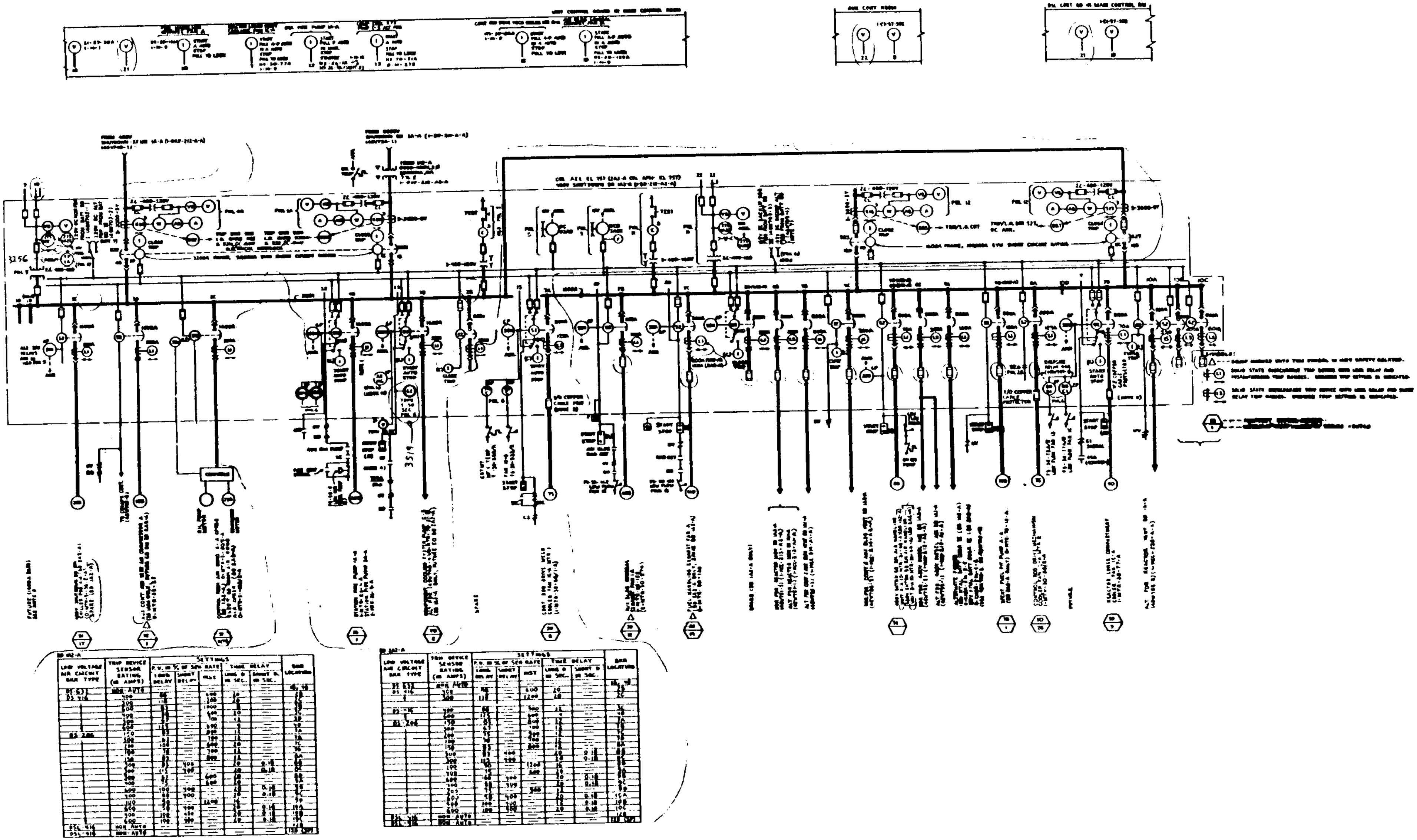


Figure 4.3. Typical One-Line Diagram for 480 V Shutdown Board

Table 4.1

Typical Load Worksheet for EMP Analyses

480 V Shutdown Board 1A1-A (TVA Drawing 45W749-1)

Prediction Required	Connectivity Code[1]	Cable Length (Ft)	Outside Connection	Item/Component	Switch Location[2]
	A	50		Aux Bldg General Supply Fan	MCR-Local-Interlocks
Yes	A	75		CCS Pump 1A-A	MCR-MCC-Local-Interlocks
	D	25		Alt Fdr-Cont and Aux Bldg Vent Bd	MCC-Local
	A	225		CRDM Cooler Fan 1A-A Motor 1	MCR-MCC-Local-Interlocks
	A (intermit)	75		Electric Board Room AHU A-A	Local-Interlocks
	A (intermit)	225		Cont Air Return Fan 1A-A	MCR-Local
	A	225		CRDM Cooler Fan 1A-A Motor 2	Interlocks
Yes	A	100		Norm Fdr 480V Reactor MOV Bd 1A-A	Local
Yes	A	125		Norm Fdr Reactor Vent Bed 1A-A	Local
Yes	A	25		Norm Fdr Cont & Aux Bldg Vent Bd 1A1-A	Local
Yes (Source)	A	750	Yes	Norm Fdr Diesel Aux Bd 1A1-A	Local
Yes (Source)	D	750	Yes	Alt Fdr Diesel Aux Bd 1A2-A	Local
	B	225		SF Pit Pump C-5	Local
	D	175		Alt Fdr 250V Charger	Local
	C	---		Spare	
Yes	A	100		Norm Fdr 125V Charge I	Local
	B	225		Reactor Lower Comp Cooler Fan	MCR-MCC-Local-Interlocks

(1) A-load on normally, B-circuit open at board, C-no connection, D-circuit open at load.

(2) MCR-Main Control Room, MCC-Motor Control Center, Local-at/on equipment, Interlocks-Ties via relays to other equipment.

Table 4.2.

Typical Current/Voltage Prediction Points

6.9 kV Shutdown Boards

Pumps (ERCW, RHR, AFW, CHG)
Pressurizer Heaters

480 V Shutdown Boards

CCS Pumps
Battery Chargers
Inverters
Air Compressors

Reactor MOV Boards

Valves (ERCW, AFW, CCS, RHR, CVCS)
Oil Circulating Pumps (AFW, CHG)
Boric Acid Tank Heaters

Diesel Auxiliary Boards

Battery Chargers
Pumps (Fuel Oil, Lube Oil)
Cooling System Valves

125 VDC Vital Boards

Shutdown Board Control Busses
Battery Chargers
Vital Instrument Inverters
AFW Controls
Relief/Isolation Valve Controls
Reactor Trip Switchgear

120 VAC Vital Instrument Boards

Process Control Groups
SSPS Relays/Power
NIS Power
NSSS Relays

5.0 EMP Interaction Analysis

5.1 Abbreviated Analysis Technique

The analysis technique employed during the EMP assessment of the example plant (Watts Bar) is an outgrowth of analysis procedures developed by Boeing to assess the EMP vulnerability of various military weapon and communication systems.[10] In an effort to reduce the level of effort, and thus the expense, required to perform detailed analyses, abbreviated analysis methods have been devised that allow vulnerability estimates to be made in an onsite environment. Although the technique outlined below is straightforward, abbreviated analyses rely heavily on the experience of the analysts and the confidence previously gained by producing predictions that have been verified by testing programs. Typically, the following tasks are performed in an abbreviated assessment:

1. Cabling attached to the critical equipment is traced to the penetrations of EMP energy which can drive it.

2. EMP-induced signals (short circuit currents) are estimated for the relevant penetration cables.

3. The penetration currents are traced back to the critical equipment taking into consideration ohmic, cross-coupling, and distribution fan-out losses.

4. If the cables under consideration are unshielded, their source impedances and the equipment load impedances are used to derive reflection coefficients at the cable-equipment interfaces. The voltages at the equipment are computed from

$$V_\ell = V_o \left[\frac{2Z_\ell}{Z_o + Z_\ell}\right] \qquad (5.1)$$

where Z_ℓ is the load impedance, Z_o is the source impedance, and V_o is the traveling voltage wave on the cable. Since $V_o = I_o Z_o$ and $I_o = I_{sc}/2$, where I_{sc} is the short circuit current.

$$V_\ell = \frac{I_{sc} Z_o Z_\ell}{Z_o + Z_\ell} \qquad (5.2)$$

For the typical case where the load impedance (particularly in the common mode) is much larger than the source impedance,

$$V_\ell \approx I_{sc} Z_o \qquad (5.3)$$

If differential mode (wire-to-wire) responses are required, it is assumed that sufficient unbalance exists in conductor topology to allow approximately half of the common mode threat to appear in the differential mode.

5. If the cables are shielded, the responses at the equipment inputs are dependent on the quality of the shields and the treatment of the shields at the cable terminations. This requires a more detailed anaysis involving pigtail effects and coupling through braided shields.

In performing the above tasks during the electromagnetic analysis, coupling model diagrams were developed that detail the connectivity of the critical equipment to sources of EMP excitation. Figure 5.1 is an example of such a model diagram, the remainder are included in Appendix A. These diagrams also serve as worksheets to trace the penetration currents back to the equipment.

The tracing of the penetration currents back to the critical equipment generally requires special consideration at points of fan out such as at distribution boards or cable bundle break-outs. For example, consider N loads or cable conductors connected to a distribution bus being driven by one or more current carrying conductors. The instantaneous currents on all the conductors connected to the bus obey Kirchoff's current law; that is, the instantaneous current out of the bus sums to the instantaneous current into the bus. Due to varying cable lengths and load impedances, the peaks of the output currents will not occur simultaneously; thus, the sum of the individual output time domain peak current levels will not necessarily be equal to the input time domain peak current. In general, the sum of the individual time domain peak currents is greater than the input peak current.

When the N loads are identical, the individual conductor cur rent out of the distribution bus is the input current, I_{in}, reduced by the number of conductors (I_{in}/N).

For non-identical loads there will be a distribution of individual peak current values, above and below I_{in}/N, with an average in the distribution occurring above I_{in}/N. For typical non-identical cable runs with N greater than five and cables of substantial electrical length ($\sim 10\lambda$ where λ is the wavelength of the frequency of interest), experience has shown that the peak of the distribution is usually bounded by the limits I_{in}/N and $I_{in}/\sqrt{N}$. The geometric mean of these two limits, $I_{in}/N^{3/4}$, yields a reasonable estimate of the average peak value of the current distribution.

Two basic configuration types were identified for estimating purposes. In the first case, essentially identical cable types and lengths connect to similar or very remote terminations. Here, the appropriate choice for the average cable current is I_{in}/N. In the second case, generally unknown or differing loads connect to cables of differing types and lengths. The average cable current here is best estimated by $I_{in}/N^{3/4}$.

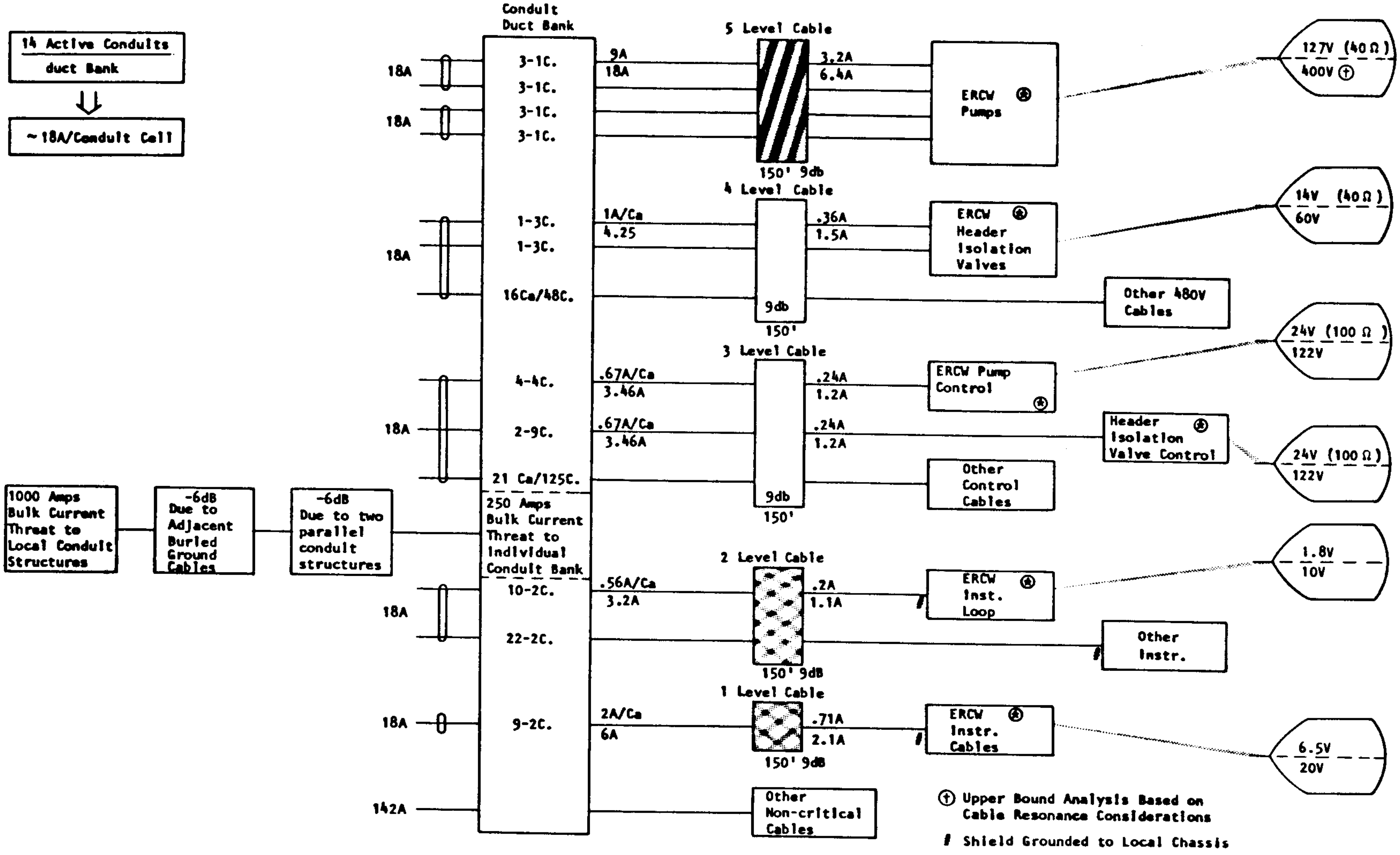


Figure 5.1. Response Model Diagram for Intake Structure.

In the computation of cable losses due to ohmic and cross-coupling effects, experience* has shown that five to six dB of attenuation can be expected for each 100 feet of cable.

5.2 Electromagnetic Features and Analyses

The construction practices employed at the example plant provide a great deal of inherent electromagnetic shielding to the areas of the plant housing safety-related critical systems. The multiple courses of steel rebar in the building walls, the extensive steel mechanical support system, and the large array of interior electrical equipment racks, panels, and cable trays all serve to greatly reduce the level of electromagnetic fields diffusing through the building structure. The least attenuated field component would be the magnetic field near the outside walls and on the upper floors near the roof. Steel-reinforced buildings of this type have exhibited magnetic field shielding effectiveness of 30 dB or more to frequencies ranging up to 75 MHz. In the central regions of the plant, diffusion field strengths are expected to be attenuated 50 dB or more below external incident fields.

Due to the consistent use of continuously connected metal conduits and cable trays within the plant, internal cabling and the associated electrical equipment will be largely decoupled from the attenuated diffusion fields. Responses due to this local excitation are expected to be below an ambient level established by the general dispersion throughout the plant cabling system of penetration currents conducted into the plant on externally excited cabling such as those in the buried conduit systems, the grounding cables and even piping. This general level of ambient response is estimated to be about 1 volt.

The onsite survey and review of plant configuration drawings identified the major penetrations of externally conducted EMP energy to critical systems. The penetrations themselves, while composed of large numbers of individual cables, are discrete, readily identifiable and well controlled. At Watts Bar, the following penetrations were investigated in detail for coupling potential to critical equipment and are depicted in Figure 5.2 by a simplified penetration connectivity diagram.

1) 500 kV overhead transmission lines to the Turbine Building. (At startup and during shutdown the 161 kV feed replaces the 500 kV source.)

2) Buried conduit duct bank cables to the Intake Pumping Station.

3) Buried conduit duct bank cables to the Diesel Generator Building.

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*Tests which are described in Section 6 were conducted to verify that this experience is also applicable to the example plant.

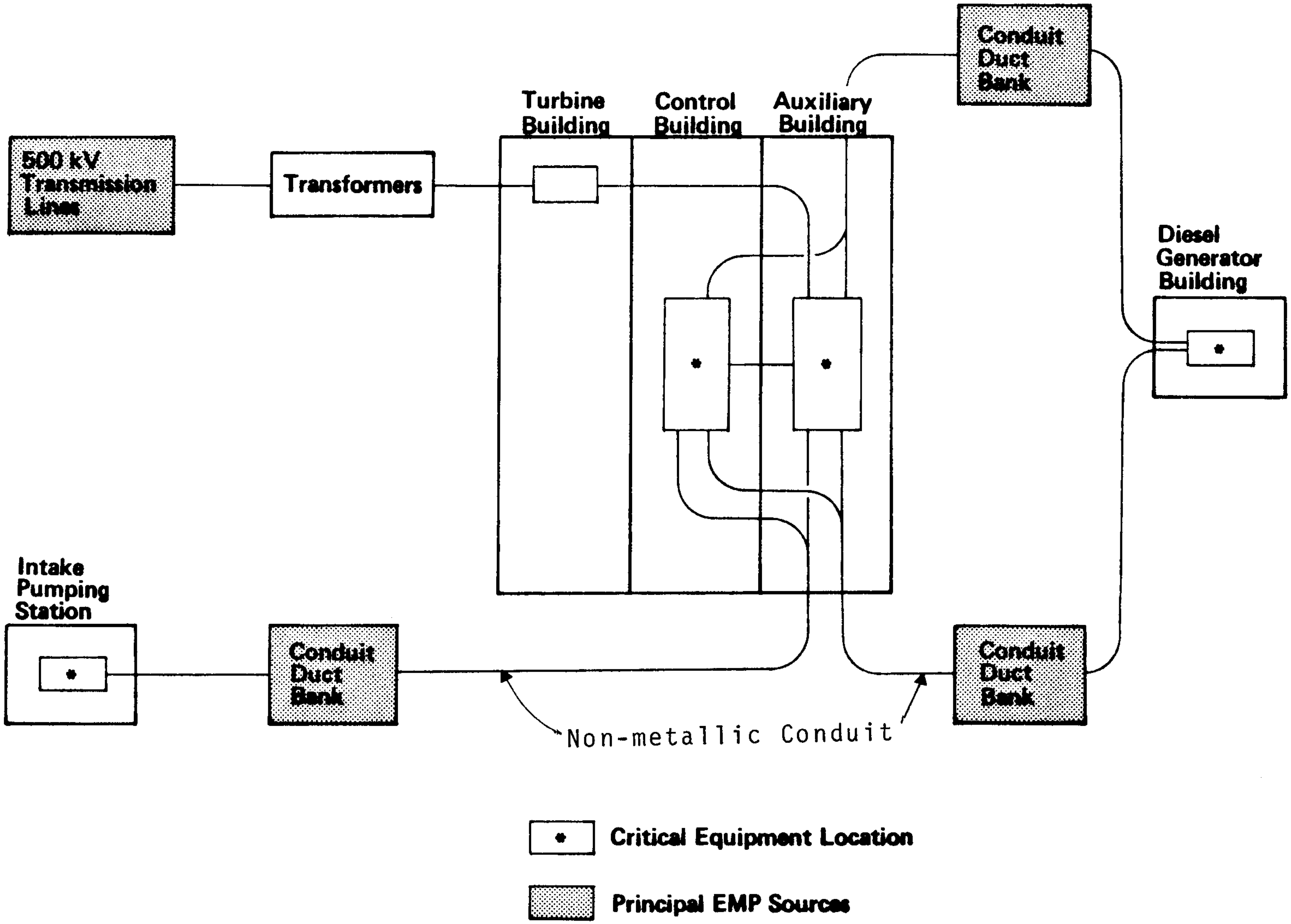

Figure 5.2. Simplified Connectivity Diagram.

4) Buried conduit duct bank cables from the Diesel Generator Building to the Auxiliary Building.

5) Buried conduit duct bank cables from the Intake Pumping Station to Auxiliary Building.

The principal source of EMP energy coupled to critical circuits in the plant is current induced on cables in the external buried conduit systems which penetrate the buildings. The level of the current induced in these conduit systems can be estimated from a model of an infinitely-long buried wire with an incident EMP in the form of a parallel-polarized plane wave of 50 kV/m amplitude. With optimum incidence angles, the response to the commonly accepted high altitude EMP waveform used here is a peak bulk current of approximately 1000 amps on the buried conduit systems. The current time history is roughly double-exponential in character, rising to a peak value in about 500 nanoseconds, and falling to half-peak value in tens of microseconds.[4] Due to the finite length of the buried conduit systems, reflections or oscillations will occur in the actual conduit current responses. Also, the existence of neighboring conduit systems, ground cables, and various mechanical piping systems as well as non-optimum relative orientation of the incident EMP will reduce the bulk current on an individual conduit system to well below that of the idealized, isolated buried conductor. The design philosophy at the plant basically assures that all metal conducting media such as trays, support structures, equipment chassis, and mechanical piping are connected together by the internal ground system. Transient current that would be conducted into the plant on mechanical piping or external buried ground cables would quickly disperse among divergent conducting paths. While the possibility of these transient currents coupling to critical equipment cannot be completely dismissed, no configurations were observed during the survey of the plant that would suggest such an occurrence. Such considerations are indicated on the model diagrams (see Figure 5.1) and serve to reduce the bulk current on the conduit systems studied to approximately 250 amps.

The 250 ampere bulk current induced on a conduit system at a building penetration is shared by the various parallel cables and conductors comprising the cabling in the conduits. Each conduit system carries hundreds of cables, most of which are multiconductor. Because of its larger conductor diameter and isolated routing in separate conduits, power cabling tends to have the largest current per conductor (5 to 10 amps per conductor). Because control cables commonly have hundreds of conductors per conduit, the individual current per conductor is significantly diminished (0.5 amps per conductor).

Power and control cables from the buried conduit systems are routed inside the plant for substantial distances in cable trays with other plant cabling that is not similarly excited. These coincident runs diminish the current response on the penetrating cables by cross-coupling energy to the other cabling in the trays. Energy is also lost through ohmic losses in the conductor resistance. When cabling is brought to a point of distribution such as a bus board, incoming current tends to divide (fan-out) among the conductors attached to the bus. Therefore, as it propagates inward from a point of penetration the EMP energy tends to be dispersed throughout the interior cabling system, attenuated by ohmic loss, and distributed at bus distribution boards.

In general, only the first or second stages of fan-out distribution will experience a substantial EMP threat. This is the case for the penetration of the 500 kV overhead transmission lines which are capable of producing a bulk current threat on the order of 15,000 amperes at the outputs of the plant main transformers. While this level of current appears formidable, it is attenuated by transformer losses, ohmic and cross-coupling losses, and distribution fan-out to the degree that only milliampere levels remain to threaten system critical equipment. This analysis appears in more detail in the 500 kV transmission line model shown in Appendix A. During periods of reactor shutdown and startup, the 500 kV transmission line connection to the plant unit boards is replaced by a connection to a 161 kV source. In this latter situation there is one less transformer in the circuit to provide attenuation. However, the topology of the connection is such that the bulk current threat is lower (approximately 10,000 A) and there is a longer cable run from the transformer to the Unit Boards. The net result is that the threat to critical systems from the 161 kV transmission lines is comparable to that from the 500 kV transmission line source. A model diagram from the 161 kV source is included in Appendix A.

5.3 EMP-Induced Signal Predictions

The predictions for the various portions of the safety-related systems are detailed on the response model diagrams in Appendix A and in Table 8.1. However it is also convenient to summarize these predictions as shown in Figure 5.3. Here the responses have been grouped according to the nominal operational levels of the equipment involved. It is observed that except for the instrumentation the predicted voltages are much less than the nominal operating levels. Furthermore, a significant fraction of the higher predictions (circled points on Figure 5.3) are observed to occur on systems in the outlying structures. Although the analysis indicates numerous signals less than 1 volt, all such predictions have been summarized as 1 volt in the subsequent vulnerability analysis. This is based upon the earlier observation that the general level of ambient response is on the order of 1 volt.

5.4 Verification Test Predictions

In order to gain confidence in the analytical techniques used to predict the response of the example plant in an EMP environment and to characterize prediction uncertainties (i.e., errors) introduced by using these techniques, it is desirable to perform verification testing. Such testing was performed on the example plant to a limited extent and involved the verification of certain assumptions used in computing the EMP responses including:

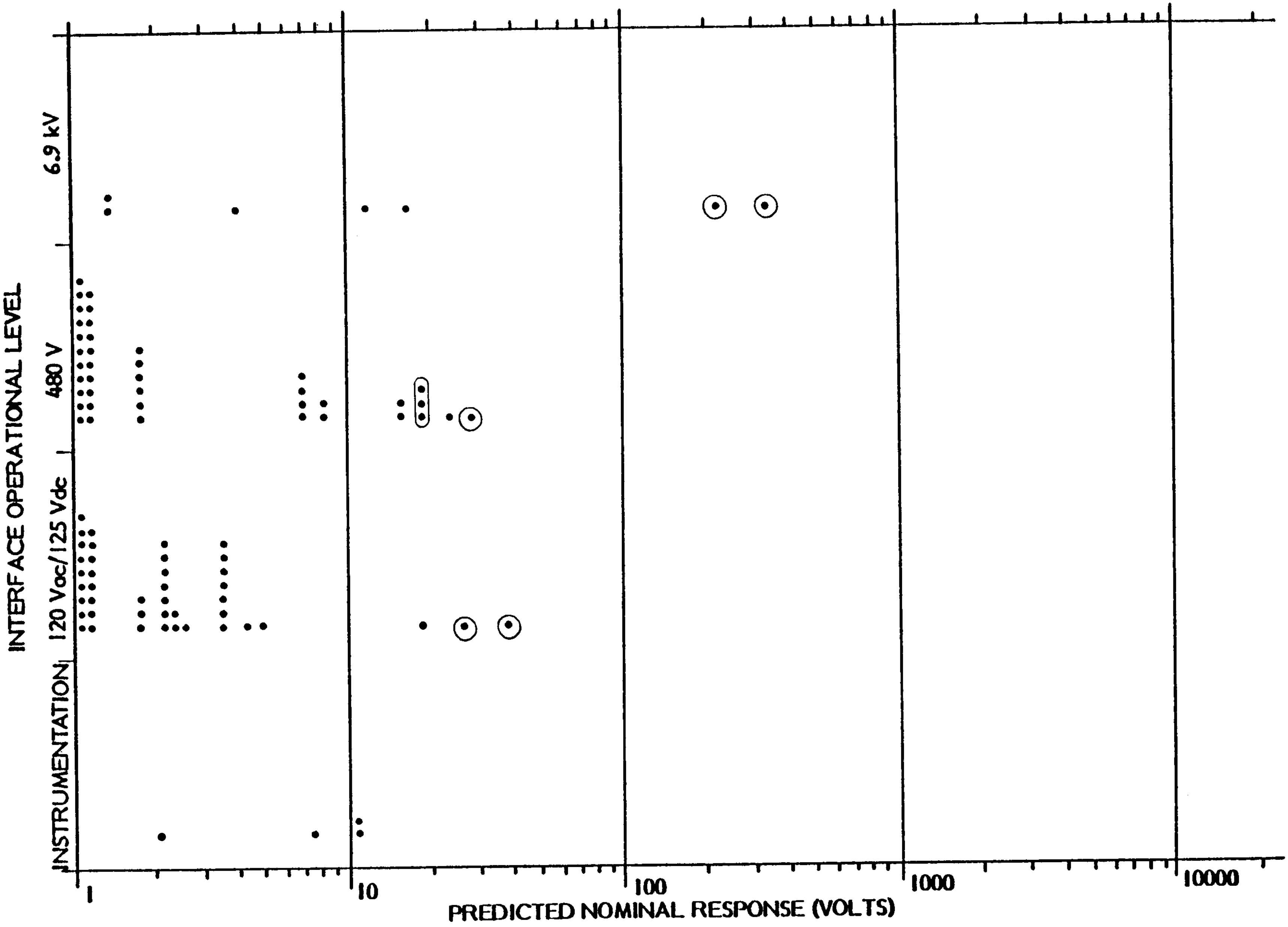

Figure 5.3. Summary of Predicted Nominal Responses.

1. Distribution of fanout currents at bus boards.

2. Attenuation of currents coupled to plant cables.

3. Shielding effectiveness of the building structure.

To accommodate verification testing, it was necessary to test at the plant during its construction phase and as such, the plant configuration did not mirror the operational configurations that were assumed in producing the EMP predictions. However, for the electrical configurations of the systems that were available at the time of testing, test configurations were devised that would allow the modeling assumptions to be checked. Because this configuration was different than the configuration assumed for EMP response predictions, test configuration predictions were performed using the same techniques and assumptions that were used to produce the EMP predictions.

The basic test configurations involved the injection of current onto plant cables or busses interfacing with cables running within the buried conduit structures outside the plant. Measurements were then made on the transmission and distribution of the induced current down into the various levels of the electrical distribution system. In this instance, the signal predictions at the test points assume a drive point bulk current of 1 ampere time-domain amplitude and a spectral content similar to that of the standard EMP double exponential pulse, but with frequencies above 10 MHz attenuated significantly (as would the spectral content of pulses conducted into the plant on buried conduit structure). The predictions are summarized in Table 5.1 with a portion of the prediction point (also the test point) locations illustrated on Figure 5.4. These predictions are also summarized in Tables 6.2 and 6.3 along with the test results.

Table 5.1

Predictions for CW Direct Injection Tests

Test Point	Predicted Response*
D	270 mA
E	90 mA
F	90 mA
G,I,J	270 mA
K,L,U	67 mA
X	11 mA
Y,Z	5.5 mA
AA,BB	11 mA
CC	9.6 mA
DD,EE,FF,GG	1.1 mA
HH	4.5 mA
II,JJ,KK,LL	0.43 mA
MM,NN	0.44 mA
VV,WW,XX	2.9 V
YY	3 mV
ZZ	5 mV
AAA	8 mV
BBB	16 mV
EEE	11 mV
C-E	2.7 V
C-G,E-G	8 V

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*Assumes one ampere peak current at drive point.

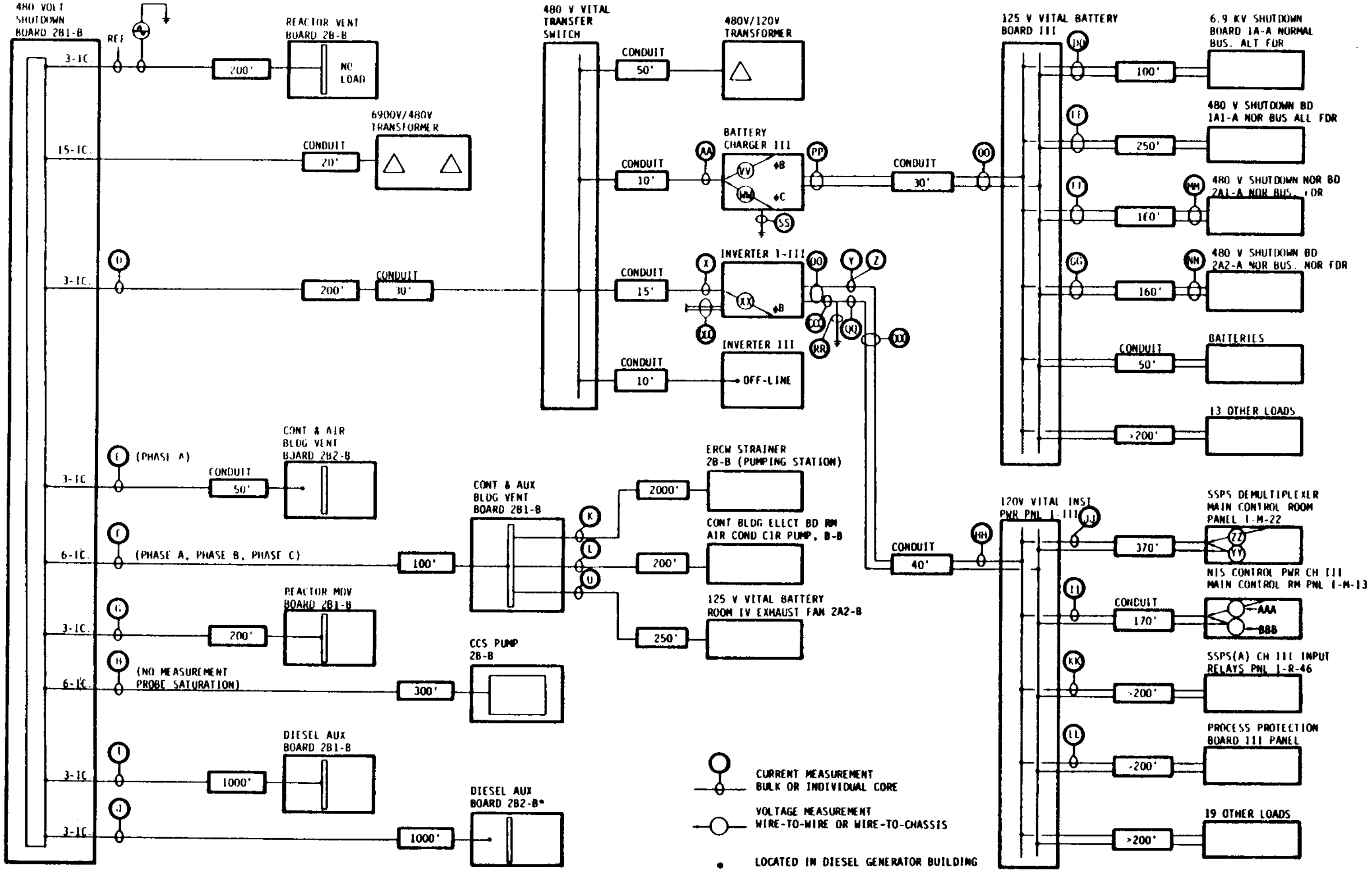


Figure 5.4. Prediction Point Locations for Verification Tests.

6.0 Verification Measurements

6.1 Introduction

Whenever a facility as complex as a communications terminal or a nuclear power plant is analyzed for EMP vulnerabilities, the question arises, "How good is the assessment?" Such concerns are frequently addressed, at least in part, by conducting experimental measurements. This program is no exception to that practice. However, it is impractical to subject a facility as large as a nuclear power plant to "threat level" simulation signals. On the other hand, it is possible to conduct a program of specialized verification measurements. Such tests were conducted at the Watts Bar Nuclear Plant and those measurements are discussed in detail in the following sections.

6.1.1 Direct Injection Tests. A test plan[11] was prepared and distributed to the NRC staff and the NRC Research Review Panel for this program to acquaint them with the test procedures and objectives, and to outline the impact of the tests on the facility operations. After review and subsequent discussions between the study team and the panel, the test objective was finalized as follows:

> "The objective of this test is to conduct a series of CW direct injection measurements on a selected sample of those points for which predictions have been made. The results of these measurements will then be used to compute the amplitude of the induced signals at the selected points. A comparison of the measured and predicted values may then be made to check the assumptions and analytical techniques used in the assessment."

It should be noted that these direct injection tests serve only as a check on the validity of the internal coupling models used and do not serve as a verification of the external to internal, i.e., incident field to facility penetration coupling mechanism.

6.1.2 CW System Description. The tests described in this section were carried out using equipment owned by the U.S. Defense Nuclear Agency and operated under contract by the IRT Corporation.

The DNA CW measurement system was built to provide a low-cost, time-efficient system to obtain estimates of EMP response at operational Command, Control and Communications (C^3) facilities, on a non-interferring basis. It has often been noted that there is an indispensible dependency of analysis on tests and tests on analysis. The CW system was built to help meet this need and to make it economically possible to obtain experimental data on the electromagnetic response of facilities at far more locations than would otherwise be possible. The designing of the system was an exercise in automation and efficiency of gathering, correcting, formatting, and outputting data. The design was not, however, intended to be a fundamental advance in the design of simulators. In that regard it is basically no better nor worse than what the EMP community has used in the past for operational, ground-based C^3 facilities.

This hybrid CW measurement system consists of two basic subsystems--the Defense Nuclear Agency (DNA) Continuous Wave Measurement system designed by Boeing and modified by EG&G, and the Data Acquisition subsystem consisting of a PDP-11 computer system and software by EG&G. These two subsystems communicate with each other to produce, detect, display, and reduce CW data in the frequency range of .01 MHz to 100 MHz. The system is designed to test facilities either by CW electromagnetic radiation or CW direct injection, collecting the response function or transfer function data, removing the effects of the instrumentation involved, plotting the results and saving the data on cassette for future processing. The system modules consist of the measurement system--a transmitter subsystem and receiver system, the command link which synchronizes the two, sensors, power supplies and generator; and the data acquisition system--a PDP-11/34 CPU, five asynchronous interfaces (RS-232), two 5-megabyte disk drives, disk packs, a Tektronix plotter, system console, and cassette tape subsystem.

<u>Equipment Description</u>. The major equipment items used in the CW system are listed in Table 6.1.

Table 6.1.

Major Equipment Items

<u>Transmitter System</u>	
Frequency Synthesizer	Systron Donner 1702
Computer Clock	Data-Chron 3170-114
Power Generator	ONAN 9AD74
Power Amplifier	Amplifier Research AR 500L
<u>Receiver System</u>	
Network Analyzer	HP8407A
Phase-Magnitude Display	HP8412A
Frequency Synthesizer (2 ea)	Systron Donner 1702
Digital Multimeter (2 ea)	Data Precision 3400
Computer Clock	Data-Chron 3170-114
Digital Plotter	Tektronix 4662
Attenuators	Wavetek Turret 5010/5070
Fiber Optics System	HDL
Wide-Band Amplifier	HP8447A

The system configuration of the CW system is shown in Figure 6.1. The block diagram for the transmitter indicates that the unit can be used in either a radiated or direct inject mode. There is essentially no restriction on the kind of antenna to be used with the system thus leaving open the possibility of using different antennas for different applications. Direct injection testing is done using a specially designed, single-turn multi-core transformer shown schematically in Figure 6.2.

The receiver block diagram shows the system being used with a reference and measurement sensor, which in practice is some combination of a current probe, voltage probe, or field sensor. In the radiated mode, the nominal operating configuration is with a B field sensor as the reference and a current or voltage probe for the measurement sensor. In the direct inject configuration, a current probe is normally used at the reference with a current or voltage probe at the measurement point. The signals detected by these sensors are amplified and then transmitted to the network analyzer via a fiber optic system.

The receiver and transmitter subsystems are supplied with three synthesizers which are used in a variety of ways. The local RF synthesizer is used as a signal source for system calibrations and also provides a stable reference for ambient noise measurements. The receiver VTO synthesizer is synchronized with the activities of the transmitter RF synthesizer via the program control units (PCUs) to ensure that the receiver and transmitter are operating at the same frequencies.

The receiver DVMs perform A/D conversion of the raw magnitude and phase data generated by the network analyzer as well as providing a front panel check point to monitor the incoming data stream.

Raw data is sent to the DEC computer via the PCU where all computations using the data and all manipulation on the data sets are performed. Storage is available on the computer disk units with long-term storage being provided on cassette tape. Hard copy plots of measured data, corrected for system instrumentation effects as well as predictions of transient time domain responses based on the measured data are available in a hard copy plot via the Tektronix flat-bed plotter, an example of which is shown in Figure 6.3.

6.1.3 The Predicted Time Domain Response. The data output from the CW system which is of primary interest is the predicted time domain response. To produce this response, the computer uses measured transfer function data, corrected for system instrumentation effects, in conjunction with the spectrum of a given time domain signal driving function. This data is used to predict what the response to the time domain signal driving function would be at the test point if the given signal was incident at the reference point. In order to accomplish this task, the computer requires that a frequency domain description of the incident time domain signal be generated and stored. This spectral data is then multiplied by

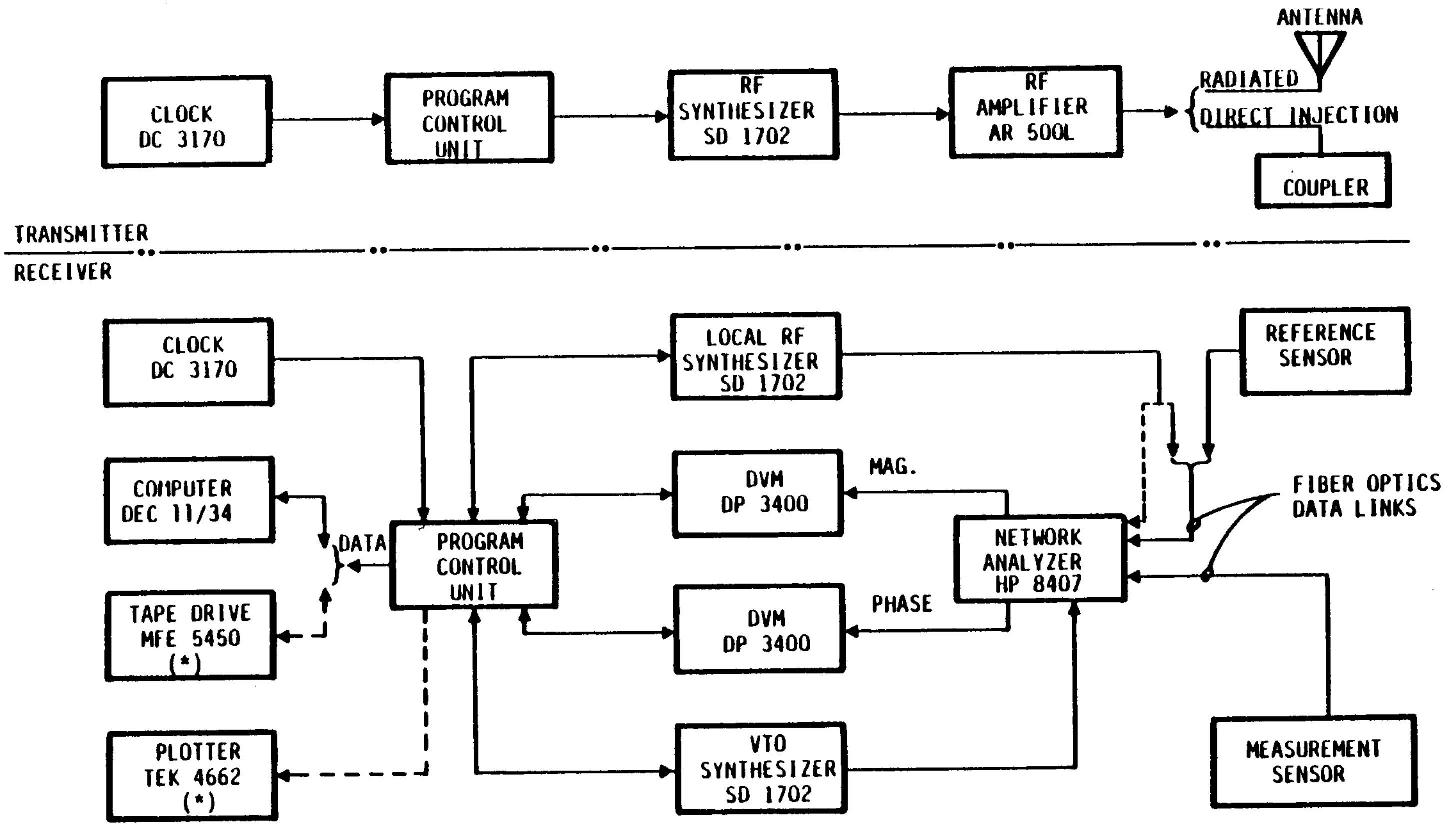


Figure 6.1. DNA CW Receiver and Transmitter Subsystems

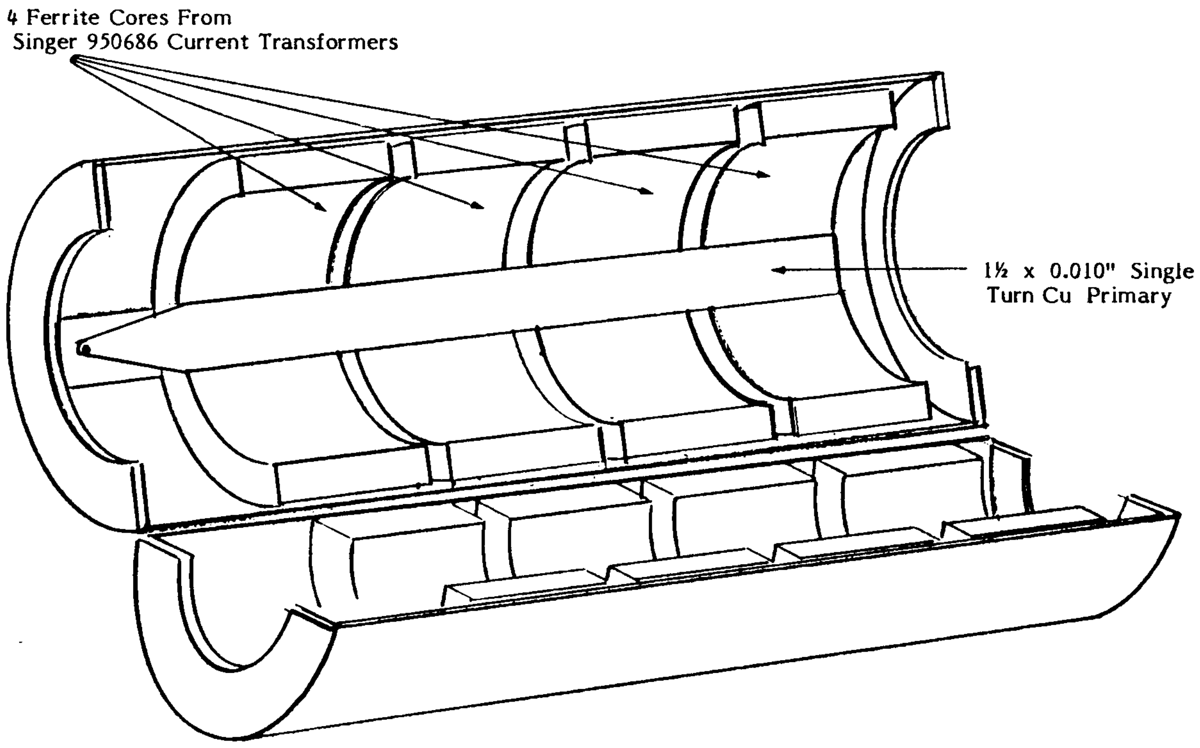
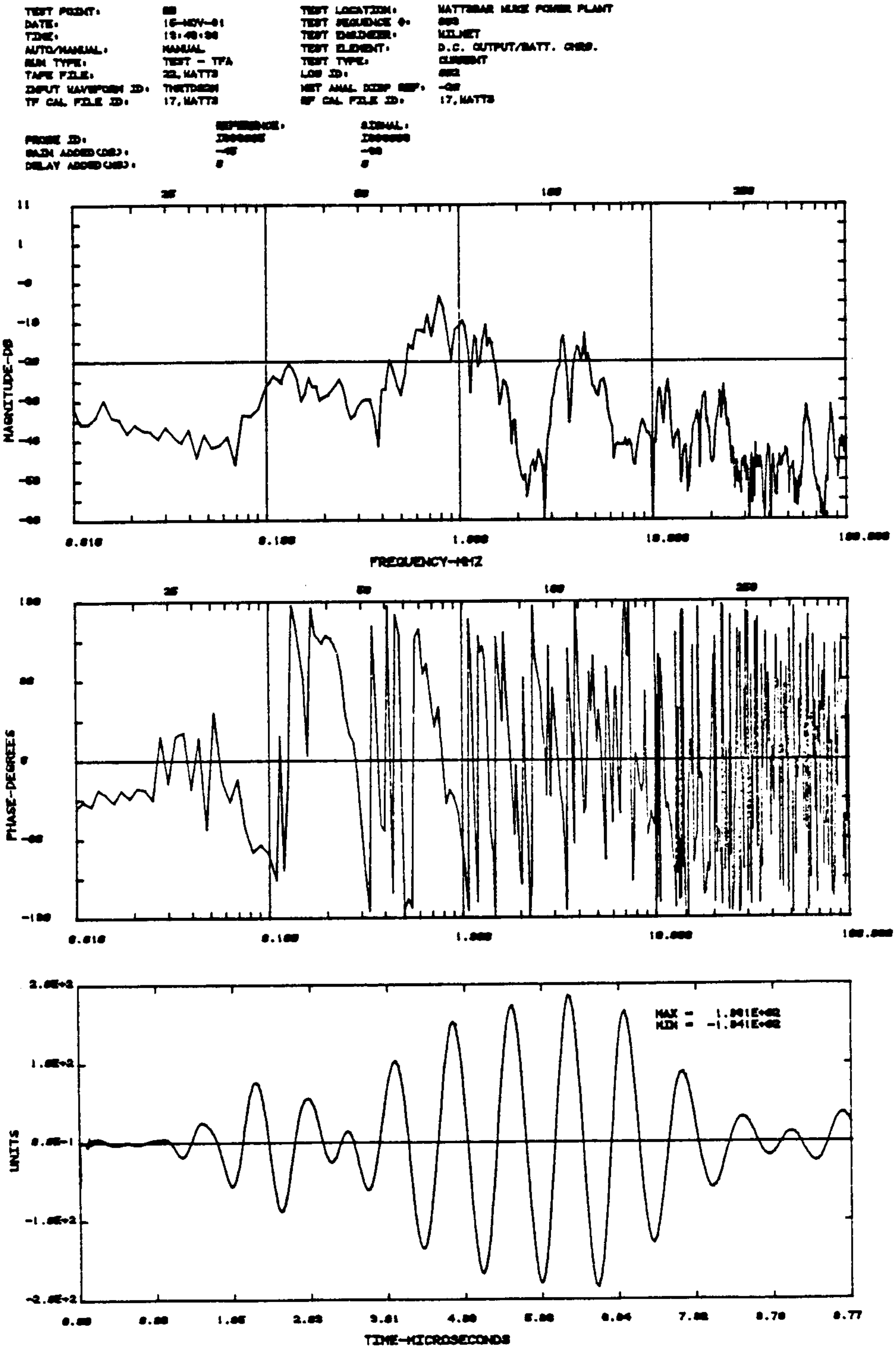


Figure 6.2. Direct Injection Current Transformer in Open Position



```
TEST POINT:             [illegible]     TEST LOCATION:          WATTSBAR NUKE POWER PLANT
DATE:                   15-NOV-81       TEST SEQUENCE #:        [illegible]
TIME:                   13:40:30        TEST ENGINEER:          MILNET
AUTO/MANUAL:            MANUAL          TEST ELEMENT:           D.C. OUTPUT/BATT. CHRG.
SIM TYPE:               TEST - TFA      TEST TYPE:              CURRENT
TAPE FILE:              22,WATTS        LOG ID:                 [illegible]
INPUT WAVEFORM ID:      [illegible]     NET ANAL DISP REF:      [illegible]
TF CAL FILE ID:         17,WATTS        SF CAL FILE ID:         17,WATTS

                              REFERENCE:           SIGNAL:
PROBE ID:                     [illegible]          [illegible]
GAIN ADDED(DB):               -45                  -60
DELAY ADDED(NS):              0                    0
```

Figure 6.3. Example of Hard Copy Plot from Tektronix Plotter

the transfer function of interest and passed to a program which computes the inverse Fourier transform of the composite data set.

The Driving Function. The driving function is referred to in the CW literature as the "threat" while the computer file containing its description is referred to as the "threat file." There are a variety of mechanisms for creating or inputting the threat file. A digitized description of a time domain waveform can be inputted and transformed inside the computer or a suitably formatted file can be input directly. In many cases the threat file is generated internally from analytical expressions. A brief discussion of the process involved in generating threat files internally illustrates this commonly used feature of the system as well as illustrating the general structure of all threat files.

The analytic threat file is defined by the following time domain expressions convolved with the impulse response of a ninth-order bandpass Butterworth filter.

$$E_i(t) = A(e^{-\alpha t} - e^{-\beta t})\,\mathrm{V/m} \qquad 0 < \alpha < \beta \qquad (6.1)$$

where

$$A = 5 \times 10^4 \; \frac{\alpha + \beta}{\alpha} \left[\left(\frac{\alpha}{\beta}\right)^{\left(\frac{\beta}{\alpha + \beta}\right)} \right] \mathrm{V/m}\ .$$

The Fourier transform of this function is given by

$$E_i(f) = \frac{A(\alpha - \beta)}{[(\alpha^2 + \omega^2)(\beta^2 + \omega^2)]^{1/2}} \;\; \mathrm{V\text{-}sec/m} \qquad (6.2)$$

$$\phi_i(f) = -\tan^{-1} \left(\frac{\omega(\alpha + \beta)}{\alpha\beta + \omega^2} \right) \mathrm{rad}$$

where α and β are operator-specified variables. The expressions in Equation 6.2 are stored in the computer, evaluated at all test frequencies, and then multiplied by the transfer function of a unity amplitude, ninth-order bandpass Butterworth filter. The upper and lower cutoff frequency of the filter are also operator-specified variables.

The primary purpose for including the Butterworth filter function is to reduce the effect of truncation error. The fact that the measured transfer function is not measured from dc to infinity, but is instead truncated at some finite frequency introduces an oscillatory type of behavior in the predicted time domain response. This effect is attenuated by using a function which terminates the data set in a more gradual manner but only at the expense of suppressing some of the real data. The Butterworth filter is simply a "windowing" function, and as such, it represents a compromise as do all windowing functions.

The threat file which results from the evaluation of equation 6.2 and the Butterworth filter function is a table of complex values with the magnitude and phase of the composite function defined at every possible test frequency that the system can use. This means that the threat function is defined at 4000 frequencies in the range of 10 KHz to 100 MHz, 1000 frequencies in each decade. Regardless of how the threat file is created, be it internally or through the transform of some waveform read into the computer, the final result has to be a table of look up values defined at a predetermined set of 4000 frequencies.

The Inverse Fourier Transform. The method used to perform the inverse transform is a variation of the Guilleman impulse train technique. In this particular application it is more accurate to say that the Guilleman algorithm is equivalent to the inverse, Fourier-integral transform, performed on a contiguous, straight line approximation, of the imaginary part, of the frequency domain data set.[12]

6.2 Prediction and Measurement Comparison

6.2.1 Data Treatment and Test Point Locations. Computing the time domain transient response at a given point, once the transfer function has been measured, requires a knowledge of the incident spectrum at the reference point, i.e., the "threat" referred to in Section 6.1.3.

The threat on the plant cabling can generally be considered broad spectrum up to about 10 MHz because earth losses on the buried penetration cables severely attenuate the higher frequency content of the EMP spectrum. Given this threat spectrum and the lengths of the cabling in the plant, the abbreviated analysis technique employed by Boeing results in the prediction of the response peak amplitudes and limited characterizations of the time histories of the response waveforms. The response waveforms are expected to be damped sinusoids (or sums of several damped sinusoids) with resonant frequencies ranging from 500 kHz to 10 MHz.

In choosing the waveform to be used for current injection on facility cables, two characterizations were considered. One threat characterization uses a 2 MHz damped sinusoid (an average value of the expected range of response resonant frequencies) for the threat signal and the other, the EMP spectrum, attenuated above 10 MHz. During on-site testing most of the transfer function data was processed with the 2 MHz damped sinusoidal threat spectrum (identified by THRTDS2M) as originally proposed. The transfer function data was subsequently reprocessed using the standard EMP double exponential spectrum that had been Butterworth filtered above 10 MHz (identified by THRTWATT).

Since the transient time domain response for the data processed with THRTDS2M is critically dependent on the amplitude of the transfer function in the vicinity of 2 MHz, the data processed with the EMP spectrum (THRTWATT) should be used to compare the test measurements to the predictions computed by Boeing. Typical formats of the measured data using THRTDS2M and the recomputed time domain transient using the threat file THRTWATT with the following characteristics:

THRTDS2M - 2 MHz Damped Sine Wave ($Q = 8$)
THRTWATT - Double Exponential $\alpha = 4 \times 10^6$, $\beta = 4.76 \times 10^8$
(Butterworth $f_l = 10^4$ Hz and $f_u = 10^7$ Hz)

are shown in Figures 6.4 and 6.5, respectively.

A comparison of measured and predicted responses for a total of thirty-seven test points has been made and consist of twenty-seven current points and ten voltage points.

The measurements were divided among the 480V distribution system, the 120V ac control system and the 120V dc control system located in the control room and adjacent equipment and board rooms.

The test point locations at which measurements were made and their identifiers are shown schematically in Figures 6.6 through 6.10. It should be noted that predictions were not made for all points at which measurements were made and consequently comparisons will only be presented for a subset of the measurement points shown in the above referenced figures.

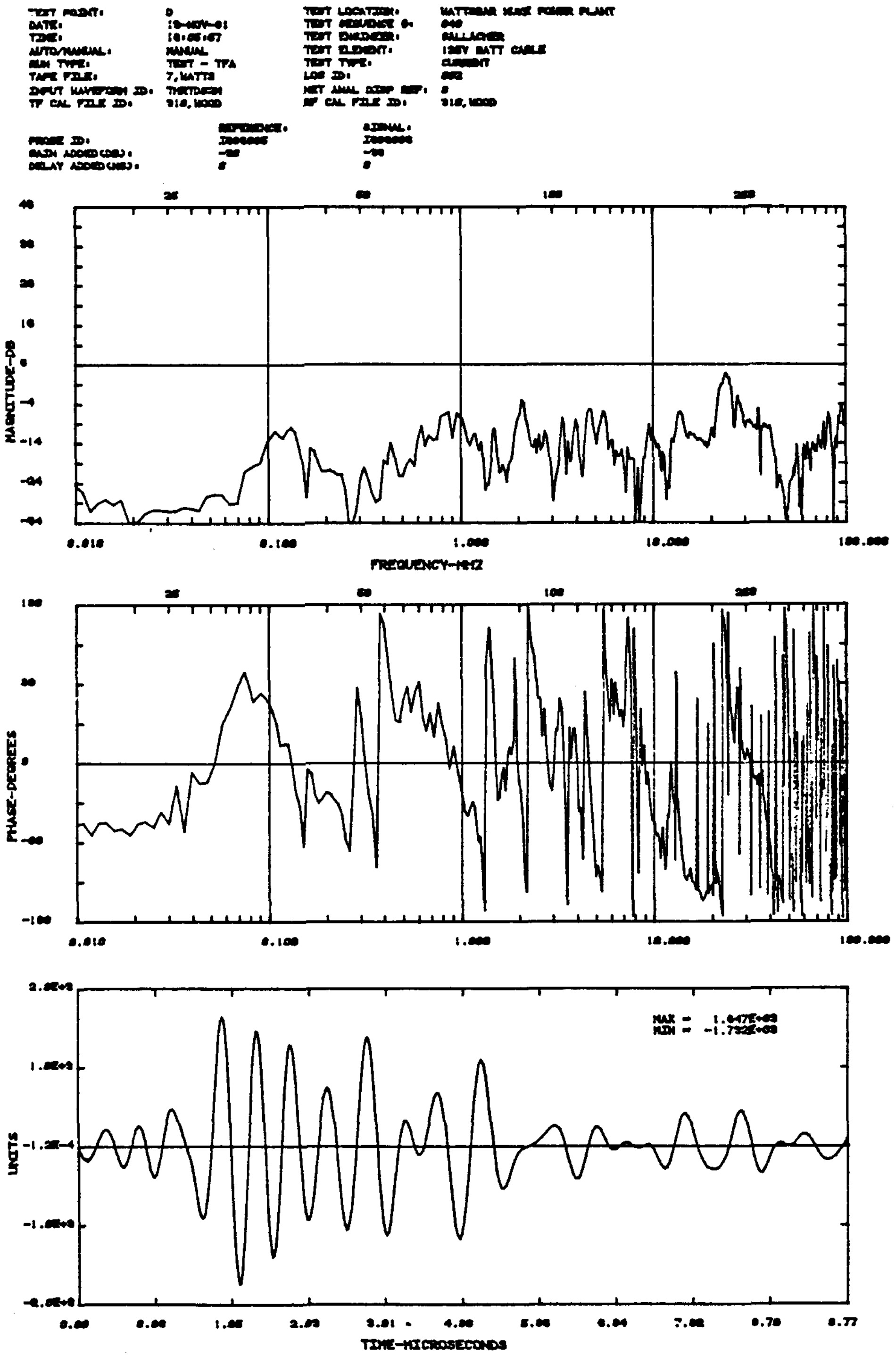
6.2.2 Format for Presentation of Data. For each point for which a prediction and measurement exists, the following ratio is computed:

$$R(t) = 20 \log_{10} \frac{\text{Peak Amplitude Measured Response}}{\text{Peak Amplitude Predicted Response}} \qquad (6.3)$$

The responses are the maximum values in the time domain with no regard being paid to the sign of the peak.

The measured responses are normalized to a one ampere peak, double exponential pulse ($\alpha = 4 \times 10^6$ and $\beta = 4.76 \times 10^8$) filtered by a ninth order, unity amplitude Butterworth filter with a lower cut-off frequency of 10 kHz and an upper cut-off frequency of 10 MHz (THRTWATT).

As noted earlier, the purpose of these tests was to provide some verification of the Boeing modeling and thus to develop additional confidence in their analytical procedure. Therefore, a convenient



```
TEST POINT:            D                 TEST LOCATION:      WATTSBAR NUKE POWER PLANT
DATE:                  19-NOV-81         TEST SEQUENCE #:    040
TIME:                  10:05:07          TEST ENGINEER:      GALLAGHER
AUTO/MANUAL:           MANUAL            TEST ELEMENT:       125V BATT CABLE
RUN TYPE:              TEST - TFA        TEST TYPE:          CURRENT
TAPE FILE:             7,WATTS           LOG ID:             002
INPUT WAVEFORM ID:     THRTDS2M          NET ANAL DISP REF:  0
TF CAL FILE ID:        310,WOOD          RF CAL FILE ID:     310,WOOD

                             REFERENCE:          SIGNAL:
PROBE ID:                    I000005             I000006
GAIN ADDED(DB):              -20                 -20
DELAY ADDED(NS):             0                   0
```

Figure 6.4. Measured Data and Computed Time Domain Response for Test Point D Using THRTDS2M

```
CYCLE MODE OF TEST . SINGLE
TEST DATE . 13-NOV-81
TEST TIME : 16.05:57
TEST TYPE : TEST
SIGNAL PROBE ID : I686096
REFERENCE PROBE ID . I686095
TEST POINT ID : D
TAPE FILE ID .  7.WATTS
THREAT WAVEFORM ID , THRTWATT
REFERENCE GAIN ADDED (DB) :  -30
SIGNAL GAIN ADDED (DB) ,  -36
SIGNAL DELAY ADDED (NS) : 0
REFERENCE DELAY ADDED (NS) . 0
NETWORK ANALYZER DISPLAY REFERENCE (DB) , 0
TRANSFER TIME BASE (US) : 10.0
CONVERSION FACTOR FOR E-FIELD CORRECTIONS . 1.0
TRANSFER FUNCTION TYPE CAL TAPE FILE ID . 310.WOOD
RESPONSE FUNCTION TYPE CAL TAPE FILE ID . 310.WOOD
TEST LOCATION . WATTSBAR NUKE POWER PLANT
TEST TYPE . CURRENT
TEST ELEMENT ,  125V BATT CABLE
LOC ID . 002
TEST ENGINEER : GALLACHER
SEQUENCE NUMBER . 040
REMARKS .
```

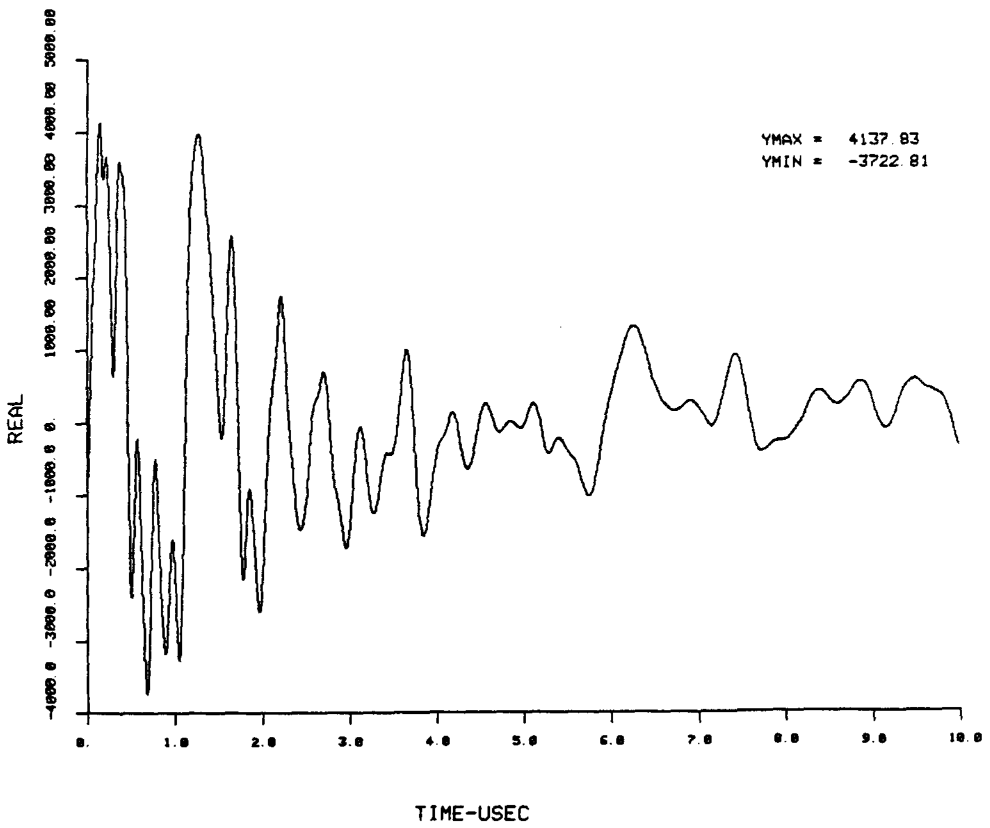


Figure 6.5. Recomputed Transient Time Domain Response for Test Point D Using Threat File THRTWATT

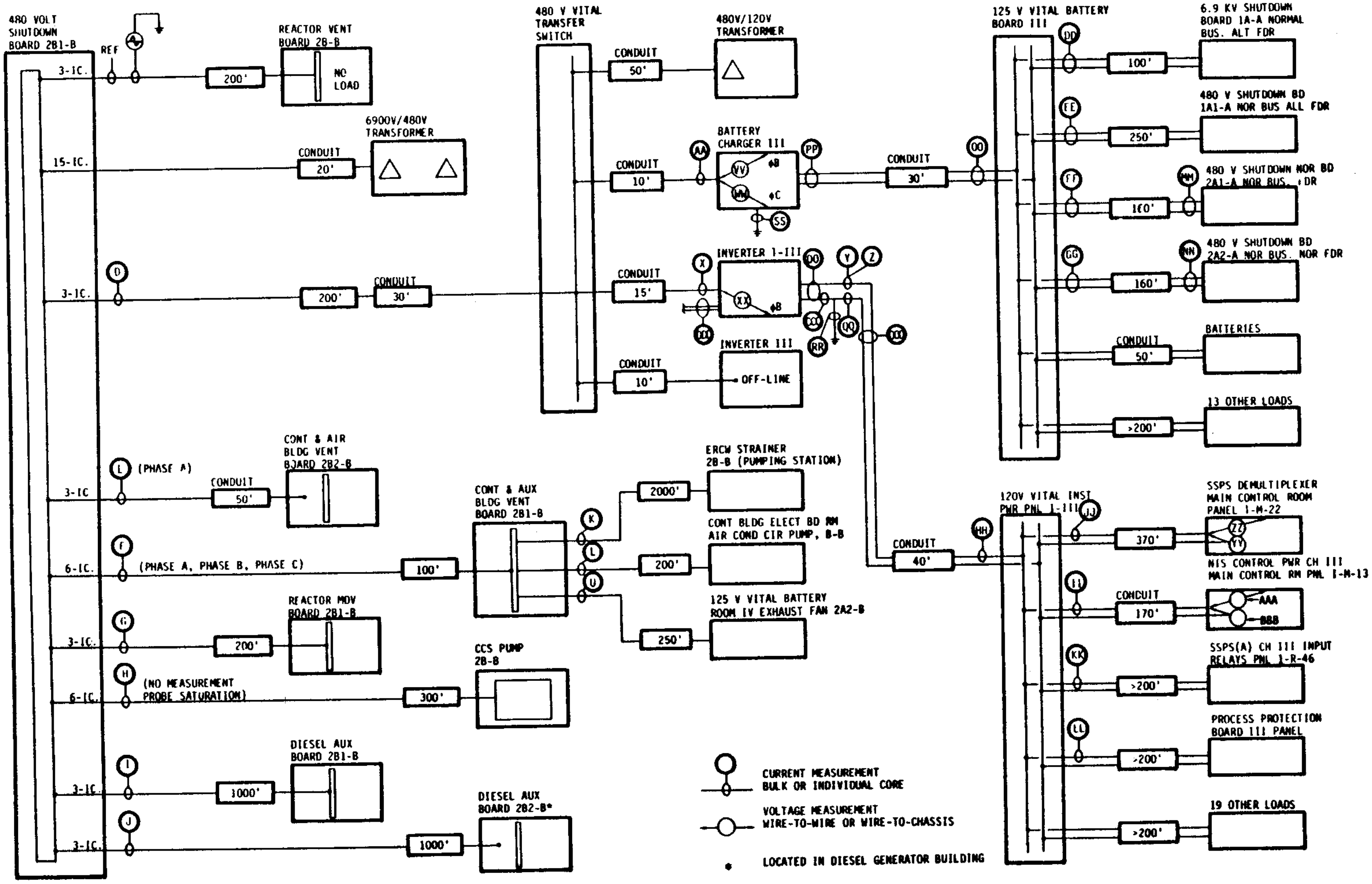


Figure 6.6. Test Point Location From 480V Shutdown Board to 125V Vital Battery Board

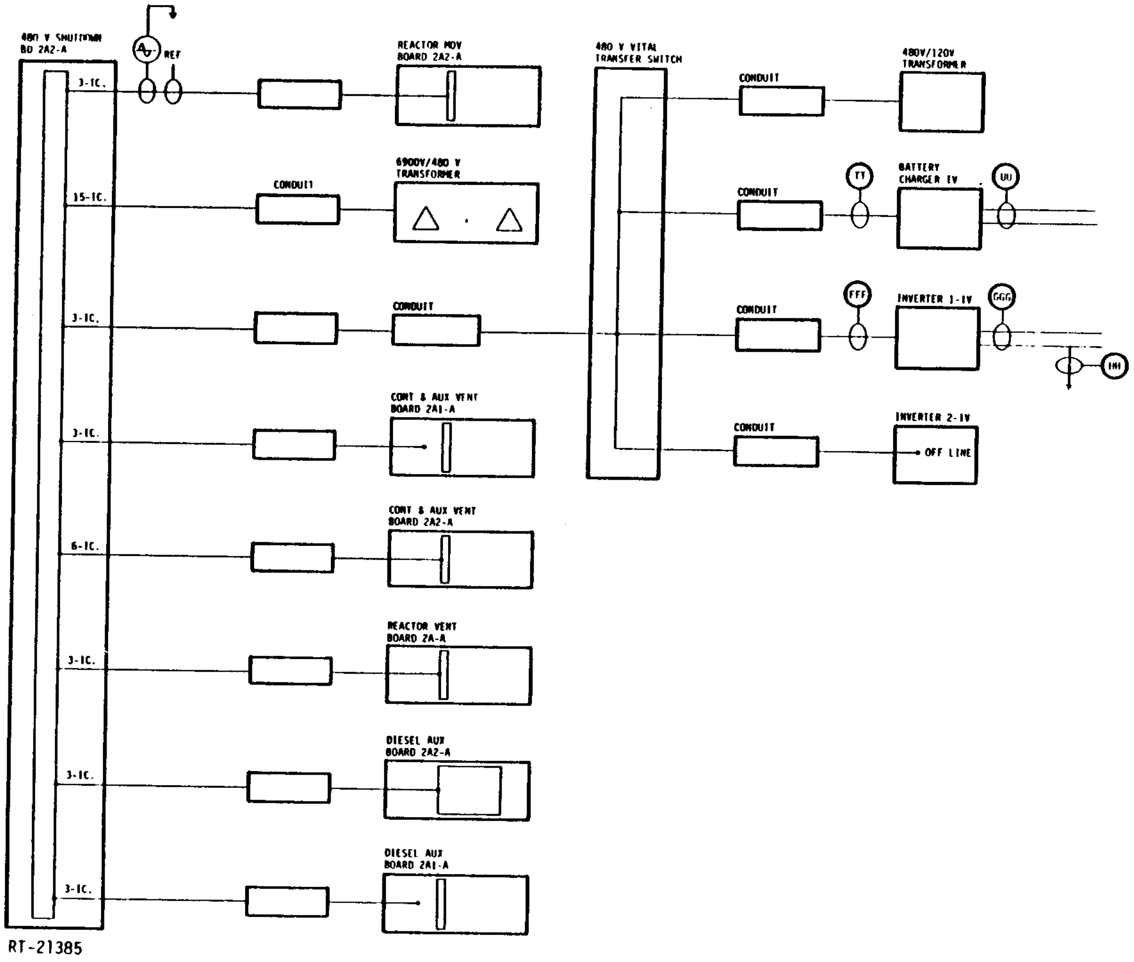


Figure 6.7. Test Point Locations Vicinity of 480V Vital Transfer Switch

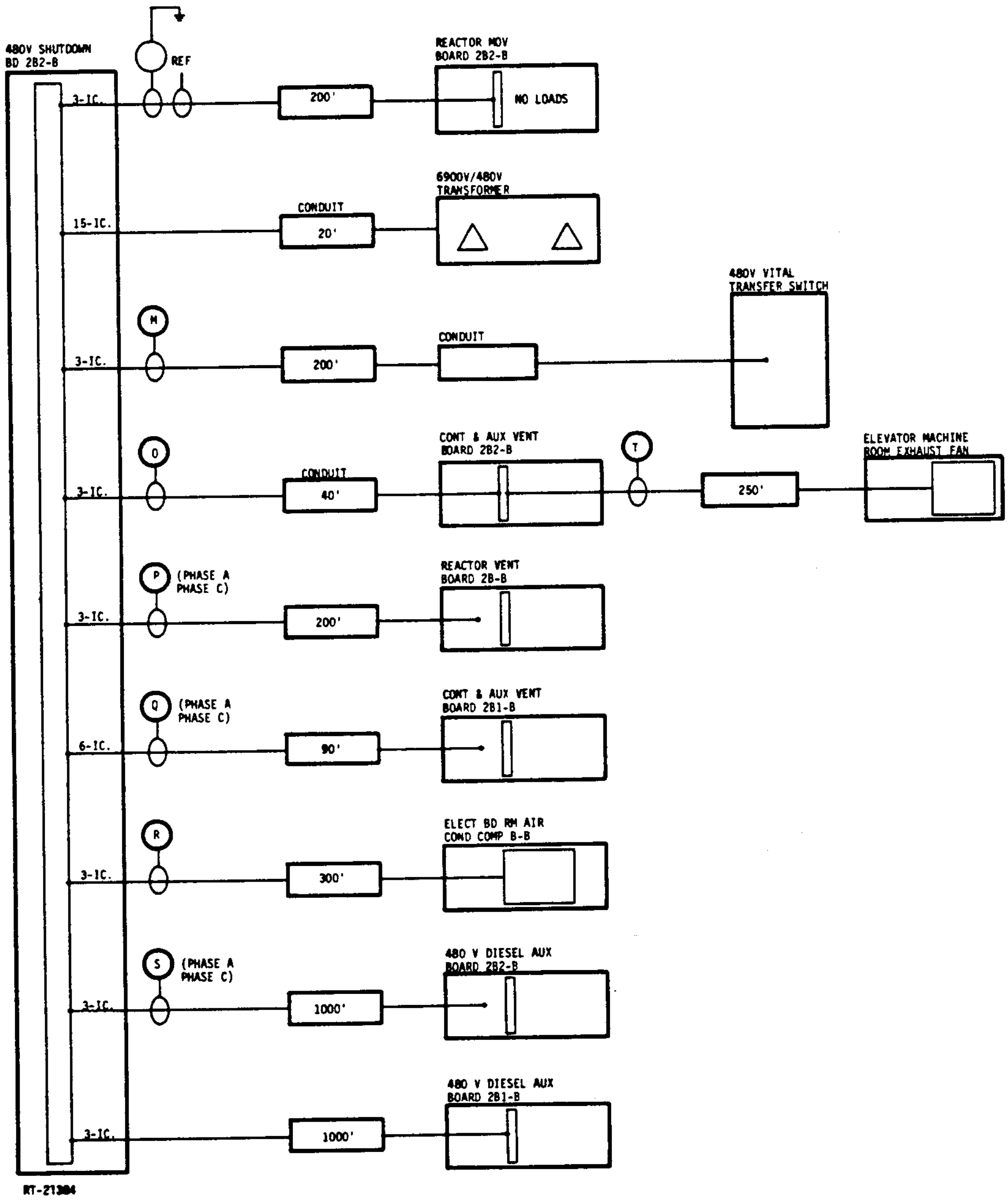


Figure 6.8. Test Point Locations Vicinity of 480V Shutdown Board

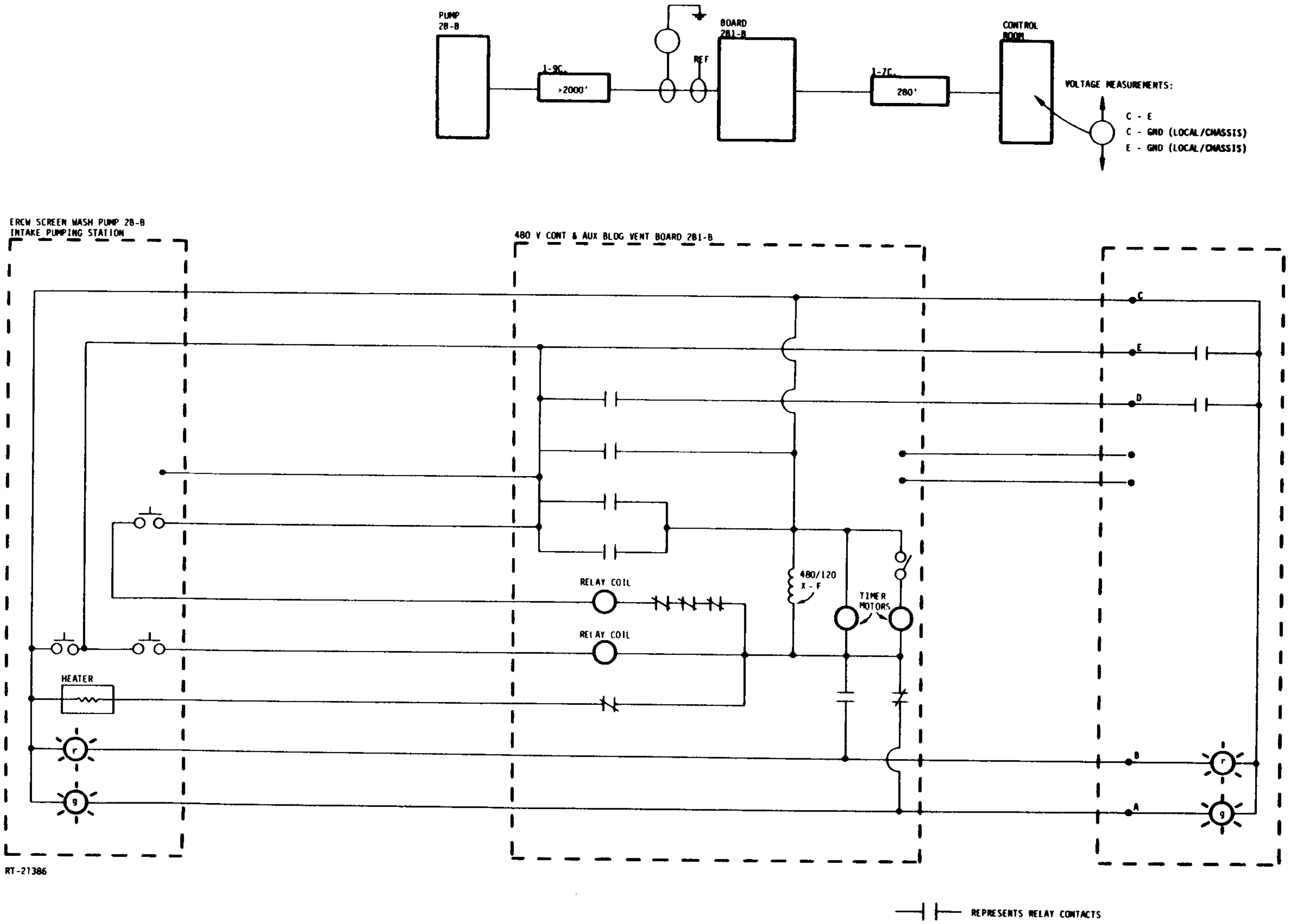


Figure 6.9. Voltage Test Point Locations in Control Room

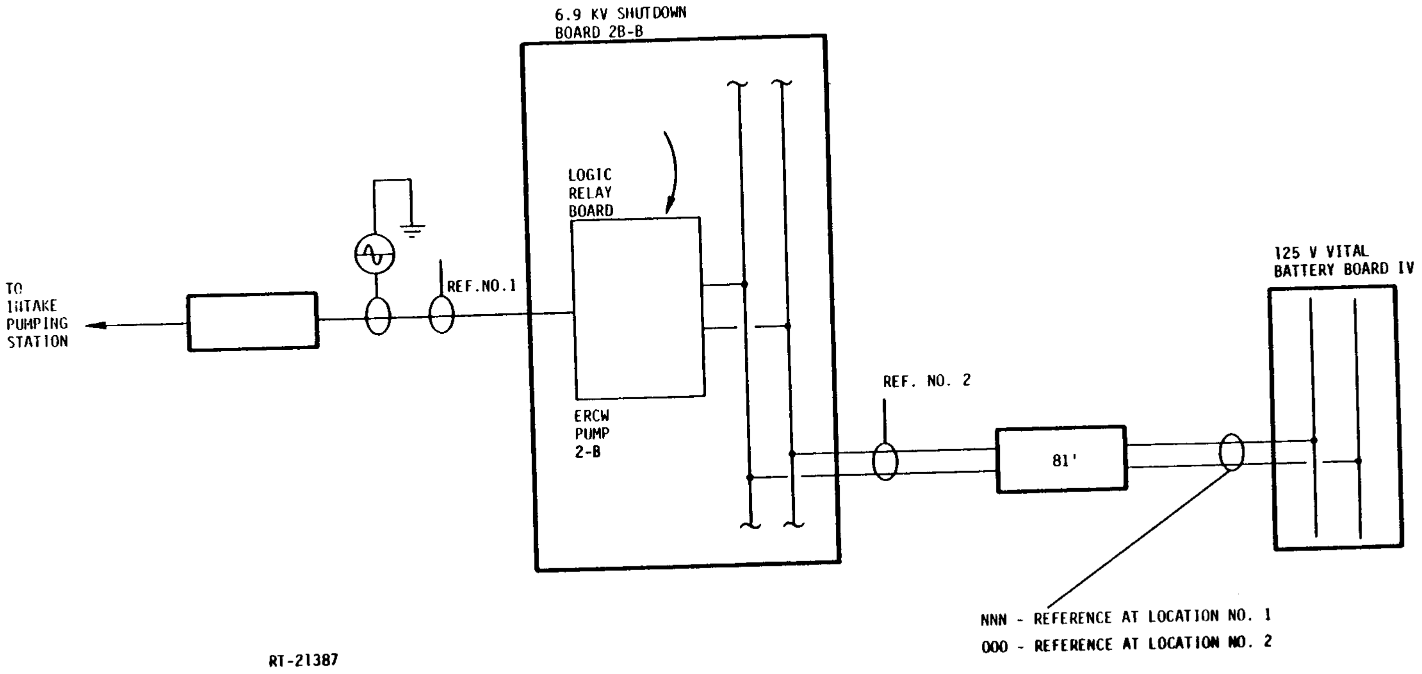


Figure 6.10. Test Point Locations at Output of 6.9kV Shutdown Board

way to summarize the overall quality of the prediction and measurement set, is to compute a mean, $\bar{X}$, of the individual ratios R(t) defined in Equation 6.3 and a sample standard deviation, that is

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} R_i(t) \qquad (6.4)$$

and

$$\sigma = \sqrt{\frac{\Sigma R^2 - (\Sigma R)^2/n}{n - 1}} \qquad (6.5)$$

Using this approach, a negative value for $\bar{X}$ would imply that, on the average, the analysis is conservative in that it generally predicts larger currents (or voltages) than measured, a positive value of $\bar{X}$ would imply a generally non-conservative analysis.

6.2.3 Comparison of Measured and Predicted Response. Comparison of the individual measured to predicted response at the 27 current points and 10 voltage points are given in Tables 6.2 and 6.3, respectively.

These reduce to

$\bar{X}$ = - 1.75 dB and σ = 8.4 dB (27 Current Points)

$\bar{X}$ = +13.2 dB and σ = 13.2 dB (10 Voltage Points)

and overall

$\bar{X}$ = + 2.3 dB and σ = 11.8 dB (37 Points)

These results and their implications are discussed further in Section 6.5.1.

6.2.4 Discussion of Measurement Accuracy. Probe and system calibrations (PROBCAL, TCAL and RCAL) were conducted each day during the test when measurements were made and no abnormalities were detected.

Repeatability of results were checked by repeating measurements at two test points over a three-day period. The results of these gave a sample standard deviation (nine measurements) of 0.8 dB.

Table 6.2.

Detailed Comparison of Measured and Predicted Responses

Current Points

Test Point Identifier	Predicted Response (mA)	Measured Response (mA)	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
D	270	82.7	-10.3
E	90	83	- 0.7
F	270	216	- 1.9
G	270	270	0.0
I	270	156	- 4.7
J	270	122	- 6.9
K	67	17.5	-11.7
L	67	15.5	-12.7
U	67	14.4	-13.3
X	11	22.9	6.4
Y	5.5	1.0	-14.8
Z	5.5	1.1	-13.9
AA	11	30.6	8.9
BB	11	21.1	5.7
CC	9.6	24	8.0
DD	1.1	6.7	15.7
EE	1.1	2.5	7.1
FF	1.1	2.1	5.6
GG	1.1	3.6	10.3
HH	4.5	1.7	- 8.5
II	0.43	0.35	- 1.8
JJ	0.43	0.14	- 9.7
KK	0.43	0.37	- 1.3
LL	0.43	0.4	- 0.6
MM	0.44	0.45	0.19
NN	0.44	0.48	0.8
EEE	11	7.5	- 3.3

$\bar{X} = -1.75$ dB $\sigma = 8.4$ dB

Table 6.3.

Detailed Comparison of Measured and Predicted Responses

Voltage Points

Test Point Identifier	Predicted Response (V)	Measured Response (V)	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
AAA	8×10^{-3}	144×10^{-3}	+25
BBB	16×10^{-3}	140×10^{-3}	+18.8
VV	2.9	3.1	+ 0.58
WW	2.9	2.8	- 0.30
XX	2.9	2.77	- 0.4
YY	3×10^{-3}	166×10^{-3}	+34.8
ZZ	5×10^{-3}	147×10^{-3}	+29.3
C-E	2.7	3.4	+ 2.0
C-G	8.0	26	+10.2
E-G	8.0	32	+12.0

$\bar{X} = +13.2$ dB $\sigma = 13.2$ dB

Ambient noise levels were made in the frequency domain from 10 kHz to 100 MHz at five test points within the facility, namely, I, G, DD, NN and GG. These ambient noise measurements were made with the probe in position on the test point and using a -10 dbm signal from the synthesizer as reference. For all points and at all frequencies the minimum level of the signal above ambient noise was > 65 dB.

6.2.5 Supplementary Measured Data. Additional measurements were made in an attempt to provide further understanding of the interaction of an EMP with a commercial type nuclear power plant. These are presented in the following sections.

Cable Attenuation Measurements. Values for cable attenuation were computed from two sets of response measurements as shown in Table 6.4.

Table 6.4.

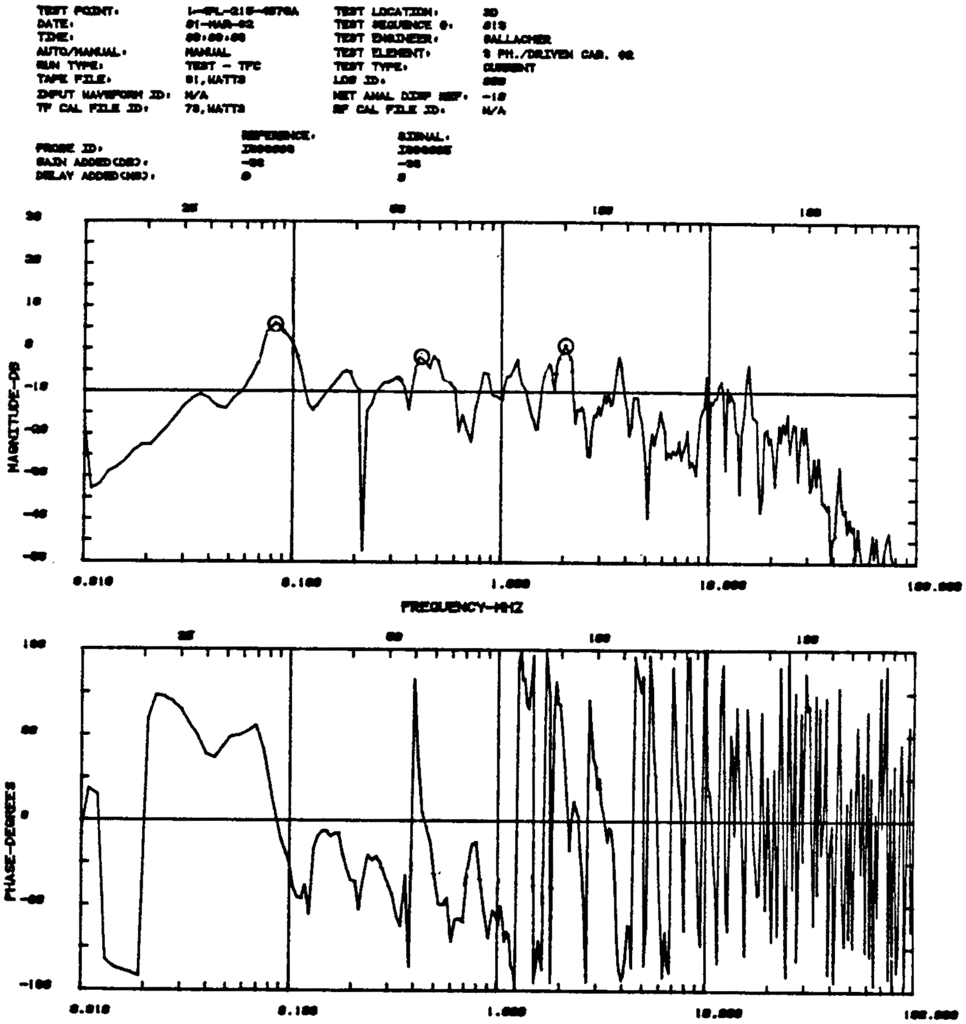
Cable Attenuation

Test Point Identifier	Cable Length	Measured Response at GG/FF	Measured Response at NN/MM	Total Att. dB	Total Att. dB/100'
GG-NN	160'	3.6×10^{-3}	0.48×10^{-3}	17.5	10.9
FF-MM	160'	2.1×10^{-3}	0.45×10^{-3}	13.4	8.3

The measured responses are peak values of the transient time domain response. The resultant average attenuation 9.6 dB/100' compares favorably to the values assumed in the analysis of 6 dB/100'.

Transfer Function From Exterior to Interior. In order to investigate the nature of the coupling from the facility exterior to some internal point, a measurement was made of the transfer function on cable 1-4PL-215-4975A running from manhole #22 on the west side of the facility (see Figure 6.14) to the auxiliary room adjacent to the control room. The measured transfer function is shown in Figure 6.11. This transfer function is multipled by the assumed double exponential threat driving function (see Section 6.1.3) and the corresponding time domain transient is shown in Figure 6.12.

Offset and Standard Deviation by Groupings of Test Points. A measure of offset and standard deviation for test points located on the same distribution board is given in Table 6.5. These are the same test points reported in Table 6.2.



```
TEST POINT:           1-4PL-215-4975A    TEST LOCATION:           3D
DATE:                 01-MAR-82          TEST SEQUENCE #:         013
TIME:                 00:00:00           TEST ENGINEER:           GALLAGHER
AUTO/MANUAL:          MANUAL             TEST ELEMENT:            3 PH./DRIVEN CAB. 02
RUN TYPE:             TEST - TFC         TEST TYPE:               CURRENT
TAPE FILE:            81,WATTS           LOG ID:                  [illegible]
INPUT WAVEFORM ID:    N/A                NET ANAL DISP REF:       -10
TF CAL FILE ID:       78,WATTS           RF CAL FILE ID:          N/A

                           REFERENCE:               SIGNAL:
PROBE ID:                  [illegible]              [illegible]
GAIN ADDED(DB):            -00                      -06
DELAY ADDED(NS):           0                        0
```

Figure 6.11. Measured Transfer Function from Manhole #22 to Auxiliary Building, Cable 1-4PL-215-4975A

```
CYCLE MODE OF TEST : SINGLE
TEST DATE . 01-MAR-82
TEST TIME : 08.08.06
TEST TYPE . TEST
SIGNAL PROBE ID . 1686095
REFERENCE PROBE ID . 1686096
TEST POINT ID . 1-4PL-215-4976A
TAPE FILE ID .  81, WATTS
THREAT WAVEFORM ID . THRTWATTICABLE
REFERENCE GAIN ADDED (DB) .  -36
SIGNAL GAIN ADDED (DB) .  -36
SIGNAL DELAY ADDED (NS) . 0
REFERENCE DELAY ADDED (NS) . 0
NETWORK ANALYZER DISPLAY REFERENCE (DB) . -10
TRANSFER TIME BASE (US) . NOT APPLICABLE
CONVERSION FACTOR FOR E-FIELD CORRECTIONS . NOT APPLICABLE
TRANSFER FUNCTION TYPE CAL TAPE FILE ID . 78, WATTS
RESPONSE FUNCTION TYPE CAL TAPE FILE ID . N/A
TEST LOCATION . SD
TEST TYPE . CURRENT
TEST ELEMENT .  3 PH./DRIVEN CAB. #2
LOC ID . 000
TEST ENGINEER . GALLAGHER
SEQUENCE NUMBER : 013
REMARKS .
```

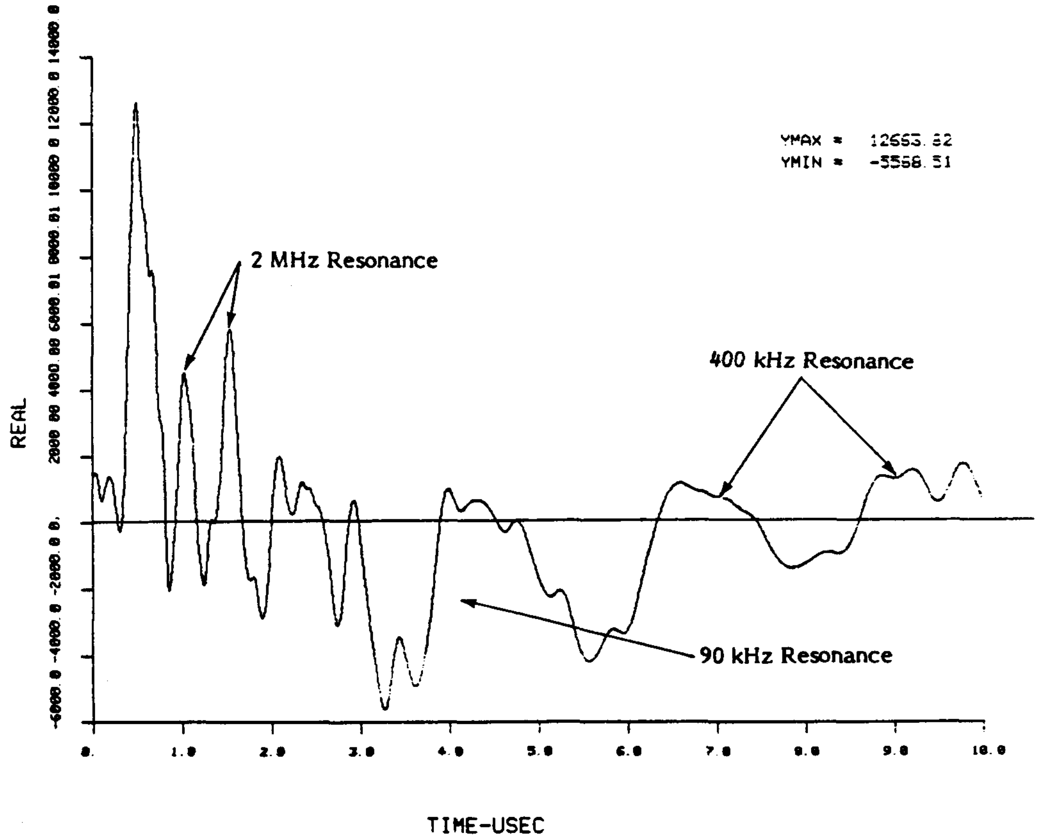


Figure 6.12. Predicted Time Domain Response from Exterior to Interior of Facility

Table 6.5.

Offset and Standard Deviation by Test Point Location

480V Shutdown Bd. 2B1-B

Test Point Identifier	Pred. Response (mA)	Meas. Response THRTWATT	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
D	270	82.7	-10.3
E (Single ϕ)	90	83	- 0.7
F (Single ϕ)	90	72	- 1.9
G	270	270	0.0
I	270	156	- 4.7
J	270	122	- 6.9

$\bar{X}$ = -4.1 dB σ = 4.0 dB

Cont. and Aux. Bldg. Vent Bd. 2B1-B

Test Point Identifier	Pred. Response (mA)	Meas. Response THRTWATT	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
K	67	17.5	-11.7
L	67	15.5	-12.7
U	67	14.4	-13.3

$\bar{X}$ = -12.5 dB σ = 0.8 dB

125V Vital Battery Bd. III (18 Loads)

Test Point Identifier	Pred. Response (mA)	Meas. Response THRTWATT	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
DD	1.1	6.7	15.7
EE	1.1	2.5	7.1
FF	1.1	2.1	5.6
GG	1.1	3.6	10.3

$\bar{X}$ = +9.7 dB σ = 4.4 dB

INPUT = CC
= 24×10^{-3} A

120V Vital Inst. Power Panel 1-111 (23 Loads)

Test Point Identifier	Pred. Response (mA)	Meas. Response THRTWATT	$\frac{\text{Meas. Resp.}}{\text{Pred. Resp.}}$ (dB)
JJ	0.43	0.14	- 9.7
KK	0.43	0.37	- 1.3
LL	0.43	0.4	- 0.6
II	0.43	0.35	- 1.8

$\bar{X}$ = -3.3 dB σ = 4.2 dB

INPUT = HH
= 1.7×10^{-3}A

6.3 Inadvertent Penetration Tests

In predicting the response of the Watts Bar NPP to an EMP event, the major contribution to the coupling of energy to the facility interior was determined by Boeing to be the cabling from the Diesel Generator Building and the Intake Structure to the Auxiliary Building. The question of the existence of other "inadvertent" or "unknown" penetrations which could contribute to the internal coupling was raised by the panel. Subsequently a test plan was developed which had as one of its objectives the determination of whether or not significant inadvertent or unknown penetrations had been overlooked in the analysis.

In the test the following procedure was adopted. First, a current probe was attached to a test point in the facility that was known to be connected directly to a known external to internal penetration. The external penetration was then excited at a given frequency by means of a multi-turn, one meter diameter loop and the response of the test point recorded. The loop was then moved around the building exterior, first parallel to the facility exterior wall and then at right angles to the facility exterior, while observing the test point response. In this way any inadvertent or unknown penetration excited by the loop, and coupling directly or indirectly to the monitored test point will be detected. This procedure is shown figuratively in Figure 6.13.

6.3.1 Search Procedures. The external penetrations were driven from a 240 turn, one meter diameter loop. The test point response was monitored using a Stoddart (#93686-3) current probe and an Ortholoc-SC 9505 Two Phase Lock-in Analyzer.

Test point response as a function of transmitter (i.e., loop) frequency was as follows:

Test Point Response	Frequency
330 μV	15 kHz
230 μV	45 kHz
180 μV	90 kHz

Since only one frequency was to be used, all measurements were carried out at the frequency giving maximum response, i.e., 15 kHz.

The location of the external manholes and the runs over which the transmitter was taken are shown in Figure 6.14. Ongoing construction activity on the east side of the facility during the testing prevented the transmitter from being moved into that location.

In order to estimate the sensitivity of the test point response to the proximity of the transmitter with respect to the external penetration, the response of the test point as a function of transmitter position with respect to the penetration was measured and is shown in Figure 6.15. It should be noted that the test point

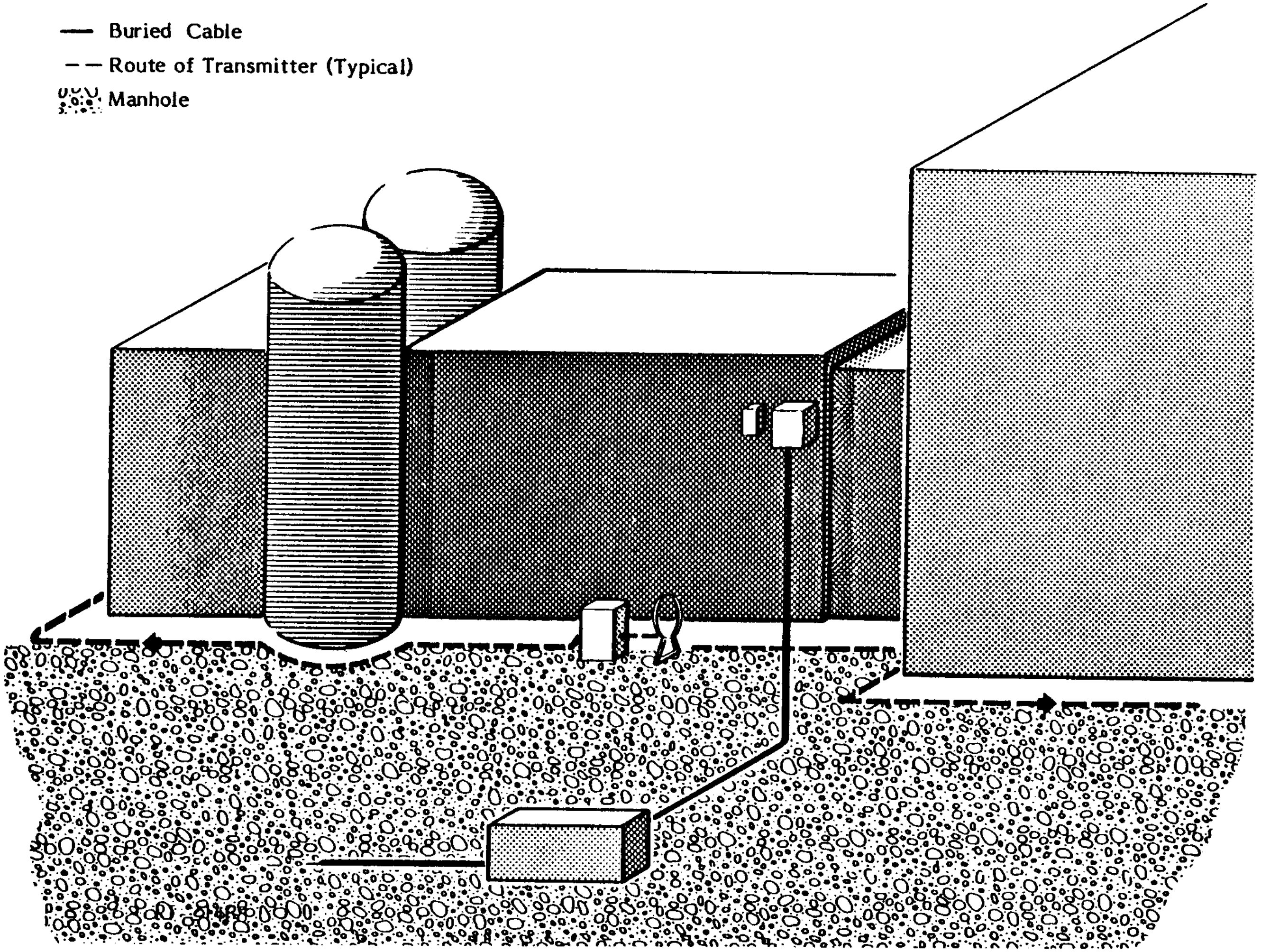


Figure 6.13. Search for Inadvertent Penetrations--Equipment Location

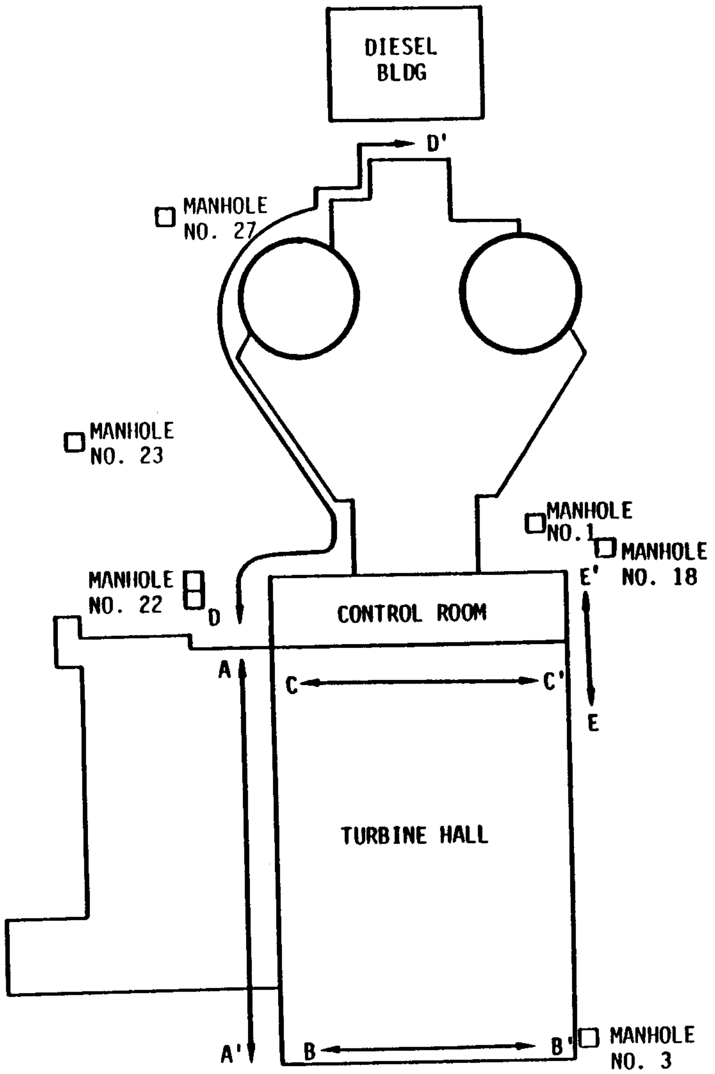


Figure 6.14. Transmitter Locations Used in Search for Inadvertent Penetrations

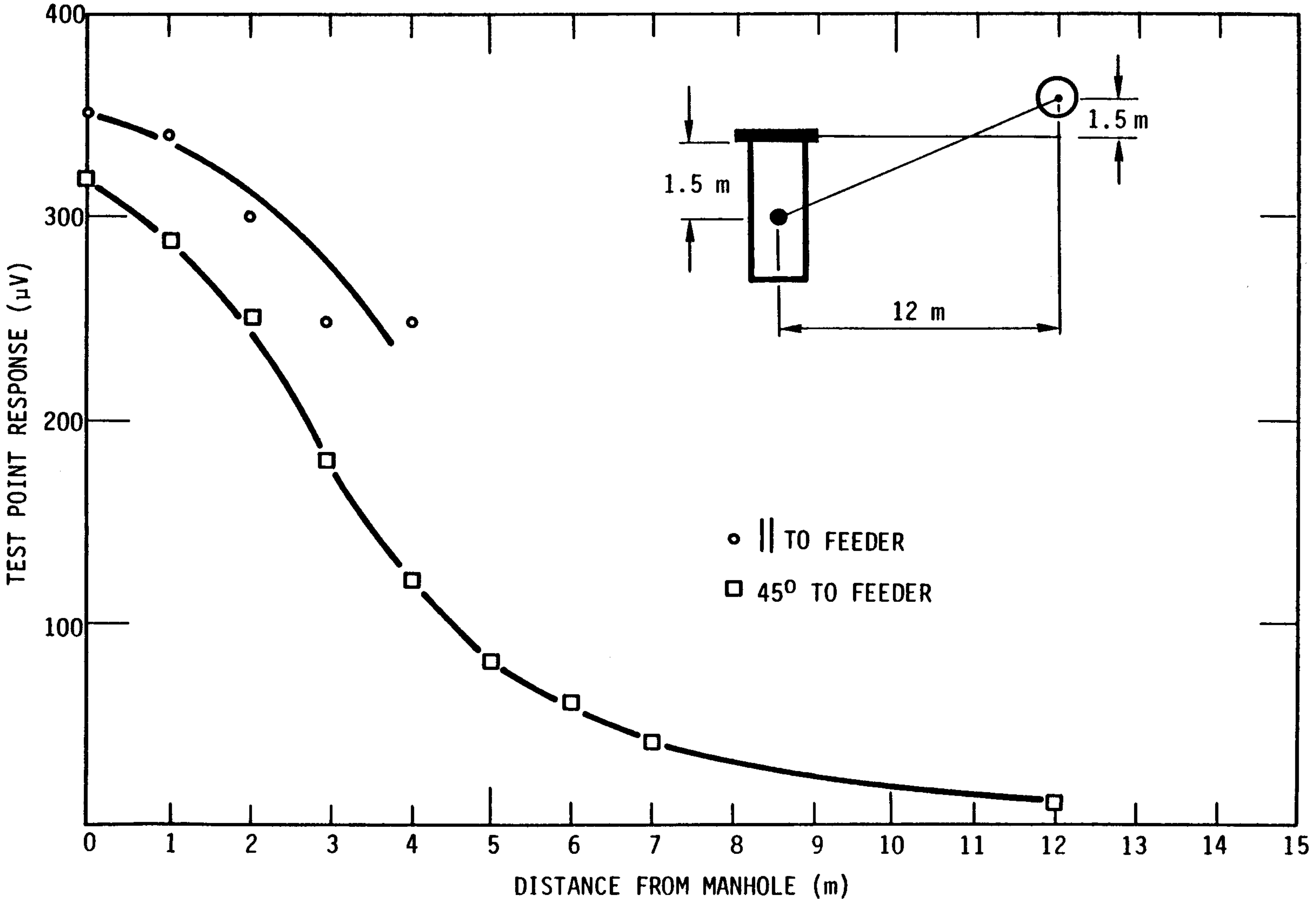


Figure 6. 15. Test Point Response as a Function of Transmitter Location

response is 6 dB above the ambient noise level with the transmitting antenna 12 meters from the penetration at an angle of 45° with respect to the penetration.

6.3.2 Search Results. In the search for inadvertent penetrations, five test point locations were chosen. A sixth point was instrumented but because the circuit breakers were open at the distribution board, the test point was not energized. The initial excitations were via manholes #1, 18 and 22.

A summary of the results of the search are given in Table 6.6.

6.4 Facility Insertion Loss Measurements

As part of a second series of tests, a measurement of the insertion loss present in the facility was undertaken. This was implemented in order to verify the Boeing assumption that the contribution to induced internal currents and voltages from diffused fields is negligible compared to the induced currents and voltages resulting from coupling to external to internal penetrations.

Two types of measurements were conducted. The first was identical in almost all respects to MIL-STD-285, in which local values of electric and magnetic insertion loss at selected frequencies are measured using electric and magnetic dipoles. The second was a measurement using a radiated CW source and the CW system described in Section 6.1.2 in order to assess the influence of penetrations and apertures on insertion loss. The radiated source in this case was a top-loaded monopole described in detail in Section 6.4.1.

6.4.1 Details of the Measurement Technique. The amplitude of the insertion loss produced by an enclosure is a function not only of the materials used in the construction of the enclosure but is also dependent on the characteristics of the fields themselves. Thus, it has become common practice to define both a magnetic and electric field shielding effectiveness or insertion loss. In essence, this represents the two practical extremes that are encountered in an operational environment. Magnetic field shielding effectiveness is the shielding associated with an electromagnetic field whose magnetic or $\bar{H}$ field component is much larger than its associated electric or $\bar{E}$ field component. The type of source that produces this field (the small loop in this case) is often referred to as a low impedance source. Electric field shielding effectiveness refers to the shielding associated with an electromagnetic field whose $\bar{E}$ field is much larger than its associated $\bar{H}$ field. This type of field is produced by a high impedance source such as short electric dipole.

Numbers which are stated as a measure of a shield's effectiveness can vary because of differences in equations used to define the term. For this reason, defining equations for magnetic and electric field SE are included in this document. It should be noted that any SE number is only meaningful when related to its defining equation and to the system used to measure the quantities in the equation.

Table 6.6.

Results of Search for Unknown or Inadvertent Penetrations

Excitation Manhole Number	Test Point	Manhole Excitation Level	Noise Level	Signal Level	Remarks
22	1-4PL-215-4976A feed from DG building	320 µV	1-10 µV	1-10 µV	30 µV response parallel to building on Run DD' - excitation of manhole #27
22	0-3FE-39-668 120V AC board 4G	420 µV	2-4 µV	2-4 µV	120 µV response Run CC' - excitation of CO_2 fire protection Cct. Feeds bus adjacent to test point. 30 µV response Run EE' - excitation of CO_2 fire protection Cct.
1	ERCW screen wash pump B-B cont. and aux. building vent BD2B1-B from cable 2-4PL-67-3905B	1-5 µV	1-5 µV	N.A.	Breaker open at vent board
1	ERCW screen wash pump B-B control cable cont. and aux. building vent board 2B1-B. From cable 2-3PL-67-3907B	30 mV	0.5 mV	0.5 mV	Preamp in (40 dB). At B' parallel to back wall 0.70 mV due to excitation of cable at manhole #3
18	Normal fdr diesel aux BD B2-B from cable 2-4PL-215 4985B	130 µV	1-5 µV	1-5 µV	
1	ERCW Strainer XMTR 67-9A cont. and aux. building vent bd. driven from cable 2-4PL-67-3913A	180 µV	1-4 µV	1-5 µV	150 µV response ‖ to E, wall turbine hall due to excitation of cable 2-4PL-67-3913A at manhole #3

* Background noise level at test point with transmitter off.

** Observed signal level at test point with transmitter on and away from manhole except as noted under Remarks.

The expressions used for computing electric and magnetic field SE are

$$S_E = 20 \log_{10} \frac{E_1}{E_2} \qquad (6.6)$$

and

$$S_H = 20 \log_{10} \frac{H_1}{H_2} \qquad (6.7)$$

where E_1 = electric field in absence of enclosure; E_2 = electric field within the enclosure; H_1 = magnetic field in absence of enclosure; H_2 = magnetic field within the enclosure.

The equations themselves along with the definitions associated with the field quantities imply the method used for measuring SE, a method often referred to as the "insertion-loss" method.

Ideally the way to measure shielding effectiveness is by the "insertion-loss" technique.[13] First, the transmitter and receiver are set up at a location, in the absence of the shield, and the field level at the receiver measured for a given output level from the transmitting antenna. Next, the shield is inserted between the transmitter and receiver locations and the field at the receiver measured a second time with the same output level from the transmitting antenna. The first quantity measured would be the field level in the absence of the enclosure and the second quantity would be the field level within the enclosure. These are the two quantities needed to solve Equations 6.6 and 6.7, whichever is applicable. However, it is seldom practical to remove and then insert the shield between transmitter and receiver. Consequently, the following method has been adopted as the preferred technique.

A series of tables are first generated, for the given measurement system, with the output level from the transmitting antenna, frequency and distance between receiver and transmitter antennas as variables. The measured received field level is then entered into the table for each combination of the three measured variables. These measurements need to be made only once and are conducted at a location where there is minimum interference from reflected signals. These measured values now become look-up tables for the values of E_1 or H_1 for the specific output level from the transmitter, frequency and distance between receiver and transmitter antenna.

For each particular enclosure for which the SE is being determined the receiver antenna is located inside the shield and the transmitting antenna outside the shield, and measurements of transmitter output level, antenna separation, frequency and receiver response E_2 or H_2 are made. This measured receiver response value of E_2 or H_2 can then be used with the appropriate E_1 or

H_1 value associated with the receiver frequency, transmitter output level and antenna separation distance and Equations 6.6 and 6.7 to compute the electric or magnetic insertion loss at that particular location.

In the radiated measurements the transmitting dipoles are replaced by a top-loaded monopole capable of operating over the frequency band from 10 kHz to 100 MHz. Response measurements are then made inside and outside the facility with $\bar{B}$ and $\bar{D}$ sensors and the measured amplitudes used to compute the ratios of electric and magnetic fields inside and outside the facility in order to assess the influence of penetrations and apertures on the overall facility shielding effectiveness.

In order to implement the measurement procedure for measuring electric and magnetic field shielding effectiveness using electric and magnetic dipoles, the system shown in a functional block diagram form in Figure 6.16 was used.

The system can be described in terms of two major and completely separate subsystems, namely the transmitter and receiver. The transmitter consists of a highly stable frequency synthesizer, power amplifier (100 watts), antenna matching network and either a small-loop magnetic dipole or short electric dipole transmitting antenna. The receiver employs similar antennas and associated matching networks in conjunction with a synchronous detection scheme to detect both in-phase and quadrature components of the received signal.

The system is intended to implement measurements similar to the "small-loop," "short dipole" tests presently employed[14,15] but with substantially greater sensitivity than presently available systems.

The system shown in Figure 6.16 has three basic operational configurations:

- Low frequency H-field configuration
- Low frequency E-field configuration
- High frequency E-field configuration

and these are shown in Figures 16A, B, and C, respectively. The basic differences in these configurations lie in the required antennas and associated matching network for the high and low frequency E-field measurements and in the availability of two different size diameter loops for the H-field measurements. These two loops are one meter and 0.305 meters in diameter; the smaller, however, has a built-in matching network and consequently can be connected directly to the attenuator bypassing the capacitor box as shown by the dashed line in Figure 6.16A.

The CW radiated measurements were conducted using the CW system described in detail in Section 6.1.2 and shown schematically in Figure 6.3, where the antenna used was the top-loaded monopole shown

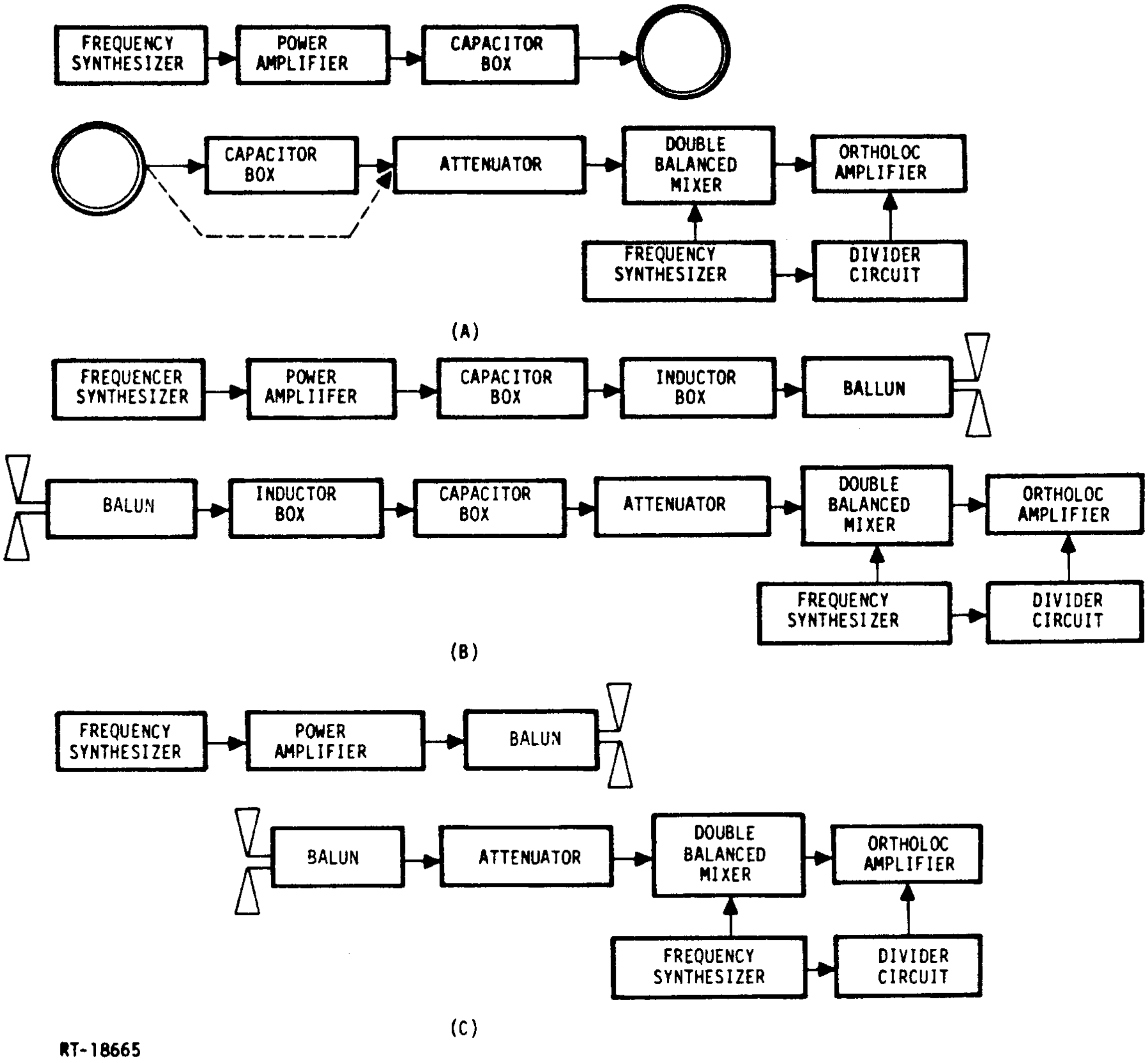


Figure 6.16. Preferred Equipment Configuration for Making Shielding Effectiveness Measurements

in Figure 6.17. This antenna, was designed by the Boeing Company for use on the APACHE (DNA/CINCPAC) Program and a typical calibration curve, at 20 MHz, is shown in Figure 6.18 and 6.19. Detailed calculations for the calibration curves at frequencies from 100 kHz to 100 MHz are available.[16]

6.4.2 Results of Facility Insertion Loss Using Small Electric and Magnetic Dipoles. The measurements were made at five locations within the facility as shown in Figure 6.20. The measure- ments were made at 15 kHz, 45 kHz, 90 kHz, and 1.5 MHz. The two wall thicknesses measured were 92 cm and 33 cm.

A summary of the results are presented in Table 6.7 and are shown plotted in Figure 6.21.

Table 6.7.

Summary of Facility Insertion Loss Measurements

	15 kHz	45 kHz	90 kHz	1.5 MHz	
AVG ATT(H)*	19.3 dB	28 dB	33 dB		92 cm Wall Thickness
AVG ATT(E)†				80 dB	
SE ATT(H)	6.8 dB	11.4 dB	11.3 dB		33 cm Wall Thickness
AVG ATT(E)				44.6 dB	

6.4.3 Results of Measurements Using Radiating Top Loaded Monopole. The location of the antenna for the radiated CW measurements is shown schematically in Figure 6.22 as positions A and B. The position of the reference sensor (B and D) with respect to the measurement points A, B and C is also shown.

The ratios of the interior and exterior electric and magnetic fields for antenna position B, test point A as a function of frequency are shown in Figure 6.23.

For test point B (antenna position B), which lies deeper within the facility the ratios are substantially greater, and are shown as function of frequency in Figure 6.24.

6.4.4 Coupling to Seismic Supports and Cable Trays. During the course of the measurements an attempt was made to determine if significant coupling existed between the building exterior and cable trays or seismic supports in the facility interior.

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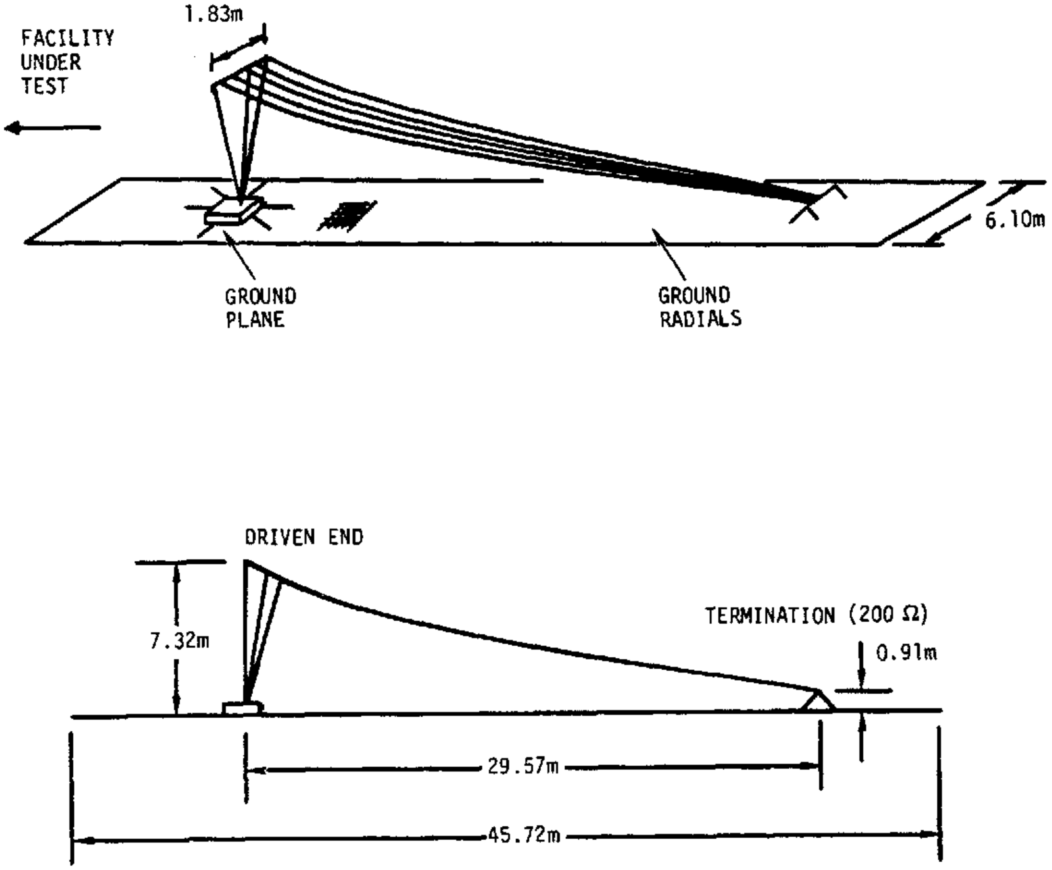
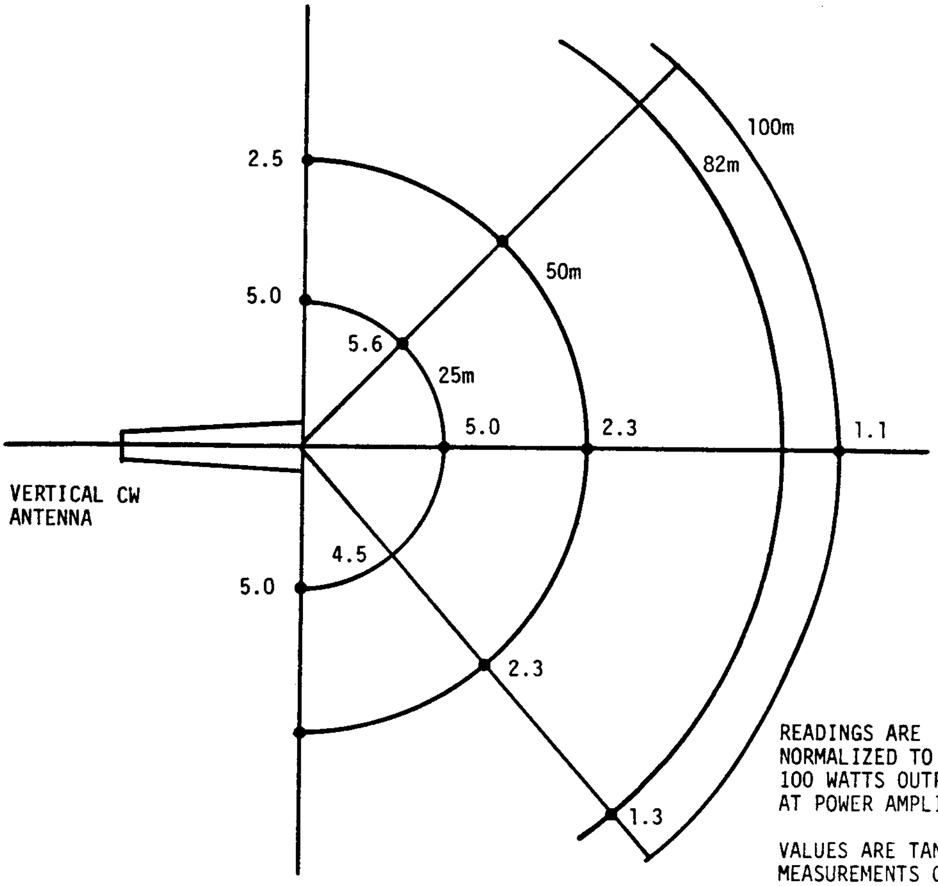
* Average of measurements at three locations.

† Average of horizontal and vertical polarizations at three locations.



RT-21481

Figure 6.17. Radiated CW Vertically Polarized Antenna



READINGS ARE NORMALIZED TO 100 WATTS OUTPUT AT POWER AMPLIFIER

VALUES ARE TANGENTIAL MEASUREMENTS COMPUTED AT 20 MHz ALL VALUES ARE IN MILLIAMPERE/METER

RT-21478

Figure 6.18. Vertical CW Antenna Field Distribution

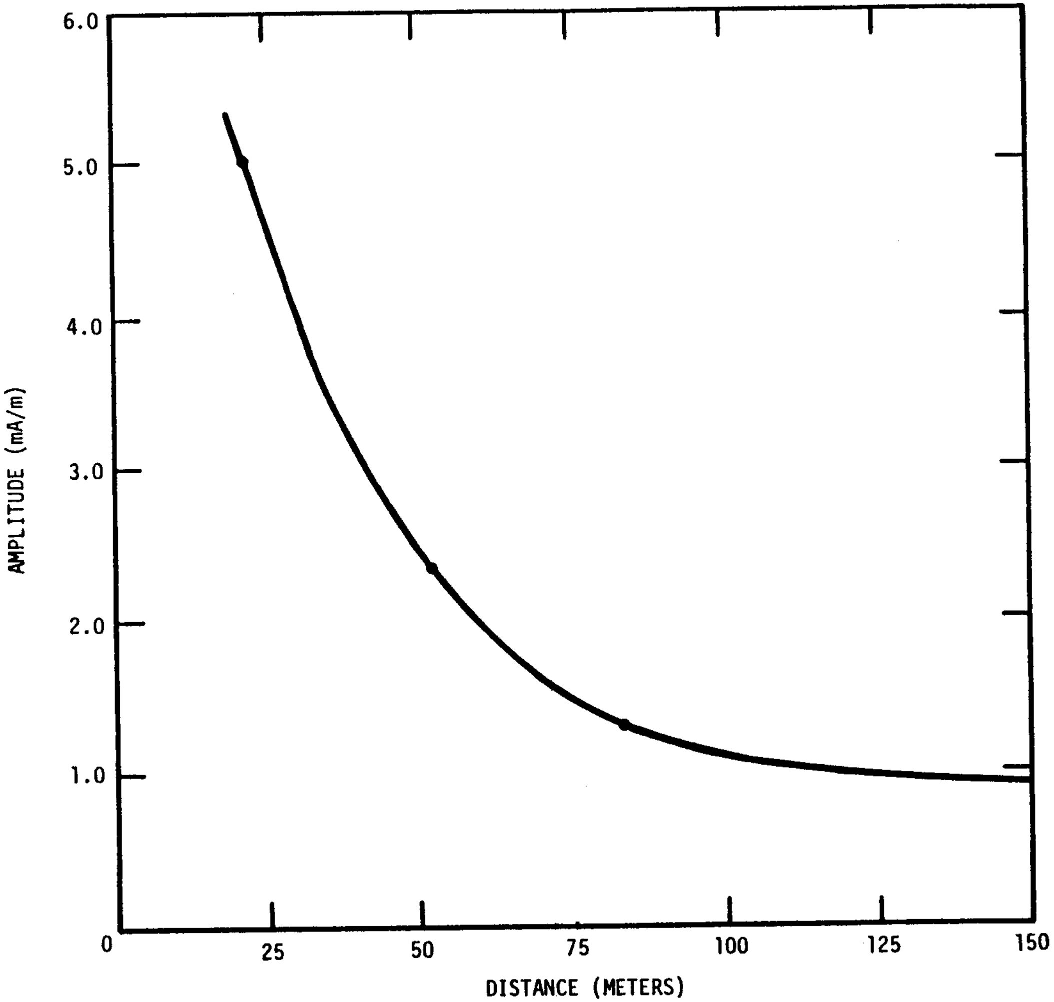


Figure 6.19. Vertical Antenna Field Strength vs Distance (On Axis)

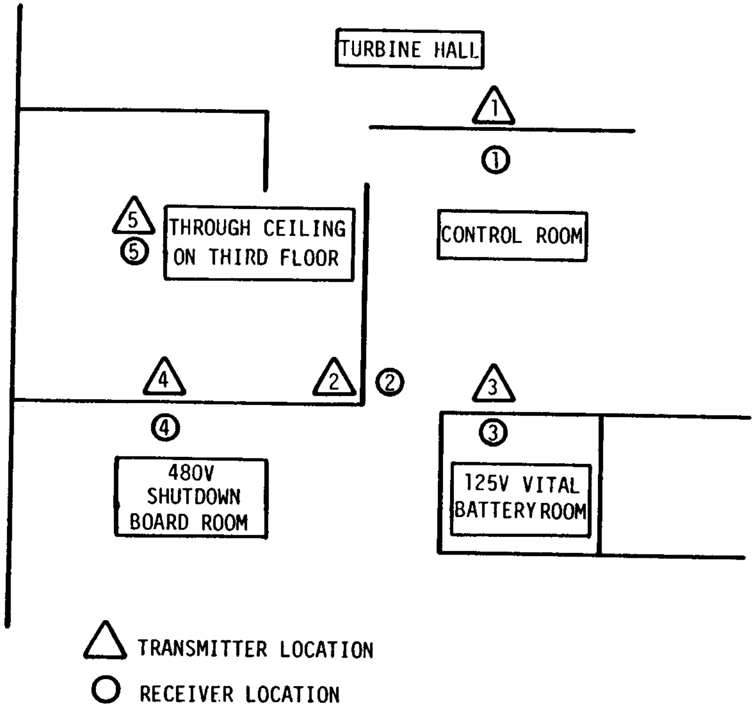


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Figure 6.20. Location of Insertion Loss Measurements Within the Facility

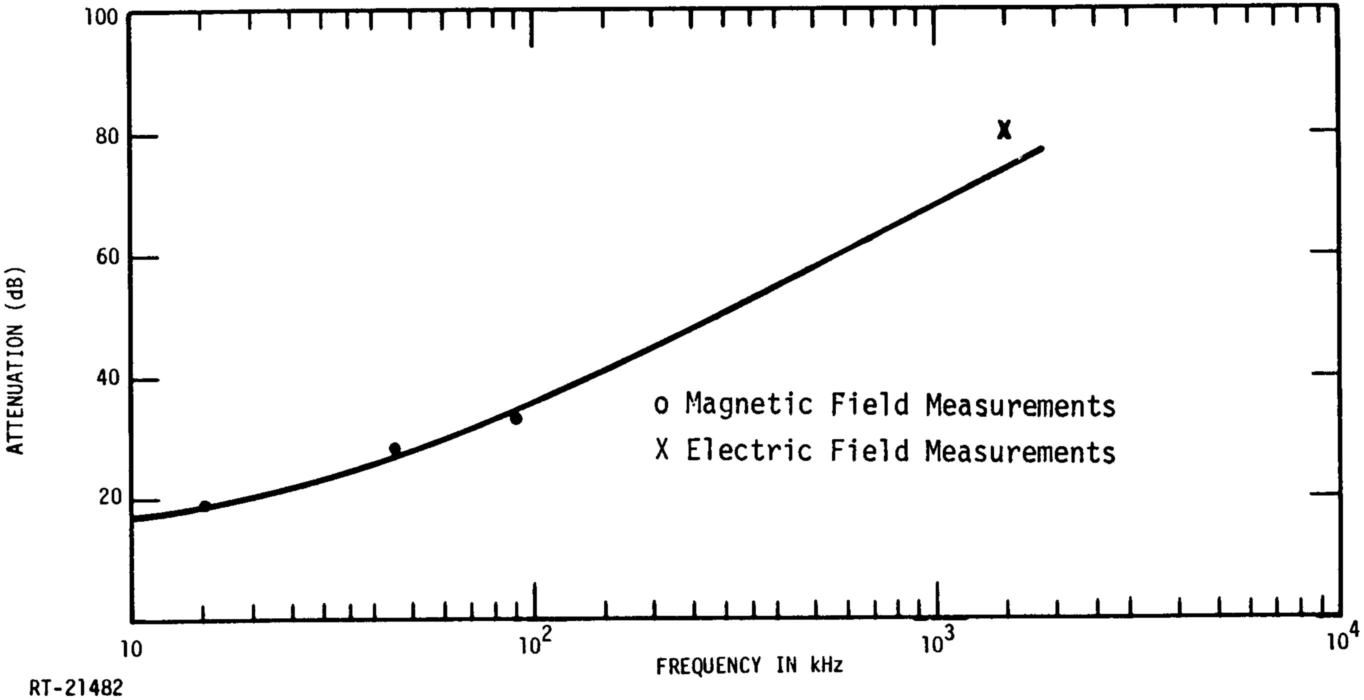


Figure 6.21. Magnetic and Electric Field Insertion Loss as a Function of Frequency (92 cm Wall Thickness)

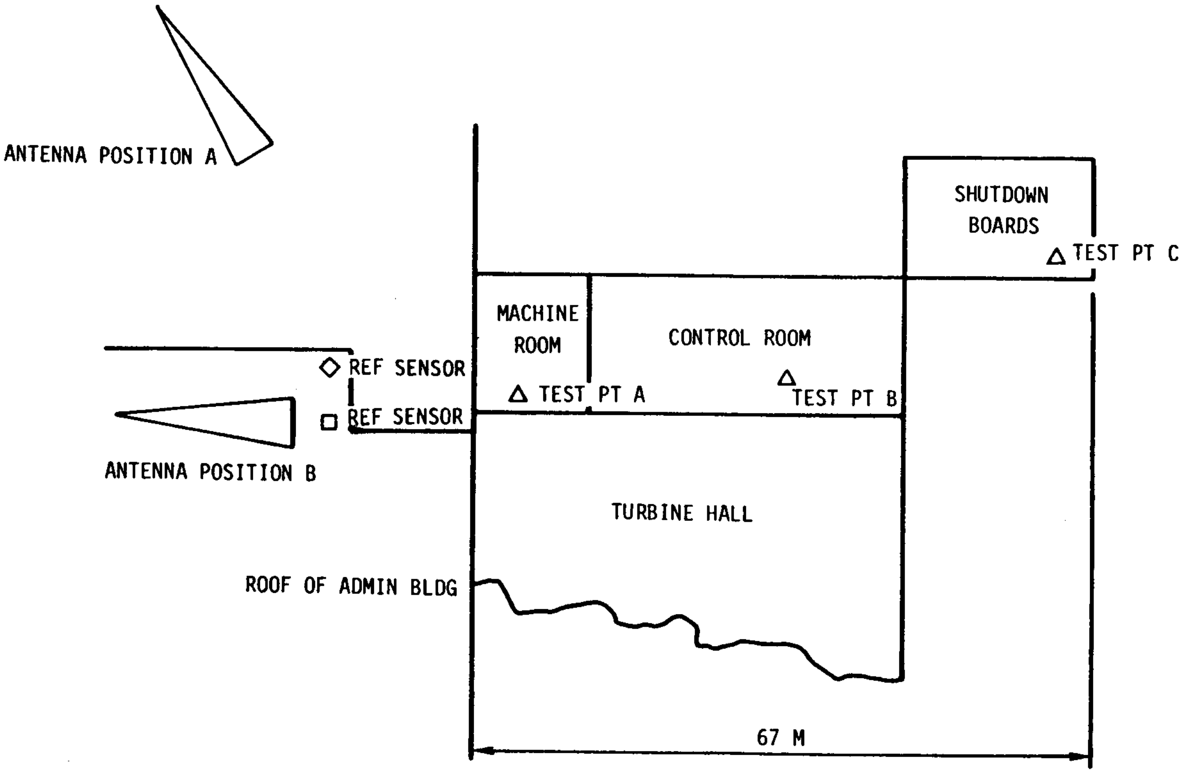


Figure 6.22. Antenna Location for Radiated CW Measurements

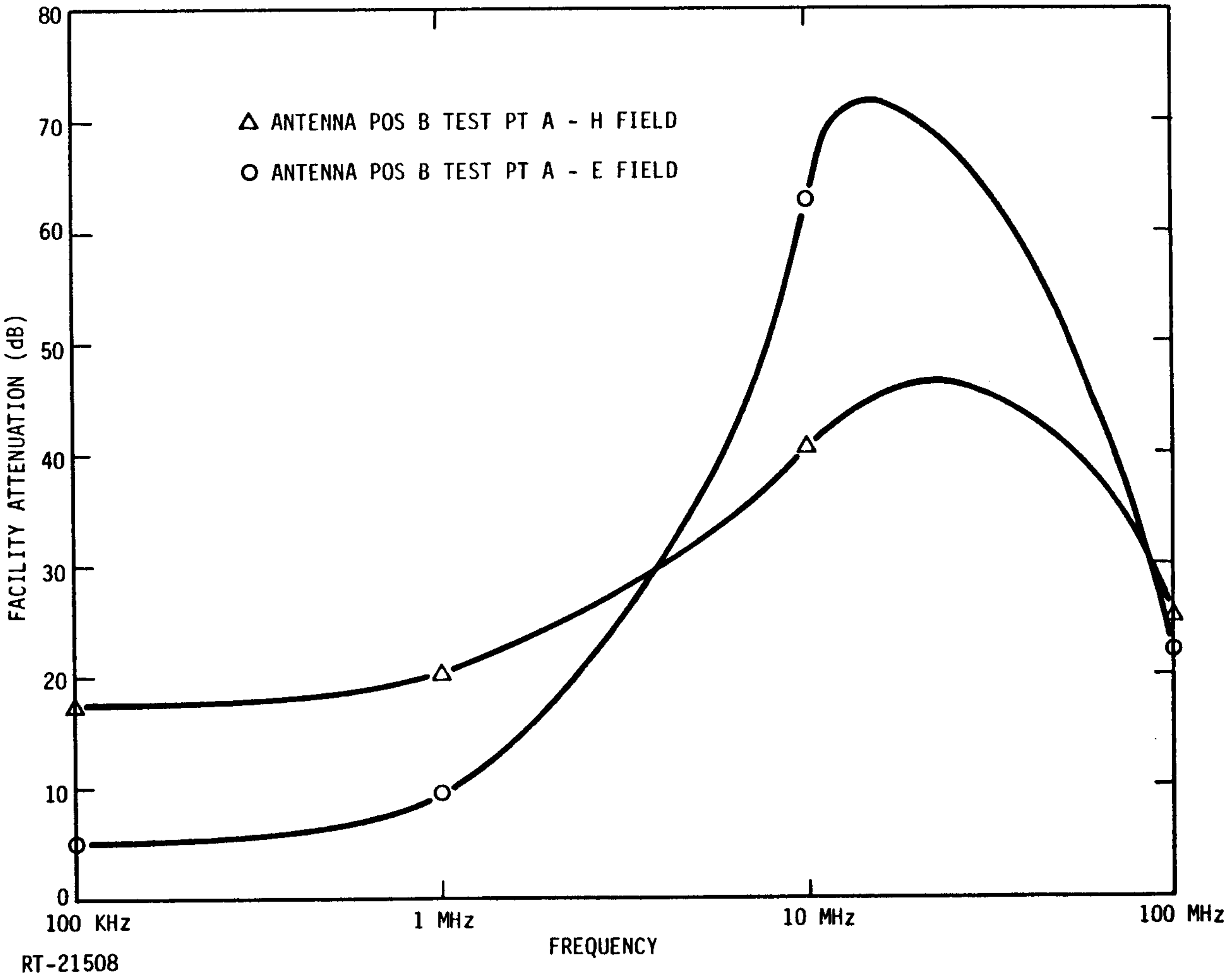


Figure 6.23. Ratios of Interior and Exterior Electric and Magnetic Fields vs Frequency, Antenna Position B, Test Point A

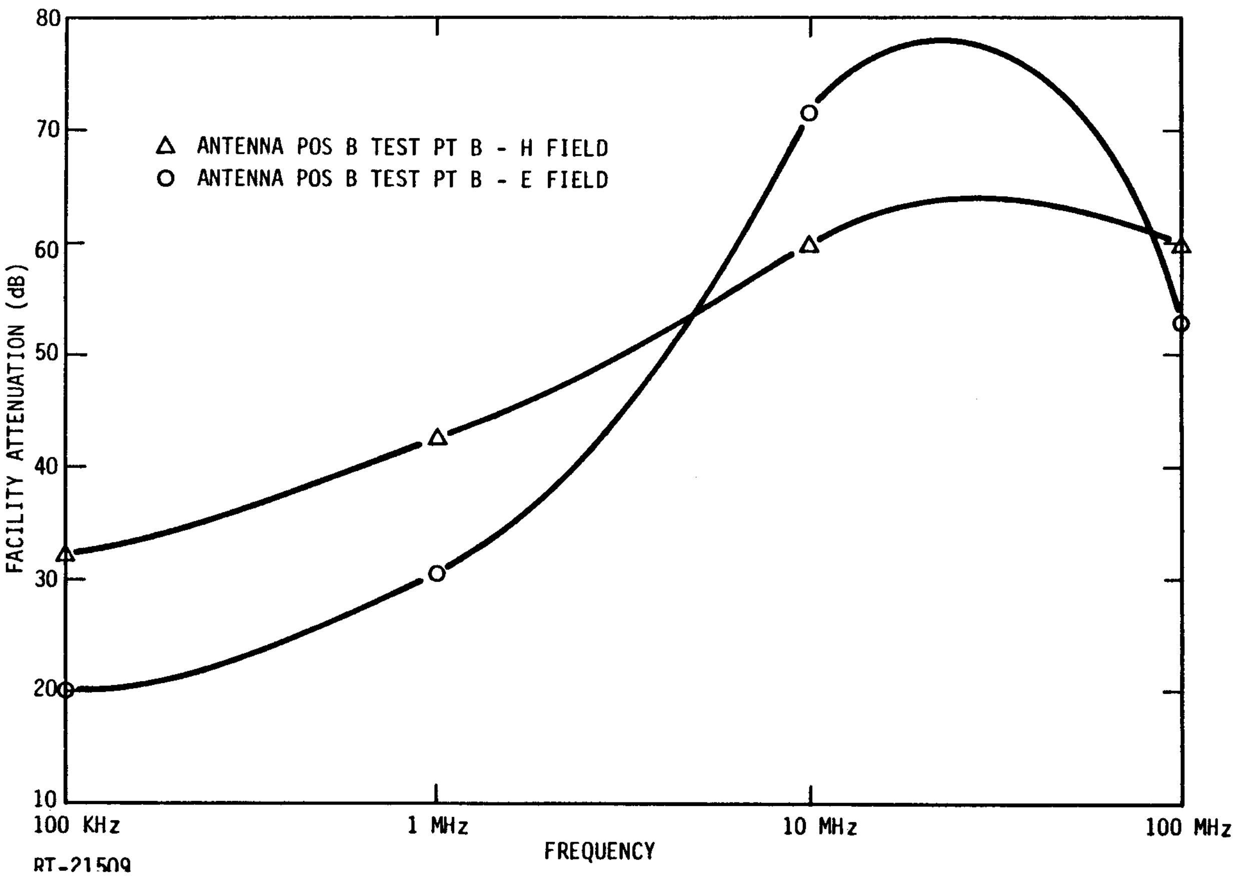


Figure 6.24. Ratios of Interior and Exterior Electric and Magnetic Fields vs Frequency, Antenna Position B, Test Point B

In order to accomplish this the roof of the auxiliary building and control room on the east side were illuminated by the magnetic dipole used in the shielding effectiveness measurements (see Section 6.4.1). A search was then made with a hand-held magnetic field probe (Electromagnetics Model # MFA 275-80) connected directly to the shielding effectiveness system receiver (See Section 6.4.1). The search was carried out in the areas of the 1-1V Inverter-Battery Charger room and along the 480V Reactor MOV Board Rack at elevation 763'. With the probe in the immediate vicinity of the seismic supports and cable trays no response greater than that observed in the open environment adjacent to the racks and seismic supports was observed.

6.5 Discussion of Results

6.5.1 Direct Injection Measurements. The measured responses resulting from CW direct injection tests are critically dependent on the nature of the mathematical function used at the driving point (see Section 6.1.3). Initially, a low Q (~10) 2 MHz damped sinusoid was chosen, and in fact was used, for the computations actually performed onsite. The choice of this function however forces the resultant predicted time domain transient to be critically dependent on the amplitude of the measured transfer function in the immediate vicinity of 2 MHz, and underestimates the contribution from the rest of the transfer function. This can be readily seen by reference to Table 6.8 which shows the response using the 2 MHz damped sine wave (THRTDS2M, column 2) compared to a more broad-band driving function (THRTWATT, column 3) which is a double exponential filtered by a 9th order Butterworth (F_l = 10 kHz f_u = 10 MHz). Increasing the upper cut-off frequency of the Butterworth to f_u = 15 MHz (THRTNWBNP) has little impact on the amplitude of the measured response as can be seen from Table 6.8. This is to be expected since the threat amplitude rolls off at -20 db/decade beginning at 636 kHz and consequently the contribution to the time domain transient from the higher frequencies is less than the contribution from the lower frequencies. The choice of 10 MHz for the upper cut-off frequency is also consistent with calculations of induced currents on buried cables, which show that for cables buried at depths of greater than one meter and for typical cable characteristics and ground conductivities, the spectral components above 10 MHz are essentially zero i.e.,

$$\frac{\text{Amplitude @ 10 MHz}}{\text{Amplitude @ 10 kHz}} < 50 \text{ dB}$$

The lower cut-off frequency of 10 kHz is dictated by the truncation of the transfer function at that frequency. Consequently, the threat file THRTWATT was used throughout for the reasons outlined above (which are also consistent with the assumptions used by the Boeing Company in their predictions).

Table 6.8.

Measured Response for Varying Threat Functions

Test Pt. Identifier	Meas. Resp. THRTDS2M (mA)	Meas. Resp. THRTWATT (mA)	Meas. Resp. THRTWBNP (mA)
D	35	82.7	105
E	126	250	240
F	116	216	222
G	124	287	304
I	38	156	169
J	35	122	137
K	9	17.5	17.7
L	7	15.5	16.7
U	8	14.4	14.4
X	9	22.9	22.8
Y	0.4	1	1.7
Z	0.4	1.1	1.7
AA	12	30.6	22
BB	4	21.1	21.2
CC	4.3	24	23.8
DD	0.4	6.7	6.7
EE	0.35	2.5	2.5
FF	0.37	2.1	2.1
GG	.39	3.6	3.6
HH	1.3	1.7	1.7
II	.26	.35	.35
JJ	.07	.14	.14
KK	.23	.37	.37
LL	.25	.4	.4
MM	.15	.45	.45
NN	.15	.48	.48

It should be noted that the CW system in its present configuration and mode of operation tends to predict responses that are lower than would be encountered with an actual incident EMP because of the truncation introduced by the Butterworth filter and the consequent reduction in the amount of energy incident on the facility.[17]

In examining the time domain transient responses produced by the threat waveform the nature of the response function becomes apparent, namely a damped sinusoid, in which the oscillatory components are dominated by two or three frequencies. These frequency components are generally found around 100 to 200 kHz, 1-2 MHz and a component around 10 MHz, with the lower frequency components usually dominant. This behavior was also commonly observed at NAVCAMS EASTPAC during the APACHE tests.[17]

A comparison of the measured data with the predictions shows that for a total of thirty-seven points an offset $\bar{X}$, of +2.3 dB and a sample standard deviation σ, of 11.8 dB result. It should be noted that when the test points are reduced to current and voltage measurements the following results are obtained,

27 Current Points $\bar{X} = -1.75$ dB, $\sigma = 8.3$ dB
10 Voltage Points $\bar{X} = +13.2$ dB, $\sigma = 13.2$ dB

When the voltage points are examined in detail (Table 6.3) it is seen that the relatively large offset and standard deviation result from four measurements (AAA, BBB, YY and ZZ) taken at one particular location in the control room (120 V Vital Instrument Power Panel 1-III, see Figure 6.6). At this point in time there exists no simple explanation for this large discrepancy between measured and predicted that would justify their removal. Consequently, the results have been retained in the overall data set. The possibility that predictive accuracy varies with the depth of test point into the facility, i.e., with respect to the number of branch outs and cable length, has been observed previously. This was investigated as a possible explanation for the disparate voltage measurements. As can be seen from the offset and standard deviations given in Table 6.5 no such trend exists and consequently this does not account for the observed results.

This discrepancy is especially puzzling because the current measurements on the cabling which supplies these voltage test points agree very well with predictions (see points II and JJ on Table 6.2 and Figure 6.5). Other test experience has shown that voltage measurements are the more difficult to accomplish in the field. The voltage probes are unshielded and thus subject to extraneous signal pickup and saturation, particularly in locations where significant normal power signals are present. In contrast, the current probes are fully shielded. Also, it is necessary to use signal attenuators with the voltage probes, and although it is unlikely, it is possible that incorrect values for attenuation were used in the data processing. Finally, it is noted that it was necessary to fabricate locally, on short notice, some signal attenuators for these measurements and this could have introduced difficulties which are not readily apparent. The co-location of these tests with the largest discrepancies certainly argues for some systematic error. But, as noted in Section 8, even if the predictions are non-conservative by a substantial amount, the estimated safety margins at these locations are large enough that the overall conclusions remain unchanged.

In computing current division when going from a single conductor to a group of conductors, e.g., at a distribution board, the division ratio is normally considered to lie between $1/n$ and $1/\sqrt{n}$ where n is the number of conductors. In the Boeing Company predictions a value of $1/n^{0.75}$ was assumed. That this is a reasonable assumption can be seen by reference to Table 6.5. For the eighteen loads on the vital battery board the division ratio is $1/n^{0.64}$ and for the 120 V vital instrument power panel the division ratio is $1/n^{0.53}$ which demonstrates a reasonable agreement.

The measured transfer function from the exterior to the interior is shown in Figure 6.11 and the computed time domain transient in Figure 6.12. The dominant resonances in the transfer function (shown circled) at 90 kHz, 400 kHz and 2 MHz can be readily seen in the time domain response. Once again the damped multi-component (three) sinusoidal nature of the response is apparent.

In the measurement of cable attenuation (Section 6.2.5) an average attenuation of 9.6 db/100 ft was obtained. The value assumed in the analysis was 6 dB/100 ft which again provides for a degree of conservatism in the predicted responses.

Finally a calculation of the current induced on a single buried cable in the environment of a full threat level incident EMP has been made using the computer code LSSYIV. This code addresses the response of a complex cable bundle buried in a lossy earth to any specified impinging electromagnetic field. Means are also available for predicting currents and voltages on the shields and wire cores of individual cables in a bundle for any specified loading. The solution is based upon a transmission-line analysis of the problem. The values of the induced peak currents for a cable length of 200 meters and varying ground conductivities and depth below ground are shown in Table 6.9. A cable length of approximately 200 meters is sufficient to reach a maximum value of EMP-induced signal.

Table 6.9.

Current Induced on a Buried Cable

Cable Radius (meters)	Length (meters)	Depth (meters)	Conductivity (mhos/m)	I_{peak} (Amps)
3×10^{-2}	200	0.2	5×10^{-4}	2800
3×10^{-2}	200	0.2	5×10^{-3}	1210
3×10^{-2}	200	0.2	1×10^{-2}	920
3×10^{-2}	200	1.0	5×10^{-4}	2700
3×10^{-2}	200	1.0	5×10^{-3}	1110
3×10^{-2}	200	1.0	1×10^{-2}	815
3×10^{-2}	200	5.0	5×10^{-4}	2300

Ground conductivity typically lies between 10^{-3} and 10^{-4} mho/m and the conduit duct banks at the Watts Bar Nuclear Plant are typically 2-5 metres below the surface. Therefore, given the results here, the assumption in Section 5 of 1000 ampere bulk current is reasonable.

6.5.2 Search for Inadvertent Penetrations. No evidence for the presence of inadvertent or unknown penetrations was discovered during the search described in detail in Section 6.3. Evidence that the measurement system performed as designed was provided during the tests when excitation of external cable runs at peripheral manholes was detected at the test point under investigation.

Two of the limitations of these tests include:

- Only five test points investigated
- Inadvertent penetrations could possibly be present but would go undetected if not connected or coupled to the test point under investigation.

6.5.3 Insertion Loss Measurements. The local values of electric and magnetic insertion loss for the 92 cm walls are shown plotted in Figure 6.21. The magnetic field values SE(H) which represent the sum of the absorbed and reflected components behave as theory predicts[18] in that the insertion loss increases with increasing frequency. Only one measurement of electric field insertion loss was made, at 1.5 MHz, and therefore the general behavior for this field component cannot be confirmed. That this value is greater than the magnetic field component is however consistent with theory[18]. It should further be noted that the electric field insertion loss increases with decreasing frequency.

In general plane wave shielding effectiveness for a semi-infinite plane wall can be deduced from these electric and magnetic field values[18]. In summary

$$\text{Plane wave SE} > \text{SE(H)}$$

$$\text{Plane wave SE} < \text{SE(E)}$$

and in fact plane wave shielding effectiveness lies midway between the values for electric and magnetic field insertion loss.

Based on the above inequalities a value for plant wave shielding effectiveness for a semi-infinite plane wall above 100 kHz would exceed 35 dB. A reduction in this value due to the fact that the facility does not represent a semi-infinite plane but is rather a finite-sized object[19,20], must also be taken into account. For example for a facility ≃20 meters radius this reduction amounts to approximately 6 dB. This implies a minimum plane wave shielding effectiveness substantially in excess of 30 dB at 100 kHz for the facility if the only source of protection is the 92 cm rebar wall, which is consistent with previously reported results for rebar structures[20].

In practive, however, this shielding effectiveness is reduced by apertures and penetrations and increased by the presence of additional structural elements, e.g., additional walls, fire doors, seismic supports, additional rebar, etc., as well as by increasing depth into the facility, as indicated by the results of Section 6.5.4.

6.5.4 Impact of Apertures and Penetrations on Shielding Effectiveness. In an attempt to address the question of the impact of apertures and penetrations on shielding effectiveness, radiated CW measurements were undertaken (see Section 6.4.3). The ratios of internal to external electric and magnetic fields using $\bar{B}$ and $\bar{D}$ sensors are plotted in Figures 6.23 and 6.24 for two different points within the facility. For antenna position B test point A, the value of the exterior to interior electric field ratio at 100 kHz is 5 dB, rising to 63 dB at 10 MHz. The corresponding ratios for the magnetic field are 17 dB and 41 dB, respectively. However, as the test point is taken deeper into the facility (test point B) these values increase significantly to 20 dB for the electric field and 32 dB for the magnetic field at 100 kHz rising to 72 dB and 60 dB respectively at 10 MHz. It should be noted that these values do not correspond to electric and magnetic field insertion loss measurements as discussed in Section 6.5.3 as these measurements are strongly influenced by reflected fields. Since the measured, incident, exterior field consists of both incident and reflected (from the facility walls) components the amplitude of the incident component alone is not uniquely defined and consequently the value of shielding effectiveness, which is defined in terms of the incident field, in turn, cannot be uniquely defined. The value of these measurements lies in the fact they provide a better understanding of the coupling of the incident field to the interior of the structure. For example, it is of interest to note that in both Figures 6.23 and 6.24 the electric field ratios are less than the magnetic at low frequencies, which is the reverse of that normally encountered in metal shielded structures[18]. Such a phenomenon would be exhibited if there were significant enhancement of the interior electric field due to penetration or aperture coupling. Such a possibility exists in this situation by virtue of the monopole azimuthal magnetic field coupling to the major penetration from the diesel generator building passing through manhole #22 to the cable spreading room in the auxiliary building. This coupling to the buried penetration however decreases with increasing frequency[16] so that the two curves eventually cross over and the electric field values are greater than the magnetic field values as is commonly encountered at higher frequencies. Since the absorption loss for magnetic shielding effectiveness increases as $\sqrt{f}$, and the reflection loss increases the logarithm of f, the sum of the two components should increase with increasing frequency. Observation of Figures 6.23 and 6.24, however, show that the sum of both components for the electric and magnetic field attenuation start to decrease above approximately 10 MHz. This is due to the increase in the aperture coupling at higher frequencies, where the aperture dimensions become comparable to the wavelength of the incident field.

In summary, these results demonstrate the presence of a significant penetration coupling mechanism, i.e., the cable run from the diesel generator building to the auxiliary room and also the presence of aperture coupling.

As previously noted, surfaces providing both reflection and absorption of an incident wave provide a plane wave shielding effectiveness which lies between the electric and magnetic field shielding effectiveness values. However, when the integrity of the shield is compromised by the presence of penetrations or apertures no such simple relationship exists.

In considering these results, it should be noted that the effect of the cable penetration has been taken into account in the analysis (see Section 5).

It should also be borne in mind that apertures which existed at the time of the tests should not exist during normal operations. That is, for other reasons, e.g., safety and security, the cable spreading room shield doors, control room doors, etc., will be closed and secured.

7.0 Component Damage Threshold Analysis

7.1 Introduction

The electrical equipment used in a commercial nuclear power plant spans the range from large horsepower, heavy duty fluid pumping systems to solid state logic devices. In order to keep the damage threshold estimate effort tractable, a number of key decisions were made early in the study. One, no attempt was made to predict damage thresholds for rotating machinery. This decision was prompted by several considerations. Initial coupling predictions suggested that EMP reduced signals would be on the order of operating levels or lower. Also, such equipment is not well represented in the existing response models or data bases. Finally, such equipment in these applications is usually heavy duty and conservatively designed. Two, only selected components, representative of classes of equipment used in the safe shutdown systems, were analyzed. This was necessary in order to keep the effort reasonably tractable. Three, the damage threshold effort is analytical only; there was no test program to verify threshold estimates.

In addition to the three decisions cited above, four additional constraints were imposed upon the damage threshold program: (1) Because semiconductor components are more susceptible to EMP induced failure than passive components, the analysis was restricted to include only semiconductors and to eliminate calculating circuit damage thresholds for passive device failures; (2) The circuit analysis was conducted at 1 MHz as experience indicated that this will be a reasonable midpoint of the damped sine wave expected inside the plant; (3) On the equipment items analyzed, only those pins that serve as interfaces to "outside-world" connections were considered, all others, i.e., those that serve as interfaces internal to the box or equipment cabinet, were excluded from analyses; (4) Only permanent damage failures were examined, that is, signal upset was not considered here.

The analytical approach used to calculate circuit damage thresholds is an application of the DEFT methodology[21] shown on Figure 7.1. Sources for the data acquisition phase are the Tennessee Valley Authority, Office of Engineering Design and Construction and the individual equipment manufacturers.

Component failure thresholds were calculated using the semiconductor failure models developed by Wunsch, et al.[22] In the Wunsch failure model, the junction failure power is related to the transient pulse width by:

$$P_F = kt_P^{-1/2}$$

where P_F is the failure power of the semiconductor junction in watts and t_P is the pulse width in seconds. The proportionality constant, k, is the damage constant for the device in W $sec^{1/2}$ and

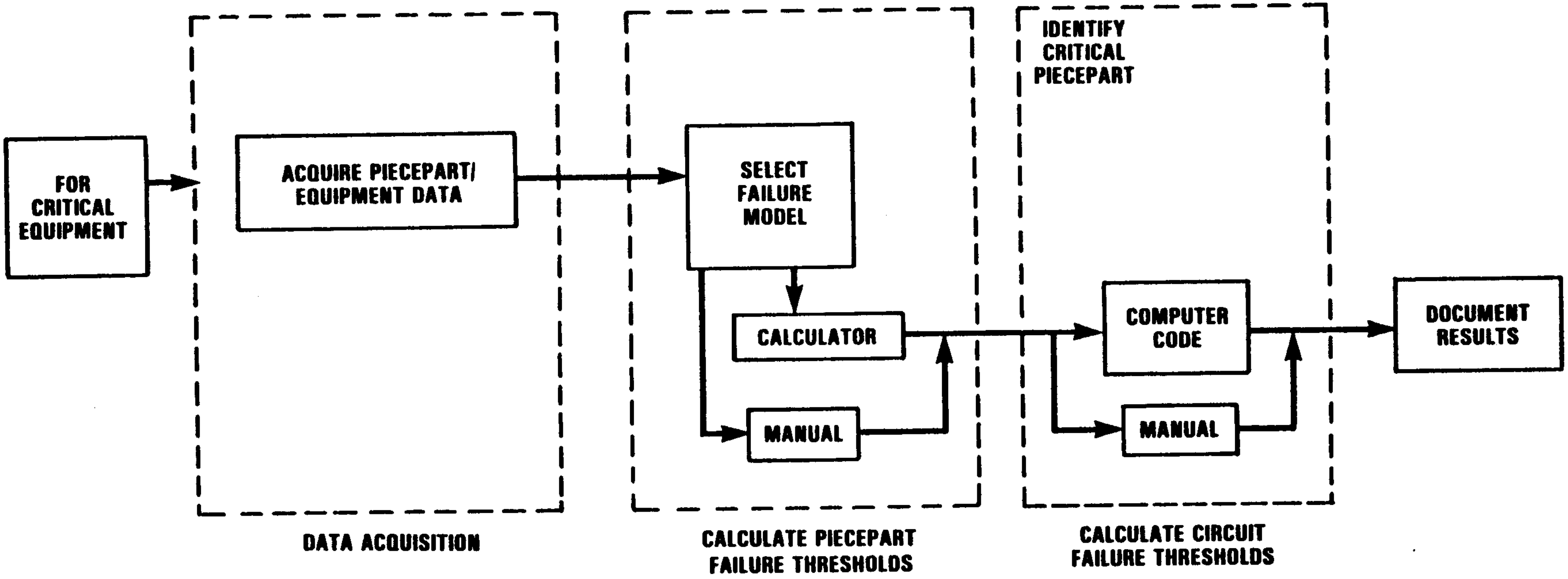


Figure 7.1. Circuit Damage Thresholds - Analytical Approach

is determined either by experiment or by applying empirical models. The existing models permit the estimation of damage parameters using published device electrical parameter values.

The most vulnerable piecepart is identified by comparing the component failure thresholds and the protection provided by the circuit. Circuit topologies often provide protection through low shunt impedances or high series impedances. The protection between the semiconductor junction and the interface pin will help determine which component is most susceptible to damage. Once the most susceptible component is identified, its damage parameters are used to calculate the levels of voltage, current, and power at the input pin which will cause the component to fail.

Based upon experience in other EMP programs the input stimulus for each interface circuit was assumed to have a damped sinusoid waveform. The circuit damage thresholds were determined by reflecting the individual component damage parameters through the network back to the pin interface using transfer functions or Kirchoff's current and voltage laws.

Using the data gathered, component damage thresholds were calculated to determine which component was susceptible to EMP induced damage. The equipment analyzed falls into two categories: power equipment and process instrumentation equipment. These categories can be further broken down into subclasses: input, output, and power signals. The equipment examined is indicated in Table 7.1. The circuit damage thresholds for these subclasses exhibit a range of values such as shown in Table 7.2. Subsequent sections describe the components, analytical methods and threshold predictions in more detail.

7.2 Equipment Descriptions

As indicated above, the systems required for safe shutdown were identified and the components identified in Table 7.1 were selected as representative for purposes of damage threshold determinations. Each of these components is described briefly below.

7.2.1 Uninterruptible Power System (UPS). The UPS is used to back up the normal source of instrument electrical power with a battery reservoir and a conversion system that produces continuous ac and dc output power. The UPS receives 480 VAC, three-phase, class 1E input power from the plant distribution system. This power is supplied through an input circuit breaker to a rectifier/battery charger which converts it to 125 VDC. This 125 VDC power supplies dc loads, drives a dc to ac static inverter to supply 120 VAC loads, and also keeps the battery at full charge. The UPS equipment is located in the vicinity of the 480 V, class 1E power distribution equipment and load centers. Figure 7.2 shows a flow diagram of the UPS.

7.2.2 AFW Turbine Governor. Auxiliary steam turbines provide a diverse source of motive power for pumps in nuclear power plant safety systems. The AFW turbine governor system investigated in

Table 7.1.

Equipment Analyzed to Estimate Damage Thresholds

- Uninterruptable Power System
  - Battery Charger
  - Inverter
  - Battery
- AFW Turbine Governor
- Instrument Power Supplies
  - Foxboro Power Supply
  - Solid State Protection System Power Supplies
  - Lambda Regulated Power Supply
  - Bailey Isolated Power Supply
- Agastat Timing Relays
- Bailey Process Instrumentation
- Beckman Process Instrumentation
- Analog Multiplex (MUX) Relay Card

Table 7.2. Nominal Circuit Damage Threshold Ranges for Example Plant Equipment Analyzed.*

EQUIPMENT TYPE	V_T (V)		I_T (A)		P_T (W)	
	MIN	MAX	MIN	MAX	MIN	MAX
POWER						
INPUT	480	$9.3\text{x}10^9$	1.9	$1.6\text{x}10^8$	890	$1.5\text{x}10^{18}$
OUTPUT	76	$3.9\text{x}10^7$	45	$2.5\text{x}10^{10}$	$4\text{x}10^4$	$9.7\text{x}10^{17}$
PROCESS INSTRUMENTATION						
INPUT	340	$5.6\text{x}10^7$	2.9	$2.9\text{x}10^3$	$6.1\text{x}10^3$	$8.4\text{x}10^8$
OUTPUT	56	$5.6\text{x}10^7$	2.1	$9.4\text{x}10^4$	470	$2.2\text{x}10^{12}$
POWER	360	$1.2\text{x}10^5$	2.1	800	740	$9.2\text{x}10^7$

*The values reported are predicted values assuming that all other portions of the circuit function. Clearly, other phenomena, insulation breakdown, arc over, etc., will occur before the maximum voltages reported here are reached. This analysis does indicate however that the semiconductor devices, though inherently more vulnerable, are for the most part well protected in these circuit designs.

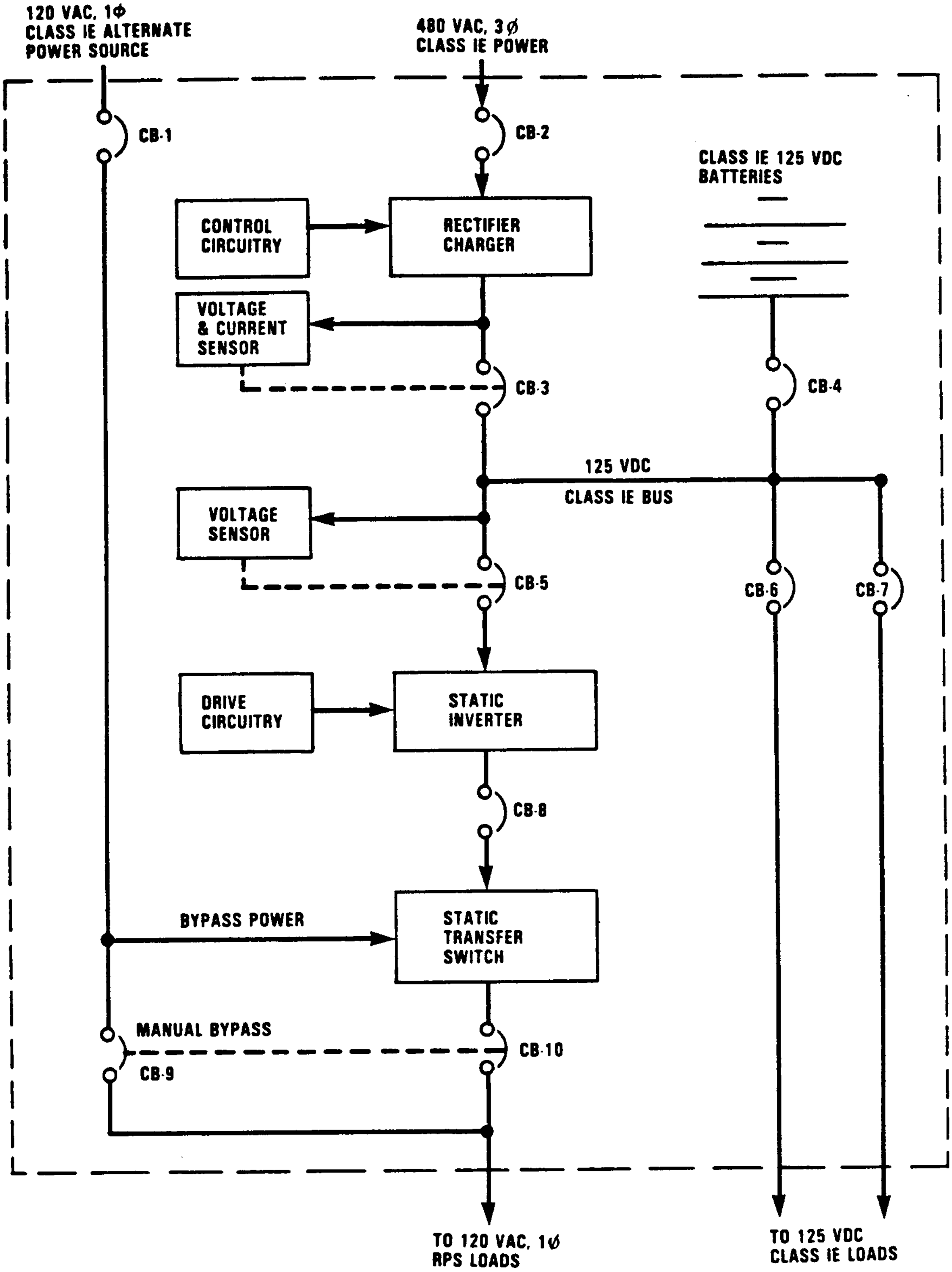


Figure 7.2. Uninterruptible Power System (UPS)

this assessment is an electronic governor (a Woodward EG). An electronic sensor monitors turbine shaft speed and provides an input to a local electrical panel that contains governor controls. Governor speed can be adjusted by varying controls in the electrical panel which change the signal out to the governor drive.

7.2.3 Instrument Power Supplies. Each of the instrumentation systems requires regulated power. Although the power supplies are similar, a number were sampled to provide a cross-section of types used.

Foxboro Power Supply. This power supply is designed to furnish power to a single electronic force-balance transmitter. The power supply employs a conventional circuit in which full wave rectification occurs across the diode bridge. Filtering is accomplished by capacitors and a resistor. Other resistors serve to improve voltage regulation by acting as a bleeder across the output of the power supply.

Solid State Protection System Power Supplies. Both the 15 V/10 A and 48 V/4.3 A regulated dc power supplies were designed for use in reactor protection systems in commercial nuclear power generation systems. The output voltages of these supplies are regulated by switching regulatory circuitry.

Lambda Power Supply. The power supply consists of an ac input circuit and transformer; a bias supply consisting of an auxiliary rectifier and filter, and preregulator; a main regulatory circuit consisting of the main rectifier and filter, a series regulator, emitter-follower driver, a current comparator, a voltage comparator, an amplifier, current and voltage sensing networks and a voltage reference circuit. The dc output voltage is regulated for line and load. Thus, this power supply operates as a constant voltage source provided the load current does not exceed the rated value.

Bailey Isolated Power Supply. The isolated power supply analyzed is designed to deliver up to five separate outputs of 52.5 VDC rated at 0-50 mA, for one to five transmitters. The ac input and all dc output connectors are available at a terminal board located at the rear of the power supply case.

7.2.4 Agastat Relays. The Agastat timing relays may have either ac or dc powered coils but control ac power. They are part of the dc powered equipment in the Auxiliary Building and are on the 6.9 kV Shutdown Board. They also appear on the various 480 V boards. For analysis purposes, it is assumed that these relays (or those similar) also appear on the 480 V Diesel Auxiliary and Diesel Relay Boards in the Diesel Generator Building.

7.2.5 Bailey Process Instrumentation. This set of equipment is one of two instrumentation systems analyzed as part of this assessment and is typical of many in the plant. The Bailey equipment was used because it is in a safety-related system (Essential Raw Cooling Water) and because the components are physically separated. The differential pressure transmitter is in the intake structure while the power supply and the square root converter are in the Auxiliary Building. This emphasizes their potential susceptibilities to a conducted transient due to EMP on the interconnecting cabling. A simplified interconnection diagram is provided in Figure 7.3.

The differential pressure transmitter is an electromechanical device used to measure flow, liquid level or specific gravity in the ERCW flow loops. It measures differential pressures in ranges of 0-20 inches of water to 0-60 psid, at static-pressures up to 2000 psi and transmits a proportional milliampere dc signal. The transmitter employs a 2-wire system, powered by 24 (or 52.5) VDC and has a solid state amplifier. In flow applications, the transmitter measures the differential pressure across an orifice plate or flow nozzle in the flow stream. The dc output signal is proportional to the differential pressure. In liquid-level applications, the transmitter measures the differential pressure produced by the static head of liquid in the tank and similarly converts this pressure to a dc signal.

The square root converter is designed to be used with flow systems in which a differential pressure transmitter output is linear with respect to differential pressure but squared with respect to flow. The output signal of the converter is linear with flow and can be applied as a standard linear flow transmission signal to a meter or controller.

7.2.6 Beckman Process Instrumentation. This instrumentation set is similar to the Bailey equipment. It is also typical of many in the plant and is located in the Auxiliary Building.

The indicating deviation controller utilizes a combination of analog and digital circuitry to provide a wide variety of functions for process control applications.

The square root extractor provides an output that is proportional to the square root of the input signal. The module incorporates adjustments for scaling the input and output and for adding a bias to the output.

The current-to-current isolator accepts a 10-50 ma input. It provides a 10-50 ma output signal that is totally isolated from the input signal.

The single alarm module accepts a 10-50 ma input signal and compares this input to a predetermined set point value and provides a DPDT relay contact closure output. The module is switch selectable to actuate the relay when the input exceeds the set point (high alarm condition) or when the input is below the set point (low alarm condition). The module also features an adjustable dead band of 1 to 10 percent of full scale input. An LED indicator is incorporated to indicate relay actuation.

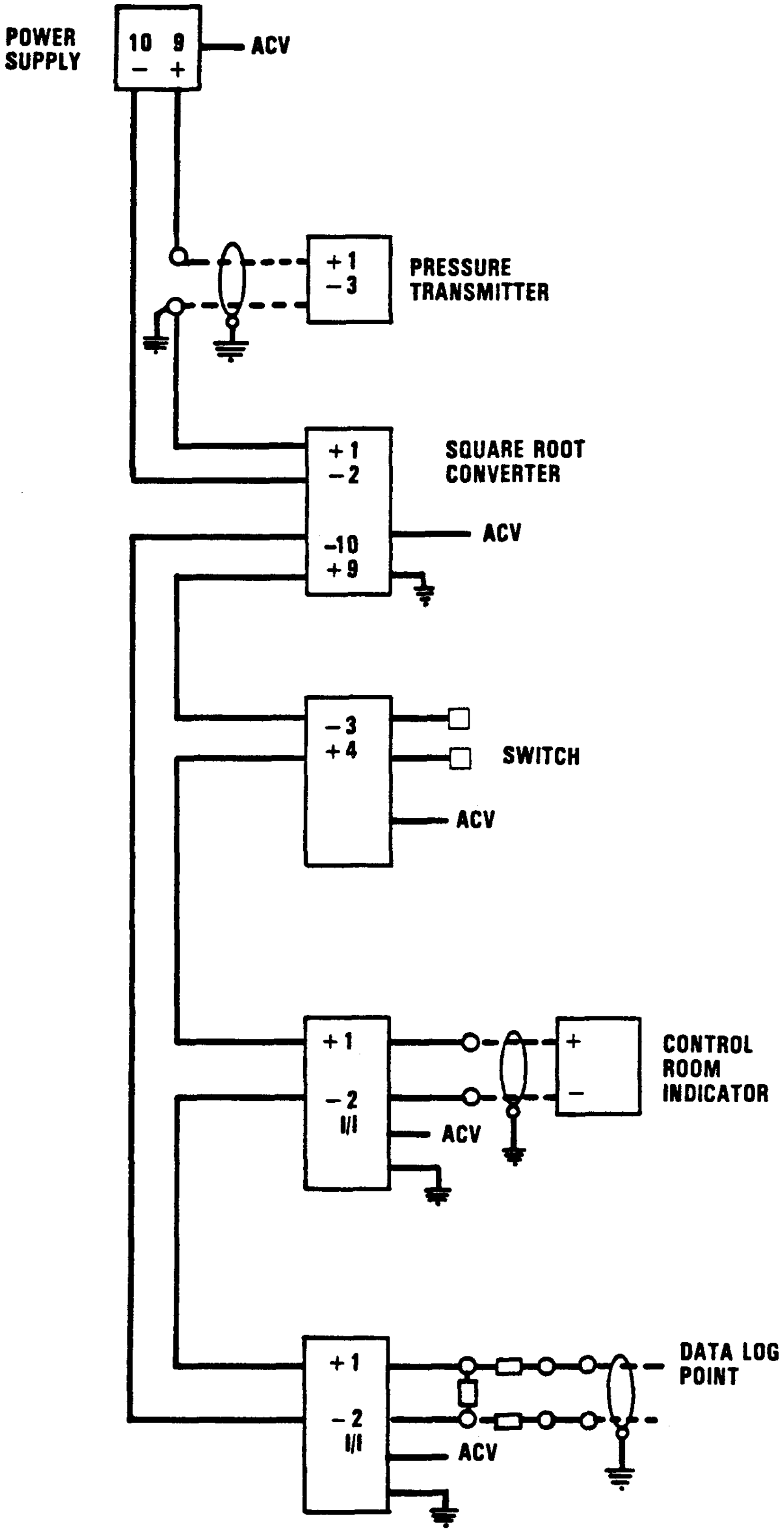


Figure 7.3. Bailey Instrumentation Interconnection Diagram

7.2.7 Analog Multiplex (MUX) Relay Card. This card contains seven identical relay circuits and one bus-guard relay circuit which are used to connect a selected analog input point to the Voltage-to-Frequency converter. As part of the data monitor computer system, the analog MUX is in the Auxiliary Building. It can be affected by EMP-induced excitations on the interconnecting cabling to the intake structure.

7.3 Analytical Methods

The general approach taken to evaluate the equipment was to acquire the necessary equipment descriptive information and component electrical characteristics, calculate component and circuit damage thresholds and document the results. This is the approach shown in Figure 7.1.

7.3.1 Equipment and Component Data Acquisition. Documentation to support the analysis was procured from the Tennessee Valley Authority (TVA). Examination was made of these data (electrical schematics, parts breakdowns, and maintenance/operation manuals) to determine what, if any, data deficiencies had to be resolved in order to allow analyses to be completed. If missing data was not available from TVA, the equipment manufacturer was consulted to complete the data set. In some cases, company-owned proprietary rights were involved and, therefore, exact part data was not provided. In these cases, data for the closest generic equivalent to that special part was used. The electrical/electronics components of each subsystem were gleaned from assembly parts lists or, in some cases, from the schematic diagram.

Once the part types that are used in the equipment items were known, the SUPERSAP2 experimental data base was consulted to determine if the specific part had been tested. If it had, then the K value determined by the experiment was used in the Wunsch models. If the SUPERSAP2 data base did not contain the part, i.e., it had not been tested; then transistor or diode D.A.T.A. books and various semiconductor vendor data books were consulted as sources of semiconductor electrical characteristics for use in empirical component damage models to compute component damage thresholds.

7.3.2 Piecepart Damage Threshold Calculation. The component set of the equipment analyzed from the Watts Bar Nuclear Plant consists of a variety of part types as shown in Table 7.3. Because this study centered only on semiconductor devices, no damage calculations were made for passive components.

The hierarchy of methods used to determine the failure thresholds of the semiconductor components is listed below:

1. The use of experimental data, from previous programs (.e.g, SUPERSAP2 experimental data base).

2. The use of empirical models that permit the estimation of damage parameters using published device electrical parameter values.

Table 7.3.

Part Types Considered for Damage Thresholds

- Transistors

    Bipolar Junction Transistors (BJTs)

    Uni-Junction Transistors (UJTs)

    Field Effect Transistors (FETs)

- Diodes

    P-N (Se and Ge)
    Diode Bridges
    Field Effect Diodes
    Light Emitting Diodes (LEDs)
    Zeners (with and without temperature compensation)
    Selenium Surge Suppressors
    Thyrectors

- Thermistors

- Thyristors

    Silicon Controlled Rectifiers (SCRs)
    Silicon Controlled Switches (SCSs)

- Linear Integrated Circuits

- Capacitors

- Inductors and Chokes

- Resistors

- Transformers

- Relays

- Circuit Breaker and Fuses

- Switches

- Lamps

- Motors

3. The estimation of damage thresholds based on general component categories, i.e., published threshold ranges for categories such as TTL integrated circuits or low-power silicon transistors.

The computed damage thresholds for each semiconductor device within each subsystem interface circuit are summarized by connector/pin in the equipment damage threshold summaries in Appendix B. The details of estimating component damage thresholds for discrete semiconductor devices and integrated circuits are different and are outlined below.

Discrete Semiconductor Devices. The mean EMP damage threshold for discrete semiconductors, which includes all transistors and diodes, was estimated using either experimental data, empirical models based on device electrical parameters, or standard models. All three approaches are based upon the relationships explored by Wunsch, et al.[22]; that is,

$$P_F = At_P^{-B} \tag{7.1}$$

$$t_P = \frac{1}{2.4f} \tag{7.2}$$

$$I_F = \frac{-V_{BD} + \sqrt{V_{BD}^2 + 4R_SP_F}}{2R_S} \tag{7.3}$$

$$V_F = V_{BD} + I_FR_S \tag{7.4}$$

where

A = Damage constant ($W \bullet S^B$)

B = Exponent of damage equation (unit-less)

V_{BD} = Equivalent breakdown voltage (volts)

R_S = Total surge resistance (ohms)

P_F = Failure power (watts)

I_F = Failure current (amperes)

V_F = Failure voltage (volts)

t_P = Pulse width of rectangular pulse (seconds)

f = Frequency (hertz)

The preferred way of determining the component failure parameters was by using experimental data. Since piecepart testing was not a part of this study, the SUPERSAP2 experimental data base was searched to determine if the part had been tested. If test data were available, e.g., a damage constant, k, then the failure power was calculated using Equation 7.1, where B = 0.5 and A = k. If the electrical parameters R_S and V_{BD} are available from experiment, then current and voltage failure levels are determined using Equations 7.3 and 7.4.

The empirical failure models are based on the observed dependence of failure threshold on certain device electrical parameters. The failure power threshold has been found by Alexander[23] to be related to both junction area and doping concentration which then provide the basis for the empirical determination of failure voltage, current, and power for untested devices. Figure 7.4 illustrates the models for calculating the failure thresholds for a given junction in a discrete semiconductor device. For all junction types, the doping concentration is estimated using the published minimum breakdown voltage in the equation shown. Relationships are then available from which to calculate the breakdown voltage at the critical failure temperature (V_{BDC}), space charge resistivity (P_{SC}), bulk resistivity (P_{BLK}), and failure current density (J_F). For each specific semiconductor junction type, there are several relationships by which to estimate the junction area. The data obtained from D.A.T.A. books or manufacturer data books will determine which model is used. The most preferred model is so designated in Figure 7.4. Each alternative is listed in order of descending preference. If enough information was available to allow more than one model to be used, the most preferable model was the one used to determine the junction area. The component damage parameters were determined using the formulas shown in Figure 7.4. Once I_F and V_F had been computed, P_F was found by

$$P_F = I_F \times V_F$$

TI-59 computer programs using these empirical models were written as computational aids. The program listings and instructions for use are presented in Appendix C.

If experimental data or published electrical characteristics to be used in empirical models were not available, the damage failure parameters for the discrete semiconductor devices were determined by using standard failure model parameters developed as part of prior hardening study programs. These failure model parameters are shown in Table 7.4.

$N_D = 4.49 \times 10^{18}(V_{BD})^{-1.5}$

$V_{BDC} = 4.07 \times 10^{12}(N_D)^{-0.87}$

$\rho_{SC} = 2.48 \times 10^{25}(N_D)^{-1.80}$

$\rho_{BLK} = 3.81 \times 10^{10}(N_D)^{-0.81}$

$$J_F = \begin{cases} 8.28 \times 10^{-11}(N_D)^{0.88} & \text{DIODE AND TRANSISTOR COLLECTOR BASE} \\ 3.8 \times 10^{-11}(N_D)^{0.88} & \text{TRANSISTOR EMITTER-BASE} \end{cases}$$

AREA MODELS			
	DIODE	TRANSISTOR COLLECTOR-BASE	TRANSISTOR EMITTER-BASE
PREFERRED	AREA $= 8.1 \times 10^{-3}(I_{MAX})^{1.16}$ $I_{MAX} = I_{ZM} V_Z$ FOR ZENER DIODES	AREA $= 0.047\ (\theta_{JC})^{-0.89}$	AREA $= 1.47(2.3 \times 10^{-6} C_{OEB} V_{BEBO}^{0.67})^{1.05}$ FOR $V_{RE} = 0.5V$ $C_{OEB} = C_{RE}(V_{RE})^{0.5}$ FOR $V_{RE} \neq 0.5V$
1st ALTERNATE	AREA $= 0.458(2 \times 10^{-6} C_{OD} V_{BD}^{0.83})^{0.83}$ FOR $V_{RD} = 1V$ $C_{OD} = C_{RD}(V_{RD})^{0.33}$ FOR $V_{RD} \neq 1V$	AREA $= 2.72 \times 10^{-3}(I_{MAX})^{0.62}$	AREA $= 6.34 \times 10^{-4}(I_{MAX})^{0.82}$
2nd ALTERNATE	AREA $= 0.489(\theta_{JL})^{-1.21}$ THERMAL RESISTANCE MEASURED WITH 1/8" LEAD	AREA $= 3.63(\theta_{JA})^{-1.47}$	AREA $= 8.75 \times 10^{-3}(2 \times 10^{-6} C_{OCB} V_{BCBO}^{0.83})^{0.58}$ FOR $V_{RC} = 1V$ $C_{OCB} = C_{RC}(V_{RC})^{0.33}$ FOR $V_{RC} \neq 1V$
3rd ALTERNATE	AREA $= 1.96(\theta_{JA})^{-1.32}$	AREA $= 1.13 \times 10^{-2}(2 \times 10^{-6} C_{OCB} V_{BCBO}^{0.83})^{0.39}$ FOR $V_{RD} = 1V$ $C_{OCB} = C_{RC}(V_{RC})^{0.33}$ FOR $V_{RC} \neq 1V$	AREA $= 1.19 \times 10^{-2}(\theta_{JC})^{-0.94}$
4th ALTERNATE			AREA $= 2.79(\theta_{JA})^{-1.7}$

$R_{BLK} = \rho_{BLK}/\text{AREA}$

$R_{SC} = \rho_{SC}/\text{AREA}$

$I_{F_{100ns}} = J_F \cdot \text{AREA}$

$V_{F_{100ns}} = V_{BDC} + I_{F_{100ns}}(R_{BLK} + R_{SC})$

$T_p = 1/2.4\,F$

$I_F = I_{F_{100ns}}(T_p/100 \times 10^{-9})^{-1/2}$

$V_F = V_{BDC} + I_F(R_{BLK} + R_{SC})$

$K = (I_{F_{100ns}} \cdot V_{F_{100ns}})(100 \times 10^{-9})^{1/2}$

Figure 7.4. Discrete Semiconductor Device Failure Models.

MODEL PARAMETERS

C_{OCB} = COLLECTOR-BASE CAPACITANCE AT 1 VOLT REVERSE BIAS (PICOFARADS)
C_{OD} = DIODE CAPACITANCE AT 1 VOLT REVERSE BIAS (PICOFARADS)
C_{OEB} = EMITTER-BASE CAPACITANCE AT 0.5 V REVERSE BIAS (PICOFARADS)
C_{RC} = COLLECTOR-BASE REVERSE BIAS CAPACITANCE (PICOFARADS)
F = FREQUENCY (HERTZ)
$I_{F_{100ns}}$ = FAILURE CURRENT FOR A 100 NANOSECOND RECTANGULAR PULSE (AMPS)
I_{MAX} = MAXIMUM TRANSISTOR COLLECTOR CURRENT (AMPS)
I_{ZM} = RATED MAXIMUM ZENER CURRENT (AMPS)
J_F = CURRENT REQUIRED FOR FAILURE (AMPS)
K = WUNSCH DAMAGE CONSTANT ($W \cdot s^{1/2}$)
N_D = LIGHT SIDE DOPING CONCENTRATION ($ATOMS/CM^3$)
R_{BLK} = RESISTANCE OF BULK SEMICONDUCTOR (OHMS)
R_{SC} = RESISTANCE ASSOCIATED WITH SPACE CHARGE IN AN AVALANCHING JUNCTION (OHMS)
T_P = RECTANGULAR PULSE WIDTH (SECONDS)
V_{BCBO} = RATED BREAKDOWN VOLTAGE OF COLLECTOR-BASE JUNCTION WITH EMITTER OPEN (VOLTS)
V_{BD} = RATED BREAKDOWN VOLTAGE OF DIODE JUNCTION (VOLTS)
V_{BDC} = BREAKDOWN VOLTAGE AT THE CRITICAL TEMPERATURE (VOLTS)
V_{BEBO} = RATED BREAKDOWN VOLTAGE OF DIODE JUNCTION (VOLTS)
V_{RC} = VOLTAGE AT WHICH C_{RC} IS MEASURED (VOLTS)
V_{RD} = VOLTAGE AT WHICH C_{RD} IS MEASURED (VOLTS)
V_{RE} = VOLTAGE AT WHICH C_{RE} IS MEASURED (VOLTS)
V_Z = RATED ZENER VOLTAGE (VOLTS)
ρ_{SC} = SPACE CHARGE RESISTIVITY ($\Omega \cdot CM^2$)
ρ_{BLK} = BULK RESISTIVITY ($\Omega \cdot CM^2$)
θ_{JA} = JUNCTION TO AMBIENT THERMAL RESISTANCE ($^{\circ}C/W$)
θ_{JC} = JUNCTION TO CASE THERMAL RESISTANCE ($^{\circ}C/W$)
θ_{JL} = JUNCTION TO LEAD THERMAL RESISTANCE ($^{\circ}C/W$)

Figure 7.4 (Con't). Discrete Semiconductor Device Failure Models.

Table 7.4

Semiconductor Standard Failure Model Parameters

Model	A	B	V_{BD}	R_S
Diode - Signal	0.02	0.5	100	25
Diode - Rectifier	0.3	0.5	50	25
Diode - Reference	0.6	0.5	10	1
Diode - Selenium	0.3	0.5	368	50
Transistor - Low Power - Collector-Base	0.06	0.5	50	10
Transistor - Low Power - Emitter-Base	0.06	0.5	5	10
Transistor - High Power - Collector-Base	0.25	0.5	100	2
Transistor - High Power - Emitter-Base	0.25	0.5	10	2

Integrated Circuits. The determination of integrated circuit mean EMP damage thresholds was accomplished by using existing category models. The only category of integrated circuit encountered in the interface analysis of the Watts Bar equipment items was linear integrated circuits. The general forms of the IC model are the same as those in Equations 7.1 through 7.4. For linear integrated circuits, the damage model parameter values are shown in Table 7.5.

Table 7.5.

Linear Integrated Circuit Damage Model Parameters

Category		Failure Model		V_{BD}	R_B
Family	Terminal	A	B	(Volts)	(Ohms)
Linear	Input	0.0743	0.600	7	13.2
	Output	0.0139	0.714	7	5.5

Agastat Timing Relays. These timing relays were specifically identified by Sandia as being important to the operation of the Watts Bar safe shutdown system. Since they contain no semiconductor components, evaluation of EMP-induced failure thresholds cannot be accomplished by using any of the models mentioned.

The failure mode defined for the Agastat components and analyzed in this study was failure due to ohmic heating. Ohmic heating would occur when EMP-induced currents through the relay coil are sufficient to cause irreversible mechanical or chemical changes in the component. In the limit, ohmic heating could cause wire melting to occur.

Ohmic heating failure can be evaluated on the basis of the quantity of energy required to raise the wire to a given temperature and comparing this energy to that available in an EMP-induced transient.

The quantity of heat, Q, required to raise a given mass, m, through a temperature difference, ΔT, is given by:

$$Q = mC\Delta T$$

where

C ≡ specific heat of the material.

The heat generated due to ohmic losses in a wire is given by:

$$Q' = \int_0^t I^2 R dt = \int_0^t \frac{V^2}{R} dt$$

where

R = wire resistance (ohms)

I = current (amps)

V = voltage drop across the wire (volts)

t = duration of the current flow (sec)

The resistance of wire is proportional to the wire length, L, the specific resistivity, ρ, and the cross-sectional area of the wire according to the equation:

$$R = \frac{\rho L}{\pi r^2}$$

where

$r \equiv$ cross-sectional radius

$\rho \equiv$ specific resistance

The mass of the wire is given by:

$$m = \delta \pi r^2 L$$

where

$\delta \equiv$ material density

Using these four equations, one can derive the result that:

$$\int_0^t V^2 dt = CL^2 \ \delta\rho\Delta T$$

For t_P = rectangular pulse of duration $t_P = \frac{1}{2.4f}$, then:

$$V_F = \left[\frac{CL^2 \ \delta\rho\Delta T}{t_P}\right]^{0.5} = \left[CL^2 \ \delta\rho\Delta T(2.4f)\right]^{0.5}$$

By noting that $P_F = V_F^2/R$, where P_F is the power or rate of heat generation, it can be seen that:

$$P_F = \frac{CL \ \delta\pi r^2\Delta T}{t_P} = 2.4 \ CL \ \delta\pi r^2\Delta Tf$$

And since

$$P_F = I_F V_F, \ I_F = \left[\frac{C\delta\pi^2 r^4\Delta T}{\rho t_P}\right]^{0.5}$$

These are the equations that were used to calculate the damage thresholds for the Agastat timing relays (both ac and dc powered coils).

7.3.3 Circuit Failure Threshold Calculations. The process for determining interface circuit damage thresholds can be subdivided into the following activities:

1. Interface circuit identification
2. Critical component identification
3. Circuit simplification
4. Damage threshold computation.

Each activity will be discussed separately in the sections to follow.

Interface Circuit Identification. Interface circuit identification and boundary definition were accomplished through inspection of electrical schematics and interconnect wiring diagrams and through application of network truncation techniques. The network truncation techniques were applied to complex circuits to limit the extent of the network.

Components which are buried in the circuit are normally protected by series elements and shunt paths located between the component and the interface pin. It was possible to define the extent of the interface circuits for analysis purposes by considering the return paths of the circuit or by applying a screening criterion to truncate the circuit path. Each electrical path from the pin was traced, stopping when one of the following conditions was met:

1. The normal return path was encountered, or
2. The cumulative series impedance along the path satisfied the condition:

$$\left| \sum_{i=1}^{n} Z_i \right| > Z_s$$

with all shunt paths open, where

Z_s = The screening impedance criterion for components in series and is given by:

$$Z_s = \frac{P_{FMAX}}{I^2_{FMIN}}$$

P_{FMAX} = The power damage threshold of the least susceptible component in the circuit (largest P_F)

I_{FMIN} = The current damage threshold of the most susceptible component in the circuit (smallest I_F)

Z_i = Impedance of the individual component in the series with the circuit terminals

n = number of components in series with the circuit terminals

3. A point is reached where the shunt impedance to the normal circuit return is such that it may be considered a short circuit.

Once the series impedance or shunt impedance criterion was met, the circuitry beyond the next path to the return was replaced by an open circuit. This further simplified the circuit and provided a worst case analysis.

In the damage analysis, the impedance of a semiconductor junction was represented by the junction surge resistance. This representation was used because it was assumed that all semiconductor junctions in the circuit had been driven into breakdown by the electrical transient.

The impedance of reactive components, such as capacitors and inductors, was computed using CW techniques. That is, it was assumed for analysis purposes that the input waveform was a continuous wave; and that the impedance can be calculated using the expressions:

$$Z_C = \frac{1}{j2\pi fC} \text{ for capacitors}$$

$$Z_L = j2\pi fL \text{ for inductors}$$

where

Z_C = Capacitor impedance in ohms

Z_L = Inductor impedance in ohms

f = Frequency in hertz

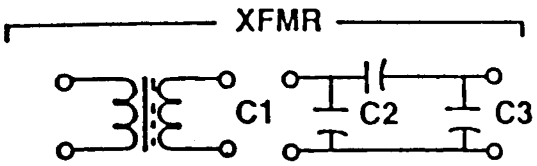
C = Capacitance in farads

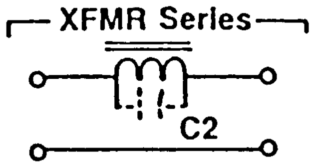
L = Inductance in henries

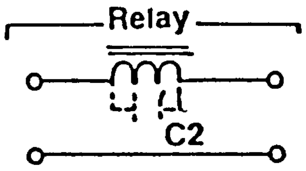
To characterize the response of transformers and relays at 1 MHz, response models were substituted into the interface circuits. The model representations and model parameters are shown in Table 7.6.

The process of defining an interface circuit for analysis purposes involved a series of network reduction steps. TI-59 programs were developed and written as computational aids to simplify these network reduction steps. The Series and Parallel Impedance program was used to calculate an equivalent impedance of an electrical network containing both resistive and reactive elements. The π-T (Δ-Y) and T-π (Y-Δ) Transformations program was used to alter the interface topology from one configuration to the other. These two programs are documented in Appendix C.

Table 7.6. Relay and Transformer Equivalent Response Models and Model Parameters.







Type	Faraday Shield	C_1(pf)	C_2(pf)	C_3(pf)
Pulse Transformer	No	5	10	.5
	Yes	50	5	
Audio Interstage Transformer	No	50	50	50
	Yes	100	10	–
Audio Output Transformer	No	20	200	20
	Yes	100	50	20
Power Transformer (100W)	No	–	200	–
	Yes	200	20	–
Power Transformer (100-1000W)	No	300	250	100
	Yes	375	50	200
Power Transformer (1000W)	No	1000	1000	–
	Yes	1000	100	–
Synchro		50	50	50
Servo		20	200	20
Transformer Winding In Series		–	500	–
Relay (Shunt Element In Circuit)		–	20	–
Relay (Series Element In Circuit)		–	50	–

Critical Component Identification. The critical component, or set of components, in the interface circuit is the device, or set of devices, whose failure will establish the damage threshold(s) for that circuit at 1 MHz. It will be the device which fails at the lowest pin-level voltage, current, or power level at 1 MHz.

The identification process involved consideration of device failure parameters and the network topology. Pieceparts located closest to the network terminals being considered are generally more susceptible to damage than those buried in the interface circuit. Buried components are afforded additional protection by series elements which attenuate transient voltages and parallel paths which shunt transient currents. The power damage threshold of each device in the interface circuit was compared to the power damage threshold of the device closest to the current terminals of interest. All devices whose failure level exceeded that of the device closest to the terminals were eliminated from further damage analysis and were replaced by an impedance or a response model in the circuit drawing. In some cases, devices were eliminated from further consideration by comparing the damage threshold of one piecepart to that of another within the buried circuitry. The remaining devices in the interface circuit were considered one at a time. Also, estimates of pin-level damage thresholds were made by considering only the series impedance between the current terminals and the device in question while ignoring the shunt path impedances. In either case, the failure voltage and current of each piecepart in question were referred back to the terminals of interest and a comparison made of the resulting thresholds at the pin. Device failure voltage and current were referred to the pin through use of transfer functions or by application of Kirchoff's voltage and current laws. Devices which produced the lowest thresholds at the pin were retained for a detailed analysis.

Circuit Simplification. The current simplification performed was accomplished systematically. As each component was eliminated from further consideration from the failure analysis, it was replaced on a circuit drawing by an impedance or a response model. The resulting network of impedances was combined using a TI-59 program to form an equivalent impedance. Network transformation, π-to-T or T-to-π, was used, when necessary, to change the circuit configuration to a form which facilitates the combining of impedances. Once the network had been reduced about the set of candidate critical devices, each remaining component was considered separately as a load; and the circuitry between the terminals of interest and the load was reduced to a T-network. Pin-level damage thresholds were then calculated using the TI-59 program. The TI-59 programs developed as computational aids are presented in Appendix C. If reduction to a T-π network was not possible (e.g., bridge circuitry), the pin-level thresholds were determined manually.

Circuit Damage Threshold Computation. The last step in the damage threshold computation process was the calculation of pin-level failure thresholds. This was accomplished by using a TI-59 program or by manual computations.

In this process, the voltage and current failure levels of the critical device or of each candidate critical device were referred back through the interface network to the circuit terminals of interest. This was accomplished through use of transfer functions or application of Kirchoff's voltage and current laws. The product of the voltage and current failure levels was taken to determine the pin-level power damage threshold. If more than one device was under consideration, the device which produced the lowest failure level at the pin was the critical device; and the associated pin-level voltage, current, and power-failure levels represent the circuit damage thresholds. The computed circuit damage failure thresholds segregated by connector/pin for each equipment item examined are presented in Appendix B. A sample calculation is presented in Appendix D.

7.3.4 Threshold Error Factors. The sources of error that must be considered when computing EMP damage thresholds are summarized in Table 7.7.

Table 7.7

Damage Threshold Error Sources

Source Category	Error Source in Calculations
Piecepart	Model Selection
	Parameter Source
	Frequency Limitations
Circuit	Circuit Simplifications
	CW Analysis
	Ideal Passive Models
	Parasitic Effects
	Waveform Conversion

The preferred method for estimating the uncertainty in the circuit-level threshold predictions is to compare the predictions with experimentally determined thresholds on an example of the circuits, assuming that the measured values have negligible error. Since no circuit test data were available for the equipment studied, the only basis for estimating prediction uncertainties is to assume that the uncertainties in the present application are the same as in other applications of the prediction methodology. In the AABNCP GFE Assessment Program[21] TRW compared predicted and measured thresholds on 40 circuits. The standard deviations of the differences between predicted and measured thresholds were found to be:

Current:	9.8 dB
Voltage:	11.6 dB
Power:	5.9 dB

These errors may be taken as approximation of the uncertainty in the reported threshold predictions.

7.4 Threshold Predictions

This study addressed only selected items of the safe shutdown systems, and circuit parameters were evaluated at only one frequency (1 MHz). Certain circuit parameters will vary with frequency, for example the impedance to ground through the shunt paths (capacitors or capacitive coupling) decreases with frequency while the component thresholds increase as the square root of the frequency. This latter increase is an observed phenomena, that is, the damage threshold is inversely proportional to the square root of the pulse width (Equations 7.1 and 7.2). Based upon the results of the calculations three specific observations can be made (1) the circuit damage thresholds calculated indicate that the design of the equipment is such as to provide protection to sensitive devices well above operational levels and (2) the estimates of circuit voltage thresholds for solid state devices are sufficiently high that other circuit failure mechanisms (dielectric breakdown, arc-over, etc.) are likely to be the controlling mechanisms if the EMP-induced drives are high enough. It should also be noted that experience suggests that EMP-induced failures of passive components (resistors, capacitors, chockes, etc.) could lead to circuit damage thresholds comparable to those estimated here from the solid state components. The following paragraphs discuss the threshold predictions in more detail to further support the contention that, for the most part, the solid state device response is not the controlling failure.

7.4.1 Circuit Damage Thresholds. As noted earlier, two classes of equipment were analyzed in the assessment: power equipment and process instrumentation equipment. The circuit damage thresholds for each class of equipment are discussed in the following paragraphs.

Power Equipment. There were five power supplies analyzed as part of this assessment. The input pins of these supplies, i.e., those that interface with 120 VAC, 50-60 Hz plant power, had higher thresholds than the power supply outputs. These power inputs are transformer coupled through a bridge rectifier to following circuitry. These power interfaces also contain shunt capacitors which provide a very low shunt impedance for any EMP signal. A simple pictorial of this interface topology is shown in Figure 7.5. The values of circuit damage thresholds for inputs exhibit the following spread:

Voltage (V_T)	1.8×10^4 to 9.3×10^9 V
Current (I_T)	62.7 to 1.6×10^8 A
Power (P_T)	1.1×10^6 to 1.5×10^{18} W

The values of shunt capacitance, C, (See Figure 7.5) range from 12 µF to 1500 µF. Using CW techniques at 1 MHz to determine the capacitive reactance at these extremes gives X_c = 13.3 mΩ and X_c = 106 Ω respectively. Because these reactances are low, high current thresholds are expected. Because the models used for transformer response to an EMP (See Table 7.6) introduce series impedances (ranging from mΩ to kΩ) between the shunt capacitor and the input pin, high current damage thresholds imply high voltage and power thresholds.

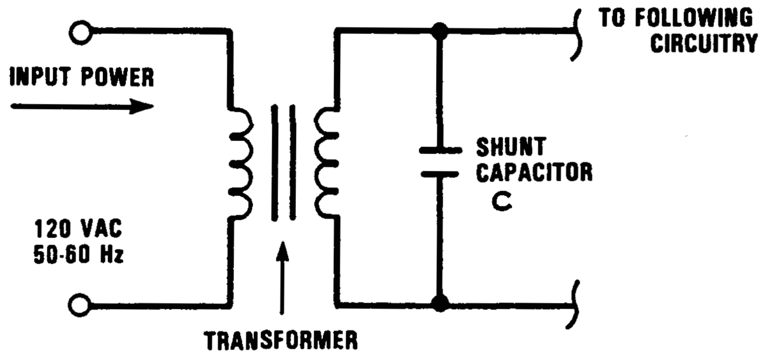


Figure 7.5. Power Supply-120 VAC Plant Power Interface

The same rationale applies to the outputs. Shunting capacitors (with the same capacitances as above) and series resistances (ranging from mΩ to kΩ) lead to high circuit damage thresholds.

The nature of the pieceparts used in the remaining power equipment is such that the component failure parameters determined by the failure models are high. As an example, consider the battery charger. A diode (a 1N4003 diode) determined the circuit damage threshold for the input pins. The application of the diode failure model (the I_{max} model was used) leads to a prediction of 2.3 kW for the component power damage threshold. Figure 7.6 shows a power curve extracted from Reference 25 for a similar part type (1N5059) with identical operating characteristics. From this curve it can be seen that the maximum surge power for a 20 sec half sinewave pulse is 1 kW. This can be scaled using the relationship $P_2 = P_1 (t_1/t_2)^{0.5}$ where P_1, P_2 are the failure powers and t_1, t_2 are the pulse widths of interest. Applying this scaling gives a value for failure power of 6.3 kW at 1 MHz. Thus, the predicted value from the empirical model is of the same order of magnitude as the manufacturer's data, and it is also a conservative estimate.

The circuit interface for this pair of pins is as shown in Figure 7.7a. It is noted that because the filtering capacitors in the original circuit have high capacitance values, the circuit can be truncated past these elements. The reduced interface is shown in Figure 7.7b. The calculated circuit damage parameters for this circuit for diode D_3 are:

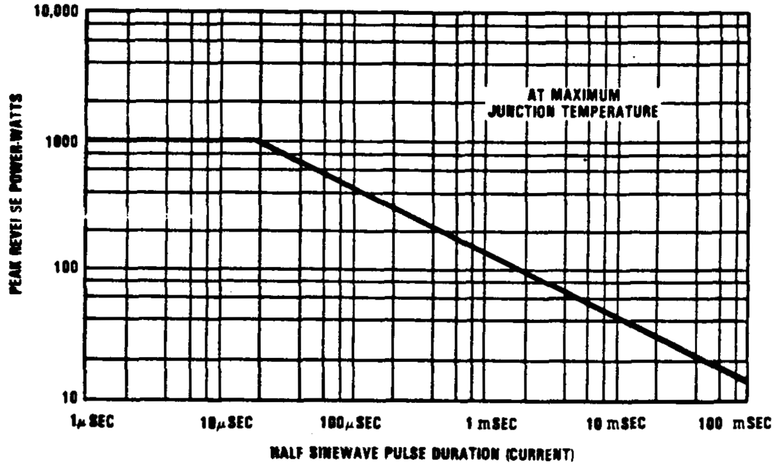


Figure 7.6. Maximum Nonrepetitive Avalanche Surge Power, 1N5059 Device

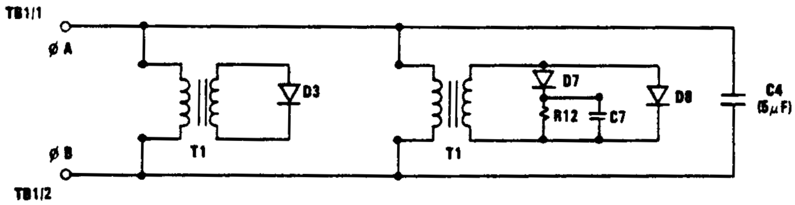
$$\text{Voltage } (V_T) = 2.5 \times 10^4 \text{ V}$$

$$\text{Current } (I_T) = 7.8 \times 10^5 \text{ A}$$

$$\text{Power } (P_T) = 1.9 \times 10^{10} \text{ W}$$

These are high thresholds for circuit damage. The full analyses details are shown in the example calculation in Appendix D.

(a) Circuit Interface - Battery Charger Input



(b) Reduced Circuit Interface

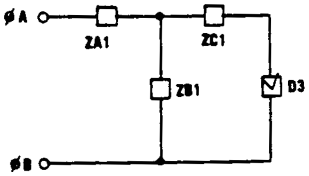


Figure 7.7. Battery Charger Interface-Analytical Circuits

The Agastat timing relays were analyzed using a thermal failure model as discussed earlier. The failure thresholds estimated are:

dc Coil	Voltage (V_T)	2.1×10^7 V
	Current (I_T)	1.1×10^4 A
	Power (P_T)	2.4×10^{12} W
ac Coil	Voltage (V_T)	3.8×10^6 V
	Current (I_T)	3.6×10^4 A
	Power (P_T)	1.4×10^{11} W

These values follow directly from the physics of the problem of failure in the coils by melting of the wires.

Process Instrumentation Equipment. The process instrumentation includes the square root converter, square root extractor, differential pressure transmitter, indicating deviation controller, single alarm module, current-to-current isolator and the analog MUX relay cards. All of these except the pressure transmitter and the relay card interface with 120 VAC, 50-60 Hz power. The discussion of power input interfaces in the proceding section applies here also. Shunting capacitors for the process instrumentation equipment range from 250 μF to 2900 μF. The values of circuit damage thresholds for these units range as follows:

Voltage (V_T)	56 to 2.4×10^7 V
Current (I_T)	2.9 to 9.4×10^4 A
Power (P_T)	4.7×10^2 to 2.2×10^{12} W

The wide variation in current damage thresholds results from a wide variation in shunt impedances of the reduced interfaces (1.1 MΩ to 1.6 mΩ). The variations in the voltage thresholds result from the differences in series impedance between the shunt element and the input pin (0 Ω to 251 Ω).

The pressure transmitter unit uses 24 VDC power. Examination of the interface circuit topology for the most sensitive component showed that there is no shunt element providing protection and the protective series element has a value of only 1.56 Ω. Virtually no protection exists between the most sensitive component and the input pin. This leads to low circuit damage threshold estimates. For this case: V_T = 360 V, I_T = 2.06 A, and P_T = 742 W.

Analog Relay Cards. The MUX relay cards operate on 26 VDC. For two cards the interface circuit shows a 21 Ω shunt impedance and no series impedance between the shunt element and the input pin. The circuit damage parameters for these interfaces were calculated as:

$$V_T = 336 \text{ V}$$

$$I_T = 18.3 \text{ A}$$

$$P_T = 6.1 \times 10^3 \text{ W}$$

In other instances a high output-impedance voltage source connected across the plus and minus buses. Interface circuitry for the power input to the most susceptible component of the voltage source shows a 1.6 KΩ shunt impedance and 15.9 KΩ series impedance. These impedances provide for circuit damage thresholds of

$$V_T = 7.3 \times 10^4 \text{ V}$$

$$I_T = 2.5 \times 10^1 \text{ A}$$

$$P_T = 1.9 \times 10^6 \text{ W}$$

Even greater thresholds are determined for the analog input signal path to the most vulnerable component in the voltage source. The values are:

$$V_T = 5.6 \times 10^7 \text{ V}$$

$$I_T = 5.1 \text{ A}$$

$$P_T = 2.8 \times 10^8 \text{ W}$$

These are the result of protection provided by 750 Ω shunt impedance and 11 MΩ series impedance between the shunt element and the interface pin. The current threshold is relatively low. This is the result of the fact that the impedance of the shunt element is approximately equal to the impedance in the branch containing the load component in the reduced circuit. Consequently, the threshold current, when input to the current divider of the reduced interface, will divide approximately equally between the shunt element and the load component.

In summary, although the circuit damage thresholds calculated for the Watts Bar equipment are varied, they are reasonable predictions of the levels needed to produce circuit failure in the solid state devices if all other circuit elements perform as designed. As noted earlier, other phenomena can occur in the circuitry before these thresholds are reached. Of course the occurrence of an arc over, for example, does not necessarily mean that the component failed. In the cases where the thresholds have large values, they are the result of inherent circuit protection by low shunt impedances and high series impedances.

7.4.2 Passive Component Failures. These devices are generally less susceptible to EMP induced damage than are the semiconductor devices. Consequently, they were not analyzed as part of this study. If the analysis of EMP free field coupling to a facility indicates that the transient signal levels induced on the cabling are comparable to the circuit damage thresholds calculated for the semiconductor components then the passive components (series resistors and shunt capacitors protecting the semiconductor components) should be analyzed for EMP-induced damage.

7.5 Other EMP-Induced Failures

System upset was not addressed as part of this study. If the EMP Coupling Analyses reveals that significant EMP-induced signals are possible at the points of concern, that is signal levels on the order of circuit logic levels, the potential for system upset may exist and should be investigated if upset is of concern.

Additionally, if localized voltage drives are high (on the order of several kV or more), arcing or other dielectric breakdown of passive components should be considered as noted earlier. To determine arcing thresholds analytically is intractable, and any such investigation would require the support of an engineering testing program.

8.0 Vulnerability Analysis for the Example Plant

8.1 Equipment Damage Threshold Analysis

In order to identify potential equipment vulnerabilities, the predicted EMP response at an item of critical equipment must be compared to an estimate of the equipment damage threshold. This comparison is conveniently specified as the equipment damage safety margin, which is defined as the ratio, expressed in decibels, of the predicted damage threshold level to the predicted EMP response level:*

$$\hat{SM}(dB) = 20 \log \frac{\text{damage threshold level}}{\text{EMP response level}}$$

An EMP response prediction has been calculated for each item of equipment that has been determined to be critical in the systems analysis. The EMP predictions take the form of peak amplitude time domain voltages or currents expected to appear across or into the critical equipment input interfaces. These response time histories are expected to be damped sinusoidal waveforms, or sums of damped sinusoidal waveforms, with resonant frequencies ranging from 500 kHz to 10 MHz.

For a selected subset of the critical equipment list that is characterized by the incorporation of semiconductor devices within the equipment circuitry, a detailed damage threshold analysis was performed. The damage threshold analysis transforms individual semiconductor device failure parameters through intervening circuit components to the equipment interface pins where they can be compared to predicted EMP responses. As noted in Section 7, the protection offered by intervening circuitry in terms of shunt paths, etc., leads to thresholds which are high compared to nominal conditions, and which are, in some cases, large compared to insulation and air breakdown levels. Therefore, in computing safety margins for these devices two threshold values are used, the first being that predicted in the analysis, the second assumes that some undesired event (not necessarily causing an equipment failure) occurs at voltage levels approximately three times the nominal operating level. Because this level is on the order of a kilovolt or less in all such cases, this is a conservative approach.

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*It is recognized that dB is normally used to represent power ratios, while the failure mechanisms of concern in this analyses are predominantly voltage sensitive. The safety margins have been expressed in dB to provide a convenient form of the ratios and to be consistent with prior practice in vulnerability assessments. If desired, the reader can convert the safety margins to voltage ratios using the defining equation.

The majority of the equipment that has been defined as being critical is electromechanical or non-solid-state in nature such as pumps, valves, motors, relays, and transformers. The damage mechanism for these types of devices is not well established but the mechanism basically involves an arc-over condition across the terminals or windings of the device that can be maintained by the equipment operational voltage for a sufficient period of time to cause physical destruction of the device. This condition is not only dependent on the physical topology of the device conductors and terminals but on the operational voltage of the equipment and its source impedance. For the purpose of this analysis, based upon experience in other installations and based upon the standards used for design purposes as cited in the Watts Bar Final Safety Analysis Report, the following damage thresholds were used for electromechanical devices and major circuit components. For that equipment operating at 6.9 kV and above a representative Basic Impulse Level (BIL) was selected from values for similar equipment presented in various American National Standards Institute publications.* For equipment operating at 480 V and below the damage threshold was taken as three times the operational voltage of the equipment interface.

Table 8.1 summarizes EMP responses, damage thresholds, and safety margins for each item of critical equipment identified by the systems analysis. Table 8.1 also includes the EMP response for various equipment and distribution points within the electrical power system. The response values shown are the largest estimated at that point whether the threat originated from the 500 kV, 161 kV or underground cabling. Table 8.2 summarizes common mode open-circuit threat responses for a number of interfaces that have not been specifically characterized by equipment type, operational level, or damage threshold and are included here in the event subsequent analysis of these interfaces is desired.

From the data in Table 8.1, it may be noted that all 102 voltage points have positive values for the safety margin, thus indicating the thresholds are always greater than the predicted response. In fact, 80 of the 102 points, or approximately 80%, have a threshold voltage (V_T) to response voltage (V_R) ratio equal to, or greater than 100, that is, SM $\geq$ 40. Sixteen (16) points have voltage ratios greater than 10 (SM $\geq$ 20), four (4) points have ratios greater than three (SM $\geq$ 10). The remaining two have safety margins less than 10, however these latter two are on the electrical distribution grid side of the main transformers and common station transformers. The loss of either or both of these transformers would not prevent safe shutdown. Even if one examines the predictions for which the V_T/V_R ratio is less than 100, it is difficult to postulate failures. The Agastat relays have a published voltage withstand capability of 1250

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*This is a conservative approach because the equipment is designed to survive and function after experiencing peak signals defined by the BIL.

Table 8.1.

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Main Power Transformers 500 kV/24 kV	AC Output	500 kV	1675 kV	740 kV	70
Unit Station Service Transformers 24 kV/6.9 kV	AC Input	24 kV	150 kV	18 kV	18
Common Station Service Transformers 161 kV/6.9 kV	AC Input	161 kV	750 kV	610 kV	2
6.9 kV Unit Boards	Distribution Bus	6.9 kV	60 kV	1070 V	55
6.9 kV Shutdown Boards	Distribution Bus	6.9 kV	60 kV	8.6 V	76
Residual Heat Removal Pump	AC Input	6.9 kV	60 kV	1.4 V	90
Centrifugal Charging Pump	AC Input	6.9 kV	60 kV	12 V	71
Essential Raw Cooling	AC Input	6.9 kV	60 kV	225 V	46
Aux Feedwater Pump	AC Input	6.9 kV	60 kV	4 V	81
Pressurizer Heater Transformer	AC Input	6.9 kV	60 kV	1.4 V	90
Shutdown Transformers 6.9 kV/480 V	AC Input	6.9 kV	60 kV	12 V	74
	AC Output	480 V	3 X	17 V	38
Diesel Generator	AC Output	6.9 kV	60 kV	346 V	42

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Component Cooling System Pump	AC Input	480 V	3 X	24 V	36
480 V Shutdown Boards	Distribution Bus	480 V	3 X	18 V	38
Instrumentation Power Transformers 480 V/120 V	AC Input	480 V	3 X	17 V	38
125 VDC Vital Battery Charger Battery Charger	AC Input	480 V	25 kV 3 X	8.3 V 8.3 V	70 45
	DC Output	125 V	8.3 kA	0.2 A	92
120 VAC Vital Inverter	AC Input	480 V	1.8 kV 3 X	8.3 V 8.3 V	47 45
	DC Input	125 V	934 V 3 X	1.0 V 1.0 V	59 51
	AC Output	120 V	887 V 3 X	2.6 V 2.6 V	51 43
Aux, Control, and Service Air Compressor	AC Input	480 V	3 X	16 V	39
Control Room Air Conditioner Compressor	AC Input	480 V	3 X	16 V	39

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Hydrogen Electric Recombiner Transformer	AC Input	480 V	3 X	1.0 V	63
Hydrogen Detector System	AC Input	480 V	3 X	1.0 V	63
RHR Pump Room Cooler Fan	AC Input	480 V	3 X	1.0 V	63
Diesel Generator Lube Oil Circulating Pump	AC Input	480 V	3 X	6.9 V	46
DG Water Heater	AC Input	480 V	3 X	19 V	39
DG Battery Charger	AC Input	480 V	3 X	19 V	39
DG Room Exhaust Fan	AC Input	480 V	3 X	6.9 V	46
DG Day Tank Fuel Oil Transfer Pump	AC Input	480 V	3 X	6.9 V	46
DC Heat Exchanger Supply Valve	AC Input	480 V	3 X	6.9 V	46
DG Building Lighting Cabinet	AC Input	480 V	3 X	19 V	37
AFW Pump Valve, Elec. Hyd. Actuator	AC Input	480 V	3 X	1.8 V	58

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
AFW Pump, Lube Oil Pump	AC Input	480 V	3 X	1.8 V	58
Boric Acid Tank Heater	AC Input	480 V	3 X	1.2 V	61
Centrifugal Charging Pump, Aux. Oil Pump	AC Input	480 V	3 X	1.8 V	58
Charging Pump Minimum Flow Valve	AC Input	480 V	3 X	1.8 V	58
RWST to RHR Pump Flow Control Valve	AC Input	480 V	3 X	1.0 V	63
Charging Flow Isolation Valve	AC Input	480 V	3 X	1.8 V	58
Seal Flow Isolation Valve	AC Input	480 V	3 X	1.8 V	58
RHR Heat Exchanger to CVCS Charging Pump	AC Input	480 V	3 X	1.2 V	61
RHR Pump Inlet Flow Control Valve	AC Input	480 V	3 X	1.0 V	63
RCS Pressure Relief Flow Control Valve	AC Input	480 V	3 X	1.0 V	63

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
RHR System Isolation Bypass Valve	AC Input	480 V	3 X	1.0 V	63
AFW Pump Turbine Steam Supply	AC Input	480 V	3 X	1.0 V	63
Steam Flow to AFW Pump Turbine Isolation Valve	AC Input	480 V	3 X	1.0 V	63
Steam Generator Feedwater Isolation Valve	AC Input	480 V	3 X	1.1 V	62
ERCW Header Isolation Valve	AC Input	480 V	3 X	29 V	34
Component Cooling Heat Exchange Isolation Valve	AC Input	480 V	3 X	1.0 V	63
Aux. Building ERCW Header Isolation Valve	AC Input	480 V	3 X	1.0 V	63
ERCW to Component Cooling Heat Exchanger	AC Input	480 V	3 X	1.1 V	62
CCS Heat Exchange Outlet Valve	AC Input	480 V	3 X	1.1 V	62

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
RHR Heat Exchange Header Inlet Valve	AC Input	480 V	3 X	1.0 V	63
CCS Heat Exchange Inlet Isolation Valve	AC Input	480 V	3 X	1.0 V	63
RHR Heat Exchange Return Header Isolation Valve	AC Input	480 V	3 X	1.0 V	63
CCS Pump to CS Outlet Isolation Valve	AC Input	480 V	3 X	1.0 V	63
RHR Heat Exchange Outlet Valve	AC Input	480 V	3 X	1.0 V	63
Vital Battery Bus Filter	DC Input	125 V	3 X	5 V	37
Vital Battery Boards	Distribution Bus	125 V	3 X	1 V	51
Rod Drive Power Supply	DC Input	125 V	3 X	1.0 V	51
Reactor Trip Switchgear	DC Input	125 V	3 X	1.0 V	51
Aux. Relay Rack	DC Input	125 V	3 X	1.0 V	51
Aux. Feed Pump Turbine	DC Input	125 V	1.1 kV	1.0 V	62

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Emergency DC Lighting Cabinet	DC Input	125 V	3 X	1.0 V	51
Main Steam Isolation	DC Input	125 V	3 X	1.0 V	51
ATM Relief Valve	DC Input	125 V	3 X	1.0 V	51
AFW Steam Generator Feed	DC Input	125 V	3 X	1.0 V	51
Remote Control 6.9 kV Shutdown Board	DC Input	125 V	3 X	1.0 V	51
Agastat Relay					
6.9 kV Shutdown Board	DC Input	125 V	21 MV	19 V	121
			1250 V	19 V	36
Instrumentation Boards (120 VAC)	Distribution Bus	120 V	3 X	3.5 V	40
AFW Turbine Flow Control					
Beckman Power Supply	AC Input	120 V	31 kV	1.1 V	89
			3 X	1.1 V	50
Beckman Square Root Converter	AC Input	120 V	115 kV	1.1 V	100
			3 X	1.1 V	50

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Beckman V to I Isolator	AC Input	120 V	115 kV	1.1 V	100
			3 X	1.1 V	50
Beckman Ind. Dev. Controller	AC Input	120 V	115 kV	1.1 V	100
			3 X	1.1 V	50
SSPS Input and Output Relays					
Basler 15V-10A Power Supply	AC Input	120 V	22 kV	1.1 V	86
			3 X	1.1 V	50
Basler 48V-3A Power Supply	AC Input	120 V	22 kV	1.1 V	86
			3 X	1.1 V	50
NIS Instrumentation Power	AC Input	120 V	3 X	3.6 V	40
NIS Control Power	AC Input	120 V	3 X	3.6 V	40
SSPS Aux. Relay Rack	AC Input	120 V	3 X	2.2 V	44
AFW Pump Pressure Control	AC Input	120 V	3 X	3.6 V	40
NSSS Aux. Relay Rack	AC Input	120 V	3 X	2.2 V	44
Aux. Relay Rack, SEP and Aux. Relays	AC Input	120 V	3 X	2.2 V	44

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Aux. Control Panel Relay Bus	AC Input	120 V	3 X	3.6 V	40
Aux. Control Panel Instrumentation Bus					
Foxboro Power Supply	AC Input	120 V	9.3 GV 3 X	1.8 V 1.8 V	194 46
Bailey Isolated Power Supply	AC Input	120 V	18 kV 3 X	1.8 V 1.8 V	80 46
	DC Output	52 V	3.4 MA	0.11 A	150
Process Protection Set	AC Input	120 V	3 X	2.2 V	44
Diesel Generator CO_2 Fire Protection	AC Input	120 V	3 X	4.4 V	38
A Rack Normal Feed	AC Input	120 V	3 X	3.6 V	40
B Rack Normal Feed	AC Input	120 V	3 X	3.6 V	40
Process Control Group I	AC Input	120 V	3 X	2.2 V	44

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Instrumentation Bus					
Beckman Alarm Module	AC Input	120 V	115 kV 3 X	1.1 V 1.1 V	100 50
Plugmold Instrumentation Bus	AC Input	120 V	3 X	3.6 V	40
Process Protection Set	AC Input	120 V	3 X	2.2 V	44
BOP Process Instrumentation					
Bailey Square Root Converter	AC Input	120 V	7.5 kV 3 X	1.8 V 1.8 V	72 50
	Signal Input (Computer)	24 V	253 kV 3 X	7.7 V 7.7 V	90 19
	Signal Input (Control Bldg. Aux. Inst.)	24 V	253 kV 3 X	11 V 11 V	87 16
Aux. Bldg. Instrument Bus B	AC Input	120 V	3 X	2.2 V	44
Agastat Relays					
480 V Reactor MOV Board	AC Input	120 V	3.8 MV 1250 V	2.4 V 2.4 V	124 54

Table 8.1 (Con't).

Watts Bar Nuclear Plant Abbreviated Assessment EMP Predictions

Critical Equipment	Interface	Operating Level	Postulated or Computed Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
480 V Control and Aux. Bldg. Vent Board	AC Input	120 V	3.8 MV	2.3 V	124
			1250 V	2.3 V	54
480 V Diesel Aux. Board	AC Input	120 V	3.8 MV	39 V	100
			1250 V	39 V	30
Diesel Relay Board	AC Input	120 V	3.8 MV	27 V	103
			1250 V	27 V	33
ERCW Instrumentation Loop					
Bailey Differential Pressure Transmitter	Signal Output	24 V	360 V	2.1 V	45
			3 X	2.1 V	31
Data Monitor Computer					
Analog Multiplex Relay	Analog Input	26 V	56 MV	11 V	134
			3 X	11 V	17

Table 8.2

EMP Responses for Non-characterized Equipment Interfaces at Watts Bar Nuclear Plant

Equipment/Interface Description	Location	Operating Level	Peak Value EMP Response
ERCW Instrumentation	Intake Pumping Station		11 V
ERCW Pump Control	Intake Pumping Station		54 V
Header Isolation Valve Control	Intake Pumping Station	120 V	54 V
Diesel Generator Control Board	Diesel Generator Building	120 V	4.4 V
480 V Diesel Aux Board (2 level)	Diesel Generator Building	120 V	5.2 V
Control Room Switches From DG (3 level)	Control Building	120/125 V	28 V
Control Room Switches From DG (2 level)	Control Building	120/125 V	15 V
Control Room Switches From Reactor MOV Board Relays	Control Building	120 V	3.4 V
Control Room Switches From 480 V Control and Aux Bldg Vent Boards	Control Building	120 V	3.4 V
Data Monitor Computer Interface to ERCW, CCW, etc.	Control Building		22 V
Reactor MOV Board Relay Inputs From Intake Pumping Station	Auxiliary Building	120 V	4.8 V
6.9 kV Shutdown Board Logic Relay Panel	Auxiliary Building	125 V	38 V
Control and Aux Bldg Vent Board Relay Inputs From Intake Pumping Station	Auxiliary Building	120 V	4.7 V

volts at power frequencies so that it is very likely that these relays can withstand considerably more voltage stress at high frequency than was assumed. On the instrumentation it was assumed that failure occurred at 3x the 24 volt dc operating level. Experience suggests that more reasonable estimates would be 10x operating level.

Because experimental data is not available to substantiate all the threshold estimates and because analytical techniques do not exist to predict dielectric failures or arc over, it is not practicable to provide a quantitative measure of the uncertainties in these predictions. However, the available experience (Reference 26, for example, which documents extensive tests on systems analyzed by Boeing) does indicate that the Boeing predictions of EMP response using the abbreviated technique described in Section 5 are generally conservative.* Likewise, the analytical techniques of the DEFT methodology[21] for threshold estimates have been shown to be conservative.[24] Furthermore, expert opinion agrees that the assumed levels of insulation breakdown or arc over 3 to 10 times nominal operating are conservative. Thus, given the built-in conservatism of the analysis, it is highly unlikely that any of the components discussed here critical to safe shutdown will fail due to exposure to the postulated EMP induced stress.

8.2 Electrical Power Systems Vulnerability

It is convenient to consider the electrical power system in three inter-related, but nevertheless, distinct segments. These segments are the normal ac power distribution system, the 6.9 kV emergency power system, and the uninterruptible power system (this latter segment includes the 125 VDC power system and the 120 VAC instrumentation power system). Each of these segments is considered separately in the following sections.

8.2.1 Normal AC Power Distribution System. As indicated earlier, the 500 kV transmission system provides a means of coupling EMP-induced signals into the plant electrical power distribution system. The analysis results presented in Table 8.1 and Appendix A indicate that signals originating in the 500 kV system will be attenuated well below nominal operating levels before reaching plant systems critical to safe shutdown. Likewise, EMP-induced signals that originate in the 161 kV distribution system when it is providing plant power (startup and shutdown) will also be attenuated below nominal operating levels. In addition, although the induced voltages in the external portions of the distribution system, that is,

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*The special verification tests discussed in Section 6 also support this view. There, 17 of 27 comparisons of predicted versus measured currents were conservative. Furthermore, even if current values are non-conservative by 10-15 dB, the estimated safety margins are large enough that damage is not expected. This discounts the results from the voltage measurements for the reasons cited in Section 6.

upstream of the 6.9 kV Unit Boards, can be quite large, on the order of mega volts at some locations, they are still on the order of the Basic Impulse Levels for the transformers and switchgear used in these applications. Obviously, at the potentials which may exist in the switchyard there could be flash overs and arcs sufficient to trip protection systems. but the analysis indicates that EMP-induced potentials within the plant are well below arc-over levels. Furthermore, it must be noted that even loss of components outboard of the 6.9 kV Unit Boards, whether due to protective actions or damage should not prevent safe shutdown of the plant because it is specifically designed to be safely shutdown in the event of a loss of offsite power.

8.2.2 Emergency AC Power System. The 6.9 kV Emergency AC Power System could experience EMP-induced signals from several sources. The normal ac power system provides one path, but as noted above, EMP-induced signals in this system are attenuated well below normal operating levels and thus do not pose a threat. These 6.9 kV systems could also be subjected to EMP-induced signals on the underground cabling that interconnects various safety systems and structures. These latter paths are illustrated in Figure 5.2 and the model diagrams appear in Figures A.5 and A.6. Again, the predictions tabulated in Figure 5.3 and Table 8.1 indicate that the induced signals in the 6.9 kV portion of the system will be well below normal operating levels. The analysis also reveals that EMP-induced signals at the auxiliary equipment and controls (480 V, 120 VAC and 125 VDC) associated with the 6.9 kV Emergency AC Power Systems will also be considerably less than normal operating levels. Therefore, it is concluded that this system will not fail due to equipment damage from EMP-induced signals.

8.2.3 Uninterruptible Power System. This system includes both the 125 V vital DC power and the 120 VAC vital instrumentation power. These systems also could be subjected to EMP-induced signals on the normal power distribution system or on buried cabling that interconnects the safety related equipment and structures. The predictions summarized in Figure 5.3 and Table 8.1 (and the model diagrams in Figures A.5 and A.6) show that signals that might be induced on the buried cabling, although larger than those appearing on the in-plant portions of the power distribution system, are still well below the nominal operating level of the equipment. The battery charger and vital inverter for example might see EMP-induced voltage peaks on the order of a few volts at points normally operating at 480 V or 120 V. Therefore, it is concluded that the Uninterruptible Power System will not fail due to equipment damage from EMP-induced signals.

8.3 Reactor Trip and Engineered Safeguards Actuation Systems Vulnerability

The Solid State Protection System (SSPS), the Nuclear Instrumentation System (NIS), and the Process Protection Sets receive electrical power from the Uninterruptible Power System. Thus a potential path exists for EMP-induced signals through their power supplies. However, the analysis again provides EMP-induced signal levels (Table 8.1, Figures A.6 and A.7) on the order of a few volts, which are below the normal operating voltages (120 VAC and 125 VDC) for the power supplies and relays. Furthermore, both of these systems use relay isolation techniques to separate inputs and outputs from each other and any intervening solid state logic, so there is little likelihood of damage to these systems. Of course any loss of offsite power will in itself cause reactor trip due to loss of power to control rod holding magnets. This is backed up by the manual scram capability.

8.4 Process Instrumentation Vulnerability

A variety of components associated with process instrumentation was examined including, power supplies, flow sensors, square root converters, I/I isolators, etc. For many of these components two potential EMP signal paths exist, one through the in-plant power system, the other through interconnecting cabling (power or signal) in the underground duct banks. Here again, the analysis indicates that potential EMP-induced signals will be less than nominal operating levels. It is noted that the estimated safety margins for some components are not as large as those for power related equipment. Nevertheless these margins are large enough to indicate that damage to such equipment is unlikely and the equipment will survive the postulated EMP environment.

8.5 Valve and Motor Controls Vulnerability

As discussed above, the power systems for these components (6.9 kV and 480 V) should easily survive the postulated EMP environment. Control of essential pump motors is accomplished with 125 VDC or 120 VAC systems. These control systems could be subjected to EMP-induced signals on the underground cabling between the Auxiliary Building and outlying structures. Here again, the analysis (Table 8.1, Figures A.2, A.4, A.5, and A.6) predicts that induced signals will be less than nominal system levels and that no damage should ensue. The valve and motor control systems should survive the postulated EMP-induced environment.

8.6 Overall Safe Shutdown Vulnerability

The various categories of equipment and components described above are combined into the safe shutdown systems described earlier (Section 4.0). As discussed above, this analysis indicates that the peak EMP-induced signal levels at particular points of interest are below the nominal operating levels and therefore no damage is expected. Obviously, if no individual component of a system fails, the system does not fail. Conversely, if an individual component should fail (such as a flow sensor or signal processor), it does not necessarily follow that the system fails because of the redundancy within individual systems. An even more important point is that safe shutdown in nuclear plants is assured by redundancy in safety related systems. Therefore, again, the failure of a single component or even several components within one safety train does not preclude safe shutdown.

It might be argued by some that the high altitude EMP has such a broad area coverage that redundancy should be discounted. That is, EMP could lead to common failures. This analysis assumed that the EMP threat was such as to optimally excite all penetrations, however such an event is essentially impossible in the real world. Incident fields will be less than the 50 kV/m used here, variations in orientation of the EMP plane wave and cabling can lead to non-optimal coupling, especially in penetrations away from the point of initial incidence. Also, significant fractions of the cabling for redundant trains do not enter the plant at common locations. Therefore, it is reasonable to take credit for system redundancy when assessing the system vulnerability. Of course, given the signal levels estimated here the question is essentially moot because no failures due to damage are anticipated.

9.0 Analysis of Additional Nuclear Power Plants for Vulnerability to EMP

9.1 Introduction

The coupling analysis and the damage threshold analysis completed on the example plant concluded that given the estimated safety margins, it was unlikely that components in the critical safe shutdown systems would be failed. Therefore, the safe shutdown capability would not be failed by the EMP environments postulated. While there is a basic commonality in nuclear power plant functions and operations, peculiarities do exist in design, equipment used, and topology that can result in variations in vulnerability to EMP transient environments. Consequently, three additional plants, each of different design, were surveyed to determine if generic features common to these plants are sufficiently analogous to the Watts Bar Nuclear Plant to allow those results to be extended to nuclear plants in general. The three plants visited were the Catawba Nuclear Station of Duke Power Company, the Clinton Power Station of the Illinois Power Company, and the Palo Verde Nuclear Generating Station of the Arizona Public Service Company.

The Catawba Nuclear Station is a two unit Westinghouse pressurized water reactor plant with each unit rated at 1145 MWe. Plant design and vintage is approximately the same as Watts Bar; each is approximately a ten year old design. There are differences in plant layout because of variations in design practice between Duke and TVA. The Clinton Power Station will be a two unit General Electric boiling water reactor (BWR/6) plant, each rated at 950 MWe. There will be differences in shutdown systems for the BWR as compared to the PWR. Palo Verde Nuclear Generating Station is a three unit site using Combustion-Engineering (C-E) pressurized water reactors each rated at 1270 MWe. Each of the independent units is an implementation of the C-E System 80 design so there will be differences when compared to Watts Bar.

In addition, discussions were held with C-E regarding their newer instrumentation and control systems.

These added studies are discussed here in the same order as those for the example plant, that is, some observations are made on EMP coupling, followed by a discussion of damage thresholds, and concluding with considerations of vulnerability.

9.2 EMP Coupling Analysis

The basic technique employed in surveying the three additional plants involved comparing features and configurations that were important from a coupling standpoint in the Watts Bar analysis to those observed in the other three plants. Differences in configuration were analyzed initially as to whether they represented an increase or decrease in vulnerability with respect to the Watts Bar plant. The basic features that were compared include the shielding effectiveness of building structures, plant physical topology, locations of satellite buildings, and numbers of buried cables interconnecting buildings. Table 9.1 summarizes many of these features; the most significant are described below.

One of the major sources of potential coupling at the Watts Bar plant is the buried cabling between the main plant building and the diesel generator building. Because the two buildings are separated by a considerable distance at Watts Bar, the interconnecting cables are potential sources of penetration energy to critical circuits in both the diesel generator building and the main plant building. At all three of the plants surveyed, the diesel generator buildings were contiguous to the main building structures. Therefore, this source of excitation simply does not exist at Catawba, Clinton, or Palo Verde.

The Palo Verde plant does, however, exhibit a potential for increased vulnerability from the buried conduit duct banks that route electrical cables between the main plant building and the pumping structure at the source of vital cooling water. Since cables running in common duct banks tend to share the bulk current induced on them, the current induced on individual cables tends to decrease as the number of cables in the duct bank increases. At Palo Verde, and to a lesser extent at Catawba, there are far fewer cables in these duct banks to share the EMP induced bulk current. At Watts Bar the lowest safety margin estimates were computed for equipment which interfaces this duct cabling, so large increases in threat levels here would significantly reduce safety margin estimates.

While the single-line electrical diagrams of the connection of the plant to the power grid are basically analogous for Watts Bar and Palo Verde, a different cabling topology and equipment arrangement exists at Palo Verde that increases the threat to the power system from the power grid. This involves the placement of intermediate voltage transformers in the Palo Verde distribution switchyard with long overhead transmission lines leading back into the plant. This would result in large threat level currents being induced by EMP at points much deeper in the electrical system than would be the case for the other plants. At Watts Bar the effect of the power grid on critical system responses was overshadowed by conduit duct bank sources. This will not be the case at Palo Verde.

The initial findings of the visits to the three additional nuclear plant suggest that sufficient differences exist in several of the plants examined to preclude straightforward extrapolations of the Watts Bar data to nuclear plants in general. Since the Palo Verde Nuclear Generating Station (PVNGS) exhibits several features indicating increased vulnerabilities to EMP environments, further analysis was performed to quantify the differences between Palo Verde and the Watts Bar Nuclear Plant.

Table 9.1 Summary of Nuclear Plant Surveys

	Watts Bar	Catawba	Clinton	Palo Verde
Operating Agency	U.S. TVA	Duke Power	Illinois Power	Arizona Public Service
Reactor Manufacturer	Westinghouse	Westinghouse	General Electric	Combustion Engineering
Reactor Type	PWR	PWR	BWR	PWR
Number of Units	2	2	1(Expandable to 2)	3(Only one examined)
Building Shielding Estimate for Seismic Structures	~30 dB	~30 dB	~30 dB	~30 dB
Diesel Generator Building Location	Satellite	Contiguous**	Contiguous**	Contiguous**
Connection to Power Grid Analogous to Watts Bar	----	Yes	Yes	No*
Safety Related Cabling Buried in Conduit Duct Bank out to Pumping Station	Yes	Yes	Yes	Yes
Conduit Construction in Duct Bank	PVC Conduits	PVC Conduits	PVC Conduits (Instrumentation Cables are run in Continuous Steel Conduits**)	PVC Conduits
Number of Cables from Pumping Station to Main Plant Building	270	81*	272	40*

*Represents an Increase in Vulnerability with respect to WBNP.
**Represents a Decrease in Vulnerability with respect to WBNP.

The plot plan of the PVNGS, Figure 9.1, shows the routing of the two major sources of EMP coupling to safety related systems; the 13.8 kV essential ac power lines and the buried cables between the diesel generator building and the spray ponds.

9.2.1 Essential AC Power Analysis. The 13.8 kV essential power source is derived from the 500 kV transmission grid by transformers located in the 500 kV switchyard. Two overhead transmission lines, one for Train A and one for Train B, parallel the 500 kV transmission output lines from the plant for approximately 350 meters to where they drop to below ground feeders leading to switchgear just outside the turbine building. Transformers to reduce the 13.8 kV down to 4160 V are located adjacent to the switchgear. From the transformers, 4160 V power is routed to distribution boards in the control building via metallic enclosed bus bars. This topology is shown in Figure 9.2.

From a functional standpoint the 4160 V distribution boards at Palo Verde are analogous to the 6900 V shutdown boards at Watts Bar. However, the threat current coupled into the 4160 V boards at Palo Verde would be larger than at Watts Bar because the overhead line source occurs at a point much deeper in the electrical system and consequently there is less fan-out and attenuation of the overhead line threat than was encountered in the Watts Bar topology.

The coupling model diagram shown in Figure 9.3 details the basic connectivity of a single train of the 13.8 kV essential electrical system down to the level of 480 V motor control centers and 480 V equipment. Also included on the diagram are estimates of EMP threat currents, attenuation, and voltages. The equipment load on distribution boards is based on the equipment complement that would be on line during normal plant operation. This equipment and its estimated EMP-induced transient voltage threat are tabulated in Table 9.2.

Although lightning arresters are installed in three locations of the essential power source (as shown in Figure 9.2), it has been assumed for this analysis that the EMP-induced transient on the power line would be faster than the reaction time of the arresters or that the arrester configurations would have inductances of such magnitude as to be essentially ineffective in limiting fast transients.

9.2.2 Spray Pond Analysis. Two separate conduit duct banks carrying nuclear safety related cables run in a parallel path from the diesel generator building cable penetration out to the Train A and B spray ponds. As was the case at Watts Bar, the cables are run in PVC conduits with control and instrumentation cables bundled in separate conduits away from the pump power cables. Figures 9.4, 9.5, and 9.6 detail the complement of equipment at each spray pond and its connectivity to systems within the control/auxiliary building.

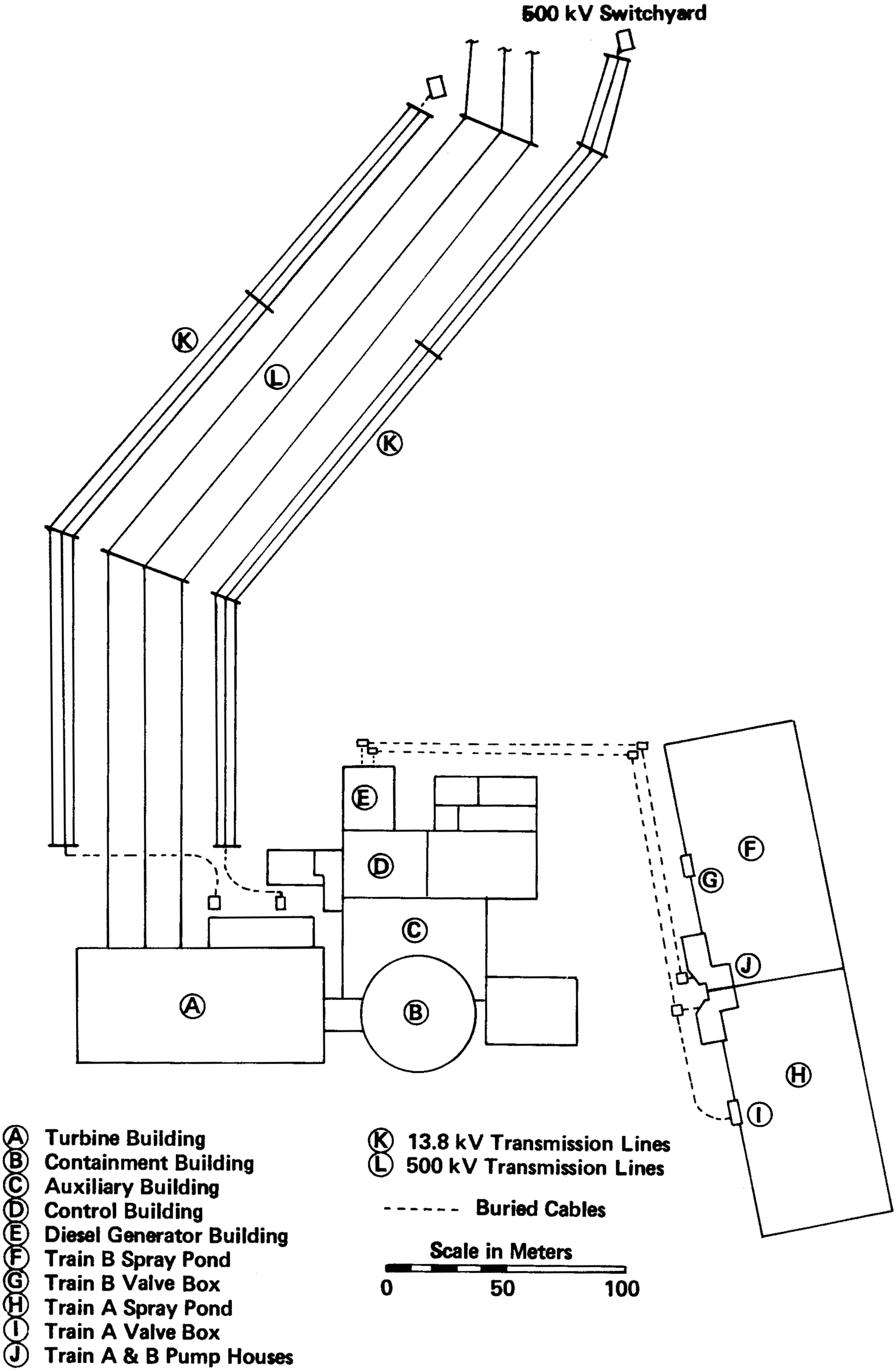


Figure 9.1. Plot Plan of Palo Verde Nuclear Generating Station

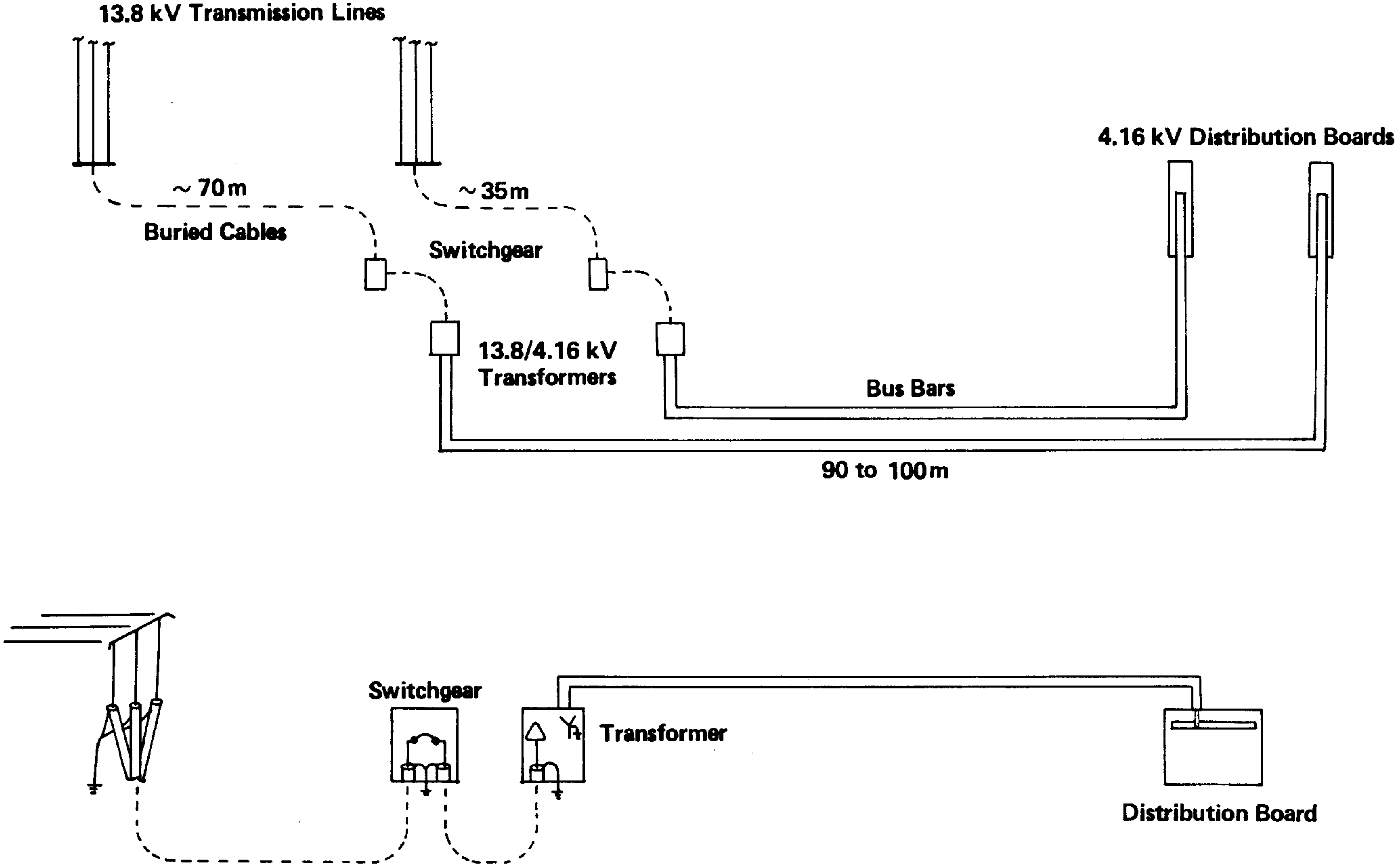


Figure 9.2. 13.8 kV Essential Power Topology

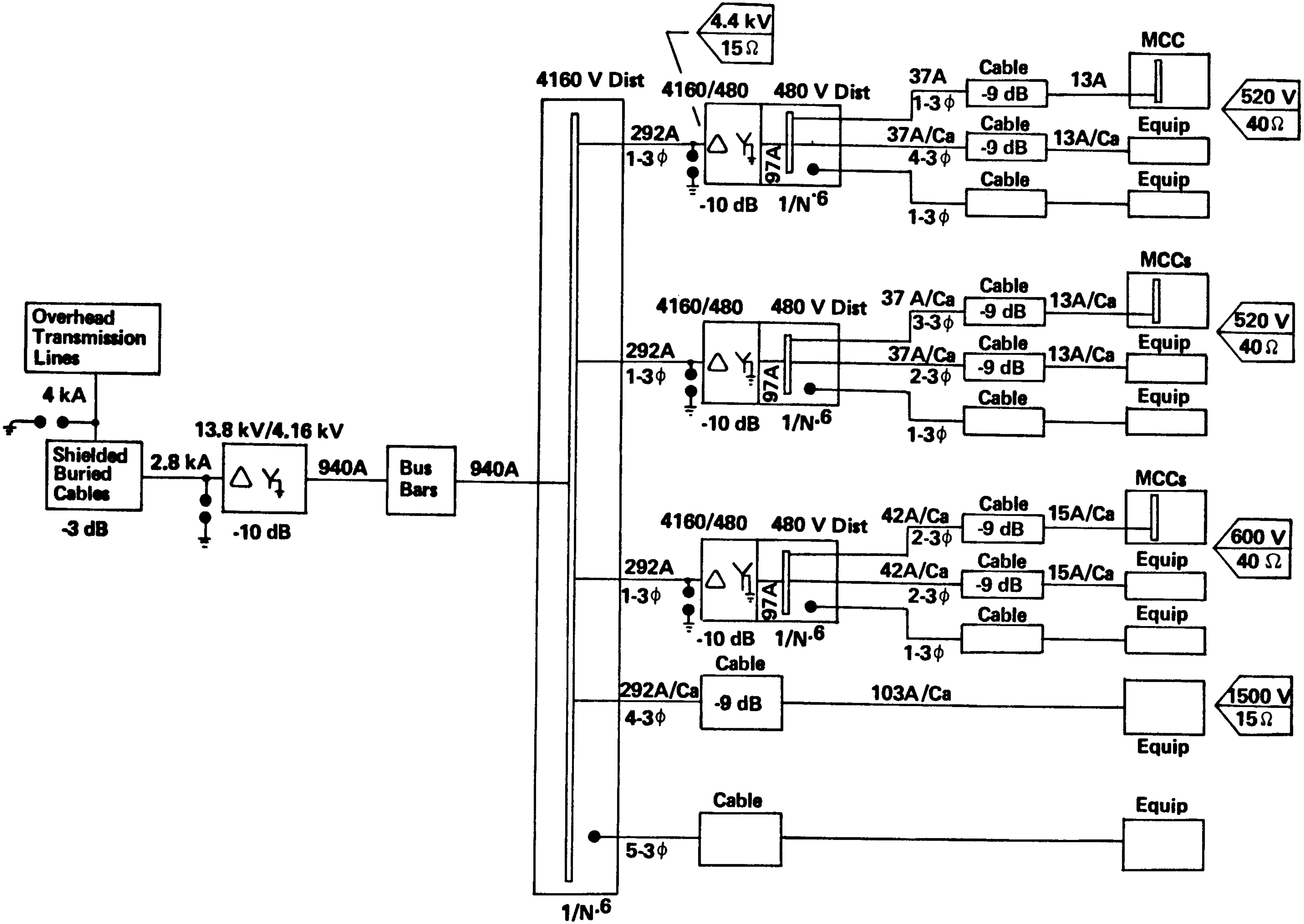


Figure 9.3. 18.8 kV Transmission Line Model

Table 9.2. EMP Response Predictions for PVNGS Essential AC Power Equipment.

Equipment	Interface	Operating Level	Peak Value EMP Response
Transformer 4160/480V	AC Input	4160 V	4400 V
Essential Chiller	AC Input	4160 V	1500 V
Essential Cooling Water Pump	AC Input	4160 V	1500 V
Normal Chiller	AC Input	4160 V	1500 V
Aux. Feedwater Pump	AC Input	4160 V	1500 V
Fuel Pool Cooling Pump	AC Input	480 V	520 V
Charging Pump	AC Input	480 V	520 V
Containment Normal ACU Fan	AC Input	480 V	520 V
CEDM Normal ACU Fan	AC Input	480 V	520 V
Control Room Essential AHU	AC Input	480 V	520 V
Main Essential Lighting Panel	AC Bus	480 V	600 V
Motor Control Centers	AC Bus	480 V	600 V

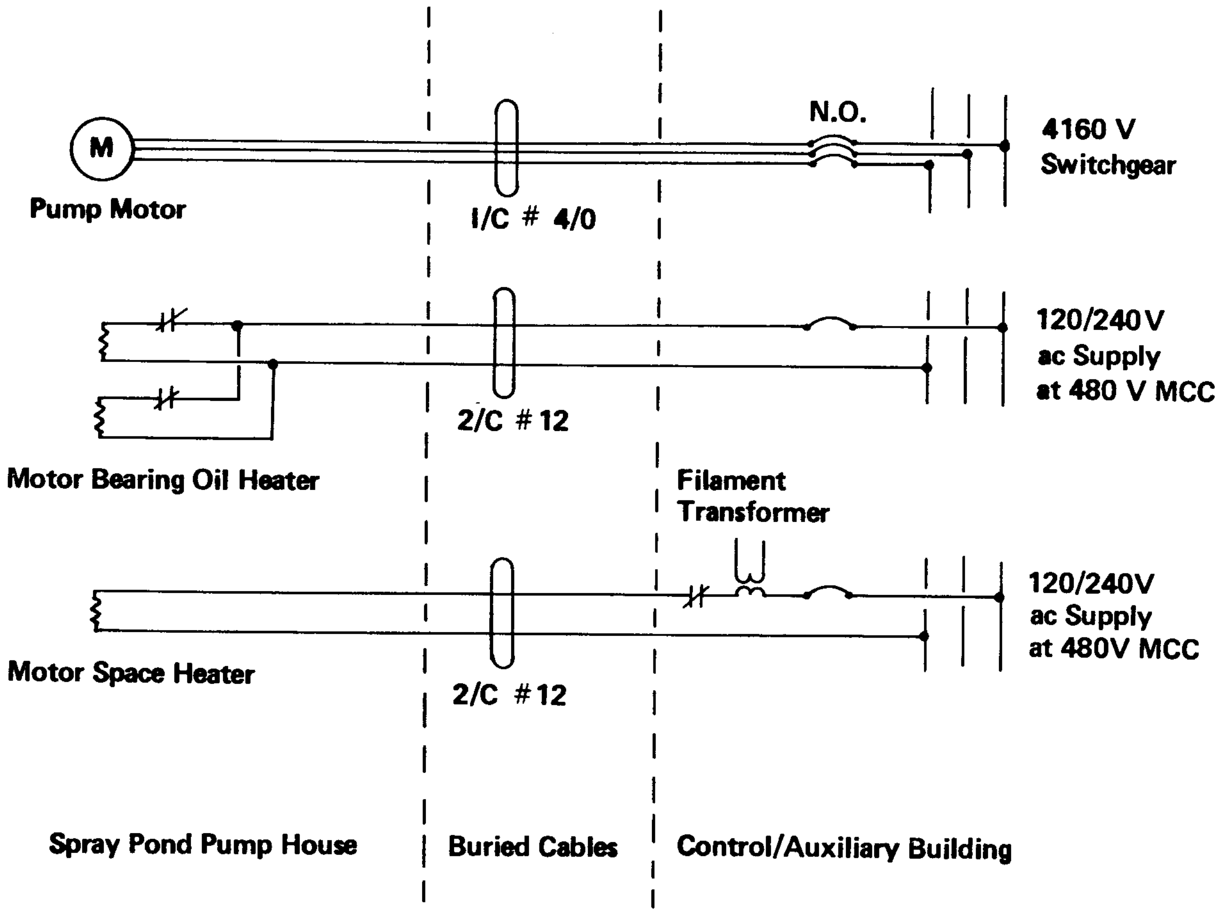


Figure 9.4. Essential Spray Pond Pump House, PVNGS

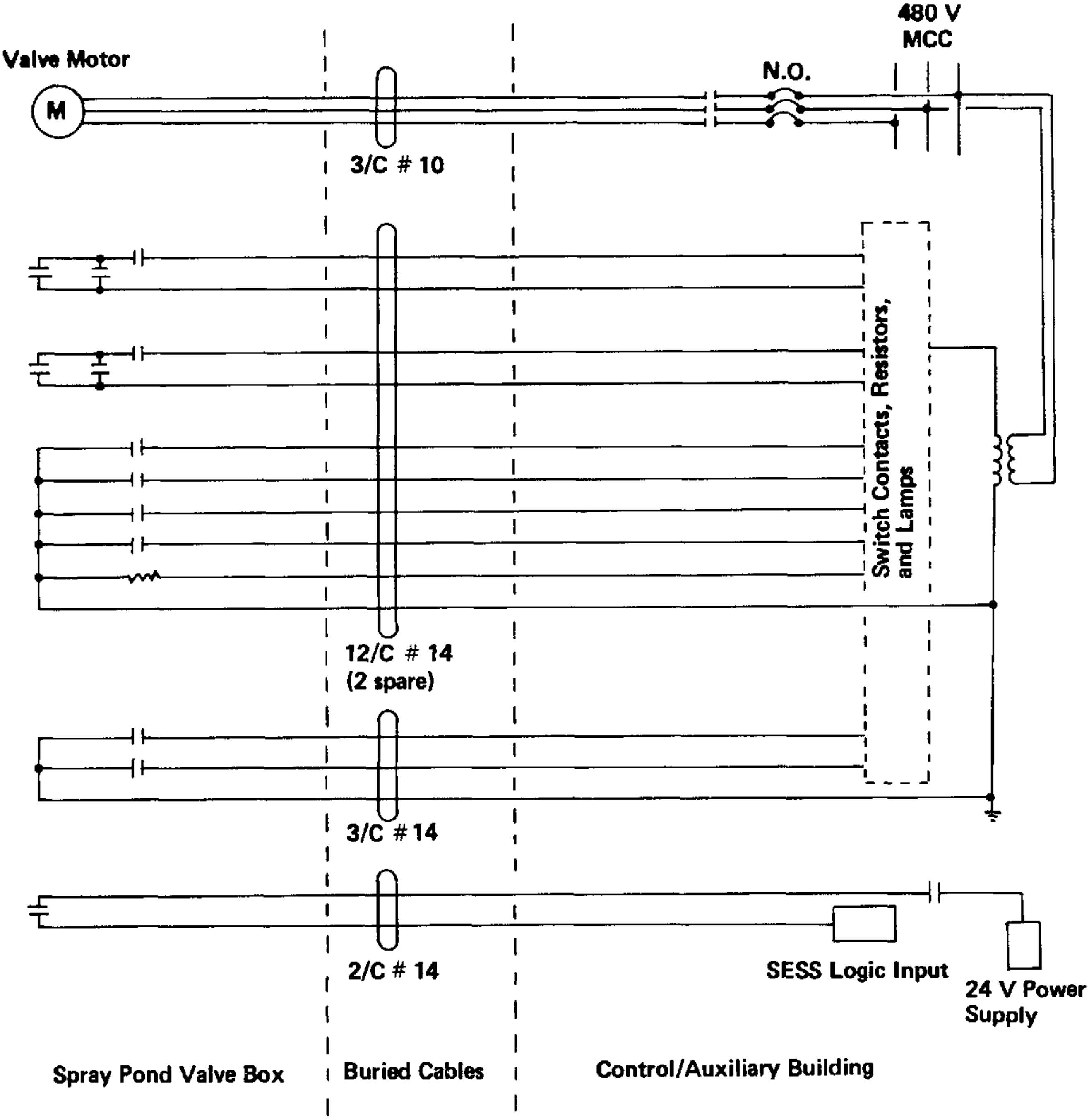


Figure 9.5. Spray Header Inlet Valve, PVNGS

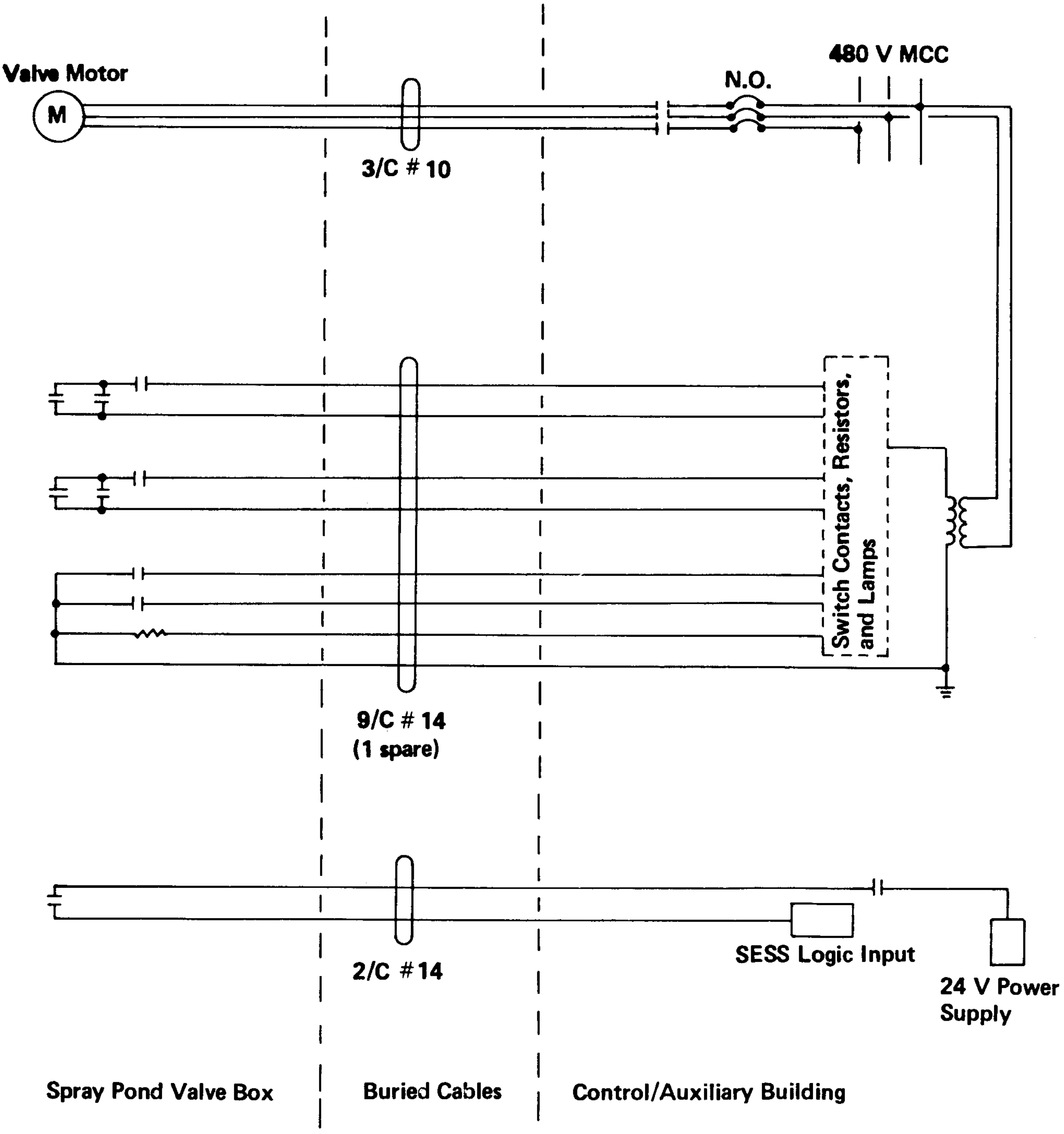


Figure 9.6. Spray Header Bypass, PVNGS

Identical equipment for each train is located in two locations: the pump house and the valve box. The only nuclear safety related equipment at the pump house is the spray pond pump itself and its associated bearing oil and space heaters. At the valve box there is a header inlet MOV and a header bypass MOV with associated sets of field contacts that signal the status of valve positions.

Under normal operating conditions the other ends of the buried cables connect to either open circuit breakers, motor control center display panels composed of switch contacts, resistors, and lamps, or to a logic input card at the Safety Equipment Status System (SESS). A schematic diagram of this card is shown in Figure 9.7. According to Palo Verde personnel, the SESS itself is not considered to be nuclear safety related equipment. The SESS cables have been run out to the spray pond with nuclear safety related cables because the SESS 24 volt power supply receives its power from the nuclear safety related 120 VAC vital instrumentation bus.

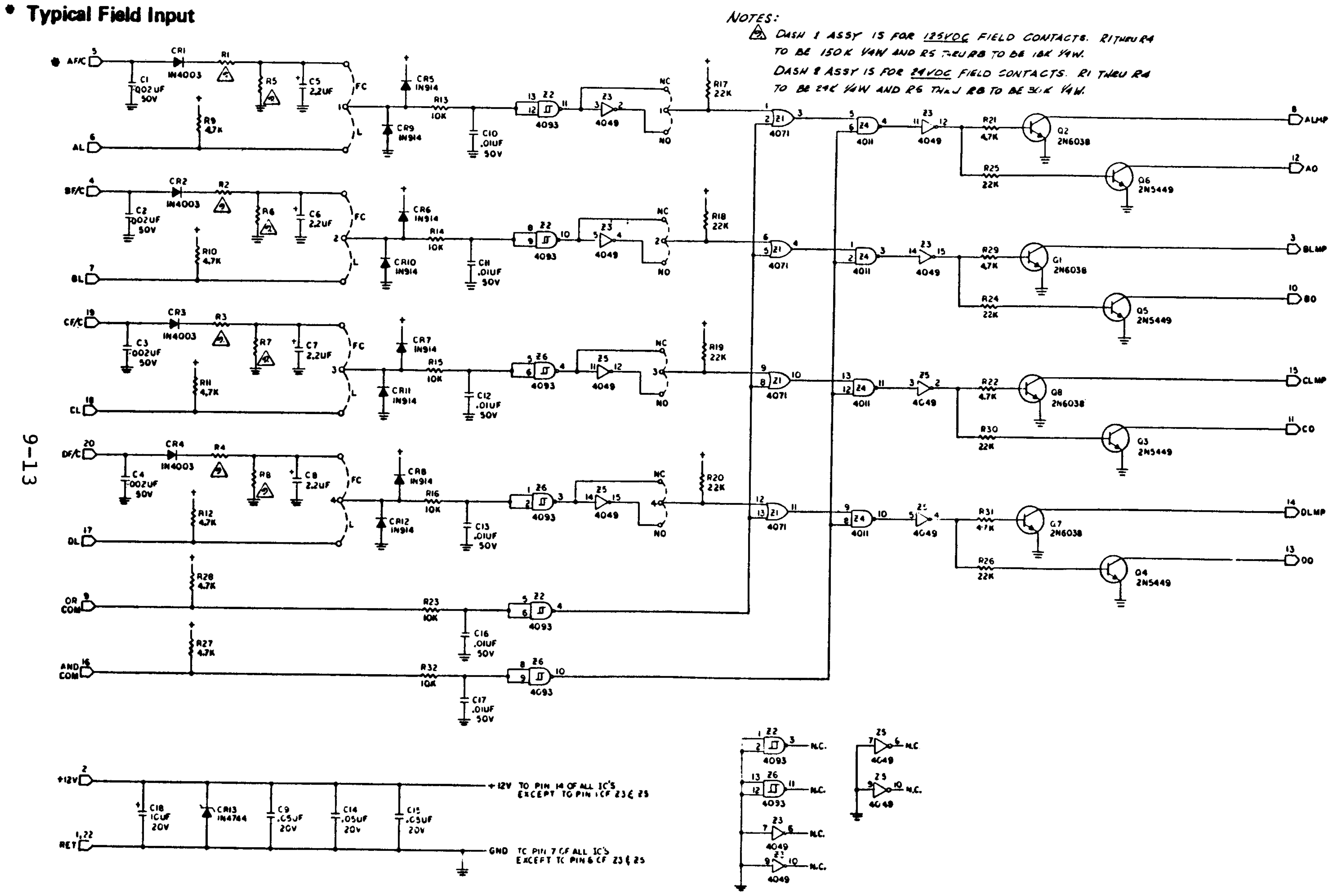
Three model diagrams have been constructed in order to compute EMP responses for spray pond associated equipment. Figure 9.8 shows the coupling from the cables in the conduit duct bank to the Train A pump house while Figure 9.9 shows the coupling to the Train A valve box. (The Train A equipment was chosen because the cables to its valve box would be more strongly driven than those for Train B.) The model diagram in Figure 9.10 details the coupling at the other ends of the buried cables as they penetrate the diesel generator building on their way to equipment located in the control/auxiliary building. The responses computed from these diagrams are tabulated in Table 9.3.

The response estimates at the Palo Verde spray pond are significantly higher than response estimates at the Watts Bar intake pumping station for two basic reasons:

1) Fewer cables exist at Palo Verde to share the bulk current induced on the buried cable runs.

2) There is no complex cable distribution system at the Palo Verde spray pond (as there was at Watts Bar) to provide additional attenuation to penetration currents coupled inside the building. The Palo Verde cables terminate within several feet of where they emerge from the duct bank.

Based upon our inspection of the Palo Verde facility we believe it unlikely that other signal attenuation mechanisms exist for the exterior structures at the spray pond. However, time did not allow us to analyze current paths within the control and auxiliary buildings to the same degree as was achieved at Watts Bar. Experience at other facilities, and at Watts Bar, indicates that as details are added, estimates of the induced currents tend to decrease. Therefore, we believe that the response values for



NOTES:

⚠ DASH 1 ASSY IS FOR 125VDC FIELD CONTACTS. R1 THRU R4 TO BE 150K 1/4W AND R5 THRU R8 TO BE 18K 1/4W.

DASH 2 ASSY IS FOR 24VDC FIELD CONTACTS. R1 THRU R4 TO BE 24K 1/4W AND R5 THRU R8 TO BE 30K 1/4W.

Figure 9.7. SESS Logic Card Schematic Diagram

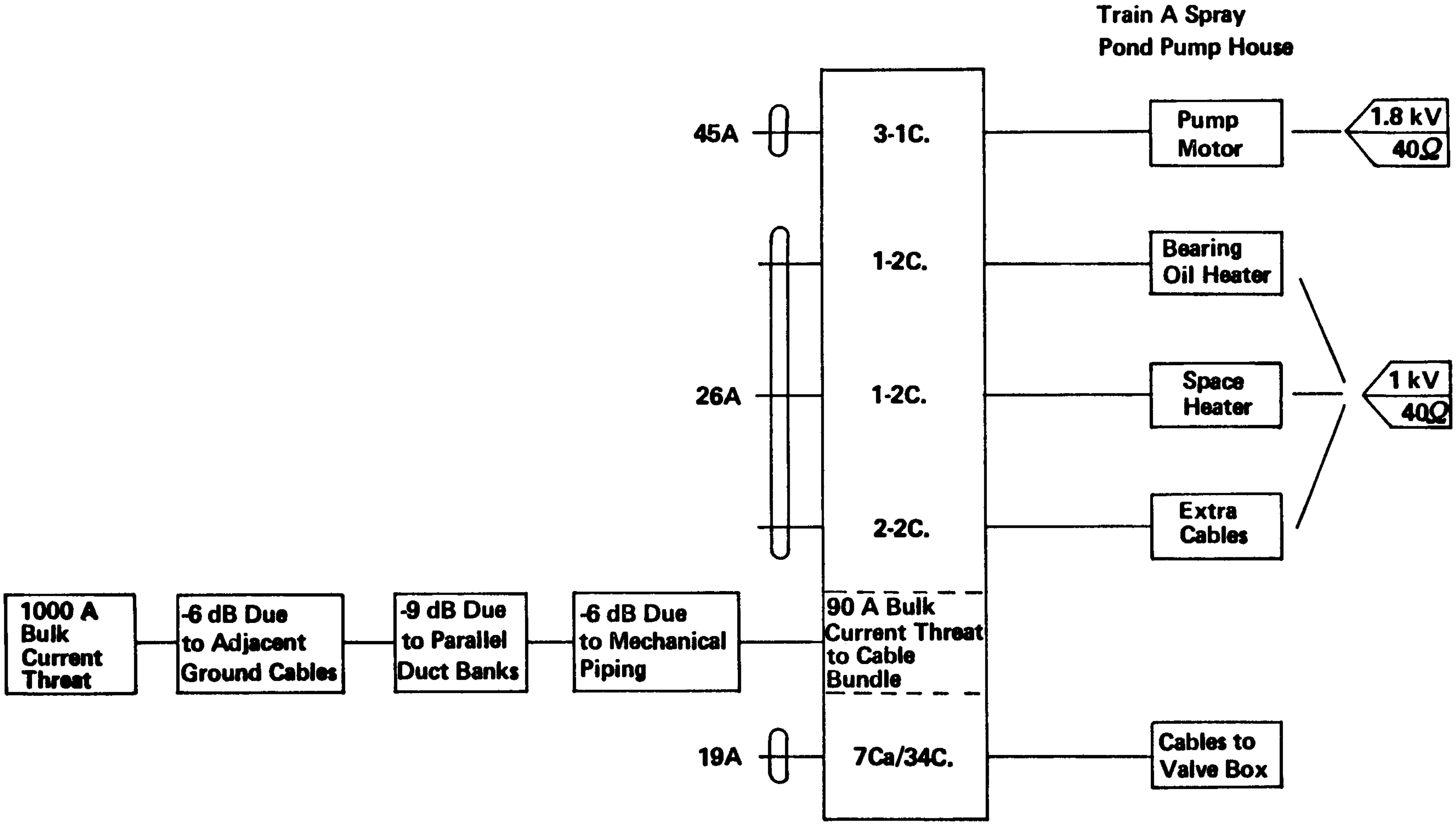


Figure 9.8. Train A Spray Pond Pump House Model

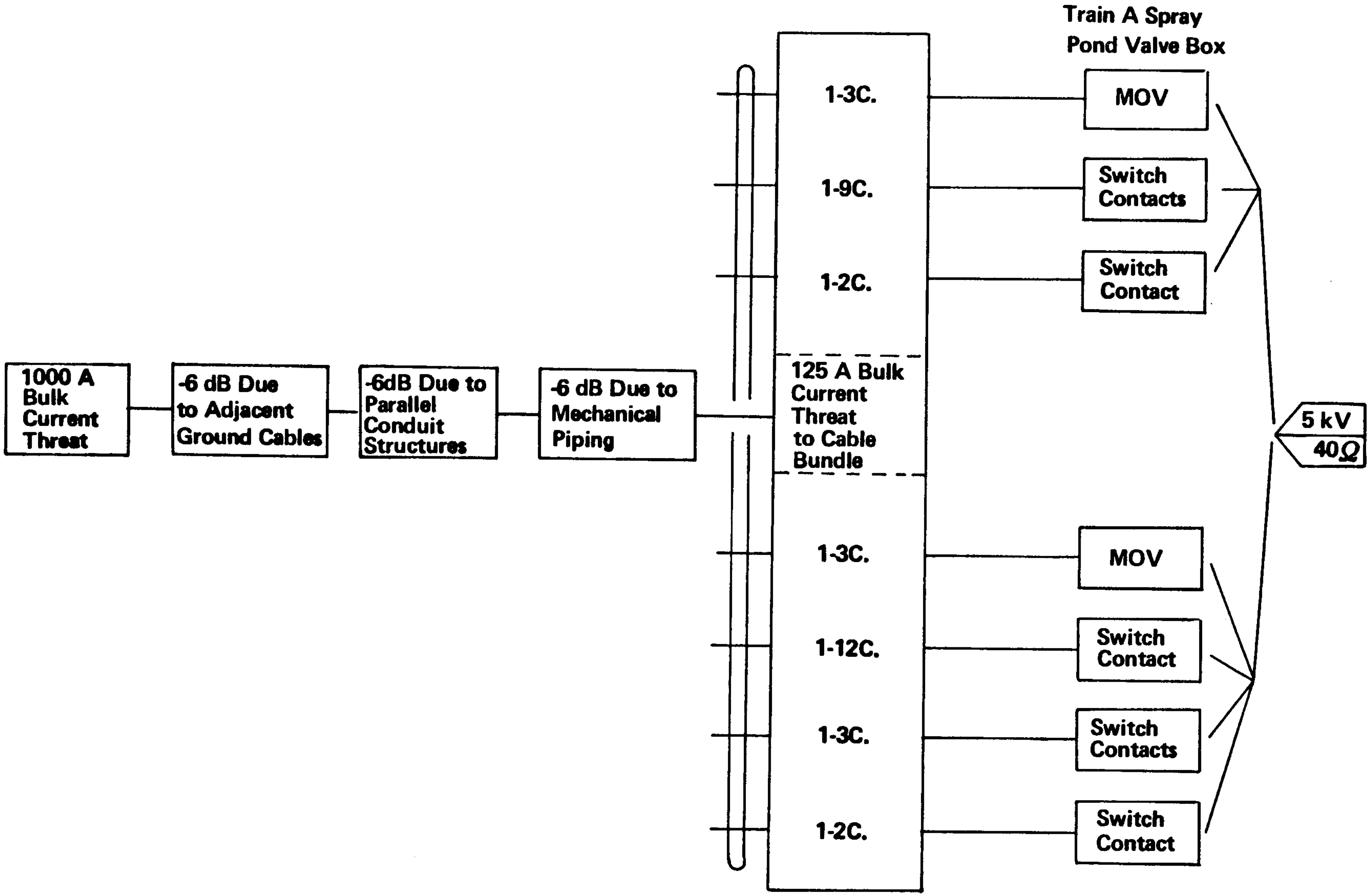


Figure 9.9. Train A Valve Box Model

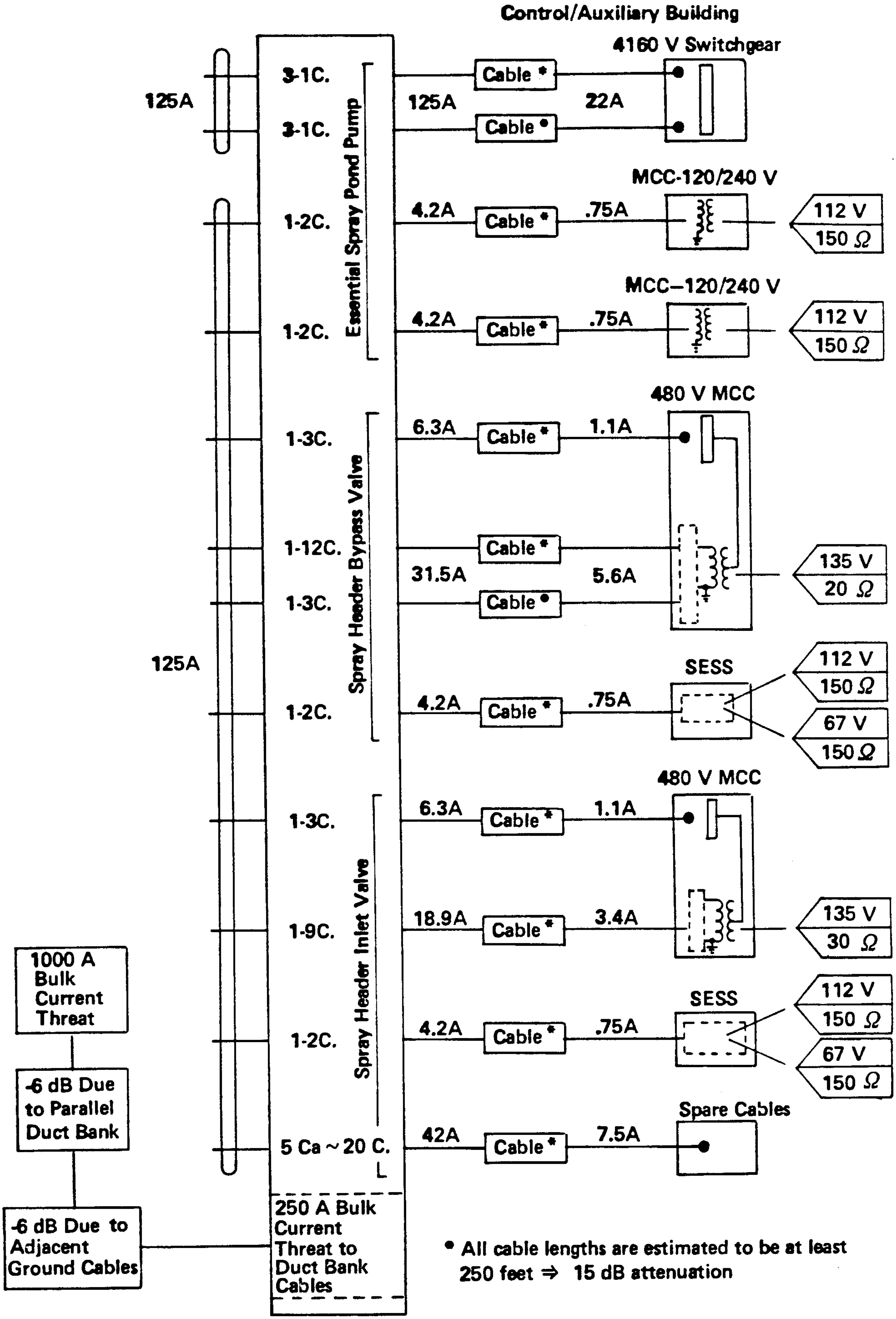


Figure 9.10. Control/Auxiliary Building Model

Table 9.3. EMP Response Predictions for PVNGS Spray Pond Equipment.

Equipment	Interface	Operating Level	Peak Value EMP Response
Essential Spray Pond Pump	AC Input	4160 V	1800 V
Pump Bearing Oil Heater and Pump Space Heater	AC Input	120 V	1000 V
Spray Header Inlet MOV	AC Input	480 V	5000 V
Spray Header Inlet Status Switches	Control Status Output	120 V	5000 V
Spray Header Bypass MOV	AC Input	480 V	5000 V
Spray Header Bypass Status Switches	Control Status Output	120 V	5000 V
Motor Control Center (for Essential Spray Pond)	120/240 V Bus	120 V	112 V
Motor Control Center (for MOVs)	Status Indicator	120 V	135 V
Safety Equipment Status System (SESS)	Logic	24 V	67 V
	Status Switch Input	24 V	112 V

the MCCs and the SESS on Table 9.3 are certainly bounding values and that additional analysis would lead to lower values.

9.2.3 Conclusions on Coupling Analysis. The EMP-induced responses at several analogous locations at Watts Bar and Palo Verde are listed in Table 9.4. As can be seen from this table, the average responses at the penetration interfaces at Palo Verde are significantly higher than those at Watts Bar. Several of the responses, particularly at the spray pond, are of such a magnitude as to suggest that an arc-over to ground from bushings, terminals or switch contacts may occur.

As indicated earlier, the higher responses at Palo Verde arise from several factors:

1) Outside, overhead ac line source couples at a point much deeper in the electrical system.
2) Fewer cables exist in the exterior duct banks to share the bulk current induced on buried cable runs.
3) There is no complex cable distribution at the spray pond to provide additional attenuation for penetration currents.

From this data it can be concluded that significant variations in responses at penetration interfaces can exist at nuclear power plants, and therefore, the Watts Bar results in themselves are not necessarily indicative of nuclear plants in general.

9.3 Damage Threshold Analysis

This task was threefold. The first part was the identification of solid state equipment and components used to perform safe shutdown functions for other, newer technology plants. The second portion was the estimation of the damage failure thresholds of that equipment. The third part consisted of a comparison of the thresholds estimated for Watts Bar equipment with the thresholds calculated in the newer technology plants.

Because of the short time over which this study was conducted, the time available for acquiring data to calculate circuit damage thresholds was limited. This was crucial to the completeness of the study because in many cases, the electrical schematics were not available directly from the electric utility. In obtaining these data from equipment vendors, it was often found that the key data were considered as proprietary to the vendor and, thus, were not available to calculate circuit damage thresholds. This limits the completeness of the study.

9.3.1 Technical Approach. The general flow of the technical effort in this task is illustrated in Figure 9.11. The general approach taken was to conduct an onsite survey of each plant:

Table 9.4 Response Comparisons Between WBNP and PVNGS

Equipment (WB/PV)	Interface	Operating Level (WB/PV)	WBNP Response	WBNP SM	PVNGS Response	PVNGS SM	Difference in dB
Transformer 6900 V/480 V 4160 V/480 V	AC Input	6.9 kV/4.16 kV	17 V	72	4400 V	20	52
Aux Feedwater Pump	AC Input	6.9 kV/4.16 kV	4 V	85	1500 V	29	56
CCS Pump/Charging Pump	AC Input	480 V	24 V	46	520 V	19	27
ERCW Pump/Essential Spray Pond Pump	AC Input	6.9 kV/4.16 kV	225 V	50	1800 V	27	23
ERCW HDR Isolation Valve/Spray HDR Inlet Valve	AC Input	480 V	29 V	44	5000 V	-0.4	44
HDR Isolation Valve Control/HDR Inlet Valve Status	Control Output	120 V	54 V	16	5000 V	-23	39
Analog Mux Relay/SESS	Input	24 V	11 V	17	112 V	-3.8	21
Logic Relay Panel 6.9 kV Shutdown Board/ 480 V Motor Control Center	Status Input	120 V	38 V	20	135 V	8.5	11

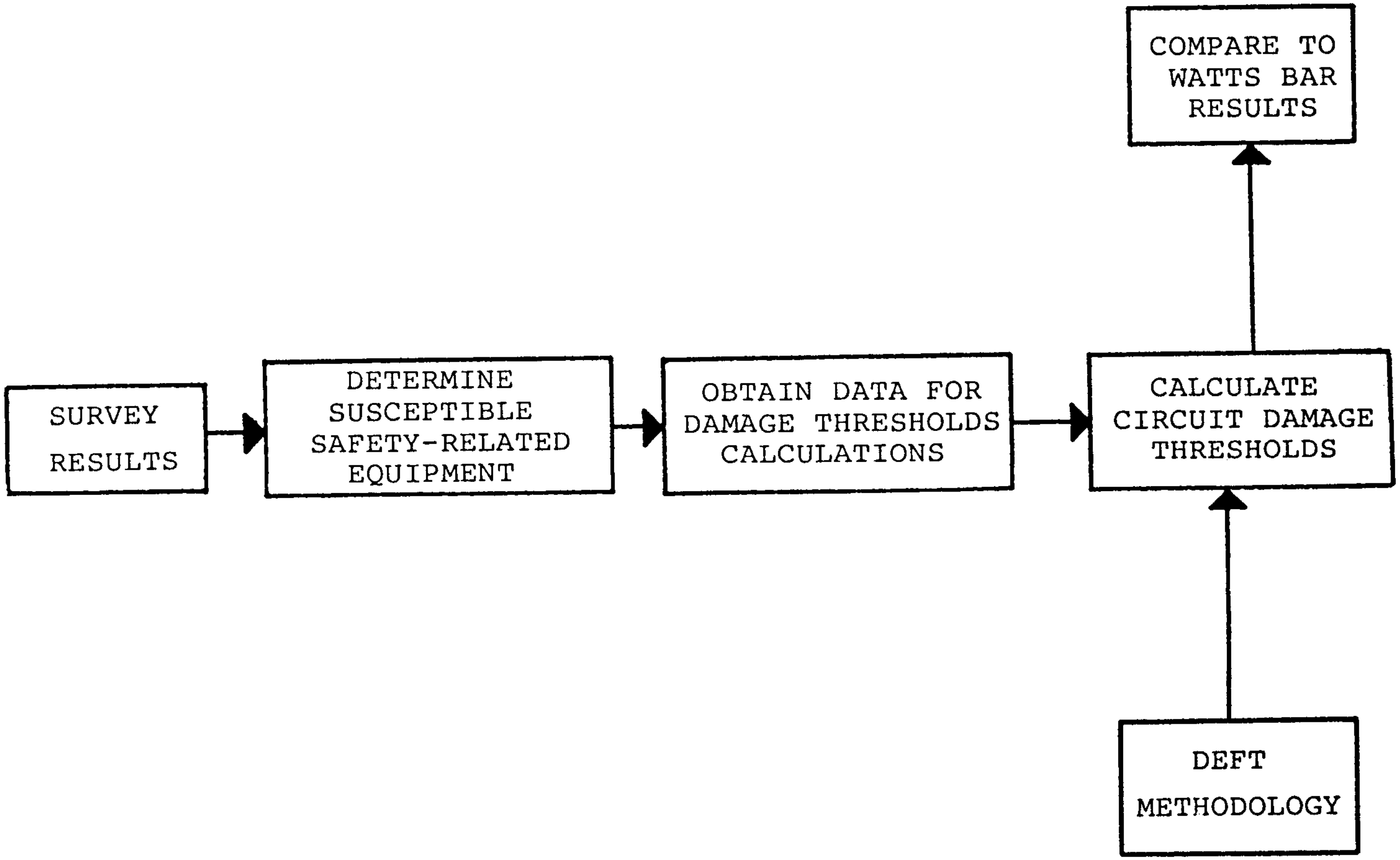


Figure 9.11. Technical Approach

1) To determine which equipment items are necessary for safe shutdown;

2) To define the critical equipment interfaces that are potentially susceptible to EMP-induce damage;

3) To acquire the necessary descriptive information on the equipment;

4) To calculate circuit damage thresholds using the DEFT methodology, and

5) To compare these thresholds with the Watts Bar results.

This represents some modification to the procedure followed in the example plant (Section 7), particularly items 2 and 5. These two items are discussed below.

Identification of Critical Equipment Interfaces. This effort consists of two major screening tasks. The first task was to determine whether the equipment items contained semiconductor components. Because the scope of this effort was limited to considering only semiconductor components, equipment items without them were excluded from further consideration. The second screening process involved the determination of the isolation of the equipment item from a primary EMP drive point. In the Watts Bar portion of the study it was determined that the threat associated with the diffused field induced by EMP on the inside of seismic Category 1 structures is negligible when compared to the amount of current induced on conductors exterior to the facility and conducted into the facility (direct penetration). It was also concluded from the Watts Bar study that only the first or second stages of fan-out distribution from direct penetrations will experience any substantial EMP threat. Consequently, any equipment item that was buried within the facility past two stages of fan-out was considered sufficiently isolated from the primary EMP drive point and was excluded from any further analysis here.

Comparison with Watts Bar Results. The thresholds of equipment items calculated for the newer plants were compared on a plant-by-plant basis to the calculated Watts Bar results.

Equipment Common to Several Plants. Although each plant is discussed separately below, there are a number of instances where it was impossible to prepare any analysis because vendors consider the necessary information proprietary. This includes the Rosemont 1153 transmitters which appear in the diesel generator fuel oil transfer systems at all three plants. These transmitters are also found in the essential cooling water and refueling water storage systems at Palo Verde and in the high pressure core spray, shutdown service water, and nuclear system protection systems at Clinton.

9.3.2 Discussion of Individual Plants and Systems

Catawba Nuclear Station. There are seven systems necessary for safe shutdown; five are considered isolated from a primary EMP drive point. The Reactor Protection System is isolated in the reactor building/containment complex. The Chemical Volume and Control System is also isolated in the reactor building/containment complex. The Component Cooling Water is totally contained within the auxiliary building/reactor building complex with no direct "outside-world" interface. The Emergency Core Cooling System components are all located in the reactor building/containment; activation signals are from the RPS and control room. These are all isolated by several stages from the primary EMP drive points. The Auxiliary Feedwater System components are placed in the turbine building and reactor building. Critical solid state components are all sufficiently isolated from primary EMP drive points to be considered insusceptible to EMP-induced damage.

The remaining systems--Auxiliary Power System and Nuclear Service Water--are considered for EMP susceptibility.

Auxiliary Power System. The Auxiliary Power System provides the power needed for safety systems as a backup to the normal source of electrical power with a battery reservoir and a conversion system that produces continuous AC and DC output power. There are four system elements that contain solid state semiconductor components:

- Diesel Generator Load Sequencer
- Diesel Generator Process Control Sensors
- Battery Charger
- AC Static Inverter

The Diesel Generator load sequencer is located in the diesel building and communicates with the diesel generator and medium-voltage switchgear. This provides sufficient isolation for the load sequencer to be excluded from further analysis.

The batter charger used at Catawba is of a similar type to that used at Watts Bar, but made by a different vendor (Solid State Controls, Inc.). No schematic information was available and circuit damage thresholds could not be determined.

The inverter used at Catawba is same type, model and vendor (Solid State Controls, Inc.) as the inverter used at Watts Bar. The circuit damage thresholds for the inverter, then, are the same as for the inverter used at Watts Bar. The values of the thresholds at the critical interfaces are (from Appendix B):

AC-Input: $V_T = 1.8 \times 10^3 V$

$I_T = 15.2\ A$

$P_T = 2.7 \times 10^4 W$

Battery Input: $V_T = 9.3 \times 10^2 V$

$I_T = 1.2 \times 10^4 A$

$P_T = 1.1 \times 10^7 W$

AC-Output: $V_T = 8.9 \times 10^2 V$

$I_T = 45.2\ A$

$P_T = 4.0 \times 10^4 W$

Nuclear Service Water (NSW) System. The NSW system is the ultimate heat sink for a variety of safe shutdown support systems. There are two system components that contain solid state semiconductor components:

- NSW level transmitter
- NSW process instrumentation

The flow in the NSW system is monitored by a Robertshaw 158-series level transmitter. No schematic information was available for this transmitter so a circuit damage threshold determination could not be made.

The output of the level transmitter is an analog signal sent to process instrumentation (a Rochester Trip Alarm) in the auxiliary building. The schematic diagram of this unit is shown in Figure 9.12. The interfaces that are potentially susceptible are the AC-Input and the signal input. The most sensitive components for these interfaces are CR1(1N2070--AC-Input) and Z1(LM324--signal input). Analyses conducted at these interfaces give the following results:

AC Input: $V_T = 773.8V$

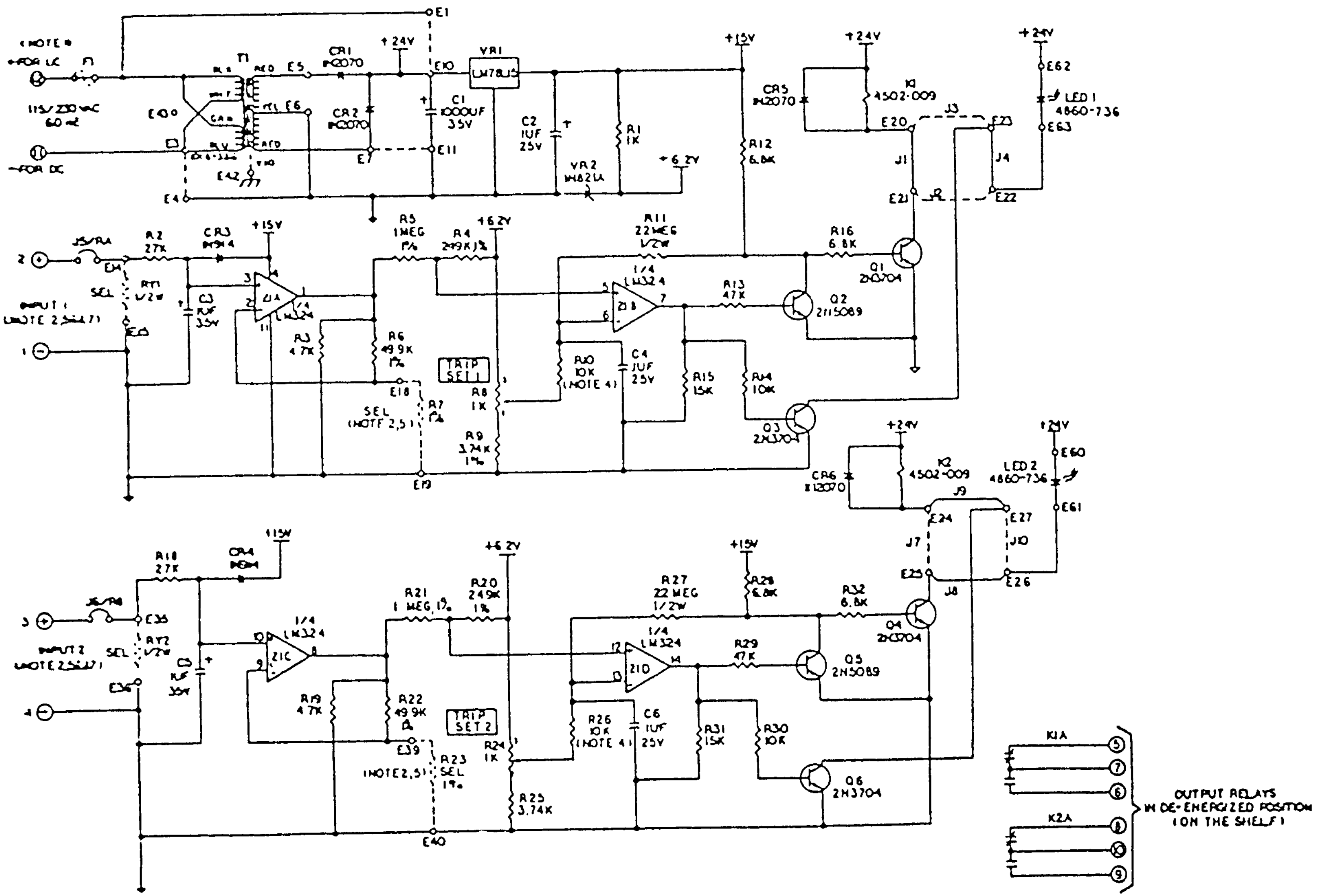
$I_T = 3.3\ A$

$P_T = 2.5\ kW$

Signal Input: $V_T = 7.7 \times 10^6 V$

$I_T = 2.8 \times 10^2 A$

$P_T = 2.2 \times 10^9 W$



ALL RESISTORS ARE 5% UNLESS OTHERWISE SPECIFIED.
ALL RESISTORS ARE 1/4W UNLESS OTHERWISE SPECIFIED.

Figure 9.12. Schematic Diagram - Rochester Trip Alarm

The signal input thresholds for the inverter and trip alarm were calculated assuming that the failure of the semiconductor components would be the primary failure mode of the circuit. It is clear from the high magnitudes of the calculated values that this is not the case; i.e., other phenomena such as arcing or other dielectric breakdown can be expected to occur before these levels are reached if EMP-induced driving signals are large enough.

Clinton Power Station. There are seven systems necessary for safe shutdown. The Residual Heat Removal (RHR) system is located in the lower level of the auxiliary building and is isolated by several stages from the "outside world." The process instrumentation that is associated with RHR is located deep within the reactor building/auxiliary building complex. The RHR system, then, is sufficiently isolated from the primary EMP drive points to be excluded from any further analysis. The Standby Liquid Control System (SLCS) components are all located within the reactor containment with process control instruments that send signals to the control room. Because of its isolation, the SLCS can be excluded from any further analysis.

The remaining systems to be considered for EMP susceptibility are:

- Reactor Core Isolation Cooling (RCIC) System
- Emergency Core Cooling System (ECCS)
- Shutdown Service Water
- Nuclear System Protection System (NSPS)
- AC/DC Emergency Power System

Reactor Core Isolation Cooling (RCIC) System. The RCIC system maintains sufficient water in the reactor pressure vessel to cool the core and then maintain the nuclear boiler in the standby condition in the event the vessel becomes isolated from the turbine steam condenser and feedwater makeup flow. There are two system components that contain solid state semiconductor components:

- RCIC Process Control Transmitters
- RCIC Turbine Overspeed Governor

The RCIC process control transmitters monitor the flow in the makeup lines. These are located outside the reactor containment but inside the reactor building. The transmitter outputs are sent to the control room inside the auxiliary building. Because these transmitters are isolated from any outside EMP source, they can be eliminated from any further analysis.

The RCIC turbine and pump automatically shut down upon turbine overspeed. The turbine is protected from this condition by an electronic overspeed governor with ramp generator. This governor is similar in type to the AFW turbine governor analyzed at Watts Bar and is provided by the same vendor (Woodward Governor). Schematic information was not available and exact verification of the model used could not be accomplished. Consequently, direct extension of the Watts Bar results was not possible and circuit damage thresholds of this equipment item were not determined.

Emergency Cool Cooling (ECCS) and Shutdown Source Water (SSW) Systems. The ECCS is designed to protect the reactor core against fuel cladding damage in the event of a loss of coolant accident. The SSW provides cooling to various components of the ECCS. The process control transmitters contain semiconductor devices and the only ones not sufficiently isolated are Rosemont 1153's discussed earlier.

Nuclear System Protection System (NSPS). The NSPS is a four-channel electrical alarm and actuating system which monitors the operation of the reactor. Upon sensing an abnormal condition, it initiates action to prevent an unsafe or potentially unsafe condition. The NSPS uses solid state electronic technology from sensor output to actuation device inputs which includes sensors, signal conditioning, combinational logic and actuator logic. The NSPS also provides for the analog indication of major variables, separation of channels, and on-line testability. There are six system components which contain solid state semiconductors:

- Process Control Transmitters
- Analog Computer Unit Trip Modules
- Digital Signal Conditioning Modules
- Decision Logic Modules
- AC/DC Load Drivers
- DC Power Supplies

The monitoring of critical analog process parameters in the NSPS is accomplished through process control transmitters of the Rosemont 1152/1153 types discussed earlier.

It is conceivable that an EMP signal could be induced at the interface to the Analog Computer Unit Trip Modules (ATMs). These ATMs are in the equipment bays near the reactor control room. The interface of interest is the transmitter excitation input. The schematic for this interface circuit is shown in Figure 9.13. the device of interest is the UPM-24/40-12 DC-DC converter. Using the methods of Section 7 for MOS integrated circuits, the device failure parameters are calculated to be:

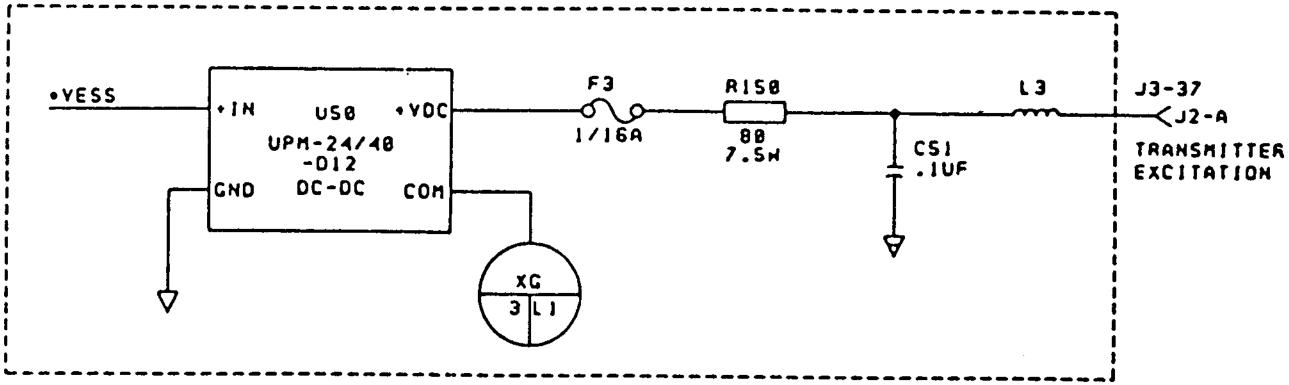


Figure 9.13. Transmitter Excitation Input - Analog Trip Module (ATM)

$$V_F = 43.8V$$

$$I_F = 1.5A$$

$$P_F = 65.9W$$

Using these values in the circuit and calculating back to the input pins gives circuit damage thresholds of:

$$V_T = 1.6 \times 10^2 V$$

$$I_T = 1.0 \times 10^2 A$$

$$P_T = 1.7 \times 10^4 W$$

Critical process parameters can also be input to the combinational logic from contact status closures. The input of these digital signals to the combinational logic is through the digital signal conditioning (DSC) boards. The signal input interface of the DSC board is shown in Figure 9.14. The inputs of the G001 card are for 24 VDC inputs; those of the G002 are for 125 VDC inputs. the most sensitive component for the 24 VDC input (G001) is the LED device in the 4N24A optical coupler. Using the methods of Section 7 the failure parameters of the LED are:

$$V_F = 33.1V$$

$$I_F = 2.8A$$

$$P_F = 92.9W$$

Calculation of circuit damage thresholds for this circuit based on these parameters yields:

$$V_T = 1.3 \times 10^6 V$$

$$I_T = 1.3 \times 10^9 A$$

$$P_T = 1.7 \times 10^{15} W$$

For the 125 VDC input (G002), the most sensitive component is the 1N4475 device. Using the methods of Reference 21 gives the failure parameters of the 1N4475 zener:

$$V_F = 78.1V$$

$$I_F = 180.4A$$

$$P_F = 1.4 \times 10^4 W$$

Calculation of circuit damage thresholds for this circuit based on these parameters yields:

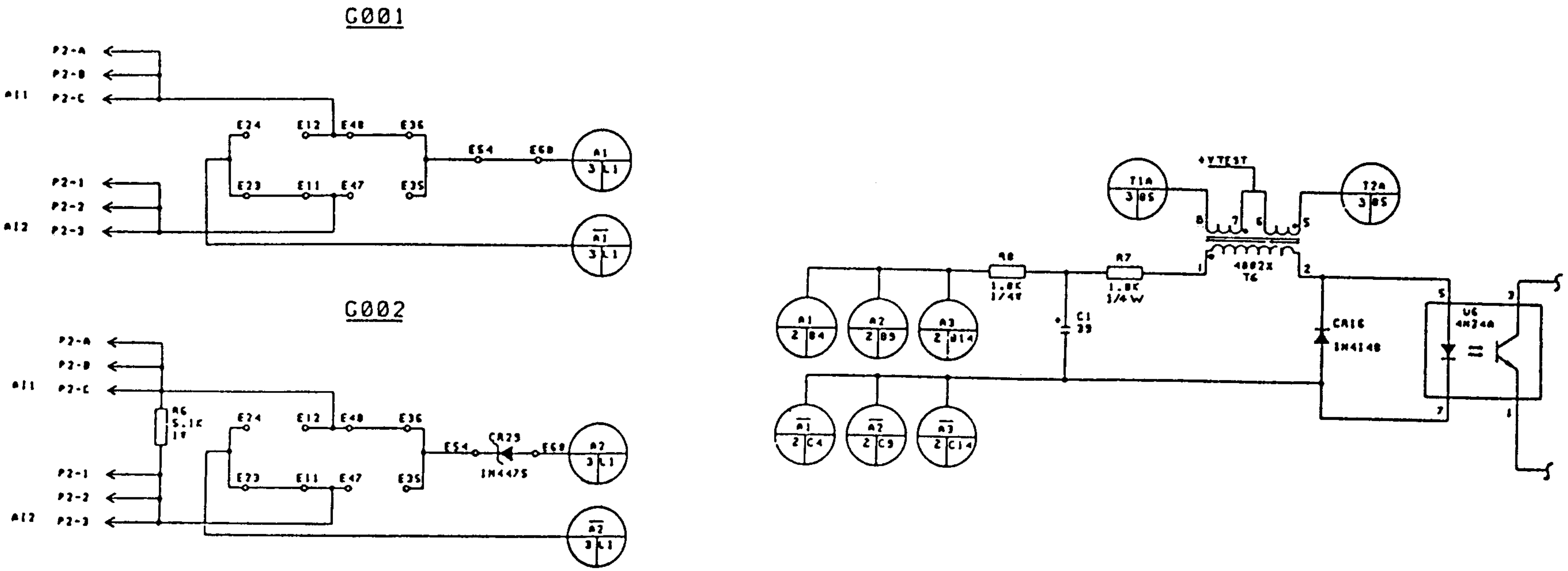


Figure 9.14. Input Interface Circuit - Digital Signal Conditioning Board

$$V_T = 1.8 \times 10^5 V$$

$$I_T = 2.2 \times 10^2 A$$

$$P_T = 3.9 \times 10^7 W$$

The NSPS decision logic modules are internal to the NSPS cabinet and have input and output that remain internal to the cabinet. Because of the layers of isolation between these circuits and a primary EMP drive point, these circuits are excluded from any further analysis.

EMP signals can be induced at the output of the AC/DC load drivers. Information was not available to determine circuit damage thresholds at these interfaces.

Power for the NSPS units is from a +12 VDC power supply mounted in the NSPS instrumentation rack. This power supply accepts 120 VAC, Class 1E power and outputs +12 VDC regulated power. The power supplies are made by Lambda Electronics and are the same as those used at Watts Bar; direct extension of the Watts Bar results are, thus, applicable. From Appendix B, the thresholds for these power supplies input are:

$$V_T = 3.1 \times 10^4 V$$

$$I_T = 2.1 \times 10^2 A$$

$$P_T = 6.6 \times 10^6 W$$

AC/DC Emergency Power System. The AC/DC Emergency Power System provides the power needed for safe shutdown systems as a backup to the normal source of electrical power and has a battery reservoir and a conversion system that provides continuous AC and DC output power. There are four system components that contain solid state semiconductor components:

- Diesel Generator Load Sequencer
- Diesel Generator Process Control Sensors
- Battery Charger
- AC Static Inverter

The Diesel Generator Load Sequencer is located in the diesel building in the loop between the diesel generator and medium-voltage switchgear. It is, therefore, sufficiently isolated to be excluded from further analysis.

The battery charger used at Clinton is the same type, model, and vendor (Power Conversion Products) as the charger used at Watts Bar. The circuit damage thresholds for the battery charger, then, are the same as for the charger used at Watts Bar. The values of the thresholds are (from Section 7 and Appendix B):

AC-Input: $V_T = 2.5 \times 10^4$ V

$I_T = 7.8 \times 10^5$ A

$P_T = 1.9 \times 10^{10}$ W

DC-Output: $V_T = 4.2 \times 10^2$ V

$I_T = 8.3 \times 10^3$ A

$P_T = 3.5 \times 10^6$ W

The AC static inverter used at Clinton is an Elgar model and type 752-1-101. No electrical schematic information was available for this inverter. Consequently, circuit damage thresholds could not be calculated for this equipment item.

All thresholds discussed above for Clinton were calculated assuming that the failure of the most sensitive semiconductor device was the primary failure mode of the circuit. It is clear that this is not the case. From the large values of the thresholds, it is clear that other phenomena such as arcing or other dielectric breakdown can be expected to occur before these levels are reached given that EMP-induced signals are large enough.

Palo Verde Nuclear Generating Station. There are seven systems necessary for safe shutdown. Four are considered totally isolated from an EMP primary drive point and are excluded from further analysis. The Reactor Trip System (RTS) is isolated in the reactor building/containment structure and is, thus, isolated and can be excluded from analysis. The Auxiliary Feedwater (AFW) System components are placed in the turbine building and reactor building. Critical solid state components are all sufficiently isolated from primary EMP drive points to be excluded from further analysis. The Chemical Volume and Control System (CVCS) components are placed inside the reactor building/containment structure and are isolated from the "outside world." The CVCS is, thus, excluded from further analysis. The Atmospheric Dump System (ADS) components are located outside the reactor containment upstream of the main steam isolation valves. Because these components are sufficiently isolated from "outside-world" connections, they are excluded from further analysis.

The three remaining systems considered for EMP susceptibility are:

- Emergency Power Distribution System
- Essential Cooling Water
- Engineered Safety Features Actuation System

Emergency Power Distribution System. The Emergency Power Distribution System provides backup power to the normal source of power with a battery reservoir and a conversion system that produces continuous AC and DC output power. There are four system components that contain semiconductor components:

- Diesel Generator Load Sequencer
- Diesel Generator Process Control Sensors
- Battery Charger
- AC Static Inverter

The Diesel Generator Load Sequencer is located in the diesel building in the loop between the diesel generator and medium-voltage switchgear. It is sufficiently isolated to be excluded from further analysis.

The battery charger used at Palo Verde is similar to that used at Watts Bar, but made by a different vendor (Solid State Controls, Inc.). Because no schematic information was available, circuit damage thresholds could not be determined for this equipment item.

The AC static inverter used at Palo Verde is similar to that used at Watts Bar and made by the same vendor (Solid State Controls, Inc.). Schematic information could not be obtained to verify that identical circuit designs were used and direct extension of Watts Bar results was not made.

Essential Cooling Water. The Essential Cooling Water (ECW) system transfers heat from critical plant components to the essential sprays (at the spray ponds). There are three system components that contain semiconductor components:

- Process Control Transmitters
- Process Control Instrumentation
- Alarms

The process control transmitters of this system measure flow rates at points within the ECW loop. These transmitters are of the Rosemont 1153 type discussed earlier.

The process control instrumentation that receives the information is located in the auxiliary control building in the process instrumentation rack. The signals are passed through I/I isolation before being sent to bistable trip units in the plant protection system rack. The I/I isolation is Foxboro 270 series instrumentation. No information was available from which to determine circuit damage thresholds.

The alarms for this system are in the control room. They are separated from the primary EMP drive point by several stages of fan-out. Therefore, they were excluded from any further analysis.

Engineered Safety Features Actuation System (ESFAS). The ESFAS is the system which contains the components involved in generating those signals required to actuate the ESF systems (containment isolation, containment spray, iodine removal, main steam isolation, safety injection, and emergency feedwater). There are four system components which contain semiconductors:

- Process Control Transmitters
- DC Power Supplies
- I/I Isolators
- Bistable Trip Units

Almost all process control transmitters are located near the pressurizer enclosure complex, and the steam generators. The only transmitter not sufficiently isolated to be excluded from analysis is a Rosemont 1153 discussed earlier which is located at the refueling water tank.

The I/I isolators that receive the transmitter output are located in the process instrumentation rack. These units are Foxboro 270-series instrumentation for which no schematic information was available so no circuit damage thresholds were calculated.

Power for the process instrumentation rack is supplied by the 120 VAC, Class 1E vital bus. This power is accepted by a Foxboro power supply which then outputs a regulated DC is similar in function to the Foxboro regulated DC power supply at Watts Bar. Schematic information was not available to verify that this was, indeed, the same power supply so extension of the calculated Watts Bar results cannot, therefore, be assumed.

Combustion-Engineering Systems

UNIPLEX System 600. The UNIPLEX System is a remote monitor and control system that is structured around a high-speed time-sharing serial data communications technology virtually immune to signal error, and isolated from electromagnetic transients. Because this system was not being implemented in any of the plants surveyed, the application of the analytical algorithm presented earlier cannot be made to this system. The identification of critical interfaces cannot be made without a specific plant architecture to screen.

Thus with no schematic data available and critical equipment interfaces not identified, circuit damage thresholds were not calculated. However, an indication of the EMP susceptibility of the EMP susceptibility of the UNIPLEX System can be gained by noting that the system components were qualified to the test specified in IEEE-STD-472, 1974/ANSI C37.90a, 1974: IEEE Guide for Surge Withstand Capability (SWC) Tests. The SWC wave is an oscillatory wave, frequency range of 1.0 MHz to 1.5 MHz, voltage range of 2.5 kV to 3.0 kV crest value of the first half cycle peak, envelope decaying to 50 percent of the crest value of the first peak in not less than 6 μs from the start of the wave. The source impedance of the surge generator used to produce the test wave is 150 Ω. The test wave is to be applied to a test specimen at a repetitive rate of not less than 50 tests per second for a period of not less than 2 seconds.

Though the UNIPLEX system components were subjected to and passed the SWC test, the EMP damage voltage thresholds of the equipment cannot be obtained from these test data without intimate knowledge of the equipment pin input impedances. The potential impedance mismatch between the test generator and the equipment interface can cause a voltage lower than the generator source voltage to appear across the circuit terminals. The constant of proportionality between these voltages is given by $Z_L/(Z_S + Z_L)$ where Z_L is the terminal input impedance and Z_S is the generator source impedance (150 Ω). It can be seen that if $Z_L << Z_S$, then the actual voltage appearing at the equipment input terminals is much less than the voltage available from the generator. Since the equipment input impedances were unavailable in this study, no statement of the EMP voltage damage thresholds of the UNIPLEX equipment can be made. However, due to the similarity of the test waveform to an EMP waveform the following statement of EMP susceptibility can be made: "The UNIPLEX system components that have qualified to the SWC test can be expected to survive an EMP transient waveform with a peak amplitude of 2.5 to 3.0 kV, a Q of 24, at a frequency of 1.0 to 1.5 MHz, and a source impedance of 150 Ω."

NUPLEX 80. The NUPLEX 80 advanced control design was developed by C-E and is characterized by extensive computer-based monitoring and information display systems. The full-scale implementation of the matured design was to have been made for TVA's Yellow Creek Units 1 and 2. The total NUPLEX 80 system can be broken into three general functional areas: monitoring systems, the safety system, and control systems. Because an implemented design was not surveyed, applications of the isolation screen was not possible and no critical interfaces were defined. No schematic diagrams was available and no critical interfaces were definable. Therefore, in this scoping exercise, no statement can be made about the EMP susceptibility of NUPLEX 80 equipment.

9.3.3 Conclusions on Damage Threshold Analysis. The objective of this effort was to characterize, to the extent possible, the effects of EMP on nuclear power plants in general based on the calculated results for the Watts Bar safe shutdown systems and on the inspections of the newer technology plants presently under construction. The data obtained in this study are insufficient to make a definitive statement on the generic EMP susceptibility of nuclear power plants. While it is true that types of equipment similar to Watts Bar equipment items were found at the various plants, not enough evidence (detailed schematics and parts lists) was available to state with authority that the Watts Bar nuclear plant susceptibilities are representative of the full spectrum of nuclear plant designs. It was demonstrated, however, that the methodology described herein provides a process by which this type of comparison can be performed.

9.4 Vulnerability Assessment for the Additional Plants

A vulnerability assessment for all three plants was not attempted for the following reasons:

1. Only the Palo Verde plant appeared to have major differences in coupling topology when compared with Watts Bar.

2. Detailed circuit information for many of the equipment items containing solid state devices is either considered proprietary or was not available in time.

3. Observations on the generic applicability of the Watts Bar results can not be made without doing complete studies on other plants.

However, because there are some significant differences between the estimates of EMP-induced signals at Palo Verde and Watts Bar, some observations on the potential vulnerabilities at Palo Verde follow.

Using the criteria discussed in Section 8.2 and the data presented in Section 9.2 for the Palo Verde response, the safety margins shown in Table 9.5 and 9.6 were estimated. It is obvious that the safety margins for Palo Verde are lower than those for Watts Bar. However, all the safety margins are positive for the equipment associated with essential ac power. Therefore, given the conservatisms discussed earlier, failures are not anticipated in this equipment. On the other hand, for some equipment associated with the spray pond pumps and valves safety margins are negative. Therefore, there is some reason for concern about the survivability of such equipment. But such concern must be tempered with the understanding that the ultimate heat sink, which at Palo Verde is the Essential Spray Pond System, is not the first line of decay heat removal if the plant is tripped because of loss of offsite power.[24] It should be recalled that we have assumed that there is a plant trip in the presence of EMP because of other effects on the grid. At Palo Verde for example, the Auxiliary Feedwater System is designed to provide for decay heat removal at hot shutdown for a minimum of 8 hours after reactor trip. Also, as noted in Section 9.2, if more detail is included in the control building/auxiliary building model, it is anticipated that the predicted responses will be lower. Therefore, as noted in the Watts Bar portion of the study, the possible loss of individual components in redundant systems does not preclude safe shutdown.

Table 9.5. Safety Margin Predictions for Essential AC Power Equipment

Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Transformer 4160/480 V	AC Input	4160 V	10X	4400 V	20
Essential Chiller	AC Input	4160 V	10X	1500 V	29
Essential Cooling Water Pump	AC Input	4160 V	10X	1500 V	29
Normal Chiller	AC Input	4160 V	10X	1500 V	29
Aux. Feedwater Pump	AC Input	4160 V	10X	1500 V	29
Fuel Pool Cooling Pump	AC Input	480 V	10X 3X	520 V	19 9
Charging Pump	AC Input	480 V	10X 3X	520 V	19 9
Containment Normal ACU Fan	AC Input	480 V	10X 3X	520 V	19 9
CEDM Normal ACU Fan	AC Input	480 V	10X 3X	520 V	19 9
Control Room Essential AHU	AC Input	480 V	10X 3X	520 V	19 9
Main Essential Lighting Panel	AC Bus	480 V	10X 3X	600 V	18 8
Motor Control Centers	AC Bus	480 V	10X 3X	600 V	18 8

Table 9.6. Safety Margin Predictions for PVNGS Spray Pond Equipment

Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Essential Spray Pond Pump	AC Input	4160 V	10 X	1800 V	27
Pump Bearing Oil Heater and Pump Space Heater	AC Input	120 V	10 X 3 X	1000 V	1.6 -8.9
Spray Header Inlet MOV	AC Input	480 V	10 X 3 X	5000 V	-0.4 -10.8
Spray Header Inlet Status Switches	Control Status Output	120 V	10 X 3 X	5000 V	-12.4 -22.9
Spray Header Bypass MOV	AC Input	480 V	10 X 3 X	5000 V	-0.4 -10.8
Spray Header Bypass Status Switches	Control Status Output	120 V	10 X 3X	5000 V	-12.4 -22.9
Motor Control Center (for Essential Spray Pond)	120/240 V Bus	120 V	10 X 3 X	112 V	20.5 10.1
Motor Control Center (for MOVs)	Status Indicator	120 V	10 X 3 X	135 V	18.9 8.5
Safety Equipment Status System (SESS)	Logic	24 V	3 X	67 V	0.6
	Status Switch Input	24 V	3 X	112 V	-3.8

10.0 Summary, Conclusions, and Recommendations

10.1 Study Approach

An analytical study was conducted on the potential interaction of the electromagnetic pulse from the high altitude detonation of a nuclear weapon with a commercial nuclear power plant and selected safe shutdown systems. The objective was to identify any undue sensitivities to EMP and recommend remedies where appropriate. The first step in this process was to examine a single example plant in detail to explore and define EMP coupling mechanisms and equipment damage thresholds. Signal upset was not considered in this study, only equipment failure. The second step was to extend these results to other nuclear plants in order to generalize the results. Each of these efforts is summarized separately below.

10.2 Example Plant Analysis

The study considered three potential paths for EMP interaction with the plant. Penetration of diffused fields into the facility was examined analytically and experimentally. After a review of construction drawings and site inspections, it was concluded that the structures offered shielding of at least 30 dB, and probably more. Subsequent tests confirmed this conclusion. EMP coupling with the power grid and onsite cabling was also examined. Cable routings and potential signal penetration points were identified and examined. The currents induced by EMP were estimated and their penetration into the plant interior traced. The estimates account for other cables in duct banks and cable trays, grounding paths and other paths for signal propagation. Inside the plants, the penetration currents were reduced by attenuation along cable runs and by ohmic losses, multi-moding, and breakout distribution. It was established that the principal source of EMP-induced signals is the excitation of the onsite buried cabling. The study includes current and voltage predictions for approximately 100 points on safety-related loads.

Early predictions suggested that EMP-induced signals would be well below nominal operating voltages for heavy duty equipment (ac motors, transformers, etc.) so the main effort in estimating damage thresholds was directed toward equipment containing solid state devices. This decision was also based upon experience which indicates that semiconductor devices are usually the most EMP susceptible components. This led to consideration of the battery chargers, inverters, regulated power supplies, process instrumentation, and controls. In general, the estimated thresholds are well above anticipated signal levels. The ranges of the predicted EMP responses and damage threshold predictions are summarized in the following table.

Table 10.1.

Summary of Analytical Predictions

Items	Predicted EMP Signal (V_R)	Predicted Damage Thresholds (V_T)
6.9 kV Equipment	50-500 V	60 kV*
480 V Equipment	2-100 V	1.4 kV**
125 VDC/120 VAC Equipment	2-100 V	70 V-9.3 GV***
Instrumentation	10 V	50 V-50 MV***

---

*Damage threshold assumed (conservatively) at 60 kV based upon Basic Impulse Level values for such equipment.

**Damage threshold assumed (conservatively) at 3X nominal operating level.

***Because these computed damage thresholds are so high, it is assumed (conservatively) in the vulnerability analysis that other circuit phenomena such as dielectric breakdown or arc-over could occur at 3X operating voltages given sufficiently large driving signals even though such events may not fail equipment.

When the individual response predictions and damage threshold estimates are combined, the minimum safety margin (SM) observed for safe shutdown equipment in the example plant is 16 dB, where $SM = 20 \log V_T/V_R$, with the bulk (>80%) being greater than 40 dB.

A limited number of tests were conducted to verify the analytical response techniques. Selected cables in the facility were driven by directly coupling an RF signal to the cable by a current transformer. The induced currents were observed at the points of interest and a transfer function derived. When this transfer function is used with the appropriate driving function, the induced current amplitude in the time domain can be established. The peak amplitudes thus derived were compared with pretest predictions to establish confidence in the basic analytical procedures. For this study, the results indicate that on the average the interior current fan out predictions are modestly conservative (1-2 dB) when compared to measurements. Additional tests were conducted to search for inadvertent or unexpected cable penetrations, and none were located.

10.3 Additional Plant Analysis

The extension of the analysis of the example plant to three additional plants proceeded along two parallel paths. On the one hand, features and configurations that were important to EMP coupling in the example plant were compared to those observed in the added plants. At the same time, equipment in safe shutdown systems of these plants which contain solid state components were identified, damage thresholds estimated where possible, and results compared to the example plant.

The analysis revealed no new coupling paths at the plants visited. Indeed, some penetrations, such as the diesel generator building to auxiliary building cabling, were eliminated by virtue of the plant design; in these plants the two buildings are contiguous. However, it was observed that average EMP-induced responses at several analogous locations are higher at Palo Verde than at Watts Bar. In fact, some predicted responses are high enough to suggest that arc-over to ground may occur in some systems. Again, such arc-overs are not necessarily indicative of system failures. Also, at Palo Verde the systems potentially affected are not the first line of decay heat removal in the event of reactor trip.

The plant visits revealed that in these plants many systems use equipment comparable to that seen at the Watts Bar plant and in many instances it is identical equipment. In those instances where data was available to use in estimating damage thresholds, the values computed are comparable to those for Watts Bar. Again, circuit thresholds for damage to solid state devices exceed levels at which other circuit phenomena can occur such as arc-over, dielectric failure, etc. This effort was handicapped by the fact that circuit information on several sensors which appeared frequently in the additional plants is considered proprietary by the equipment vendor.

10.4 Conclusions

Based upon the analyses performed on the example plant and the three additional plants, the following specific conclusions were reached:

1) Diffuse fields inside Seismic Class 1 or structurally equivalent buildings due to the incident plant wave are negligible sources of EMP energy.

2) The principal sources of EMP energy coupled to critical circuits in the plant are currents induced by the incident EMP on external cables which then penetrate into the plant buildings. These EMP signal entry points are readily identifiable.

3) Attenuation of EMP-induced signals in the plant electrical circuitry can be reasonably modeled.

4) Damage thresholds for the components examined are substantial. These thresholds are high enough that if EMP-induced signals approach threshold levels, other phenomena (arc-overs for example) will occur before device failure.

5) Predicted EMP-induced signals at the critical equipment in the example plant are substantially less than nominal operating levels. The likelihood that individual components examined will be failed is small.

6) The analysis methods used in the example plant can be extended to plants in general, and no new coupling paths were found in the examination of the additional plants.

7) Plant topology and cabling practice have a strong influence on EMP-induced response. Response levels at some plants may be higher than those estimated for the example plant. Therefore, discretion must be used in extending the example plant results to other plants.

8) The magnetohydrodynamic (MHD) EMP, which follows and is of much longer duration but lower intensity than the immediate EMP, is not a serious threat to the safe shutdown capability of nuclear power plants.

9) Signal generators capable of producing EMP-like effects employed by terrorists or saboteurs are not considered to be a significant threat to the safe shutdown capability of nuclear power plants.

These specific conclusions provide a reasonable basis for the following summary conclusions:

- The safe shutdown capability of the example plant would not be disabled by an EMP event.

- In view of the similarities in the design and construction of nuclear power plants, and based upon the conservatisms in the analyses, it is the technical judgement of the study team that the safe shutdown capability of nuclear power plants in general would survive the postulated EMP event. However, greater uncertainty is associated with this judgement when applied to those plants which include design features that enhance coupling with incident EMP (e.g., unshielded overhead or buried electrical cables between the main building and satellite structures).

10.5 Comparison of Program Objectives and Conclusions

As stated in Section 1.2, this program was established as a scoping study with three objectives:

1. Determine the vulnerability of systems required for safe shutdown of a specific nuclear plant to the effects of EMP.

2. Establish how any safe shutdown systems vulnerable to EMP may best be hardened against it.

3. Characterize to the extent possible, the effects of EMP on nuclear plants in general based upon the results for systems in the example plant.

In addition, as noted in Section 1.5, certain constraints and assumptions were adopted early in the study to keep the problem tractable. The three most important are:

1. The study is limited to those systems required for safe shutdown of the nuclear plant.

2. The study is based upon a "worst case" EMP threat situation. That is, it was assumed that the incident EMP plane wave embodied a bounding peak field intensity and an orientation relative to the plant systems such as to optimally excite every point of interaction. No singular nuclear burst can be targeted to accomplish this even for one nuclear power plant.

3. Permanent damage was the failure criterion used to assess system vulnerability; that is, signal upset effects were not considered.

The results of the study must be viewed in light of the objectives and the constraints and assumptions.

The analysis called for in the first objective has been completed. The results indicate that although the nuclear power plant is complex, it can be analyzed in a straightforward and reasonable manner. The analyses further shows that peak EMP-induced signal levels at the points of interest are below the nominal operating levels and therefore no damage is expected. As noted in Section 8.6, if no component fails, the system does not fail.

Because no system failures were identified in the analyses, no effort was made to suggest hardening approaches. It should be noted, however, that identification of plant design features that are susceptible to EMP is intrinsic to the analysis methods used. These same methods also provide insights into appropriate means of adding protection or hardening systems if such measures are required. In both instances, features at the topological, structural, system and component levels are included. If EMP protection should be required in other applications, there are numerous methods availble for EMP protection which are documented (References 4 and 20, for example).

The study was extended to several other plants in order to reach some general conclusions. The analytical technique used is applicable in other situations, and the coupling mechanisms analyzed at Watts Bar appear to be representative in that no new paths were found. On the other hand it was observed that plant topology and cabling practice can strongly influence the EMP-induced response. Response levels at particular locations in some plants may be higher than those estimated for Watts Bar. Nevertheless, safe shutdown should be possible.

10.6 Recommendations for Further Study

From the results of the damage threshold portions this study, four areas may merit further consideration in order to evaluate the response of a typical nuclear power plant to an EMP. These areas are: (1) completion of the application of the damage threshold methodology to the selected facilities, (2) evaluation of the applicability of other EM design specifications to nuclear plant design and their implications for EMP mitigation, (3) performance of an engineering test program to validate the threshold calculations, and (4) evaluation of EMP-induced operational upsets. These are discussed separately in the following paragraphs.

10.6.1 Baseline Completion. The damage threshold analysis method described here provides a reasonable vehicle by which to determine whether in-depth studies should be conducted of other plants. More complete analysis of equipment not covered in Section 9 will provide a better baseline for answering the question of the extensibility of the Watts Bar results to other plants.

10.6.2 Other EM Specifications. Other EM specifications that presently are being applied to nuclear systems (EMI, lightning, etc.) can afford some protection from EMP. These specifications should be investigated to examine EMP mitigation implications inherent in the compliance to these specifications. An example would be to further investigate the implications of the IEEE-STD-472 tests and further explore whether a provision for a lower bound on an EMP threshold can be determined. It is recommended therefore, that other EM specifications be examined to determine if any inherent EMP protection is provided by complying with these specifications.

10.6.3 Engineering Tests. It was determined in this study that circuit damage thresholds, for the most part, were high. It is clear, especially in the cases of calculated voltage thresholds greater than 2-3 kV, that arcing or other dielectric breakdown of passive components may be expected to occur first given sufficiently high driving signals. To determine analytically the levels at which arcing phenomena occur is intractable. If further investigation of the circuit damage threshold mechanisms is desired, the support of an engineering test program is required and, thus, recommended.

10.6.4 EMP-Induced Upsets. The nuclear power industry and the Nuclear Regulatory Commission have been, and continue to be, concerned with the potential plant operational upsets that have been observed to occur due to electrical transients from various sources such as switching, inductive surges, lightning, and other sources of electromagnetic interference. The results of the previous and ongoing studies relating to transient-induced operational upset combined with the evaluation of current or proposed transient tolerance specifications will permit the identification of the unique upset implications of an EMP threat and the identification of areas of investigation (including required tests) that should be considered if it is found that EMP transients can produce upset modes that are unlikely to be mitigated as a result of existing studies or specifications.

The drive characteristics of EMP-induced transients (identified by the IRT/Boeing portion of this study) can form the basis for determining if EMP drive modes are significantly different (worse) than other transient sources. It is recommended that EMP-induced operational upsets be studied, in the light of previous and ongoing studies, to determine any unique upset implications of EMP.

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APPENDIX A

ELECTROMAGNETIC COUPLING MODELS

In order to compute predictions for the complement of equipment identified as being critical to safe plant shutdown, five electromagnetic coupling models were developed. These diagrams detail the electrical connectivity from penetrations of EMP energy to equipment interface terminals and were originally the analysts worksheets. They are included here in order to provide additional insight into the technique involved in producing abbreviated predictions. The purpose of including them is to show overall trends in attenuation and distribution fanout of the threat current as it couples inward from the penetrations to the critical equipment.

In the diagrams the analysis can be seen to progress on two levels. The top level analysis sets the lower bound on the prediction current distribution with a $1/N$ analysis as explained in Section 4.1 while the bottom level analysis sets the upper bound on the prediction current distribution with a $1/\sqrt{N}$ analysis. Both upper and lower bound open circuit voltage predictions are computed at the equipment interfaces with estimates of cable source impedances and short circuit currents. The geometric mean of these upper and lower bound estimates produces the actual open circuit predictions.

A key diagram, interpreting certain symbols used in the model diagrams, appears in Figure A-1. Figures A-2 through A-6 present the following five coupling models:

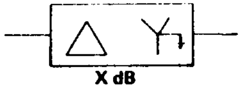
1) 500 kV Transmission Line Model - This model details the coupling analysis from EMP currents generated on the 500 kV transmission lines to critical equipment located in the Auxiliary Building.

2) Intake Pumping Station Model - This model details the coupling analysis from the EMP currents generated on buried conduit duct banks to critical equipment located in the Intake Pumping Station.

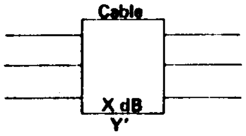
3) Diesel Generator Building Model - This model details the coupling analysis from the EMP currents generated on buried conduit duct banks to critical equipment located in the Diesel Generator Building.

4) Auxiliary Building (D.G. Bldg. Source) Model - This model details the coupling analysis from the EMP currents generated on buried conduit duct banks connecting the Diesel Generator Building to critical equipment located in the Auxiliary Building.

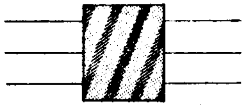
5) Auxiliary Building (Pump Station Source) Model - This model details the coupling analysis from the EMP currents generated on buried conduit duct banks connecting the Intake Pumping Station to critical equipment located in the Auxiliary Building.



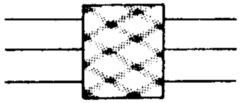
Indicates 60Hz transformer having delta/wye connections with X dB of EMP attenuation across the transformer.



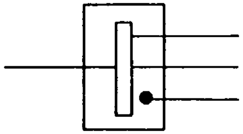
Indicates a section of distribution cable having a length of Y in feet with X dB of EMP ohmic and cross-coupling attenuation. Cables are grouped according to similar lengths and electrical connectivities.



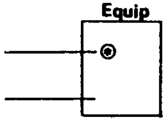
Indicates cables have a helically wound overlapping foil shield.



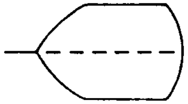
Indicates cables have a braided shield.



Indicates a power distribution bus board showing groupings of similar load types. Loads normally connected and normally disconnected are shown.



Indicates equipment connections to distribution cables.
⊙ indicates the location of an item of critical equipment for which a prediction has been computed.



⇦ Lower bound open-circuit voltage prediction (and estimated source impedance if applicable)

⇦ Upper bound open-circuit voltage prediction.

A	Amps
A/Ca	Amps per Cable
ACM	Amps Common Mode
C	Conductors
CR	Circuit Breaker Control Relay
kA	Kiloamps
kV	Kilovolts
V	Volts
ϕ	Phase

Figure A-1. Symbol Interpretations for Electromagnetic Models

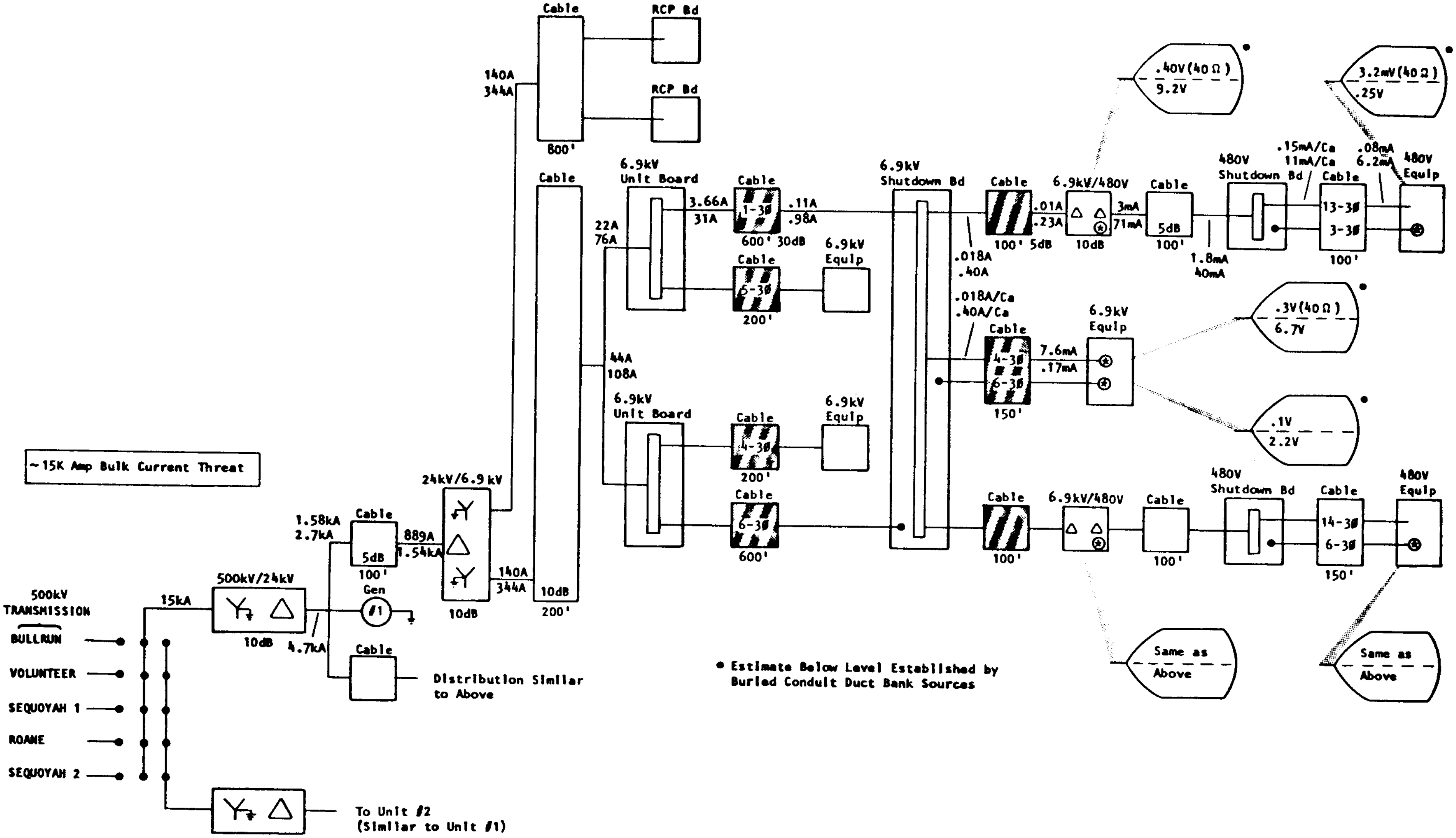


Figure A-2a. 500 kV Transmission Line Model

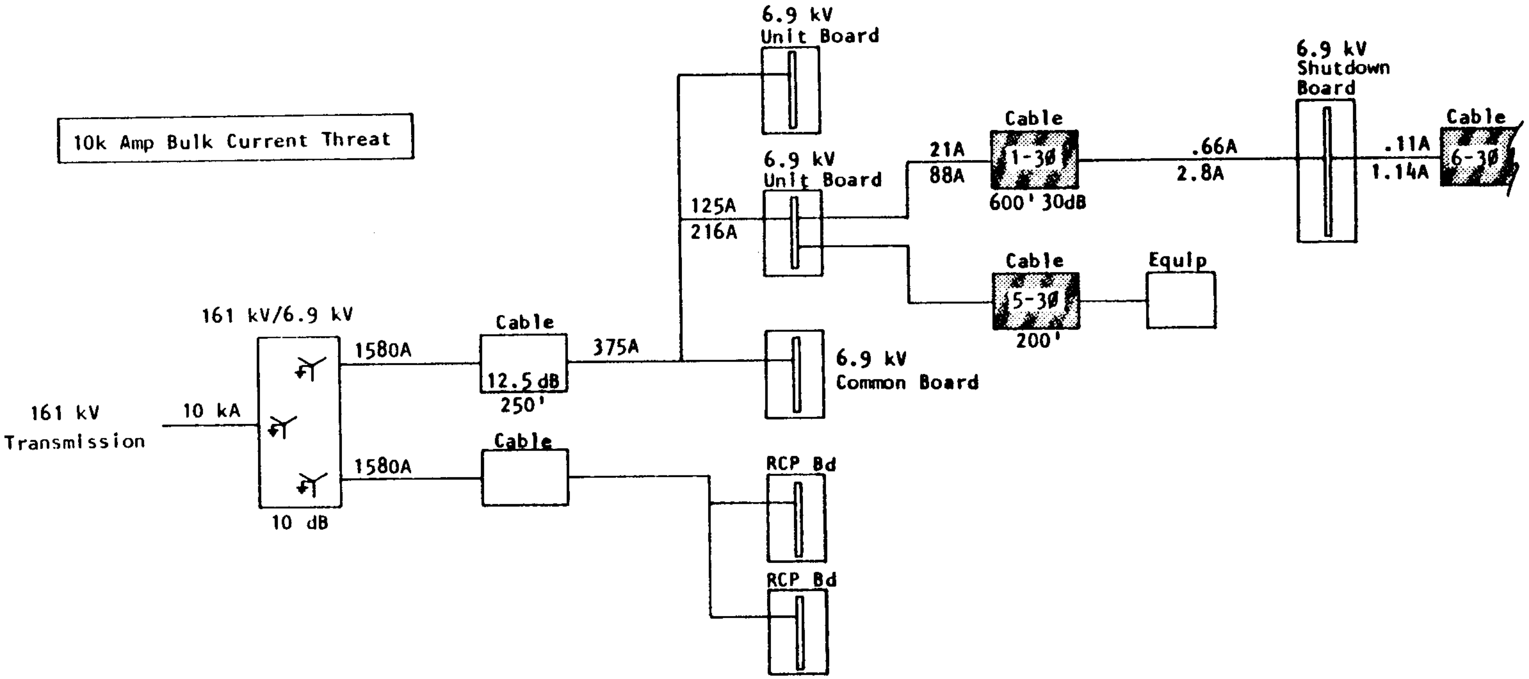


Figure A-2b. 161 kV Transmission Line Model

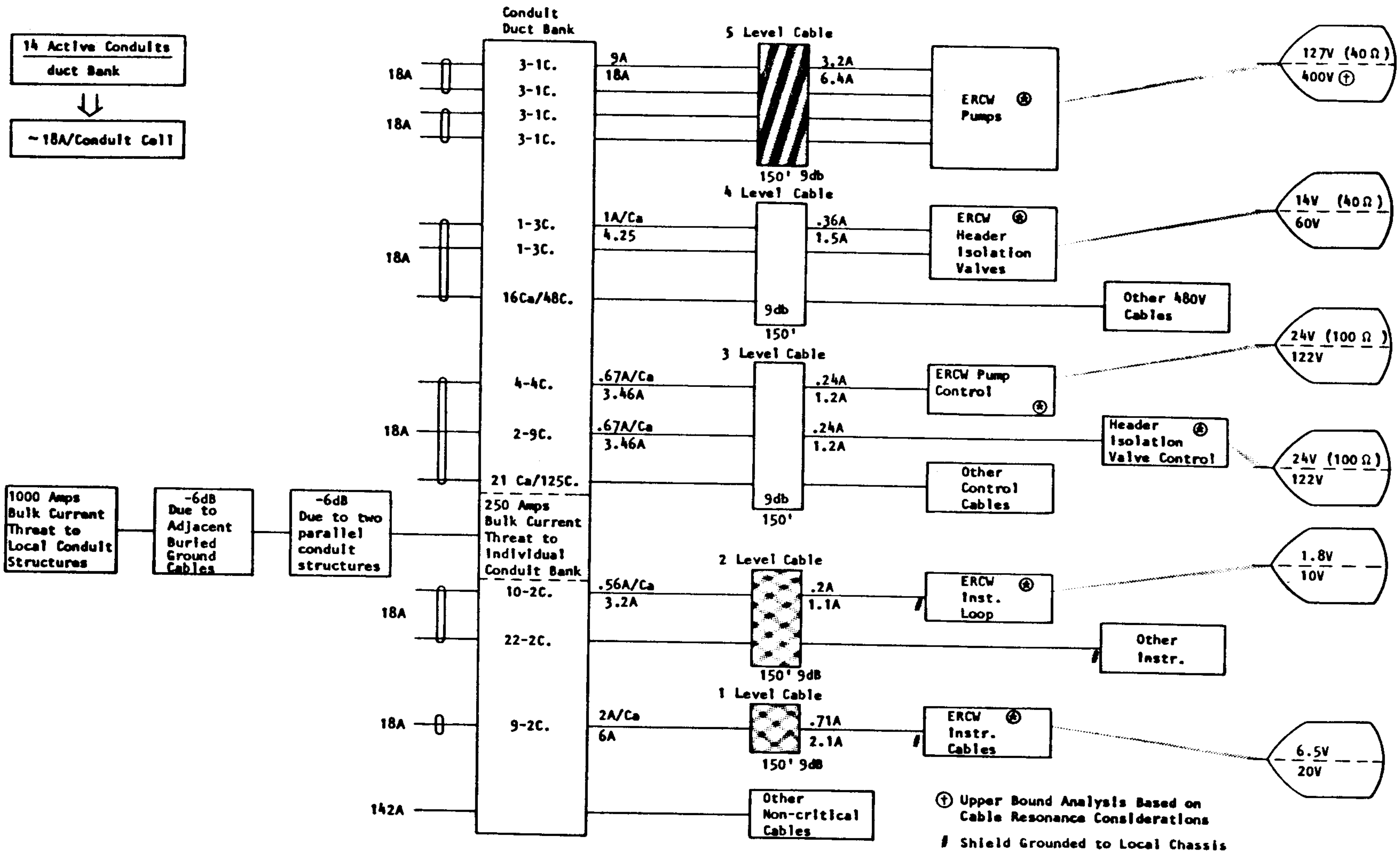


Figure A-3. Intake Pumping Station Model

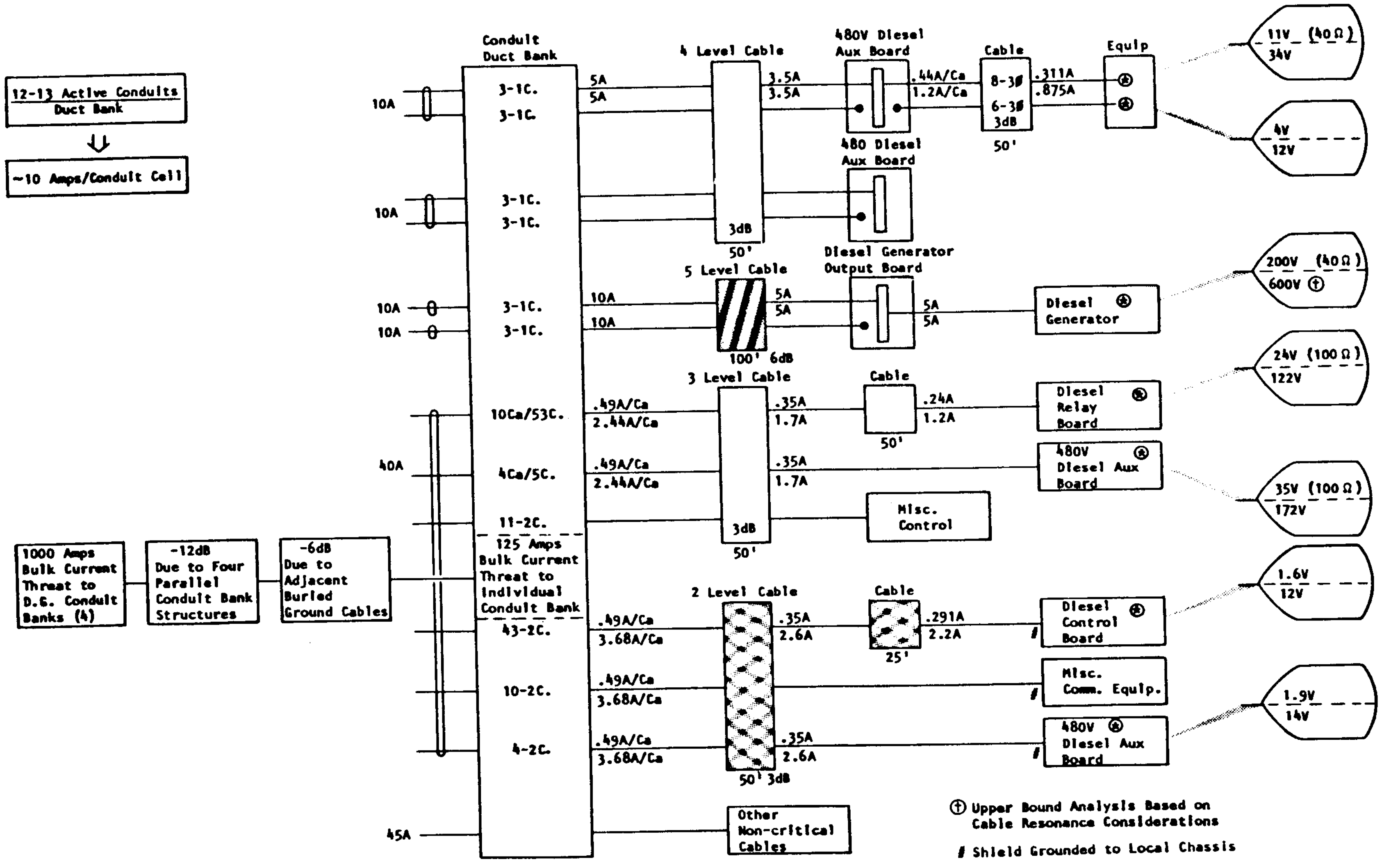
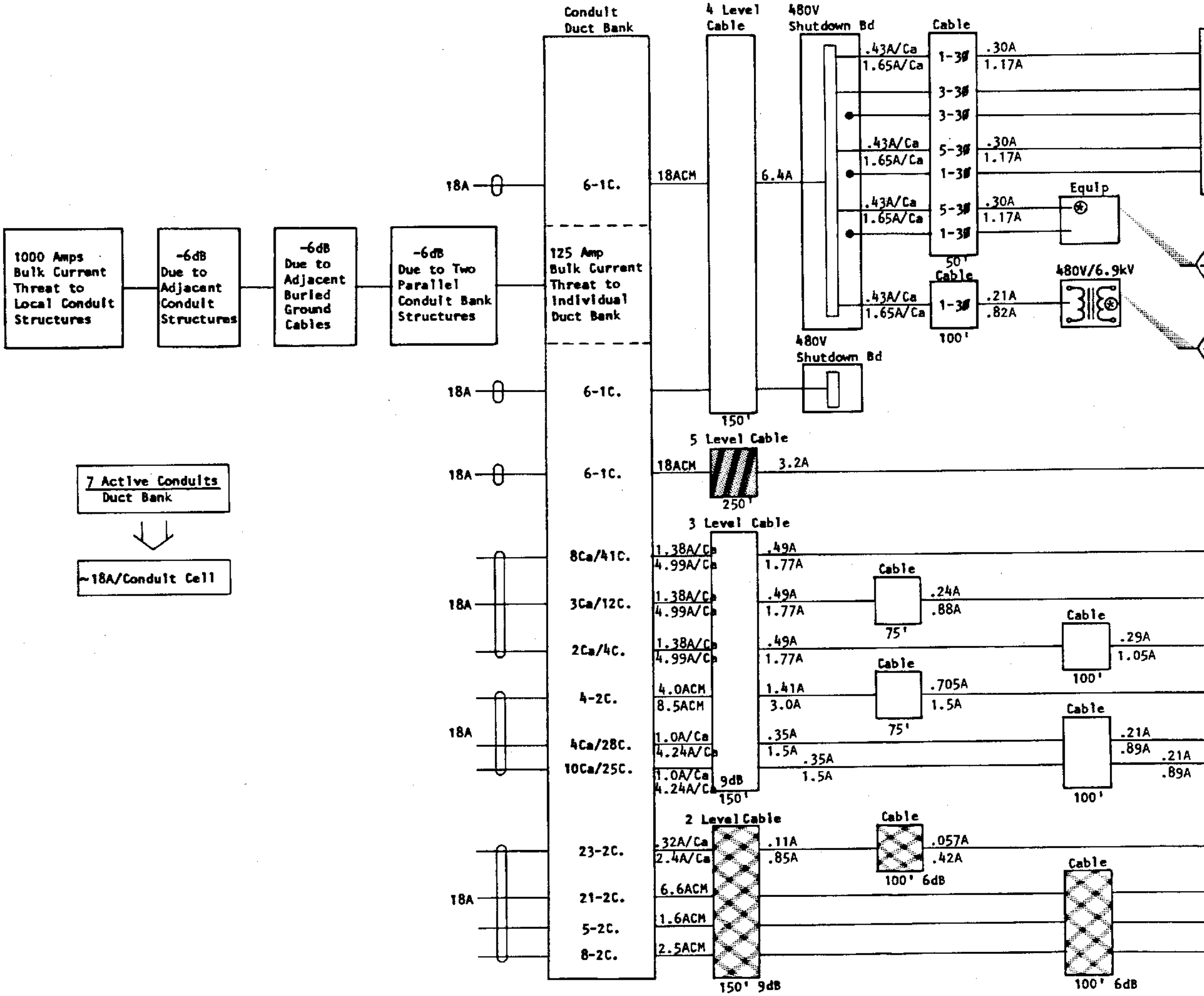


Figure A-4. Diesel Generator Building Model



1000 Amps Bulk Current Threat to Local Conduit Structures
-6dB Due to Adjacent Conduit Structures
-6dB Due to Adjacent Buried Ground Cables
-6dB Due to Two Parallel Conduit Bank Structures
7 Active Conduits Duct Bank
~18A/Conduit Cell
Conduit Duct Bank
125 Amp Bulk Current Threat to Individual Duct Bank
18A
6-1C.
6-1C.
6-1C.
8Ca/41C.
3Ca/12C.
2Ca/4C.
4-2C.
4Ca/28C.
10Ca/25C.
23-2C.
21-2C.
5-2C.
8-2C.
18ACM
6.4A
4 Level Cable
150'
480V Shutdown Bd
.43A/Ca
1.65A/Ca
Cable
1-3Ø
3-3Ø
3-3Ø
5-3Ø
1-3Ø
5-3Ø
1-3Ø
50'
1-3Ø
100'
.30A
1.17A
.21A
.82A
Equip
480V/6.9kV
5 Level Cable
18ACM
3.2A
250'
3 Level Cable
1.38A/Ca
4.99A/Ca
.49A
1.77A
4.0ACM
8.5ACM
1.41A
3.0A
1.0A/Ca
4.24A/Ca
.35A
1.5A
9dB
150'
.24A
.88A
75'
.29A
1.05A
100'
.705A
1.5A
75'
.21A
.89A
100'
2 Level Cable
.32A/Ca
2.4A/Ca
.11A
.85A
6.6ACM
1.6ACM
2.5ACM
150' 9dB
.057A
.42A
100' 6dB
100' 6dB

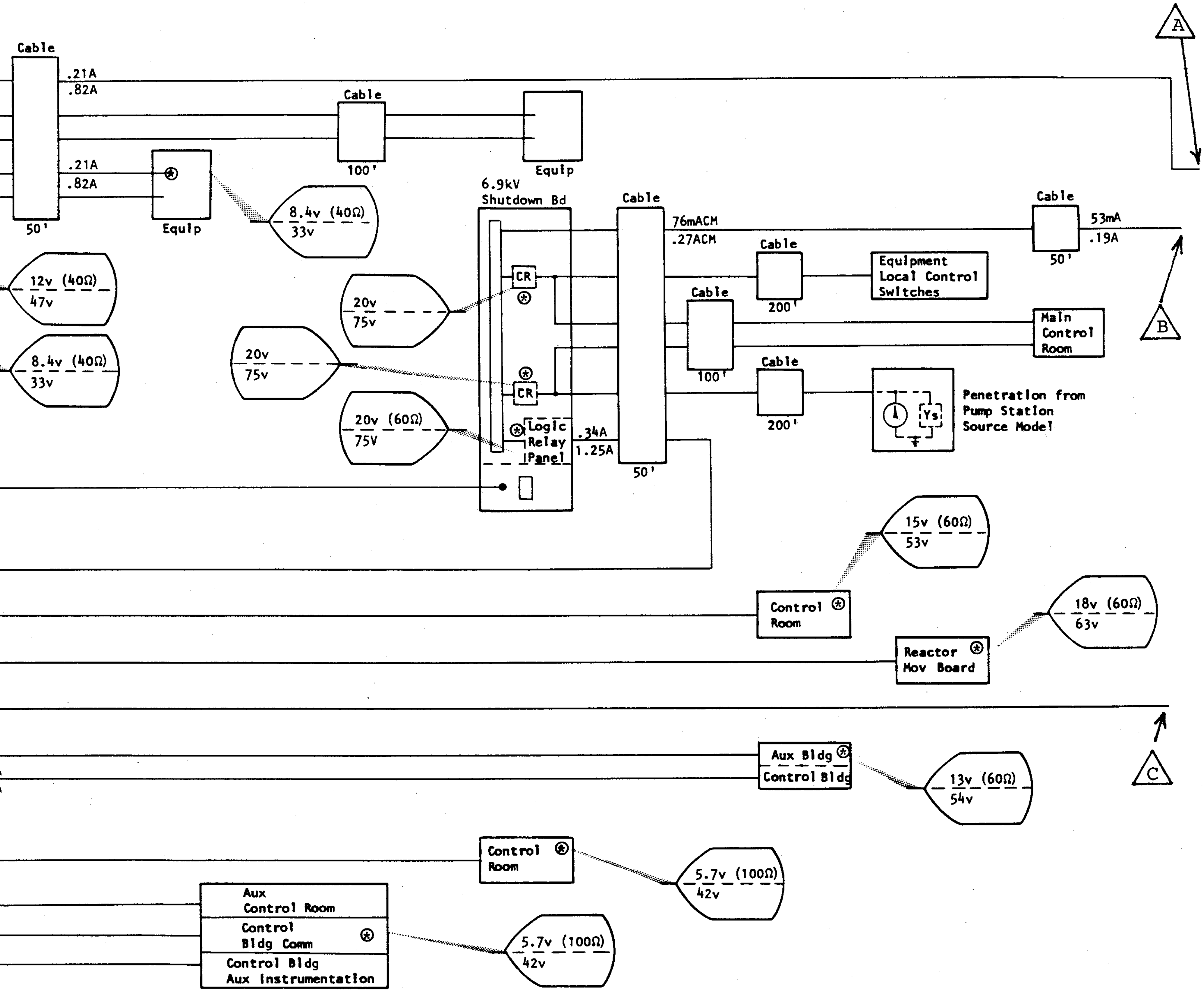


Figure A-5. Auxiliary Building (D. G. Building Source) Model

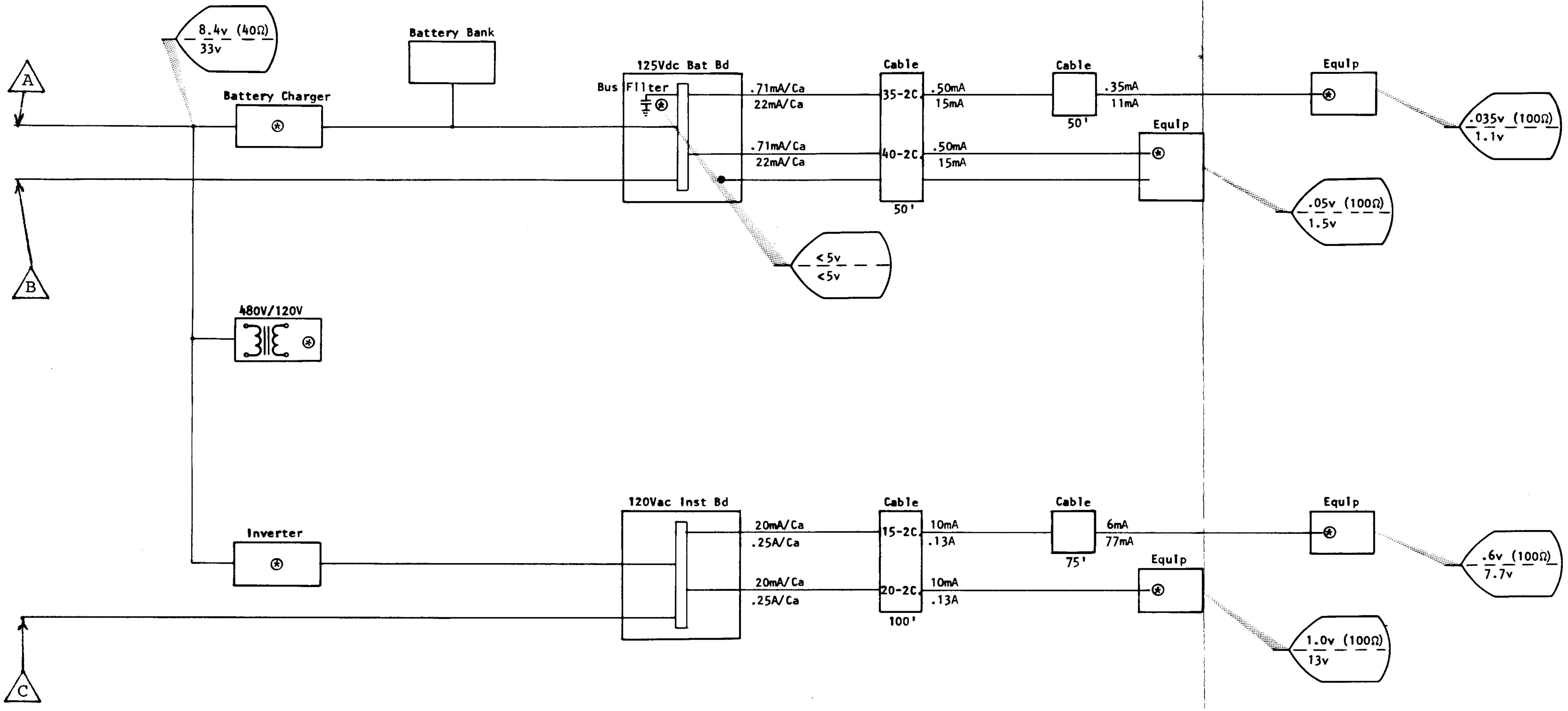
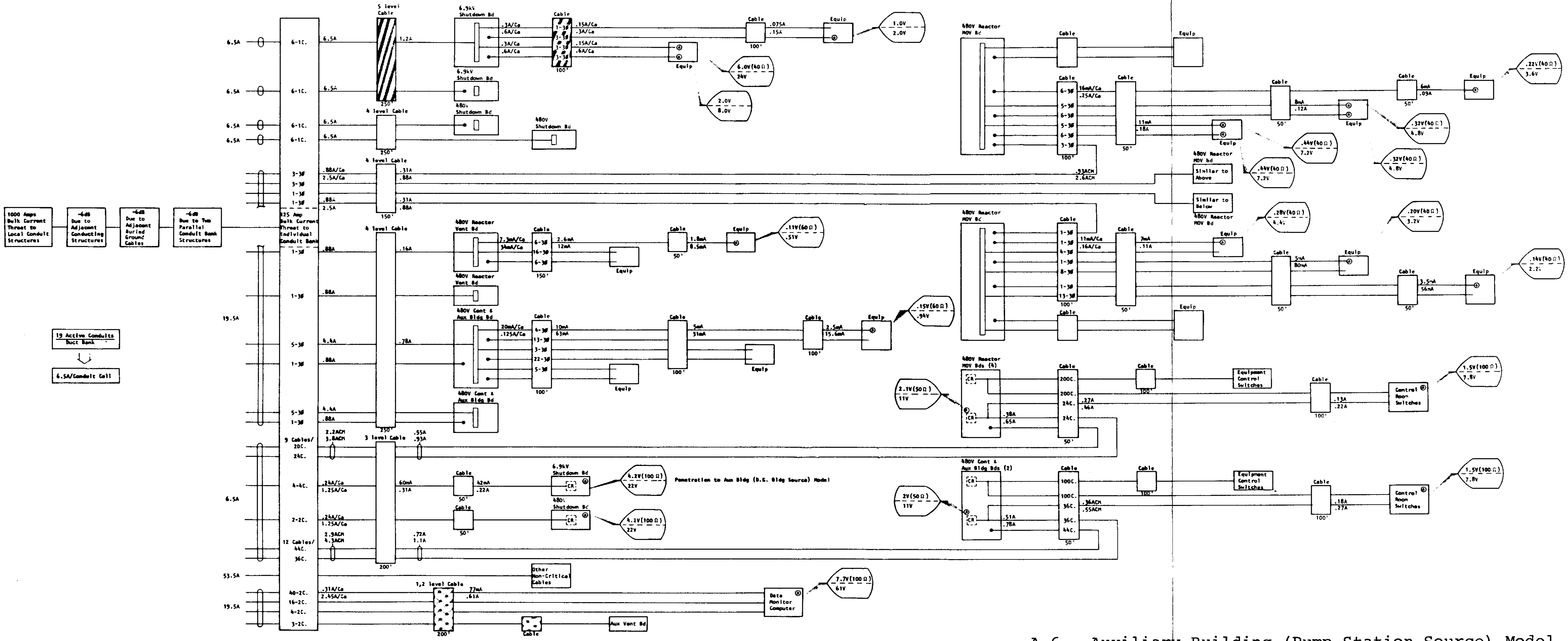


Figure A-5. Auxiliary Building (D.G. Building Source) Model (Continued)



A-6. Auxiliary Building (Pump Station Source) Model

APPENDIX B

EQUIPMENT DAMAGE THRESHOLD SUMMARIES

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: BOX: AGASTAT TIMING RELAYS

	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	NO. REF.
		7012PD	2.142×10^7	1.142×10^4	2.447×10^{11}	1.0	2.142×10^7	1.142×10^4	2.447×10^{11}	1.876×10^3	45.4
		7012AC	3.828×10^6	3.647×10^4	1.396×10^{11}	1.0	3.828×10^6	3.647×10^4	1.396×10^{11}	104.963	45.4

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** INSTRUMENTATION LOOP **BOX:** ANALOG MUX RELAY CARD G05

	COMPONENT FAILURE DATA					FREQ.	CIRCUIT DAMAGE PARAMETERS				CALC.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	(MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	NO. REF.
X_1-X_{12}	RELAY CONTACTS (NO FURTHER ANALYSIS)										
$X_{13}-X_{16}$	NO CONNECTION										
$X_{17}-X_{32}$	RELAY CONTACTS (NO FURTHER ANALYSIS)										
L1	NOT USED										
L2-L4	RELAY CONTACTS (NO FURTHER ANALYSIS)										
H2-H14	845A343-6 Sh. 21	D6-1	328.547	2.307	757.972	1.0	336.347	18.267	6.144×10^3	18.413	42.6

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** INSTRUMENTATION LOOP **BOX:** ANALOG MUX RELAY CARD GO2 (CONT)

	COMPONENT FAILURE DATA						CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
x_3, x_7 x_{11}, x_{19} x_{23}, x_{27} x_{31}, L3	845A343-5 Sh. 15	D6-40	328.547	2.307	757.972	1.0	5.557×10^7	5.052	2.808×10^8	11×10^6	44.3

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: ANALOG MUX RELAY CARD G02

	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
H1	845A343-5 Sh. 15	D6-39	328.547	2.307	757.972	1.0	7.345×10^4	2.538×10^1	1.864×10^6	2.894×10^3	43.6
H2-H4	845A343-5 Sh. 15	D6-1, D6-3,									
		D6-5, D6-7									
		D6-9, D6-11	328.547	2.307	757.972	1.0	3.363×10^2	1.827×10^1	6.144×10^3	18.407	42.6
		D6-13									
L1, H17	CIRCUIT	RETURN									
X_{13}-X_{16}	NO CONNECTION										
X_1, X_4											
X_5, X_8											
X_9, X_{12}											
X_{17}, X_{20}											
X_{21}, X_{24}											
X_{25}, X_{28}											
X_{29}, X_{32}											
L2											
X_2, X_6											
X_{10}, X_{18}											
X_{22}, X_{26}											
X_{30}, L4											

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: ANALOG MUX RELAY CARD G01

	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
X_1-X_{12}	RELAY CONTACTS (NO FURTHER ANALYSIS)										
$X_{13}-X_{16}$	NO OUTSIDE	CONNECTION									
$X_{17}-X_{32}$	RELAY CONTACTS (NO FURTHER ANALYSIS)										
L1	NOT USED										
L2-L4	RELAY CONTACTS (NO FURTHER ANALYSIS)										
H2-H14	Sh. 14 845A343-5	D6-1	328.547	2.307	757.972	1.0	336.347	18.267	6.144×10^3	18.413	42.6
H17	CIRCUIT RETURN										

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** INSTRUMENTATION LOOP **BOX:** REGULATED POWER SUPPLY

TB1	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1	LCS-2-01	CR1	154.816	19.478	3.016×10^3	1.0	3.101×10^4	2.143×10^2	6.644×10^6	144.704	40.2
2	CIRCUIT RETURN										
3	SENSOR SIGNAL (NO CONNECTION)										
4	CIRCUIT RETURN										
5	GROUND										
6	LCS-2-01	CR7	154.816	19.478	3.016×10^3	1.0	1.548×10^2	4.572×10^4	7.079×10^6	3.386×10^{-3}	41.18
7	SENSOR SIGNAL (NO CONNECTION)										
8	P.O.SIGNAL	(NO CONNECTION)									

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: I/I ISOLATOR

J1	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1-4	NOT USED										
5	SPS-610151	Z2	45.290	2.901	131.376	1.0	2.355×10^2	1.509×10^2	3.554×10^4	1.561	37.3
6	CIRCUIT RETURN										
7	COMMON										
8	SPS-610151	Z1	45.290	2.901	131.376	1.0	2.901×10^5	2.904×10^3	8.427×10^8	99.897	38.1
N	NEUTRAL	(CKT RETURN)									
G	GROUND										
H	SPS-610155	CR4-CR5	576.946	5.001	2.886×10^3	1.0	1.153×10^5	7.966×10^2	9.182×10^7	144.74	39.2

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** INSTRUMENTATION LOOP **BOX:** SQUARE ROOT EXT. (BECKMAN)

	COMPONENT FAILURE DATA							CIRCUIT DAMAGE PARAMETERS				
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	CALC. NO. REF.
1-6	NOT USED										
7	637959	AR1	45.290	2.901	131.376	1.0	2.901×10^6	5.802	$1,684 \times 10^7$	5×10^5	33.6
8	637959	AR1	45.290	2.901	131.376	1.0	2.901×10^6	5.802	1.684×10^7	5×10^5	34.6
9	637959	AR2	56.028	8.914	499.443	1.0	56.028	8.920	499.770	6.3	35.5
10	COMMON										
11-14	NOT USED										
15	CHASSIS	GROUND									
N	NEUTRAL (C	IRCUIT RETURN)									
G	GROUND										
H	637959	CR3-CR4	576.946	5.001	2.886×10^3	1.0	1.153×10^5	7.966×10^2	9.182×10^7	144.74	36.2

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** INSTRUMENTATION LOOP **BOX:** SINGLE ALARM MODULE

J1	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1-6	RELAY CONTACTS - NO ANALYSIS NEEDED										
7	SPS-610155	Z1	45.290	2.901	131.376	1.0	2.901×10^6	2.901	8.416×10^6	10^6	30.4
8	SPS-610155	Z1	45.290	2.901	131.376	1.0	2.901×10^6	2.901	8.418×10^6	10^6	31.1
N	NEUTRAL										
G	GROUND										
H	SPS-610155	CR6-CR7	576.946	5.001	2.886×10^3	1.0	1.153×10^5	7.966×10^2	9.812×10^7	144.74	32.2

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: BATTERY CHARGER BOX:

	COMPONENT FAILURE DATA						CIRCUIT DAMAGE PARAMETERS				
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	CALC. NO. REF.
1,2	IDF-579	D3	293.475	7.802	2.290×10^3	1.0	2.487×10^4	7.816×10^5	1.944×10^{10}	3.182×10^{-2}	28.8
1,3	SAME AS	FOR 1,2									
2,3	SAME AS	FOR 1,2									
+/-	IDF-579	Q1	399.045	1.120	446.782	1.0	4.236×10^2	8.318×10^3	3.523×10^6	5.093×10^{-2}	29.15

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR   SUBSYSTEM: INSTRUMENTATION LOOP   BOX: IND. DEV. CONTROLLER (BECKMAN)

DERATING FACTORS: VOLTAGE: 24dB   CURRENT: 20dB

CONN.	COMPONENT FAILURE DATA					FREQ.	CIRCUIT DAMAGE PARAMETERS				POWER CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	(MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1-7	NO OUTSIDE	CONNECTION									
8	648684	AR13	45.290	2.901	131.376	1.0	2.901×10^6	2.901	8.416×10^6	10^6	23.1
9	648684	AR13	45.290	2.901	131.376	1.0	2.901×10^6	2.901	8.416×10^6	10^6	24.5
10	SPS-610142	CR1	154.816	3.011	466.185	1.0	1.550×10^2	3.011	4.667×10^2	51.48	25.2
11	CIRCUIT	RETURN									
12-16	NO OUTSIDE	CONNECTION									
17-19	DIGITAL	COMMON									
20-24	NO OUTSIDE	CONNECTION									
25	SPS-610147	CR1-CR3	154.816	3.011	466.185	1.0	1.551×10^4	3.011	4.670×10^4	5.151×10^3	26.4
26	RELAY CONTACTS (NO FURTHER ANALYSIS)										
27,28	SAME ANALYSIS AS PIN25										
29,30	NOT USED										
31,32	RELAY CONTACTS (NO FURTHER ANALYSIS)										
G	GROUND										
N	NEUTRAL										
H	648726	CR2	576.946	5.001	2.886×10^3	1.0	1.153×10^5	7.966×10^2	9.182×10^7	144.74	27.2

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: 20KVA INVERTER BOX:

	COMPONENT FAILURE DATA						CIRCUIT DAMAGE PARAMETERS				
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	CALC. NO. REF.
54F*	014D9802	TY1	422.94	1.099	464.76	1.0	1.80×10^3	15.204	2.736×10^4	118.4	19.17
55F*	014D9802	TY1	422.94	1.099	464.76	1.0	1.80×10^3	15.204	2.736×10^4	118.4	19.17
56F*	014D9802	TY1	422.94	1.099	464.76	1.0	5.74×10^3	30.408	1.745×10^5	188.8	19.18
31P†	014D9802	D12	8.653×10^2	1.367×10^3	1.183×10^6	1.0	9.340×10^2	1.197×10^4	1.118×10^7	7.803×10^{-2}	20.2
32P†	014D9802	D12	8.653×10^2	1.367×10^3	1.183×10^6	1.0	9.340×10^2	1.197×10^4	1.118×10^7	7.803×10^{-2}	20.2
215M§	014D9802	D4	576.95	3.125	1.803×10^3	1.0	8.868×10^2	45.238	4.012×10^4	19.6	21.1
198M§	014D9802	D4	576.95	3.125	1.803×10^3	1.0	8.868×10^2	45.238	4.012×10^4	19.6	21.1
10A¶	014D9802	THY1	422.94	1.099	464.76	1.0	477.85	1.860	888.745	256.9	22.1
12A¶	014D9802	THY1	422.94	1.099	464.76	1.0	477.85	1.860	888.745	256.9	22.1

* AC INPUT

† BATTERY INPUT

§ AC OUTPUT

¶ EXTERNAL SYNC.

NOTE: LINE DESIGNATIONS ON SCHEMATIC 014D9802 ARE USED AS IDENTIFIERS INSTEAD OF PIN DESIGNATIONS

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: AFW TURBINE GOVERNOR BOX:

	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1,2	9930-145	CR1-CR6	576.946	3.125	1.803×10^3	1.0	1.104×10^3	1.587×10^2	1.751×10^5	6.957	14.3
3	GROUND										
4	FX43094-08	747-INPUT	45.290	2.901	131.376	1.0	2.921×10^4	8.626×10^4	2.519×10^9	3.396×10^{-1}	15.5
5	9930-145	Q9-EB	23.967	64.356	1.542×10^3	1.0	2.139×10^3	1.306×10^2	2.794×10^5	16.38	16.11
6	FX43094-08	747-INPUT	45.290	2.901	131.376	1.0	2.906×10^4	2.353×10^2	6.839×10^6	123.5	17.0
7,8	NOT USED										
9	9930-145	VR1	32.576	167.371	5.289×10^3	1.0	1.755×10^5	2.425×10^2	4.256×10^7	723.7	18.19
10	SIGNAL	RETURN									

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: DIFFERENTIAL PRESSURE TRANSMITTER

	COMPONENT FAILURE DATA						CIRCUIT DAMAGE PARAMETERS				
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	CALC. NO. REF.
+24V	D-3049K11-050	CR50	356.7	2.062	735.4	1.0	359.82	2.062	741.95	174.5	13.35
OUTPUT	D-3049K11-050	CR50	356.7	2.062	735.4	1.0	359.82	2.062	741.95	174.5	13.35

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR **SUBSYSTEM:** SOLID STATE PROTECTION SYSTEM **BOX:** 48V/4.3A POWER SUPPLY

	COMPONENT FAILURE DATA					FREQ.	CIRCUIT DAMAGE PARAMETERS				CALC.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	(MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	NO. REF.
1	9074000912	CR3	293.475	12.487	3.665×10^3	1.0	2.249×10^4	152.47	3.429×10^6	147.5	11.6
2	9074000912	CR3	293.475	12.487	3.665×10^3	1.0	2.249×10^4	152.47	3.429×10^6	147.5	11.6
3	CIRCUIT	RETURN									
4	9074000912	CR5	44.92	11.64	522.8	1.0	81.95	7.775×10^5	6.372×10^7	1.054×10^{-4}	12.2
5	CIRCUIT	RETURN									

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: SQUARE ROOT CONVERTER

TB1	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1,2	4532K25-001	CR5	328.547	2.307	757.972	1.0	2.527×10^5	1.329×10^3	3.357×10^8	190.143	7.5
3-7	NOT USED										
8	GROUND										
9, 10	4532K25-001	Q4-CB	107.224	3.612	387.3	1.0	2.355×10^7	9.383×10^4	2.210×10^{12}	251	9.4
9, 12	4532K25-001	Q4-CB	107.224	3.612	387.3	1.0	9.383×10^4	9.383×10^4	8.805×10^9	1.0	10.0
13-14	NOT USED										
15,16	4532K25-001	CR3	328.547	2.307	757.972	1.0	7.524×10^3	2.007×10^1	1.510×10^5	374.9	8.1

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: SOLID STATE PROTECTION SYSTEM BOX: 15V /10A POWER SUPPLY

	COMPONENT FAILURE DATA						FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)			V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1	9037800912	CR3	293.475	12.487	3.665×10^3		1.0	2.249×10^4	1.525×10^2	3.429×10^6	147.475	5.3
2	9037800912	CR3	293.475	12.487	3.665×10^3		1.0	2.249×10^4	1.525×10^2	3.429×10^6	147.475	5.3
3	CIRCUIT	RETURN										
4	9037800912	CR5	33.277	11.639	387.3		1.0	76.288	1.102×10^4	8.410×10^5	6.923×10^{-3}	6.18
5	CIRCUIT	RETURN										

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR SUBSYSTEM: INSTRUMENTATION LOOP BOX: MODEL 610A POWER SUPPLY (FOXBORO)

	COMPONENT FAILURE DATA						CIRCUIT DAMAGE PARAMETERS				
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ. (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	CALC. NO. REF.
L1,L2	18-635	CR1-CR4	576.946	1.079	622.806	1.0	9.293×10^9	1.567×10^8	1.456×10^{18}	59.3	3.7
A,U	18-635	CR1-CR4	576.946	1.079	622.806	1.0	3.924×10^7	2.47×10^{10}	9.68×10^{17}	1.589×10^{-3}	4.7

EQUIPMENT DAMAGE THRESHOLD SUMMARY

FACILITY: WATTS BAR   SUBSYSTEM: INSTRUMENTATION LOOP   BOX: ISOLATED POWER SUPPLY

	COMPONENT FAILURE DATA					FREQ. (MHZ)	CIRCUIT DAMAGE PARAMETERS				CALC. NO. REF.
PINS	SCHEMATIC REFERENCE	REF. DES. / PART NO.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)		V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	V_T/I_T (Ω)	
1,2	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	3.578×10^2	3.371×10^6	1.206×10^9	1.061×10^{-4}	1.3
3,4	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	3.578×10^2	3.371×10^6	1.206×10^9	1.061×10^{-4}	1.3
5,6	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	3.578×10^2	3.371×10^6	1.206×10^9	1.061×10^{-4}	1.3
7	NC										
8	GROUND										
9,10	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	3.578×10^2	3.371×10^6	1.206×10^9	1.061×10^{-4}	1.3
11,12	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	3.578×10^2	3.371×10^6	1.206×10^9	1.061×10^{-4}	1.3
13	NC										
14	NC										
15,16	3080K62-112	CR1-CR4	328.547	2.307	757.972	1.0	1.815×10^4	6.269×10^1	1.138×10^6	289.52	2.6

APPENDIX C

TI-59 CALCULATOR PROGRAMS

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 1 OF 20

TI Programmable
Program Record

PROGRAMMER ROY HANSON DATE 9/4/80

Partitioning (Op 17) 8 7 9 0 9 Library Module ______ Printer ______ Cards 2

PROGRAM DESCRIPTION

This program expands the capabilities of the first Semiconductor Failure Model Program. In this program, the Surge Resistance (R_S) and Wunsch Damage Constant (K) are computed in the Derivative Model. Also, a hybrid failure model (Partial Test) is available in which the Surge Resistance used in the Wunsch (Test) model is computed by the Derivative (No Test) model. The next three pages describe each failure model, and outline the procedures for using them.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY

USER DEFINED KEYS	
A	Frequency
B	No Test Model
C	Test Model
D	Partial Test Model
E	
A'	P_F
B'	I_F
C'	V_F
D'	K
E'	R_S

DATA REGISTERS (INV lnx)

0	V_{BD}	0	
1	N_D	1	
2	R_S	2	
3	AREA	3	
4	Frequency	4	
5	P_F	5	
6	I_F	6	
7	V_F	7	
8	K	8	
9	Temp. Storage	9	

LABELS (Op 08)

INV	X	lnx		CE		CLR	X	x:t	X	x²	X
√x	X	1/x	X	STO	X	RCL	X	SUM	X	y^x	X
EE	X	(	X	)	X	÷	X	GTO	X	×	
SBR		−		RST		+		R/S		.	
+/−		=		CLR		INV		log		CP	
tan		Pgm		P→R		sin		cos	X	CMs	
Exc		Prd		|x|		Eng		Fix		Int	
Deg	X	Pause		x=t		Nop		Op		Rad	
Lbl	X	x≥t		Σ+		x̄		Grad		St flg	
If flg		D.MS		π		List		Write		Dsz	
Adv		Prt									

FLAGS	0	1	2	3	4	5	6	7	8	9
	Test	P. Test	T_{EB}							

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 2 OF 20

PROGRAMMER ROY HANSON DATE 9/4/80

TI Programmable Program Record

Partitioning (Op 17) 8, 7, 9. 0, 9 Library Module ______ Printer ______ Cards 2

PROGRAM DESCRIPTION

Test Model: The Wunsch Failure Model is used to compute P_F, I_F and V_F after breakdown voltage, Wunsch damage constant, measured surge resistance, and frequency have been given to the program. This model is applicable to all semiconductor junctions, and failure thresholds for a given junction may be computed at any number of frequencies. The instructions for using this model are given below. Steps 7 through 11 are optional and order independent.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1.	Partition Calculator	1	2nd	Op	17	879.09
2.	Read Cards	-				1,2,3,or 4
3.	Enter V_{BD}	V_{BD}		C		V_{BD}
4.	Enter Wunsch damage constant	K		R/S		K
5.	Enter surge resistance	R_S		R/S		R_S
6.	Enter frequency	F		A		V_F
7.	Display I_F	-	2nd	B'		I_F
8.	Display P_F	-	2nd	A'		P_F
9.	Display K	-	2nd	D'		K
10.	Display R_S	-	2nd	E'		R_S
11.	To Re-Display V_F	-	2nd	C'		V_F
	For computations at another frequency go to step 6 anytime after step 5 has been completed.					
	For computations for another junction, go to step 3 anytime.					

USER DEFINED KEYS		DATA REGISTERS (INV Lst)			
A	Frequency	0	V_{BD}	0	
B	No Test Model	1	N_D	1	
C	Test Model	2	R_S	2	
D	Partial Test Model	3	Area	3	
E		4	Frequency	4	
A'	P_F	5	P_F	5	
B'	I_F	6	I_F	6	
C'	V_F	7	V_F	7	
D'	K	8	K	8	
E'	R_S	9	Temp.Storage	9	

LABELS (Op 08)

INV	X	lnx		CE		CLR	X	x⇌t	X	x^2	X
√x	X	1/x	X	STO	X	RCL	X	SUM	X	y^x	X
EE	X	(	X	)	X	÷	X	GTO		×	
SBR		−		RST		+		R/S		.	
+/−		=		CLR		INV		log		CP	
Tan		Pgm		P→R		sin		cos		[illegible]	
Exc		Prd		|x|		Eng		Fix		Int	
Deg	X	Pause		x=t		Nop		Op		Rad	
Lbl	X	x≥t		Σ+		x̄		Grad		St flg	
If flg		D.MS		π		Lst		Write		Dsz	
Adv		Prt									

FLAGS 0	Test 1	P. Test 2	T_{EB} 3	4	5	6	7	8	9

1014966-1

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 3 OF 20

PROGRAMMER ROY HANSON DATE 9/4/80

TI Programmable Program Record

Partitioning (Op 17) 8 7 9 . 0 9 Library Module Printer Cards 2

PROGRAM DESCRIPTION

No Test Model: This is the Derivative model, which computes V_F, I_F, P_F, K, R_S, and AREA once V_{BD}, junction area estimator, and frequency have been given to the program. A complete list of junction area estimators is found on pages 6 and 7. As for the previous model, failure data may be computed at any number of frequencies, and steps 6 through 10 are optional and order independent. The procedure for using this model is outlined below.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1.	Enter V_{BD}	V_{BD}		B		V_{BD}
2.	Enter Junction Type - 1 - Diode, 2 - T_{CB}, 3 - T_{EB}	1,2, or 3		R/S		1,2, or 3
3.	Enter Area Model Number	1,2,3,4, or 5		R/S		1,2,3,4, or 5
4.	Enter Area Estimator	Data		R/S		Data or AREA
5.	Enter frequency	F		A		V_F
6.	Display I_F	-	2nd	B'		I_F
7.	Display P_F	-	2nd	A'		P_F
8.	Display K	-	2nd	D'		K
9.	Display R_S	-	2nd	E'		R_S
10.	To Re-Display V_F	-	2nd	C'		V_F
	For computations at another frequency, go to step 5 anytime after step 4 has been completed.					
	For computations for another junction, to to step 1 anytime.					

USER DEFINED KEYS	DATA REGISTERS (INV)		
A Frequency	0 V_{BD}	0	
B No Test Model	1 N_D	1	
C Test Model	2 R_S	2	
D Partial Test Model	3 Area	3	
E	4 Frequency	4	
A' P_F	5 P_F	5	
B' I_F	6 I_F	6	
C' V_F	7 V_F	7	
D' K	8 K	8	
E' R_S	9 Temp. Storage	9	

LABELS (Op 08)

INV X lnx _ CE _ CLR X x:t X x² X
√x X 1/x X STO X RCL X SUM X yˣ X
EE X (X) X ÷ X GTO X × _
SBR _ − _ RST _ + _ R/S _ . _
+/− _ = _ CLR _ INV _ log _ CP _
tan _ Pgm _ P→R _ sin _ cos X CMs _
Exc _ Prd _ |x| _ Eng _ Fix _ Int _
Deg X Pause _ x=t _ Nop _ Op _ Rad _
Lbl X x≥t _ Σ+ _ x̄ _ Grad _ St flg _
If flg _ D.MS _ π _ List _ Write _ Dsz _
Adv _ Prt _

FLAGS	0	1	2	3	4	5	6	7	8	9
		Test	P.Test	T_{EB}						

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 4 OF 20
PROGRAMMER ROY HANSON DATE 9/4/80

TI Programmable Program Record

Partitioning (Op 17) 8,7,9.0,9 Library Module ____ Printer ____ Cards 2

PROGRAM DESCRIPTION

Partial Test Model: This hybrid model computes P_F, I_F, V_F, R_S, and area once V_{BD}, K, junction area estimator, and frequency have been entered into the program. Again, computations may be performed at any number of frequencies, and steps 7 through 11 are optional and order independent. The instructions for using this model are listed below. (See pages 6 & 7 for a description of the area estimators)

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS		DISPLAY
1.	Enter V_{BD}	V_{BD}		D	V_{BD}
2.	Enter K	K		R/S	K
3.	Enter Junction Type	1,2,or 3		R/S	1,2,or 3
	1 - Diode, 2 - T_{CB}, 3 - T_{EB}				
4.	Enter Area Model Number	1,2,3,4,or5		R/S	1,2,3,4, or 5
5.	Enter Area Estimator	Data		R/S	Data or Area
6.	Enter Frequency	F		A	V_F
7.	Display I_F	-	2nd	B'	I_F
8.	Display P_F	-	2nd	A'	P_F
9.	Display K	-	2nd	D'	K
10.	Display R_S	-	2nd	E'	R_S
11.	To Re-Display V_F	-	2nd	C'	V_F
	For computations at a different frequency,				
	to to step 6 anytime after step 5 has been				
	completed.				
	For computations for another junction, go				
	to step 1 any time.				

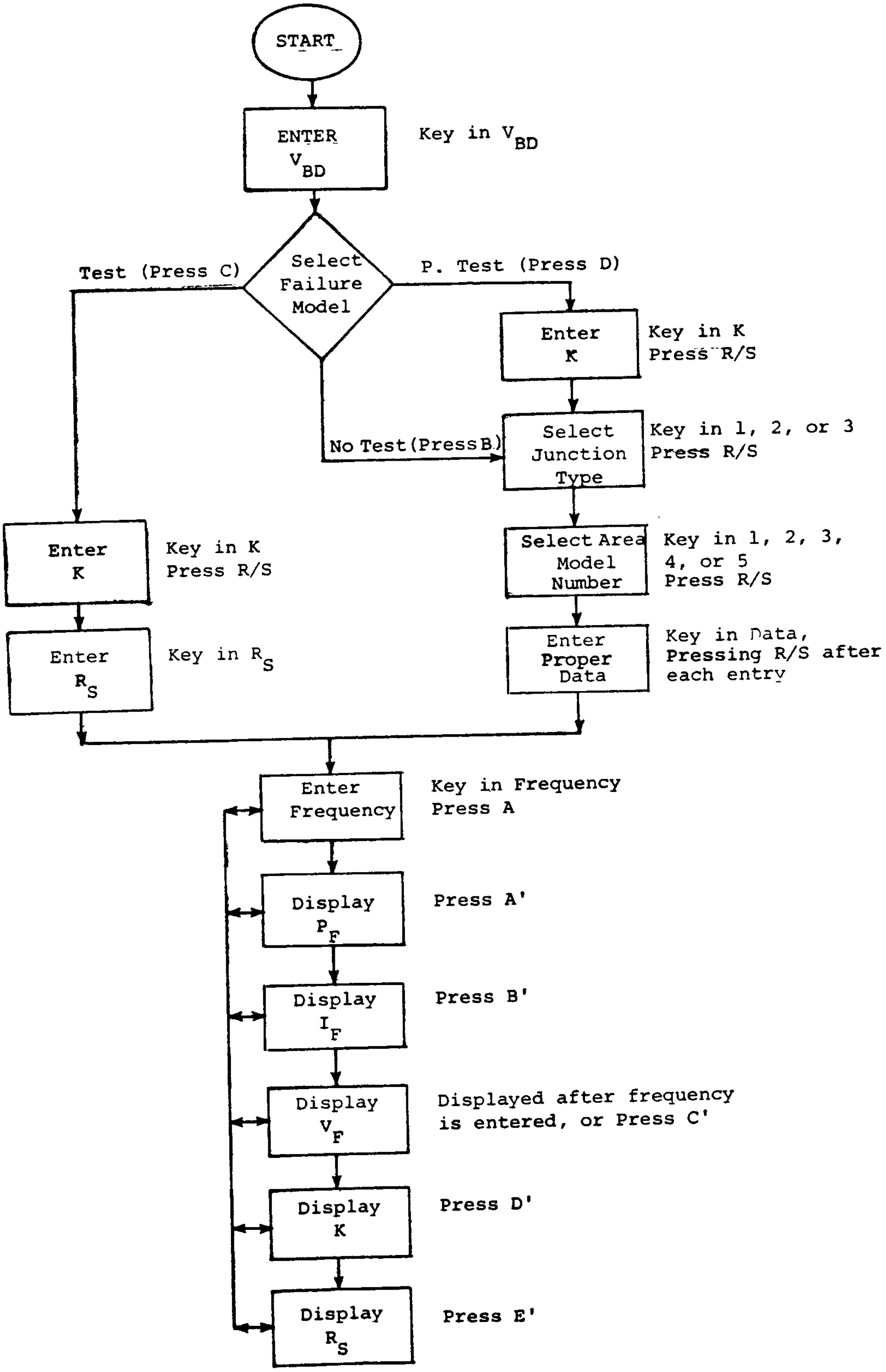
USER DEFINED KEYS		DATA REGISTERS (INV List)			
A	Frequency	0	V_{BD}	0	
B	No Test Model	1	N_D	1	
C	Test Model	2	R_S	2	
D	Partial Test Mode	3	Area	3	
E		4	Frequency	4	
A'	P_F	5	P_F	5	
B'	I_F	6	I_F	6	
C'	V_F	7	V_F	7	
D'	K	8	K	8	
E'	R_S	9	Temp. Storage	9	

LABELS (Op 08)

INV	X	lnx	_	CE	_	CLR	X	x⇌t	X	x²	X
√x	X	1/x	X	STO	X	RCL	X	SUM	X	yˣ	X
EE	X	(	X	)	X	÷	X	GTO	X	×	_
SBR	_	−	_	RST	_	+	_	R/S	_	.	_
+/-	_	=	_	CLR	_	INV	_	log	_	CP	_
tan	_	Pgm	_	P→R	_	sin	_	cos	X	CMs	_
Exc		Prd	_	|x|	_	Eng	_	Fix	_	Int	_
Deg	X	Pause	_	x=t	_	Nop	_	Op	_	Rad	_
Lbl	X	x≥t	_	Σ+	_	x̄	_	Grad	_	St flg	_
If flg	_	D.MS	_	π	_	List	_	Write	_	Dsz	_
Adv	_	Prt	_								

FLAGS 0	Test 1	P.Test 2	T_{EB} 3	4	5	6	7	8	9

USER FLOWCHART



Junction Type	Model Number	After Model Number has been Entered, Input the following data in the given order and units
DIODE (1)	1.	1. a. I_{max} - Maximum rated forward current (Amps) b. I_{Zm} - Maximum rated Zener Current (Amps) 2. a. 0. (must be entered!) b. V_z - maximum rated Zener Voltage (Volts) Note: a. for any but Zener diodes b. for Zener diodes only
	2.	1. C_{rd} - reverse - bias capacitance (Pico-Farads) 2. V_{rd} - voltage at which C_{rd} is measured (Volts)
	3.	1. θ_{JL} - Junction-to-lead thermal resistance (°C./W.) (specified for 1/8" lead length)
	4.	1. θ_{JA} - junction to ambient thermal resistance (°C./W.)
TRANSISTOR COLLECTOR BASE (2)	1.	1. θ_{JC} - junction to case thermal resistance (°C./W.)
	2.	1. I_{max} - Maximum rated collector current (Amps)
	3.	1. θ_{JA} - junction to ambient thermal resistance (°C./W.)
	4.	1. C_{rc} - Collector-base reverse bias capacitance (Pico-Farads) 2. V_{rc} - Voltage at which C_{rc} is measured. (Volts)
TRANSISTOR EMITTER-BASE (3)	1.	1. C_{re} - Emitter-base reverse bias capacitance (Pico-Farads) 2. V_{re} - Voltage at which C_{re} is measured (Volts)
	2.	1. I_{max} - Maximum rated collector current (Amps)

Junction Type	Model Number	After model number has been entered, Input the following data in the given order.
TRANSISTOR EMITTER-BASE (3)	3.	1. V_{BCBO} - rated Collector-base breakdown Voltage (Volts) 2. C_{rc} - collector-base reverse bias capacitance (Pico-Farads) 3. V_{rc} - Voltage at which C_{rc} is measured (Volts)
	4.	1. Θ_{JC} - Junction to case thermal resistance (°C./W.)
	5.	1. Θ_{JA} - Junction to ambient thermal resistance (°C./W.)

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 8 OF 20

PROGRAMMER ROY HANSON DATE 9/4/80

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
0	76	LBL	
1	11	A	
2	42	STO	Store F
3	04	04	
4	87	If.FLG.	Go to Wun-
5	01	1	sch Model
6	22	INV	If Test
7	43	RCL	Derivative
8	00	00	Failure
9	45	Y^X	Model
10	01	1	↑
11	93	•	
12	05	5	
13	94	+/-	Compute
14	65	X	N_D
15	04	4	
16	93	•	
17	04	4	
18	09	9	
19	52	EE	
20	01	1	
21	08	8	
22	95	=	↓
23	42	STO	Store N_D
24	01	01	↑
25	45	Y^X	
26	01	1	
27	93	•	
28	08	8	
29	94	+/-	
30	65	X	
31	02	2	
32	93	•	
33	04	4	
34	08	8	
35	52	EE	Compute
36	02	2	R_S
37	05	5	
38	95	=	
39	85	+	
40	53	(	
41	43	RCL	
42	01	01	
43	45	Y^X	
44	93	•	
45	08	8	
46	01	1	
47	94	+/-	
48	65	X	
49	03	3	
50	93	•	
51	06	6	
52	01	1	
53	52	EE	
54	01	1	

LOC	CODE	KEY	COMMENTS
55	00	0	
56	95	=	
57	55	÷	
58	43	RCL	
59	03	03	
60	95	=	↓
61	42	STO	Store R_S
62	02	02	
63	87	If. FLG.	Go to Wun-
64	02	2	sch Model
65	22	INV	If P. Test
66	65	X	↑
67	53	(	
68	43	RCL	
69	01	01	
70	45	Y^X	
71	93	•	
72	08	8	
73	08	8	
74	65	X	
75	43	RCL	
76	03	03	
77	65	X	
78	87	If. FLG.	Go to DEG.
79	03	3	If T_{EB}
80	60	DEG	Junction
81	08	8	
82	93	•	
83	02	2	
84	06	6	
85	52	EE	Compute
86	01	1	I_F
87	01	1	
88	94	+/-	
89	61	GTO	
90	76	LBL	
91	76	LBL	
92	60	DEG	
93	03	3	
94	93	•	
95	08	8	
96	04	4	
97	52	EE	
98	01	1	
99	01	1	
100	94	+/-	
101	76	LBL	
102	76	LBL	
103	65	X	
104	43	RCL	
105	04	04	
106	34	$\sqrt{X}$	
107	65	X	
108	04	4	
109	93	•	

LOC	CODE	KEY	COMMENTS
110	08	8	
111	09	9	
112	08	8	
113	09	9	
114	08	8	
115	52	EE	
116	04	4	
117	94	+/-	
118	54	)	↓
119	42	STO	Store
120	06	06	I_F
121	95	=	
122	85	+	↑
123	53	(	
124	43	RCL	
125	01	01	
126	45	Y^X	
127	93	•	
128	06	6	Compute
129	07	7	V_F
130	94	+/-	
131	65	X	
132	04	4	
133	93	•	
134	00	0	
135	07	7	
136	52	EE	
137	01	1	
138	02	2	
139	95	=	↓
140	42	STO	Store
141	07	07	V_F
142	65	X	↑
143	43	RCL	Compute
144	06	06	P_F
145	95	=	↓
146	42	STO	Store
147	05	05	P_F
148	43	RCL	↑
149	07	07	
150	75	-	
151	53	(	
152	43	RCL	
153	00	00	
154	45	Y^X	
155	01	1	Compute
156	93	•	K
157	00	0	
158	00	0	
159	05	5	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE SEMICONDUCTOR FAILURE MODEL II PAGE 9 OF 20

PROGRAMMER ROY HANSON DATE 9/4/80

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
160	65	X		215	42	STO	Store K	270	91	R/S	
161	01	1		216	08	08		271	76	LBL	Test Prog.
162	93	'		217	43	RCL	Display	272	13	C	Segment
163	02	2		218	07	07	V_F	273	42	STO	Store V_{BD}
164	09	9		219	91	R/S		274	00	00	
165	05	5		220	76	LBL	Wunsch	275	86	St.FLG.	Set Test
166	09	9		221	22	INV	Failure	276	01	1	Flag
167	54	)		222	43	RCL	Model	277	91	R/S	Enter K
168	42	STO		223	04	04		278	42	STO	
169	09	09		224	65	X		279	08	08	
170	95	=		225	02	2		280	91	R/S	Enter R_S
171	65	X		226	93	'	Compute	281	42	STO	
172	02	2		227	04	4	P_F	282	02	02	
173	00	0		228	95	=		283	91	R/S	Enter f
174	04	4		229	34	$\sqrt{x}$		284	76	LBL	P. Test
175	01	1		230	65	X		285	14	D	Segment
176	93	'		231	43	RCL		286	42	STO	Store V_{BD}
177	02	2		232	08	08		287	00	00	
178	04	4		233	95	=		288	86	St.FLG.	Set P. Test
179	55	÷		234	42	STO	STORE	289	02	2	Flag
180	43	RCL		235	05	05	P_F	290	91	R/S	Enter
181	04	04		236	65	X		291	42	STO	K
182	34	$\sqrt{x}$		237	04	4		292	08	08	
183	95	=		238	65	X		293	61	GTO	Go to C_{OS}
184	85	+		239	43	RCL		294	39	COS	
185	43	RCL		240	02	02		295	76	LBL	No Test
186	09	09		241	95	=		296	12	B	Segment
187	95	=		242	85	+		297	42	STO	Store V_{BD}
188	65	X		243	43	RCL	COMPUTE	298	00	00	
189	53	(		244	00	00	I_F	299	22	INV	Clear P.
190	43	RCL		245	33	x^2		300	86	St.FLG.	Test Flag
191	06	06		246	95	=		301	02	2	
192	65	X		247	34	$\sqrt{x}$		302	76	LBL	Clear
193	02	2		248	75	-		303	39	COS	Wunsch
194	00	0		249	43	RCL		304	22	INV	Model
195	04	4		250	00	00		305	86	St.FLG.	Flag
196	01	1		251	95	=		306	01	1	
197	93	'		252	55	÷		307	91	R/S	Enter
198	02	2		253	02	2		308	32	X≲t	Junction
199	04	4		254	55	÷		309	01	1	Type
200	55	÷		255	43	RCL		310	67	X = t	
201	43	RCL		256	02	02		311	25	CLR	Route
202	04	04		257	95	=		312	02	2	Processing
203	34	$\sqrt{x}$		258	42	STO	STORE	313	67	X = t	to Proper
204	54	)		259	06	06	I_F	314	32	X≲t	Junction
205	95	=		260	65	X		315	32	X≲t	T_{EB} Segment
206	65	X		261	43	RCL		316	86	St. Flg.	Set T_{EB}
207	01	1		262	02	02	Compute	317	03	3	Flag
208	00	0		263	95	=	V_F	318	91	R/S	Enter Area
209	00	0		264	85	+		319	32	X≲t	Model No.
210	52	EE		265	43	RCL					
211	09	9		266	00	00					
212	94	+/-		267	95	=					
213	34	$\sqrt{x}$		268	42	STO	STORE				
214	95	=		269	07	07	V_F				

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TITLE Semiconductor Failure Model II PAGE 10 OF 20

TI Programmable Coding Form

PROGRAMMER Roy Hanson DATE 9/2/80

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
320	01	1	Route	375	43	RCL		430	65	X	
321	67	x=t	Processing	376	00	00		431	43	RCL	
322	33	x^2	To Proper	377	45	Y^x		432	03	03	
323	02	2	Area Model	378	93	.		433	95	=	
324	67	x=t		379	07	7		434	45	Y^x	
325	34	$\sqrt{x}$		380	00	0		435	93	.	Compute
326	03	3		381	03	3		436	05	5	Area
327	67	x=t		382	05	5		437	08	8	
328	35	1/x		383	65	X		438	65	X	
329	04	4		384	01	1		439	43	RCL	
330	67	x=t		385	93	.		440	09	09	
331	42	STO		386	07	7		441	45	Y^x	
332	32	$X \gtrless t$		387	06	6		442	93	.	
333	91	R/S	Enter θJA	388	06	6		443	04	4	
334	45	Y^x	(Model 5)	389	05	5		444	08	8	
335	01	1		390	07	7		445	01	1	
336	93	.		391	52	EE		446	04	4	
337	07	7		392	06	6		447	65	X	
338	94	+/-	Compute	393	94	+/-		448	04	4	
339	65	X	Area	394	95	=		449	93	.	
340	02	2		395	42	STO	Store	450	03	3	
341	93	.		396	03	03	Area	451	03	3	
342	07	7		397	91	R/S	Enter F	452	01	1	
343	09	9		398	76	LBL		453	02	2	
344	95	=		399	34	$\sqrt{x}$		454	52	EE	
345	42	STO	Store	400	91	R/S	Enter I_{max}	455	06	6	
346	03	03	Area	401	45	Y^x	(Model 2)	456	94	+/-	
347	91	R/S	Enter F	402	93	.		457	95	=	
348	76	LBL		403	08	8		458	42	STO	Store
349	33	x^2		404	02	2		459	03	03	Area
350	91	R/S	Enter CRE	405	65	X		460	91	R/S	
351	42	STO	(Model 1)	406	06	6	Compute	461	76	LBL	
352	09	09		407	93	.	Area	462	42	STO	
353	91	R/S	Enter VRE	408	03	3		463	91	R/S	Enter θJC
354	32	$X \gtrless t$		409	04	4		464	45	Y^x	(Model 4)
355	93	.		410	52	EE		465	93	.	
356	05	5		411	04	4		466	09	9	
357	67	X=t		412	94	+/-		467	04	4	Compute
358	43	RCL		413	95	=		468	94	+/-	Area
359	32	$X \gtrless t$		414	42	STO	Store	469	65	X	
360	45	Y^x	Compute	415	03	03	Area	470	93	.	
361	93	.	Area	416	91	R/S	Enter F	471	00	0	
362	05	5		417	76	LBL		472	01	1	
363	65	X		418	35	1/X		473	01	1	
364	76	LBL		419	91	R/S	Enter V_{BCBO}	474	09	9	
365	43	RCL		420	42	STO	(Model 3)	475	95	=	
366	43	RCL		421	09	09		476	42	STO	Store
367	09	09		422	91	R/S	Enter CRC	477	03	03	Area
368	95	=		423	42	STO		478	91	R/S	Enter F
369	45	y^x		424	03	03		479	76	LBL	
370	01	1		425	91	R/S	Enter VRC				
371	93	.		426	45	Y^x					
372	00	0		427	93	.					
373	05	5		428	03	3					
374	65	X		429	03	3					

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TI-24181

TITLE Semiconductor Failure Model II PAGE 11 OF 20

PROGRAMMER Roy Hanson DATE 9/4/80

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
480	25	CLR	Diode	535	08	8		590	01	1	
481	22	INV	Segment	536	93	.		591	93	.	
482	86	St. FLG	Clear TEB	537	01	1		592	02	2	
483	03	3	Flag	538	52	EE		593	01	1	
484	91	R/S	Enter Area	539	03	3		594	94	+/-	Compute
485	32	X≷t	Model No.	540	94	+/-		595	65	X	Area
486	01	1		541	95	=		596	93	.	
487	67	X=t	Route	542	42	STO	Store	597	04	4	
488	44	SUM	Processing	543	03	03	Area	598	08	8	
489	02	2	to Proper	544	91	R/S	Enter F	599	09	9	
490	67	X=t	Area Model	545	76	LBL		600	95	=	
491	45	Y^x		546	45	Y^x		601	42	STO	Store
492	03	3		547	91	R/S	Enter CRC	602	03	03	Area
493	67	X=t		548	42	STO	(Model 2)	603	91	R/S	Enter F
494	52	EE		549	09	09		604	76	LBL	TCB Segment
495	32	X≷t		550	91	R/S	Enter VRC	605	32	X≷t	
496	91	R/S	Enter θJA	551	45	Y^x		606	22	INV	Clear TEB
497	45	Y^x	(Model 4)	552	93	.		607	86	St. FLG	Flag
498	01	1		553	03	3		608	03	3	
499	93	.		554	03	3		609	91	R/S	Enter Area
500	03	3		555	65	X		610	32	X≷t	Model No.
501	02	2	Compute	556	43	RCL		611	01	1	
502	94	+/-	Area	557	09	09		612	67	X=t	
503	65	X		558	95	=		613	54	)	Route
504	01	1		559	45	Y^x		614	02	2	Processing
505	93	.		560	93	.		615	67	X=t	to Proper
506	09	9		561	08	8	Compute	616	55	÷	Area Model
507	06	6		562	03	3	Area	617	03	3	
508	95	=		563	65	X		618	67	X=t	
509	42	STO	Store	564	43	RCL		619	61	GTO	
510	03	03	Area	565	00	00		620	32	X≷t	
511	91	R/S	Enter F	566	45	Y^x		621	91	R/S	Enter CRC
512	76	LBL		567	93	.		622	42	STO	(Model 4)
513	44	SUM		568	06	6		623	09	09	
514	91	R/S	Enter I_{max}	569	08	8		624	91	R/S	Enter VRC
515	42	STO	(Model 1)	570	08	8		625	45	Y^x	
516	09	09		571	09	9		626	93	.	
517	91	R/S	Enter Vz	572	65	X		627	03	3	
518	32	X t		573	08	8		628	03	3	
519	25	CLR		574	93	.		629	65	X	
520	67	X=t		575	05	5		630	43	RCL	
521	53	(		576	02	2		631	09	09	
522	32	X≷t		577	05	5		632	95	=	Compute
523	65	X		578	05	5		633	45	Y^x	Area
524	76	LBL	Compute	579	52	EE		634	93	.	
525	53	(	Area	580	06	6		635	03	3	
526	43	RCL		581	94	+/-		636	09	9	
527	09	09		582	95	=		637	65	X	
528	95	=		583	42	STO	Store	638	43	RCL	
529	45	Y^x		584	03	03	Area	639	00	00	
530	01	1		585	91	R/S	Enter F				
531	93	.		586	76	LBL					
532	01	1		587	52	EE					
533	06	6		588	91	R/S	Enter θJC				
534	65	X		589	45	Y^x	(Model 4)				

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Semiconductor Failure Model II PAGE 12 OF 20

PROGRAMMER Roy Hanson DATE 9/4/80

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
640	45	Y^x		695	76	LBL					
641	93	.		696	61	GTO					
642	03	3		697	91	R/S	Enter θJA				
643	02	2		698	45	Y^x	(Model 3)				
644	03	3		699	01	1					
645	07	7		700	93	.					
646	65	X		701	04	4					
647	06	6		702	07	7					
648	93	.		703	94	+/-	Compute				
649	07	7		704	65	X	Area				
650	06	6		705	03	3					
651	08	8		706	93	.					
652	03	3		707	06	6					
653	52	EE		708	03	3					
654	05	5		709	95	=					
655	94	+/-		710	42	STO	Store				
656	95	=		711	03	03	Area				
657	42	STO	Store	712	91	R/S	Enter F				
658	03	03	Area	713	76	LBL	P_F				
659	91	R/S	Enter F	714	16	A'	Display				
660	76	LBL		715	43	RCL					
661	54	)		716	05	05					
662	91	R/S	Enter θJC	717	91	R/S					
663	45	Y^x	(Model 1)	718	76	LBL	I_F				
664	93	.		719	17	B'	Display				
665	08	8		720	43	RCL					
666	09	9		721	06	06					
667	94	+/-		722	91	R/S					
668	65	X	Compute	723	76	LBL	V_F				
669	93	1	Area	724	18	C'	Display				
670	00	0		725	43	RCL					
671	04	4		726	07	07					
672	07	7		727	91	R/S					
673	95	=		728	76	LBL	K				
674	42	STO	Store	729	19	D'	Display				
675	03	03	Area	730	43	RCL					
676	91	R/S	Enter F	731	08	08					
677	76	LBL		732	91	R/S					
678	55	÷		733	76	LBL	R_S				
679	91	R/S	Enter I_{max}	734	10	E'	Display				
680	45	Y^x	(Model 2)	735	43	RCL					
681	93	.		736	02	02					
682	06	6		737	91	R/S					
683	02	2									
684	65	X									
685	93	.	Compute								
686	00	0	Area								
687	00	0									
688	02	2									
689	07	7									
690	02	2									
691	95	=									
692	42	STO	Store								
693	03	03	Area								
694	91	R/S	Enter F								

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Semiconductor Failure Model II PAGE 13 OF 20

PROGRAMMER Roy Hanson DATE 9/4/80

TI Programmable Program Record

Partitioning (Op 17) 8 7 9 . 0 9 Library Module ______ Printer ______ Cards ______

PROGRAM DESCRIPTION

This example demonstrates the computation of failure thresholds for three separate devices, two diodes and a transistor, at frequencies of 10 KHz and 1 MHz. The available data on the devices is found in Table 1, p. 16, and the computed failure data is found in Table 2. The computations are done in order, beginning with the IN914, and ending with the collector base junction of the 2N706.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY	
1	Partition Memory	1	2nd	Op	17	879.09	
2	Read Cards	-				1, 2, 3, or 4	
3	Enter V_{BD} (1N914)	80				80	
4	Choose Test Model			C		80.	
5	Enter K	0.689		R/S		0.689	
6	Enter R_S	1.32		R/S		1.32	
7	Enter First Frequency	10 EE 03		A		8.1724046 01	(V_F)
8	Display I_F	-	2nd	B'		1.3060956 00	(I_F)
9	Display P_F	-	2nd	A'		1.0673942 02	(P_F)
10	Enter second frequency	1 EE 06		A		9.4853991 01	(V_F)
11	Display I_F	-	2nd	B'		1.1253024 01	(I_F)
12	Display P_F	-	2nd	A'		1.0673942 03	(P_F)
13	Enter V_{BD} (IN915)	100				100	
14	Choose Partial Test Model			D		100.	
15	Enter K	0.721		R/S		0.721	
16	Indicate Junction Type(1-diode,2-T_{CB},3-T_{EB}	1		R/S		1.	
17	Enter Area Model Number	1		R/S		1.	
18	Enter I_{Max}	0.75		R/S		0.75	

USER DEFINED KEYS		DATA REGISTERS (INV List)			
A	Frequency	0	V_{BD}	0	
B	No Test Model	1	N_D	1	
C	Test Model	2	R_S	2	
D	Partial Test Model	3	Area	3	
E		4	Frequency	4	
A'	P_F	5	P_F	5	
B'	I_F	6	I_F	6	
C'	V_F	7	V_F	7	
D'	K	8	K	8	
E'	R_S	9	Temp.Storage	9	

LABELS (Op 08)

INV X	lnx _	CE _	CLR X	x:t X	x² X
√x X	1/x X	STO X	RCL X	SUM X	yˣ X
EE X	(X	) X	÷ X	GTO X	× _
SBR _	− _	RST _	+ _	R/S _	. _
+/- _	= _	CLR _	INV _	log _	CP _
tan _	Pgm _	P→R _	sin _	cos X	CMs _
Exc _	Prd _	|x| _	Eng _	Fix _	Int _
Deg X	Pause _	x=t _	Nop _	Op _	Rad _
Lbl X	x≥t _	Σ+ _	x̄ _	Grad _	St flg _
If flg _	D.MS _	π _	List _	Write _	Dsz _
Adv _	Prt _				

FLAGS	0 Test	1 P.Test	2 T_{EB}	3	4	5	6	7	8	9

1014966-1

TI Programmable Program Record

TITLE Semiconductor Failure Model II PAGE 14 OF 20

PROGRAMMER Roy Hanson DATE 9/4/80

Partitioning (Op 17) 879.09 Library Module Printer Cards 2

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY	
19	Enter V_z for Zener; or 0 for others	0		R/S		5.8017109 -03	(A)
20	Enter frequency 1	10 EE 03		A		1.01747 02	(V_F)
21	Display I_F	--	2nd	B'		1.09779 00	(I_F)
22	Display P_F	--	2nd	A'		1.1169684 02	(P_F)
23	Enter frequency 2	1 EE 06		A		1.1540279 02	(V_F)
24	Display I_F	--	2nd	B'		9.678868 00	(I_F)
25	Display P_F	--	2nd	A'		1.1169684 03	(P_F)
26	Display R_S	--	2nd	E'		1.5913836 00	(R_S)
27	Enter V_{BD} (2N706 EB)	3	-	-	-	3.	
28	Choose No Test Model			B		3.	
29	Indicate Junction	3		R/S		3.	
30	Choose Area Model Number	3		R/S		3.	
31	Enter V_{BCBO}	25		R/S		25.	
32	Enter C_{RC}	6		R/S		6.	
33	Enter V_{RC}	10		R/S		8.9599231 -05	(A)
34	Enter frequency 1	10 EE 03		A		5.133962 00	(V_F
35	Display I_F	--	2nd	B'		1.025458 00	(I_F
36	Display P_F	--	2nd	A'		5.2646627 00	(P_F

USER DEFINED KEYS	DATA REGISTERS (INV Lst)		
A Frequency	0	V_{BD}	0
B No Test Model	1	N_D	1
C Test Model	2	R_S	2
D Partial Test Model	3	Area	3
E	4	Frequency	4
A' P_F	5	P_F	5
B' I_F	6	I_F	6
C' V_F	7	V_F	7
D' K	8	K	8
E' R_S	9	Temp. Storage	9

LABELS (Op 08)

INV	X	lnx	_	CE	_	CLR	X	x⇄t	X	x²	X
√x	X	1/x	X	STO	X	RCL	X	SUM	X	yˣ	X
EE	X	(	X	)	X	÷	X	GTO	X	×	_
SBR	_	−	_	RST	_	+	_	R/S	_	.	_
+/−	_	=	_	CLR	_	INV	_	log	_	CP	_
tan	_	Pgm	_	P→R	_	sin	_	cos	X	CMs	_
Exc	_	Prd	_	|x|	_	Eng	_	Fix	_	Int	_
Deg	X	Pause	_	x=t	_	Nop	_	Op	_	Rad	_
Lbl	X	x≥t	_	Σ+	_	x̄	_	Grad	_	St flg	_
If flg	_	D.MS	_	π	_	List	_	Write	_	Dsz	_
Adv	_	Prt	_								

FLAGS TEST 0	P.TEST 1	T_{EB} 2	3	4	5	6	7	8	9

TITLE Semiconductor Failure Model II PAGE 15 OF 20

TI Programmable Program Record

PROGRAMMER Roy Hanson DATE 9/4/80

Partitioning (Op 17) 8 7 9 . 0 9 Library Module Printer Cards 2

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY	
37	Display K	--	2nd	D'		1.9137186 -01	(K)
38	Display R_S	--	2nd	E'		1.1942829 00	(R_S
39	Enter frequency 2	1 EE 06		A		1.6156145 01	(V_F
40	Display I_F	--	2nd	B'		1.025458 01	(I_F
41	Display P_F	--	2nd	A'		1.6567449 02	(P_F
42	Enter V_{BD} (2N706 CB)	25				25.	
43	Choose No Test Model			B		25.	
44	Indicate Junction Type	2		R/S		2.	
45	Choose Area Model Number	1		R/S		1.	
46	Enter Θ_{JC}	35.5		R/S		.0019606254	(A)
47	Enter frequency 1	10 EE 03		A		3.50895 01	(V_F
48	Display I_F		2nd	B'		2.9388425 00	(I_F
49	Display P_F	--	2nd	A'		1.0312251 02	(P_F
50	Display K	--	2nd	D'		1.4634285 00	(K)
51	Display R_S	--	2nd	E'		7.366876 -01	(R_S
52	Enter frequency 2	1 EE 06		A		5.4574579 01	(V_F
53	Display I_F	--	2nd	B'		2.9388425 01	(I_F
54	Display P_F	--	2nd	A'		1.6038609 03	(P_F

USER DEFINED KEYS

A	Frequency
B	No Test Model
C	Test Model
D	Partial Test Model
E	
A'	P_F
B'	I_F
C'	V_F
D'	K
E'	R_S

DATA REGISTERS (INV 2nd)

0	V_{BD}	0	
1	N_D	1	
2	R_S	2	
3	Area	3	
4	Frequency	4	
5	P_F	5	
6	I_F	6	
7	V_F	7	
8	K	8	
9	Temp. Storage	9	

LABELS (Op 08)

INV	X	lnx		CE		CLR	X	x:t	X	x²	X
√x	X	1/x	X	STO	X	RCL	X	SUM	X	y^x	X
EE	X	(	X	)	X	÷	X	GTO	X	×	
SBR		−		RST		+		R/S		.	
+/−		=		CLR		INV		log		CP	
tan		Pgm		P→R		sin		cos	X	CMs	
Exc		Prd		|x|		Eng		Fix		Int	
Deg	X	Pause		x=t		Nop		Op		Rad	
Lbl	X	x≥t		Σ+		x̄		Grad		St flg	
If flg		D.MS		π		List		Write		Dsz	
Adv		Prt									

FLAGS	0	1	2	3	4	5	6	7	8	9
	Test	P.Test	T_{EB}							

Device Number	Available Data			
	V_{BD}	K	R_S	Area Estimators
1N914	80	0.689	1.32	
1N915	100	0.721	—	I_{max} = 0.75 A.
2N706(EB)	3	—	—	C_{RC} = 6 pf., V_{RC} = 10 V.
2N706(CB)	25	—	—	θ_{JC} = 35.5 °C/W

Figure 1. Device Available Data

Device Number	Frequency	P_F (Watts)	I_F (Amps)	V_F (Volts)	K ($W \cdot s^{1/2}$)	R_S (Ohms)
1N914	10 KHz	106.74	1.306	81.724	0.689	1.32
	1 MHz	1067.39	11.25	94.854	0.689	1.32
1N915	10 KHz	111.69	1.098	101.75	0.721	1.591
	1 MHz	1116.97	9.679	115.40	0.721	1.591
2N706 (EB)	10 KHz	5.625	1.025	5.134	0.191	1.194
	1 MHz	165.67	10.255	16.156	0.191	1.194
2N706 (CB)	10 KHz	103.12	2.939	35.09	1.463	0.737
	1 MHz	1603.86	29.388	54.575	1.463	0.737

Figure 2. Device Failure Data

SEMICONDUCTOR FAILURE MODEL II

PROGRAM EQUATIONS

Source:

"Electronic Component Modeling and Testing Program"
Final Report
AFWL-TR-78-62

A. Test Failure Model:

$$P_F = K\sqrt{2.4f}$$

$$I_F = \frac{-V_{BD} + \sqrt{V_{BD}^2 + 4\,P_F R_S}}{2\,R_S}$$

$$V_F = I_F R_S + V_{BD}$$

B. No Test Failure Model:

$$N_D = 4.49 \times 10^{18}\,(V_{BD})^{-1.5}$$

$$R_S = \left[2.48 \times 10^{25}\,(N_D)^{-1.8} + 3.61 \times 10^{10}\,(N_D)^{-0.81}\right] \Big/ (\text{AREA})$$

$$I_F = \begin{cases} 8.26 \times 10^{-11}(N_D)^{0.88}\ (\text{AREA})\ (4.89898 \times 10^{-4})\sqrt{f} & \text{For } T_{CB} \text{ \& Diode} \\ 3.84 \times 10^{-11}(N_D)^{0.88}\ (\text{AREA})\ (4.89898 \times 10^{-4})\sqrt{f} & \text{For } T_{EB} \end{cases}$$

$$V_F = 4.07 \times 10^{12}\,(N_D)^{-0.67} + I_F R_S$$

$$P_F = V_F I_F$$

$$K = \left[1.2959(V_{BD})^{1.005}\left\{1 - \frac{2041.24}{\sqrt{f}}\right\} + \frac{2041.24\,V_F}{\sqrt{f}}\right]\left[\frac{2041.24 I_f}{\sqrt{f}}\right]\sqrt{100 \times 10^{-9}}$$

C. Partial Test Failure Model:

$$N_D = 4.49 \times 10^{18}\,(V_{BD})^{-1.5}$$

$$R_S = \left[2.48 \times 10^{25}(N_D)^{-1.8} + 3.61 \times 10^{10}\,(N_D)^{-0.81}\right] / (\text{AREA})$$

$$P_F = K\sqrt{2.4F}$$

$$I_F = \frac{-V_{BD} + \sqrt{V_{BD}^2 + 4\,P_F R_S}}{2\,R_S}$$

$$V_F = I_F R_S + V_{BD}$$

D. Diode Area Estimation Models:

1. $AREA = 8.1 \times 10^{-3} (I_{ZM} V_Z)^{1.16}$ For Zener Diodes

   $AREA = 8.1 \times 10^{-3} (I_{max})^{1.16}$ For all others

2. $AREA = 8.5255 \times 10^{-6} \left(C_{RD} \left[V_{RD}\right]^{0.33}\right)^{0.83} (V_{BD})^{0.6889}$

3. $AREA = 0.489 (\theta_{JL})^{-1.21}$

4. $AREA = 1.96 (\theta_{JA})^{-1.32}$

E. Transistor Emitter-Base Junction Area Estimation Models:

1. $AREA = 1.76657 \times 10^{-6} (C_{RE})^{1.05} (V_{BEBO})^{0.7035}$ For $V_{RE} = 0.5V.$

   $AREA = 1.76657 \times 10^{-6} (C_{RE} [V_{RE}]^{0.5})^{1.05} (V_{BEBO})^{0.7035}$ For $V_{RE} \neq 0.5V.$

2. $AREA = 6.34 \times 10^{-4} (I_{max})^{0.82}$

3. $AREA = 4.3312 \times 10^{-6} (C_{RC} [V_{RC}]^{0.33})^{0.58} (V_{BCBO})^{0.4814}$

4. $AREA = 0.0119 (\theta_{JC})^{-0.94}$

5. $AREA = 2.79 (\theta_{JA})^{-1.7}$

F. Transistor Collector-Base Junction Area Estimation Models:

1. $AREA = 0.047 (\theta_{JC})^{-0.89}$

2. $AREA = 0.00272 (I_{max})^{0.62}$

3. $AREA = 3.63 (\theta_{JA})^{-1.47}$

4. $AREA = 6.7683 \times 10^{-5} \left(C_{RC} [VRC]^{0.33}\right)^{0.58} (V_{BCBO})^{0.4814}$

DEFINITION OF TERMS

A or AREA - Effective junction area in cm^2.

C_{RC} - Collector base reverse bias capacitance in picofarads.

C_{RD} - Diode reverse bias capacitance in picofarads.

C_{RE} - Emitter base reverse bias capacitance in picofarads.

F - Frequency in hertz.

I_F - Current required to permanently damage a semiconductor junction (amps).

I_{max} - Refers to maximum rated dc forward current (I_F) for diodes, and maximum rated dc collector (I_C) for transistors (amps).

I_{ZM} - Maximum reverse dc current for zener diodes (amps).

K - Wunsch damage constant ($W \cdot S^{1/2}$)

N_D - Junction light side doping density (cm^{-3}).

P_F - Power required to permanently damage a semiconductor junction (watts).

R_S - Junction surge resistance, the sum of the junction bulk and space charge resistances (ohms).

T_{EB} - Transistor emitter-base junction.

T_{CB} - Transistor collector-base junction.

tp or t - Pulse width (seconds)

V_{BCBO} - Collector-base reverse breakdown voltage (volts).

V_{BD} - Reverse breakdown voltage (any junction) (volts).

V_{BEBO} - Emitter-base reverse breakdown voltage (volts).

V_F - Voltage required to permanently damage a semiconductor junction (volts).

V_{RC} - Voltage at which C_{RC} is measured (volts).

V_{RD} - Voltage at which C_{RD} is measured (volts)

V_{RE} - Voltage at which C_{RE} is measured (volts).

V_Z - Reverse voltage across a zener diode when zener current is flowing (volts).

θ_{JA} - Junction to ambient thermal resistance $(^{OC}/W)$.

θ_{JC} - Junction to case thermal resistance $(^{OC}/W)$.

θ_{JL} - Junction to lead thermal resistance, specified for a 1/8 inch (31.75 cm) lead length $(^{OC}/W)$.

TITLE Series & Parallel Impedance PAGE 1 OF 4

PROGRAMMER Gary Rensner DATE 9/15/81

TI Programmable Program Record

Partitioning (Op 17) 4,5,9,5,9 Library Module Master Printer - Cards 1

PROGRAM DESCRIPTION

This program allows a circuit analyst to collapse an impedance network to its simplest form. The calculated (new) Z_A is the result of a series or parallel combination of impedances (Z_A and Z_B). The use of Z_B' is to allow the analyst to preserve the result of a calculation (new Z_A) while combining a multiple set or parallel impedances into a new Z_B. This intermediate result (new Z_B) can then be further combined into the next new Z_A. Note: the impedances are assumed to

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
01	Read card					1 or 2
02	Enter first impedance, Z_A	Re{Z_A}		A		Re{Z_A}
		Im{Z_A}		R/S		Im{Z_A}
03	Enter second impedance, Z_B	Re{Z_B}		B		Re{Z_B}
		Im{Z_B}		R/S		Im{Z_B}
04	If network has an impedance parallel to Z_B enter the values as shown. Otherwise go to step 06.	Re{Z_B'} Im{Z_B'}	2nd	B' R/S		Re{Z_B'} Im{Z_B'}
05	Compute new Z_B (repeat steps 4 & 5 as many times as necessary)			R/S x⇌t		Re{Z_B} Im{Z_B}
06	To calculate a new $Z_A = Z_A \| \| Z_B$			C x⇌t		Re{Z_A} Im{Z_A}
	To calculate a new $Z_A = Z_A + Z_B$			D x⇌t		Re{Z_A} Im{Z_A}
07	To calculate the magnitude and phase angle (in degrees) of the new Z_A.			E x⇌t		$\|Z_A\|$ Θ_A

USER DEFINED KEYS	
A	Z_A
B	Z_B
C	$Z_A \| \| Z_B$
D	$Z_A + Z_B$
E	r, Θ
A'	$\| \| Z_B$'
B'	
C'	
D'	
E'	

DATA REGISTERS (INV Ind)

0	ML-04, ML-05	10	Im{Z_A}
1	ML-04, ML-05	1	$\|Z_A\|$
2	ML-04, ML-05	2	Θ_A (in degrees)
3	ML-04, ML-05	3	
4	ML-04, ML-05	4	
5	Re{Z_B}	5	
6	Im{Z_B}	6	
7	Re{Z_B'}	7	
8	Im{Z_B'}	8	
9	Re{Z_A}	9	

LABELS (Op 08)

INV __	lnx __	CE __	CLR __	x⇌t __	x² __
√x __	1/x __	STO __	RCL __	SUM __	y^x __
EE __	(__	) __	÷ __	GTO __	× __
SBR __	− __	RST __	+ __	R/S __	. __
+/-	=	CLR	[illegible]	[illegible]	[illegible]
tan __	Pgm __	P→R __	[illegible] __	[illegible] __	[illegible] __
Exc __	Prd X	|x| __	Eng __	Fix __	Int __
Deg __	Pause __	x=t __	Nop __	Op __	Rad __
Lbl __	x≥t __	Σ+ __	x̄ __	Grad __	St flg __
If flg __	D.MS __	π __	List	Write __	Dsz __
Adv __	Prt __				

FLAGS	0	1	2	3	4	5	6	7	8	9

TITLE Series & Parallel Impedance PAGE 2 OF 4

PROGRAMMER Gary Rensner DATE 9/15/81

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
00	76	LBL		55	02	02		110	06	06	
01	11	A		56	42	STO		111	44	SUM	
02	42	STO		57	10	10		112	10	10	
03	09	09		58	32	x▶◀t		113	43	RCL	
04	91	R/S		59	43	RCL		114	10	10	
05	42	STO		60	09	09		115	32	x▶◀t	
06	10	10		61	91	R/S		116	43	RCL	
07	91	R/S		62	76	LBL		117	09	09	
08	76	LBL		63	49	PRD		118	91	R/S	
09	12	B		64	43	RCL		119	76	LBL	
10	42	STO		65	05	05		120	15	E	
11	05	05		66	42	STO		121	43	RCL	
12	91	R/S		67	01	01		122	09	09	
13	42	STO		68	43	RCL		123	42	STO	
14	06	06		69	06	06		124	01	01	
15	91	R/S		70	42	STO		125	43	RCL	
16	76	LBL		71	02	02		126	10	10	
17	17	B'		72	43	RCL		127	42	STO	
18	42	STO		73	07	07		128	02	02	
19	07	07		74	42	STO		129	36	PGM	
20	91	R/S		75	03	03		130	05	05	
21	42	STO		76	43	RCL		131	12	B	
22	08	08		77	08	08		132	42	STO	
23	91	R/S		78	42	STO		133	11	11	
24	71	SBR		79	04	04		134	32	x▶◀t	
25	49	PRD		80	36	PGM		135	65	X	
26	43	RCL		81	04	04		136	01	1	
27	01	01		82	13	C		137	08	8	
28	42	STO		83	43	RCL		138	00	0	
29	05	05		84	05	05		139	55	÷	
30	43	RCL		85	85	+		140	89	π	
31	02	02		86	43	RCL		141	95	=	
32	42	STO		87	07	07		142	42	STO	
33	06	06		88	95	=		143	12	12	
34	32	x▶◀t		89	42	STO		144	32	x▶◀t	
35	43	RCL		90	03	03		145	43	RCL	
36	05	05		91	43	RCL		146	11	11	
37	91	R/S		92	06	06		147	91	R/S	
38	76	LBL		93	85	+					
39	13	C		94	43	RCL					
40	43	RCL		95	08	08					
41	09	09		96	95	=					
42	42	STO		97	42	STO					
43	07	07		98	04	04					
44	43	RCL		99	36	PGM					
45	10	10		100	04	04					
46	42	STO		101	18	C'					
47	08	08		102	92	RTN					
48	71	SBR		103	76	LBL					
49	49	PRD		104	14	D					
50	43	RCL		105	43	RCL					
51	01	01		106	05	05					
52	42	STO		107	44	SUM					
53	09	09		108	09	09					
54	43	RCL		109	43	RCL					

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TI-24151

TITLE Series & Parallel Impedance PAGE 3 OF 4

PROGRAMMER Gary Rensner DATE 9/15/81

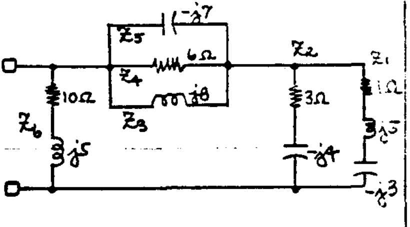
TI Programmable Program Record

Partitioning (Op 17) 4 5 , 9 5 9 Library Module Master Printer - Cards 1

PROGRAM DESCRIPTION

be complex. For totally real impedance, enter zero for the imaginary portion.

Example Problem - Given the impedance network:



What is Zeq?

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
01	Read Cards					1 or 2
02	Enter most distant impedance (Z_1)	$Re\{Z_A\}$	1	A		1.000
		$Im\{Z_A\}$	2	R/S		2.000
03	Enter next impedance (Z_2)	$Re\{Z_B\}$	3	B		3.000
		$Im\{Z_B\}$	4	+/-	R/S	-4.000
04	Compute new impedance, $Z_A = Z_1 \| \| Z_2$			C		2.000
05	Enter next impedance, Z_3 (any of the	$Re\{Z_B\}$	0	B		0.000
	three is acceptable)	$Im\{Z_B\}$	8	R/S		8.000
06	Enter one of the impedances parallel	$Re\{Z_B'\}$	6	2nd	B'	6.000
	to Z_3 (either is acceptable), Z_4	$Im\{Z_B'\}$	0	R/S		0.000
07	Compute new Z_B			R/S		3.840
08	Enter next impedance in the smaller	$Re\{Z_B'\}$	0	2nd	B'	0.000
	parallel network, Z_5	$Im\{Z_B'\}$	7	+/-	R/S	-7.000
09	Compute new Z_B			R/S		5.932
10	Compute new Z_A			D		7.932
11	Enter last impedance, Z_6	$Re\{Z_B\}$	10	B		10.000
		$Im\{Z_B\}$	5	R/S		5.000

USER DEFINED KEYS	DATA REGISTERS (INV lnx)	
A	0	0
B	1	1
C	2	2
D	3	3
E	4	4
A'	5	5
B'	6	6
C'	7	7
D'	8	8
E'	9	9

LABELS (Op 08)

INV _ lnx _ CE _ CLR _ x⇌t _ x^2 _
√x _ 1/x _ STO _ RCL _ SUM _ y^x _
EE _ (_) _ ÷ _ GTO _ × _
SBR _ − _ RST _ + _ R/S _ . _
+/- _ = _ CLR _ INV _ log _ CP _
tan _ Pgm _ P→R _ sin _ cos _ CMs _
Exc _ Prd _ |x| _ Eng _ Fix _ Int _
Deg _ Pause _ x=t _ Nop _ Op _ Rad _
Lbl _ x≥t _ Σ+ _ x̄ _ Grad _ St flg _
If flg _ D.MS _ π _ List _ Write _ Dsz _
Adv _ Prt _

FLAGS 0	1	2	3	4	5	6	7	8	9

TITLE Series & Parallel Impedance PAGE 4 OF 4

PROGRAMMER Gary Rensner DATE 9/15/81

TI Programmable Program Record

Partitioning (Op 17) 4,5,9,0,9 Library Module Master Printer - Cards 1

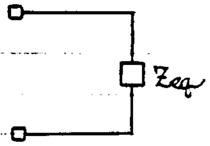
PROGRAM DESCRIPTION

Example (cont.)

The solution is the equivalent impedance

where Zeq = 4.574 + j1.198 Ω

$= 4.728\Omega \angle 14.675^{\circ}$



USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
12	Compute new impedance, Z_A = Zeq & display real part of result			C		4.574
13	To display imaginary part of result			x⇌t		1.198
14	To determine magnitude and phase angle (in degrees)			E		4.728
				x⇌t		14.675

USER DEFINED KEYS	DATA REGISTERS (INV [illegible])		LABELS (Op 08)
A	0	0	INV lnx CE CLR x⇌t x²
B	1	1	√x 1/x STO RCL SUM yˣ
C	2	2	EE ( ) ÷ GTO ×
D	3	3	SBR − RST + R/S ·
E	4	4	+/− = CLR
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS	0	1	2	3	4	5	6	7	8	9

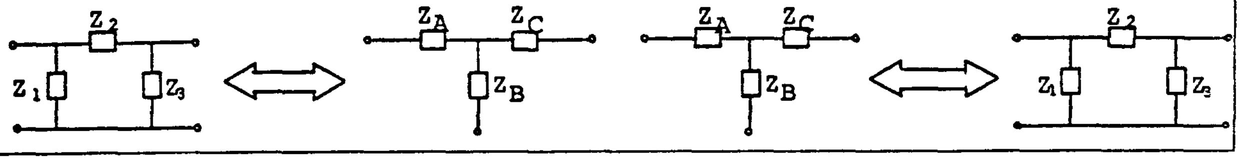
TITLE Π-T and T-Π Transformation PAGE 1 OF 6 **TI Programmable Program Record**

PROGRAMMER Gary Rensner DATE 9/1/81

Partitioning (Op 17) 6.3.9.3.9 Library Module --- Printer --- Cards 2

PROGRAM DESCRIPTION

This program allows a circuit analyst to transform from Π-topology to T-topology (or Δ-Y) or T-topology to Π-topology (or Y-Δ) with the definitions as defined below. Note that all the Z's maybe complex:



USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
01	Select direction to transform:			
	Π-T		A	0.
	T-Π		A'	0.
02	Enter the data (impedances): Π-T:	Re{Z_1}	E	Re{Z_1}
	note: data must be entered	Im{Z_1}	R/S	Im{Z_1}
	in the order shown.	Re{Z_2}	R/S	Re{Z_2}
		Im{Z_2}	R/S	Im{Z_2}
		Re{Z_3}	R/S	Re{Z_3}
		Im{Z_3}	R/S	Im{Z_3}
	: T-Π:	Re{Z_A}	E	Re{Z_A}
		Im{Z_A}	R/S	Im{Z_A}
		Re{Z_B}	R/S	Re{Z_B}
		Im{Z_B}	R/S	Im{Z_B}
		Re{Z_C}	R/S	Re{Z_C}
		Im{Z_C}	R/S	Im{Z_C}
03	To calculate the transform impedances		E'	0.

USER DEFINED KEYS		DATA REGISTERS (INV List)			
A	Π-T	0		10	Re{Z_2}
B	Z_1	1	Scratch Pad	11	Im{Z_2}
C	Z_2	2		12	Re{Z_3}
D	Z_3	3		13	Im{Z_3}
E	Data	4		14	Re{Z_A}
A'	T-Π	5		15	Im{Z_A}
B'	Z_A	6	Re{$Z_1+Z_2+Z_3$}	16	Re{Z_B}
C'	Z_B	7	Im{$Z_1+Z_2+Z_3$}	17	Im{Z_B}
D'	Z_C	8	Re{Z_1}	18	Re{Z_C}
E'	Run	9	Im{Z_1}	19	Im{Z_C}

LABELS (Op 08)

INV X lnx X CE CLR x⇄t x²
√x 1/x STO RCL SUM yˣ X
EE ( ) ÷ GTO ×
SBR − RST + R/S .
+/− =

FLAGS 0	1	2	3	4	5	6	7	8	9
	x								

TITLE Π-T and T-Π Transformation PAGE 2 OF 6 **TI Programmable Program Record**

PROGRAMMER Gary Rensner DATE 9/1/81

Partitioning (Op 17) 6 3 9 3 9 Library Module --- Printer --- Cards 2

PROGRAM DESCRIPTION

The equations used are as follows:

Π-T: $Z_A = \dfrac{Z_1 Z_2}{Z_1+Z_2+Z_3}$, $Z_B = \dfrac{Z_1 Z_3}{Z_1+Z_2+Z_3}$, $Z_C = \dfrac{Z_2 Z_3}{Z_1+Z_2+Z_3}$

T-Π: $Z_1 = \dfrac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_C}$, $Z_2 = \dfrac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_B}$, $Z_3 = \dfrac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_A}$

USER INSTRUCTIONS

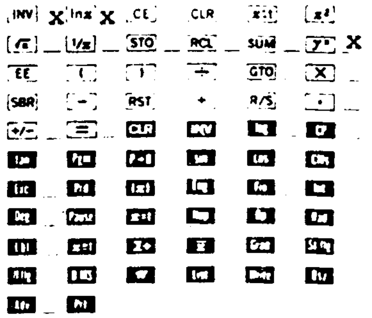
STEP	PROCEDURE		ENTER	PRESS	DISPLAY
04	To recall data:	Z_1		B	Re{Z_1}
				R/S	Im{Z_1}
		Z_2		C	Re{Z_2}
				R/S	Im{Z_2}
		Z_3		D	Re{Z_3}
				R/S	Im{Z_3}
		Z_A		B'	Re{Z_A}
				R/S	Im{Z_A}
		Z_B		C'	Re{Z_B}
				R/S	Im{Z_B}
		Z_C		D'	Re{Z_C}
				R/S	Im{Z_C}

USER DEFINED KEYS	
A	
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

DATA REGISTERS (INV [illegible])

20	Re{$Z_A * Z_B$}	0	
21	Im{$Z_A * Z_B$}	1	
22	Re{$Z_B * Z_C$}	2	
23	Im{$Z_B * Z_C$}	3	
24	Re{$Z_A * Z_C$}	4	
25	Im{$Z_A * Z_C$}	5	
26	Re{$Z_A Z_B + Z_B Z_C + Z_A Z_C$}	6	
27	Im{$Z_A Z_B + Z_B Z_C + Z_A Z_C$}	7	
8		8	
9		9	

LABELS (Op 08)



FLAGS 0	1	2	3	4	5	6	7	8	9

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TITLE Π-T and T-Π Transformations PAGE 3 OF 6

PROGRAMMER Gary Rensner DATE 9/1/81

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS
00	76	LBL	
01	11	A	
02	29	CP	
03	47	CMS	
04	86	STF	
05	01	01	
06	91	R/S	
07	76	LBL	
08	16	A'	
09	29	CP	
10	47	CMS	
11	22	INV	
12	86	STF	
13	01	01	
14	91	R/S	
15	76	LBL	
16	15	E	
17	22	INV	
18	87	IFF	
19	01	01	
20	00	00	
21	40	40	
22	42	STO	
23	08	08	
24	91	R/S	
25	42	STO	
26	09	09	
27	91	R/S	
28	42	STO	
29	10	10	
30	91	R/S	
31	42	STO	
32	11	11	
33	91	R/S	
34	42	STO	
35	12	12	
36	91	R/S	
37	42	STO	
38	13	13	
39	91	R/S	
40	42	STO	
41	14	14	
42	91	R/S	
43	42	STO	
44	15	15	
45	91	R/S	
46	42	STO	
47	16	16	
48	91	R/S	
49	42	STO	
50	17	17	
51	91	R/S	
52	42	STO	
53	18	18	
54	91	R/S	
55	42	STO	

LOC	CODE	KEY	COMMENTS
56	19	19	
57	91	R/S	
58	76	LBL	
59	10	E'	
60	22	INV	
61	87	IFF	
62	01	01	
63	02	02	
64	11	11	
65	43	RCL	
66	08	08	
67	42	STO	
68	01	01	
69	43	RCL	
70	09	09	
71	42	STO	
72	02	02	
73	43	RCL	
74	10	10	
75	42	STO	
76	03	03	
77	43	RCL	
78	11	11	
79	42	STO	
80	04	04	
81	71	SBR	
82	45	y^x	
83	43	RCL	
84	12	12	
85	42	STO	
86	03	03	
87	43	RCL	
88	13	13	
89	42	STO	
90	04	04	
91	71	SBR	
92	45	y^x	
93	43	RCL	
94	01	01	
95	42	STO	
96	06	06	
97	43	RCL	
98	02	02	
99	42	STO	
100	07	07	
101	43	RCL	
102	08	08	
103	42	STO	
104	01	01	
105	43	RCL	
106	09	09	
107	42	STO	
108	02	02	
109	43	RCL	
110	10	10	

LOC	CODE	KEY	COMMENTS
111	42	STO	
112	03	03	
113	43	RCL	
114	11	11	
115	42	STO	
116	04	04	
117	71	SBR	
118	23	LNX	
119	43	RCL	
120	06	06	
121	42	STO	
122	03	03	
123	43	RCL	
124	07	07	
125	42	STO	
126	04	04	
127	71	SBR	
128	22	INV	
129	43	RCL	
130	01	01	
131	42	STO	
132	14	14	
133	43	RCL	
134	02	02	
135	42	STO	
136	15	15	
137	43	RCL	
138	08	08	
139	42	STO	
140	01	01	
141	43	RCL	
142	09	09	
143	42	STO	
144	02	02	
145	43	RCL	
146	12	12	
147	42	STO	
148	03	03	
149	43	RCL	
150	13	13	
151	42	STO	
152	04	04	
153	71	SBR	
154	23	LNX	
155	43	RCL	
156	06	06	
157	42	STO	
158	03	03	
159	43	RCL	
160	07	07	

MERGED CODES

62	Pgm	Ind	72	STO	Ind	83	GTO	Ind
63	Exc	Ind	73	RCL	Ind	84	Op	Ind
64	Prd	Ind	74	SUM	Ind	92	INV	SBR

TEXAS INSTRUMENTS
INCORPORATED

TI 24151

TITLE Π-T and T-Π Transformations PAGE 4 OF 6

PROGRAMMER Gary Rensner DATE 9/1/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
161	42	STO	
162	04	04	
163	71	SBR	
164	22	INV	
165	43	RCL	
166	01	01	
167	42	STO	
168	16	16	
169	43	RCL	
170	02	02	
171	42	STO	
172	17	17	
173	43	RCL	
174	10	10	
175	42	STO	
176	01	01	
177	43	RCL	
178	11	11	
179	42	STO	
180	02	02	
181	43	RCL	
182	12	12	
183	42	STO	
184	03	03	
185	43	RCL	
186	13	13	
187	42	STO	
188	04	04	
189	71	SBR	
190	23	LNX	
191	43	RCL	
192	06	06	
193	42	STO	
194	03	03	
195	43	RCL	
196	07	07	
197	42	STO	
198	04	04	
199	71	SBR	
200	22	INV	
201	43	RCL	
202	01	01	
203	42	STO	
204	18	18	
205	43	RCL	
206	02	02	
207	42	STO	
208	19	19	
209	25	CLR	
210	91	R/S	
211	43	RCL	
212	14	14	
213	42	STO	
214	01	01	
215	43	RCL	
216	15	15	
217	42	STO	
218	02	02	
219	43	RCL	
220	16	16	
221	42	STO	
222	03	03	
223	43	RCL	
224	17	17	
225	42	STO	
226	04	04	
227	71	SBR	
228	23	LNX	
229	43	RCL	
230	01	01	
231	42	STO	
232	20	20	
233	43	RCL	
234	02	02	
235	42	STO	
236	21	21	
237	43	RCL	
238	16	16	
239	42	STO	
240	01	01	
241	43	RCL	
242	17	17	
243	42	STO	
244	02	02	
245	43	RCL	
246	18	18	
247	42	STO	
248	03	03	
249	43	RCL	
250	19	19	
251	42	STO	
252	04	04	
253	71	SBR	
254	23	LNX	
255	43	RCL	
256	01	01	
257	42	STO	
258	22	22	
259	43	RCL	
260	02	02	
261	42	STO	
262	23	23	
263	43	RCL	
264	14	14	
265	42	STO	
266	01	01	
267	43	RCL	
268	15	15	
269	42	STO	
270	02	02	
271	43	RCL	
272	18	18	
273	42	STO	
274	03	03	
275	43	RCL	
276	19	19	
277	42	STO	
278	04	04	
279	71	SBR	
280	23	LNX	
281	43	RCL	
282	01	01	
283	42	STO	
284	24	24	
285	43	RCL	
286	02	02	
287	42	STO	
288	25	25	
289	43	RCL	
290	22	22	
291	42	STO	
292	03	03	
293	43	RCL	
294	23	23	
295	42	STO	
296	04	04	
297	71	SBR	
298	45	y^x	
299	43	RCL	
300	20	20	
301	42	STO	
302	03	03	
303	43	RCL	
304	21	21	
305	42	STO	
306	04	04	
307	71	SBR	
308	45	y^x	
309	43	RCL	
310	01	01	
311	42	STO	
312	26	26	
313	43	RCL	
314	02	02	
315	42	STO	
316	27	27	
317	43	RCL	
318	14	14	
319	42	STO	
320	03	03	

MERGED CODES

62 ■ ■	72 STO ■	83 GTO ■
63 ■ ■	73 RCL ■	84 ■ ■
64 ■ ■	74 SUM ■	92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TITLE Π-T and T-Π Transformations PAGE 5 OF 6

PROGRAMMER Gary Rensner DATE 9/1/81

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS
321	43	RCL	
322	15	15	
323	42	STO	
324	04	04	
325	71	SBR	
326	22	INV	
327	43	RCL	
328	01	01	
329	42	STO	
330	12	12	
331	43	RCL	
332	02	02	
333	42	STO	
334	13	13	
335	43	RCL	
336	26	26	
337	42	STO	
338	01	01	
339	43	RCL	
340	27	27	
341	42	STO	
342	02	02	
343	43	RCL	
344	16	16	
345	42	STO	
346	03	03	
347	43	RCL	
348	17	17	
349	42	STO	
350	04	04	
351	71	SBR	
352	22	INV	
353	43	RCL	
354	01	01	
355	42	STO	
356	10	10	
357	43	RCL	
358	02	02	
359	42	STO	
360	11	11	
361	43	RCL	
362	26	26	
363	42	STO	
364	01	01	
365	43	RCL	
366	27	27	
367	42	STO	
368	02	02	
369	43	RCL	
370	18	18	
371	42	STO	
372	03	03	
373	43	RCL	
374	19	19	
375	42	STO	
376	04	04	
377	71	SBR	
378	22	INV	
379	43	RCL	
380	01	01	
381	42	STO	
382	08	08	
383	43	RCL	
384	02	02	
385	42	STO	
386	09	09	
387	25	CLR	
388	91	R/S	
389	76	LBL	
390	12	B	
391	43	RCL	
392	08	08	
393	91	R/S	
394	43	RCL	
395	09	09	
396	91	R/S	
397	76	LBL	
398	13	C	
399	43	RCL	
400	10	10	
401	91	R/S	
402	43	RCL	
403	11	11	
404	91	R/S	
405	76	LBL	
406	14	D	
407	43	RCL	
408	12	12	
409	91	R/S	
410	43	RCL	
411	13	13	
412	91	R/S	
413	76	LBL	
414	17	B'	
415	43	RCL	
416	14	14	
417	91	R/S	
418	43	RCL	
419	15	15	
420	91	R/S	
421	76	LBL	
422	18	C'	
423	43	RCL	
424	16	16	
425	91	R/S	
426	43	RCL	
427	17	17	
428	91	R/S	
429	76	LBL	
430	19	D'	
431	43	RCL	
432	18	18	
433	91	R/S	
434	43	RCL	
435	19	19	
436	91	R/S	
437	76	LBL	
438	45	y^x	
439	43	RCL	
440	04	04	
441	44	SUM	
442	02	02	
443	43	RCL	
444	03	03	
445	44	SUM	
446	01	01	
447	92	RTN	
448	76	LBL	
449	23	LNX	
450	53	(	
451	43	RCL	
452	01	01	
453	65	x	
454	43	RCL	
455	03	03	
456	75	-	
457	43	RCL	
458	02	02	
459	65	x	
460	43	RCL	
461	04	04	
462	54	)	
463	32	X⇌T	
464	53	(	
465	43	RCL	
466	01	01	
467	65	x	
468	43	RCL	
469	04	04	
470	85	+	
471	43	RCL	
472	02	02	
473	65	x	
474	43	RCL	
475	03	03	
476	54	)	
477	42	STO	
478	02	02	
479	32	X⇌T	
480	42	STO	

MERGED CODES
62 ■ ■ 72 STO ■ 83 GTO ■
63 ■ ■ 73 RCL ■ 84 ■ ■
64 ■ ■ 74 SUM ■ 92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

T. 24191

TITLE Π-T and T-Π Transformations PAGE 6 OF 6

PROGRAMMER Gary Rensner DATE 9/1/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
481	01	01									
482	92	RTN									
483	76	LBL									
484	22	INV									
485	01	1									
486	94	+/-									
487	49	PRD									
488	04	04									
489	53	(									
490	43	RCL									
491	03	03									
492	33	x^2									
493	85	+									
494	43	RCL									
495	04	04									
496	33	x^2									
497	54	)									
498	35	1/x									
499	49	PRD									
500	01	01									
501	49	PRD									
502	02	02									
503	71	SBR									
504	23	LNX									
505	92	RTN									

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Circuit Failure Thresholds PAGE 1 OF 7

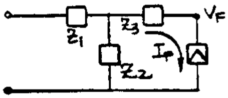
PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable Program Record

Partitioning (Op 17) 7,1,9,2,9 Library Module ---- Printer ✓ Cards 2

PROGRAM DESCRIPTION

Calculates Circuit Failure Thresholds for the following circuit:



where Z₁, Z₂, & Z₃ are complex impedances and V_F/I_F is the failure voltage/current for the device under analysis. For impedance elements not present in the interface, enter zero for series elements (Z₁ or Z₃) or 1E20 for parallel element (Z₂).

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
01	Enter Re{Z₁}	Re{Z₁}	A	Re{Z₁}
02	Im{Z₁}	Im{Z₁}	R/S	Im{Z₁}
03	Enter Re{Z₂}	Re{Z₂}	B	Re{Z₂}
04	Im{Z₂}	Im{Z₂}	R/S	Im{Z₂}
05	Enter Re{Z₃}	Re{Z₃}	C	Re{Z₃}
06	Im{Z₃}	Im{Z₃}	R/S	Im{Z₃}
07	Enter I_F	I_F	D	I_F
08	Enter V_F	V_F	E	V_F
09	Enter P_F	P_F	A'	P_F
10	Enter CKT#	CKT#	B'	CKT#
11	Enter frequency & calculate thresholds	Freq	C'	0.
12	To get printed output		E'	0.
13	To recall $\lvert I_T \rvert$		D'	$\lvert I_T \rvert$
	$\lvert V_T \rvert$		R/S	$\lvert V_T \rvert$
	$\lvert P_T \rvert$		R/S	$\lvert P_T \rvert$

USER DEFINED KEYS		DATA REGISTERS (INV List)			
A	Z₁	0	CKT#	10	Im{I_F}
B	Z₂	1	Scratch Pad	1	Re{Z_1}
C	Z	2		2	Im{Z_1}
D	I_F	3		3	Re{Z_2}
E	V_F	4		4	Im{Z_2}
A'	P_F	5	$\lvert V_T \rvert$	5	Re{Z_3}
B'	CKT#	6	$\lvert I_T \rvert$	6	Im{Z_3}
C'	FREQ	7	Re{V_F}	7	Re{V_T}
D'	RECALL DATA	8	Im{V_F}	8	Im{V_T}
E'	OUTPUT	9	Re{I_F}	9	Re{I_T}

LABELS (Op 08)

INV X lnx X CE _ CLR _ x⇌t _ x² _

√x _ 1/x _ STO _ RCL _ SUM _ yˣ X

EE _ (_) _ ÷ _ GTO _ × _

FLAGS	0	1	2	3	4	5	6	7	8	9

TITLE Circuit Failure Thresholds PAGE 2 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable
Program Record

Partitioning (Op 17) 7, 1, 9 2,9 Library Module ---- Printer ✓ Cards 2

PROGRAM DESCRIPTION

The equations used are as follows:

$$I_T = \frac{V_F + I_F(Z_2 + Z_3)}{Z_2} \quad \text{and} \quad V_T = V_F\frac{(Z_1 + Z_2)}{Z_2} + I_F\frac{(Z_1 + Z_3 + Z_1 Z_3)}{Z_2}$$

$$P_T = I_T \times V_T$$

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY

USER DEFINED KEYS	
A	
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

DATA REGISTERS (INV Lst)

2 0	$Im\{I_T\}$	0	
1	$Re\{P_T\}$	1	
2	$Im\{P_T\}$	2	
3	$\|P_T\|$	3	
4	P_F	4	
5		5	
6		6	
7	Frequency	7	
8		8	
9		9	

LABELS (Op 08)

INV X	lnx X	CE	CLR	x:t	x²
√x	1/x	STO	RCL	SUM	yˣ X
EE	(	)	÷	GTO	×
SBR	−	RST	+	R/S	.
+/−	=	CLR			
tan	Pgm	P→R	sin	cos	CMs
Exc	Prd	|x|	Eng	Fix	Int
Deg	Pause	x=t	Nop	Op	Rad
log	x≥t	Σ+	x̄	Grad	St flg
If flg	D.MS	π	Lst	Write	Dsz
Adv	Prt				

FLAGS	0	1	2	3	4	5	6	7	8	9

TITLE Circuit Failure Thresholds PAGE 3 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
00	76	LBL		55	42	STO		110	17	17	
01	11	A		56	02	02		111	43	RCL	
02	47	CMS		57	43	RCL		112	02	02	
03	42	STO		58	15	15		113	42	STO	
04	11	11		59	42	STO		114	18	18	
05	91	R/S		60	03	03		115	43	RCL	
06	42	STO		61	43	RCL		116	11	11	
07	12	12		62	16	16		117	42	STO	
08	91	R/S		63	42	STO		118	01	01	
09	76	LBL		64	04	04		119	43	RCL	
10	12	B		65	71	SBR		120	12	12	
11	42	STO		66	23	LNX		121	42	STO	
12	13	13		67	43	RCL		122	02	02	
13	91	R/S		68	13	13		123	43	RCL	
14	42	STO		69	42	STO		124	13	13	
15	14	14		70	03	03		125	42	STO	
16	91	R/S		71	43	RCL		126	03	03	
17	76	LBL		72	14	14		127	43	RCL	
18	13	C		73	42	STO		128	14	14	
19	42	STO		74	04	04		129	42	STO	
20	15	15		75	71	SBR		130	04	04	
21	91	R/S		76	22	INV		131	71	SBR	
22	42	STO		77	43	RCL		132	45	Y^X	
23	16	16		78	15	15		133	71	SBR	
24	91	R/S		79	42	STO		134	22	INV	
25	76	LBL		80	03	03		135	43	RCL	
26	14	D		81	43	RCL		136	07	07	
27	42	STO		82	16	16		137	42	STO	
28	09	09		83	42	STO		138	03	03	
29	91	R/S		84	04	04		139	43	RCL	
30	76	LBL		85	71	SBR		140	08	08	
31	15	E		86	45	Y^X		141	42	STO	
32	42	STO		87	43	RCL		142	04	04	
33	07	07		88	11	11		143	71	SBR	
34	91	R/S		89	42	STO		144	23	LNX	
35	76	LBL		90	03	03		145	43	RCL	
36	16	A'		91	43	RCL		146	01	01	
37	42	STO		92	12	12		147	44	SUM	
38	24	24		93	42	STO		148	17	17	
39	91	R/S		94	04	04		149	43	RCL	
40	76	LBL		95	71	SBR		150	02	02	
41	17	B'		96	45	Y^X		151	44	SUM	
42	42	STO		97	43	RCL		152	18	18	
43	00	00		98	09	09		153	43	RCL	
44	91	R/S		99	42	STO		154	13	13	
45	76	LBL		100	03	03		155	42	STO	
46	18	C'		101	43	RCL		156	01	01	
47	42	STO		102	10	10		157	43	RCL	
48	27	27		103	42	STO		158	14	14	
49	43	RCL		104	04	04		159	42	STO	
50	11	11		105	71	SBR					
51	42	STO		106	23	LNX					
52	01	01		107	43	RCL					
53	43	RCL		108	01	01					
54	12	12		109	42	STO					

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 [illegible] Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TI 24151

TITLE Circuit Failure Thresholds PAGE 4 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable
Coding Form

LOC	CODE	KEY	COMMENTS
160	02	02	
161	43	RCL	
162	15	15	
163	42	STO	
164	03	03	
165	43	RCL	
166	16	16	
167	42	STO	
168	04	04	
169	71	SBR	
170	45	Y^x	
171	43	RCL	
172	09	09	
173	42	STO	
174	03	03	
175	43	RCL	
176	10	10	
177	42	STO	
178	04	04	
179	71	SBR	
180	23	LNX	
181	43	RCL	
182	07	07	
183	44	SUM	
184	01	01	
185	43	RCL	
186	08	08	
187	44	SUM	
188	02	02	
189	43	RCL	
190	13	13	
191	42	STO	
192	03	03	
193	43	RCL	
194	14	14	
195	42	STO	
196	04	04	
197	71	SBR	
198	22	INV	
199	43	RCL	
200	01	01	
201	42	STO	
202	19	19	
203	43	RCL	
204	02	02	
205	42	STO	
206	20	20	
207	43	RCL	
208	17	17	
209	42	STO	
210	01	01	
211	43	RCL	
212	18	18	
213	42	STO	
214	02	02	

LOC	CODE	KEY	COMMENTS
215	43	RCL	
216	19	19	
217	42	STO	
218	03	03	
219	43	RCL	
220	20	20	
221	42	STO	
222	04	04	
223	71	SBR	
224	23	LNX	
225	43	RCL	
226	01	01	
227	42	STO	
228	21	21	
229	43	RCL	
230	02	02	
231	42	STO	
232	22	22	
233	53	(	
234	43	RCL	
235	19	19	
236	33	X^2	
237	85	+	
238	43	RCL	
239	20	20	
240	33	X^2	
241	54	)	
242	34	$\sqrt{X}$	
243	42	STO	
244	06	06	
245	53	(	
246	43	RCL	
247	17	17	
248	33	X^2	
249	85	+	
250	43	RCL	
251	18	18	
252	33	X^2	
253	54	)	
254	34	$\sqrt{X}$	
255	42	STO	
256	05	05	
257	53	(	
258	43	RCL	
259	21	21	
260	33	X^2	
261	85	+	
262	43	RCL	
263	22	22	
264	33	X^2	
265	54	)	
266	34	$\sqrt{X}$	
267	42	STO	
268	23	23	
269	25	CLR	

LOC	CODE	KEY	COMMENTS
270	91	R/S	
271	76	LBL	
272	10	E'	
273	25	CLR	
274	58	FIX	
275	00	00	
276	69	OP	
277	00	00	
278	01	1	
279	05	5	
280	02	2	
281	06	6	
282	03	3	
283	07	7	
284	69	OP	
285	04	04	
286	43	RCL	
287	00	00	
288	69	OP	
289	06	06	
290	98	ADV	
291	58	FIX	
292	00	00	
293	69	OP	
294	00	00	
295	02	2	
296	01	1	
297	03	3	
298	05	5	
299	01	1	
300	07	7	
301	03	3	
302	04	4	
303	69	OP	
304	04	04	
305	58	FIX	
306	03	03	
307	53	(	
308	43	RCL	
309	27	27	
310	65	X	
311	01	1	
312	52	EE	
313	54	)	
314	69	OP	
315	06	06	
316	22	INV	
317	52	EE	
318	58	FIX	
319	00	00	

MERGED CODES

62 Pgm Ind
63 Exc Ind
64 Prd Ind
72 STO Ind
73 RCL Ind
74 SUM Ind
83 GTO Ind
84 Op Ind
92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TI 24151

TITLE Circuit Failure Thresholds PAGE 5 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
320	69	OP	
321	00	00	
322	03	3	
323	05	5	
324	01	1	
325	07	7	
326	04	4	
327	06	6	
328	00	0	
329	02	2	
330	69	OP	
331	04	04	
332	58	FIX	
333	03	03	
334	53	(	
335	43	RCL	
336	11	11	
337	65	X	
338	01	1	
339	52	EE	
340	54	)	
341	69	OP	
342	06	06	
343	27	INV	
344	52	EE	
345	58	FIX	
346	00	00	
347	69	OP	
348	00	00	
349	02	2	
350	04	4	
351	03	3	
352	00	0	
353	04	4	
354	06	6	
355	00	0	
356	02	2	
357	69	OP	
358	04	04	
359	58	FIX	
360	03	03	
361	53	(	
362	43	RCL	
363	12	12	
364	65	X	
365	01	1	
366	52	EE	
367	54	)	
368	69	OP	
369	06	06	
370	58	FIX	
371	00	00	
372	27	INV	
373	52	EE	
374	69	OP	
375	00	00	
376	03	3	
377	05	5	
378	01	1	
379	07	7	
380	04	4	
381	06	6	
382	00	0	
383	03	3	
384	69	OP	
385	04	04	
386	58	FIX	
387	03	03	
388	53	(	
389	43	RCL	
390	13	13	
391	65	X	
392	01	1	
393	52	EE	
394	54	)	
395	69	OP	
396	06	06	
397	58	FIX	
398	00	00	
399	22	INV	
400	52	EE	
401	69	OP	
402	00	00	
403	02	2	
404	04	4	
405	03	3	
406	00	0	
407	04	4	
408	06	6	
409	00	0	
410	03	3	
411	69	OP	
412	04	04	
413	58	FIX	
414	03	03	
415	53	(	
416	43	RCL	
417	14	14	
418	65	X	
419	01	1	
420	52	EE	
421	54	)	
422	69	OP	
423	06	06	
424	58	FIX	
425	00	00	
426	22	INV	
427	52	EE	
428	69	OP	
429	00	00	
430	03	3	
431	05	5	
432	01	1	
433	07	7	
434	04	4	
435	06	6	
436	00	0	
437	04	4	
438	69	OP	
439	04	04	
440	58	FIX	
441	03	03	
442	53	(	
443	43	RCL	
444	15	15	
445	65	X	
446	01	1	
447	52	EE	
448	54	)	
449	69	OP	
450	06	06	
451	58	FIX	
452	00	00	
453	22	INV	
454	52	EE	
455	69	OP	
456	00	00	
457	02	2	
458	04	4	
459	03	3	
460	00	0	
461	04	4	
462	06	6	
463	00	0	
464	04	4	
465	69	OP	
466	04	04	
467	58	FIX	
468	03	03	
469	53	(	
470	43	RCL	
471	16	16	
472	65	X	
473	01	1	
474	52	EE	
475	54	)	
476	69	OP	
477	06	06	
478	58	FIX	
479	00	00	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO
63	73 RCL Ind	84
64	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Circuit Failure Thresholds PAGE 6 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
480	22	INV		535	04	04		590	22	INV	
481	52	EE		536	58	FIX		591	57	ENG	
482	69	OP		537	03	03		592	58	FIX	
483	00	00		538	43	RCL		593	00	00	
484	02	2		539	24	24		594	03	3	
485	04	4		540	57	ENG		595	03	3	
486	02	2		541	69	OP		596	03	3	
487	01	1		542	06	06		597	07	7	
488	69	OP		543	98	ADV		598	69	OP	
489	04	04		544	58	FIX		599	04	04	
490	58	FIX		545	00	00		600	58	FIX	
491	03	03		546	22	INV		601	03	03	
492	53	(		547	57	ENG		602	53	(	
493	43	RCL		548	69	OP		603	43	RCL	
494	09	09		549	00	00		604	23	23	
495	65	X		550	02	2		605	65	X	
496	01	1		551	04	4		606	01	1	
497	52	EE		552	03	3		607	52	EE	
498	54	)		553	07	7		608	54	)	
499	57	ENG		554	69	OP		609	69	OP	
500	69	OP		555	04	04		610	06	06	
501	06	06		556	58	FIX		611	22	INV	
502	58	FIX		557	03	03		612	57	ENG	
503	00	00		558	53	(		613	58	FIX	
504	22	INV		559	43	RCL		614	00	00	
505	57	ENG		560	06	06		615	98	ADV	
506	69	OP		561	65	X		616	25	CLR	
507	00	00		562	01	1		617	91	R/S	
508	04	4		563	52	EE		618	76	LBL	
509	02	2		564	54	)		619	45	Y^x	
510	02	2		565	69	OP		620	43	RCL	
511	01	1		566	06	06		621	04	04	
512	69	OP		567	22	INV		622	44	SUM	
513	04	04		568	57	ENG		623	02	02	
514	58	FIX		569	58	FIX		624	43	RCL	
515	03	03		570	00	00		625	03	03	
516	53	(		571	69	OP		626	44	SUM	
517	43	RCL		572	00	00		627	01	01	
518	07	07		573	04	4		628	92	RTN	
519	65	X		574	02	2		629	76	LBL	
520	01	1		575	03	3		630	23	LNX	
521	52	EE		576	07	7		631	53	(	
522	54	)		577	69	OP		632	43	RCL	
523	57	ENG		578	04	04		633	01	01	
524	69	OP		579	58	FIX		634	65	X	
525	06	06		580	03	03		635	43	RCL	
526	58	FIX		581	53	(		636	03	03	
527	00	00		582	43	RCL		637	75	-	
528	22	INV		583	05	05		638	43	RCL	
529	57	ENG		584	65	X		639	02	02	
530	03	3		585	01	1					
531	03	3		586	52	EE					
532	02	2		587	54	)					
533	01	1		588	69	OP					
534	69	OP		589	06	06					

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS
INCORPORATED

TITLE Circuit Failure Thresholds PAGE 7 OF 7

PROGRAMMER Gary Rensner DATE 9/14/81

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
640	65	X	
641	43	RCL	
642	04	04	
643	54	)	
644	32	X⇄T	
645	53	(	
646	43	RCL	
647	01	01	
648	65	X	
649	43	RCL	
650	04	04	
651	85	+	
652	43	RCL	
653	02	02	
654	65	X	
655	43	RCL	
656	03	03	
657	54	)	
658	43	STO	
659	02	02	
660	32	X⇄T	
661	42	STO	
662	01	01	
663	92	RTN	
664	76	LBL	
665	22	INV	
666	01	1	
667	94	+/-	
668	49	PRD	
669	04	04	
670	53	(	
671	43	RCL	
672	03	03	
673	33	X²	
674	85	+	
675	43	RCL	
676	04	04	
677	33	X²	
678	54	)	
679	35	1/X	
680	49	PRD	
681	01	01	
682	49	PRD	
683	02	02	
684	71	SBR	
685	23	LNX	
686	92	RTN	
687	76	LBL	
688	19	D'	
689	58	FIX	
690	03	03	
691	43	RCL	
692	06	06	
693	65	X	
694	01	1	
695	52	EE	
696	95	=	
697	91	R/S	
698	43	RCL	
699	05	05	
700	65	X	
701	01	1	
702	52	EE	
703	95	=	
704	91	R/S	
705	43	RCL	
706	23	23	
707	65	X	
708	01	1	
709	52	EE	
710	95	=	
711	91	R/S	

MERGED CODES

62 Pgm Ind 72 STO Ind 83 GTO Ind
63 Exc Ind 73 RCL Ind 84 Op Ind
64 Prd Ind 74 SUM Ind 92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TI-24151

APPENDIX D

SAMPLE CIRCUIT DAMAGE THRESHOLD CALCULATION

CIRCUIT LEVEL DAMAGE THRESHOLD SUMMARY

CONN.

SUBSYSTEM: BATTERY CHARGER

BOX:

ANALYST: G. RENSNER

	COMPONENT FAILURE DATA								CIRCUIT DAMAGE PARAMETERS			
PINS	SCHEMATIC REFERENCE	COMPONENT REF. DESIG.	PART TYPE	FAIL MOD	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	FREQ (MHZ)	V_T (VOLTS)	I_T (AMPS)	P_T (WATTS)	CALC. NO. REF
1/2	IDF-579	D3	DIODE	IMAX	293.475	7.802	2.290×10^3	1.0	2.487×10^4	7.816×10^5	1.944×10^{10}	28.8
1/3	same as 1/2											
2/3	same as 1/2											
+/-	IDF-579	Q1	XSTR	IMAX	399.045	1.120	446.782	1.0	4.236×10^2	8.318×10^3	3.523×10^6	29.15

COMPONENT DAMAGE THRESHOLD SUMMARY

CONN. TB2

SYS: BATTERY CHARGER **BOX:** HIGH DC VOLTAGE ALARM

FREQ: 1.0

ANALYST: G. RENSNER

PIN	DEVICE NUMBER	PART TYPE	JUNCTION / FAMILY & TERMINAL	SCHEMATIC REF. NO.	COMPONENT REF. DES.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	AREA (cm^2)	R_S (OHMS)	MODEL REF.
+/−	1N456A	DIODE		ID-1575	CR1	60.965	14.755	899.543	1.252×10^{-3}	1.452	IMAX
	1N4822	DIODE		ID-1575	CR3	865.279	2.929	2.534×10^{3}	1.296×10^{-2}	21.319	IMAX
	1N4733A	ZENER		ID-1576	$Z_1 - Z_2$	31.615	884.756	2.797×10^{4}	7.240×10^{-3}	0.028	IZM
	1N4737A	ZENER		ID-1575	Z_3	33.828	531.580	1.798×10^{4}	7.237×10^{-3}	0.045	IZM
	2N5655	XSTR	EMITTER-BASE	ID-1575	Q1	19.257	16.463	317.028	3.591×10^{-4}	0.693	IMAX
			COLLECTOR-BASE	ID-1575	Q1	399.045	1.120	446.782	1.770×10^{-3}	29.034	IMAX
	MC1458PC1	OP. AMP	LINEAR-INPUT	ID-1575	IC1	45.290	2.901	131.376		13.2	IC. STD.
			LINEAR-OUTPUT	ID-1575	IC1	56.028	8.914	499.443		5.5	IC. STD.

COMPONENT DAMAGE THRESHOLD SUMMARY

CONN.	SYS: BATTERY CHARGER BOX: CHARGER FAILURE ALARM					FREQ: 1.0 MHz			ANALYST: G. RENSNER		
TB2 PIN	DEVICE NUMBER	PART TYPE	JUNCTION FAMILY & TERMINAL	SCHEMATIC REF. NO.	COMPONENT REF. DES.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	AREA (cm^2)	R_S (OHMS)	MODEL REF.
+/-	1N456A	DIODE		ID-1577	CR1-CR2	60.965	14.755	899.543	1.252×10^{-3}	1.452	I_{MAX}
	1N4822	DIODE		ID-1577	CR3	865.279	2.929	2.534×10^3	1.296×10^{-2}	21.319	I_{MAX}
	1N4733A	ZENER		ID-1577	Z_1-Z_2	31.615	884.756	2.797×10^4	7.240×10^{-3}	0.028	I_{ZM}
	1N4740A	ZENER		ID-1577	Z_3	36.463	364.784	1.330×10^4	7.261×10^{-3}	0.067	I_{ZM}
	2N5655	XSTR	EMITTER-BASE	ID-1577	Q1	19.257	16.463	317.028	3.991×10^{-4}	0.693	I_{MAX}
			COLLECTOR-BASE	ID-1577	Q1	399.045	1.120	446.782	1.770×10^{-3}	27.034	I_{MAX}
	CA3130S	OP-AMP	LINEAR-INPUT	ID-1577	IC1	45.290	2.901	131.376		13.2	IC. STD.
			LINEAR-OUTPUT	ID-1577	IC1	56.028	8.914	499.443		5.5	IC. STD.
	741TC	OP-AMP	LINEAR-INPUT	ID-1577	IC2	45.290	2.901	131.376		13.2	IC. STD.
			LINEAR-OUTPUT	ID-1577	IC2	56.028	8.914	499.443		5.5	IC. STD.
	521-9200	LED		ID-1577	PL1	3.000	145.590	436.770			Similar to FLV-152
	1N4052	DIODE		IDF-579	CR8	865.279	1.236×10^3	1.069×10^6	5.472	0.051	I_{MAX}

COMPONENT DAMAGE THRESHOLD SUMMARY

CONN. TB1 | **SYS:** Battery Charger | **BOX:** — | **FREQ:** 1.0 MHz | **ANALYST:** G. Rensner

PIN	DEVICE NUMBER	PART TYPE	JUNCTION / FAMILY & TERMINAL	SCHEMATIC REF. NO.	COMPONENT REF. DES.	V_F (VOLTS)	I_F (AMPS)	P_F (WATTS)	AREA (cm^2) / R_S (OHMS)	MODEL REF.
1/2, 1/3, 2/3	1N4003	DIODE		VPH-4058-460 WCR-1091-240-360-1	D3, D7, D8	293.475	7.802	2.290×10^3	8.100×10^{-3} 3.503	IMAX

DIODE ELECTRICAL CHARACTERISTICS

DEVICE NUMBER	ALTERNATE NUMBER	DEVICE MFR.	DATA SOURCE	EXPERIMENTAL DATA			MANUFACTURER SPECIFICATION DATA							
				MEAS. V_{BD}	K	R_s	RATED V_{BD}	AREA 1			AREA 2		AREA 3	AREA 4
								I_{MAX}			C_{OD}		θ_{JL}	θ_{JA}
								$I_{F(MAX)}$	I_{ZM}	V_Z	C_{RC}	V_{RD}		
1N4003			D.A.T.A.				200V	1.0A						
1N456A			D.A.T.A.				30V	0.2A						
1N4822			D.A.T.A.				600V	1.5A						
1N4733A		General Semic.	Vendor catalog						0.178A	5.1V				
1N4737A		General Semic.	vendor catalog						0.121A	7.5V				
1N4740A		General Semic.	Vendor catalog						0.091A	10.0V				
521-9200		Dialco	Vendor catalog				3.0							
1N4052			D.A.T.A.				600V	275A						

MODEL PREFERENCE: EXPERIMENTAL IS MOST PREFERRED, THEN MODELS USING AREA 1, AREA 2, AREA 3, OR AREA 4.

NOTE: $I_{MAX} = I_{ZM} V_Z$ FOR ZENER DIODES $I_{MAX} = I_{F(MAX)}$ FOR OTHER DIODES

TRANSISTOR ELECTRICAL CHARACTERISTICS

DEVICE NUMBER	ALTERNATE NUMBER	DEVICE MFR	DATA SOURCE	EXPERIMENTAL DATA			MANUFACTURER SPECIFICATION DATA													
							EMITTER-BASE								COLLECTOR BASE					
							RATED V_{BEBO}	AREA 1		AREA 2	AREA 3		AREA 4	AREA 5	RATED V_{BCBO}	AREA 1	AREA 2	AREA 3	AREA 4	
								C_{OEB}			C_{OCB}								C_{OCB}	
				MEAS. V_{BD}	K	R_S		C_{RE}	V_{RE}	I_{MAX}	C_{RC}	V_{RC}	θ_{JC}	θ_{JA}		θ_{JC}	I_{MAX}	θ_{JA}	C_{RC}	V_{RC}
2N5655			D.A.T.A.				6.0V			0.5A					275V		0.5A			

MODEL PREFERENCE: EXPERIMENTAL IS MOST PREFERRED, THEN MODELS USING EITHER EMITTER-BASE AREA 1 THROUGH AREA 5 OR COLLECTOR BASE AREA 1 THROUGH AREA 4.

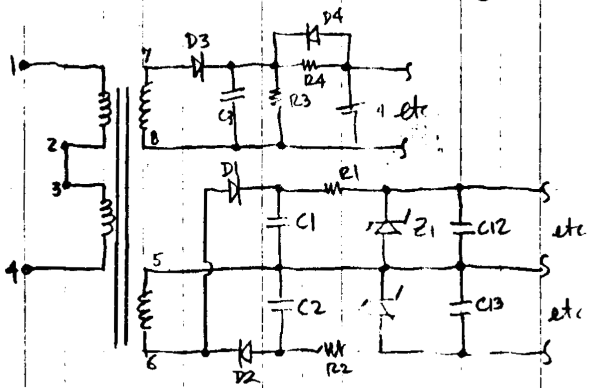
* NOTE: V_{BCBO} IS ALSO REQUIRED FOR CALCULATION OF AREA 3 FOR TRANSISTOR EMITTER-BASE JUNCTIONS

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER
BOX: —
ANALYST: G. Rensner

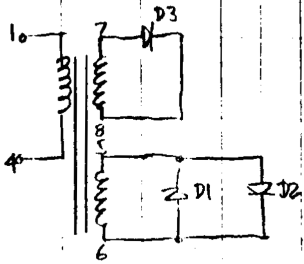
CONN.-PIN NO. TB1/1
CALCULATION NO. 28.0

For 3φ AC input, a line to line analysis will be conducted. An examination of schematic IDF-579 indicates that capacitor C4 is 5μF. Because of the low impedance of C4 at 1MHz (−j0.032 Ω), the remainder of the network following C4 may be eliminated from analysis. Pin failure thresholds will be determined from vulnerable semiconductors in circuitry between C4 and TB1/1. Two circuit boards are connected to the φA/φB input line: 3φ AMPLIFIER AND 3φ Firing Module. In the 3φ Amplifier (see schematic WCR 1001), two secondary loop circuits are coupled to the primary:



Capacitor C3 (50μF) and capacitors C1 & C2 (100μF) appear almost as short circuits at 1MHz and serve to short out any downstage circuitry. Circuit thresholds will be determined by diodes (1N4003) D_1, D_2, D_3.

The interface is thus reduced:



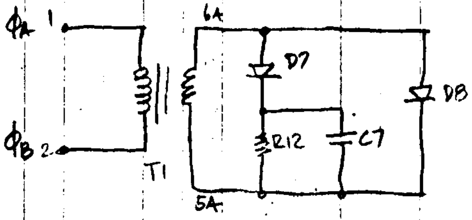
D_1 & D_2 have more protection (due to each providing shunt for the other) than D3. Thus D3 will be the most vulnerable semiconductor in this circuit. A worst case analysis for D3 will be to open ckt pins 5 & 6

ANALYST WORKSHEET

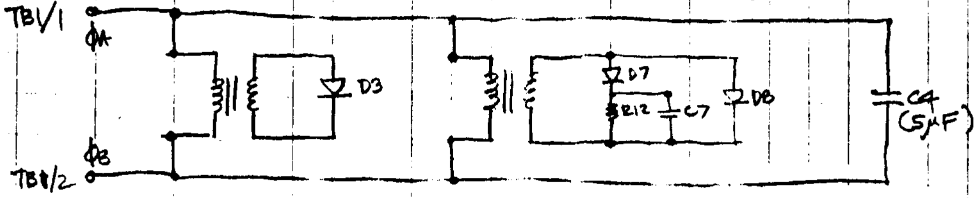
SUBSYSTEM: BATTERY CHARGER **BOX:** – **ANALYST:** G. RENSNER

CONN.-PIN NO. TB1/1 **CALCULATION NO.** 28.1

In the 3ϕ Firing Module (see schematic IDH-492), it may be seen that diodes D7 & D8 (in 6A-5A secondary) has less protection than D1 (in the 3A-4A secondary). It is expected, then, that either D7 or D8 will determine the circuit threshold. Further capacitor C8 (100μF) appears as a short circuit at 1MHz and effectively removes SCR1 from analytical consideration. The interface circuit for this board then reduces to:



Integrating these two circuit board interfaces and truncating the network past capacitor C4 gives the total pin interface circuit of:



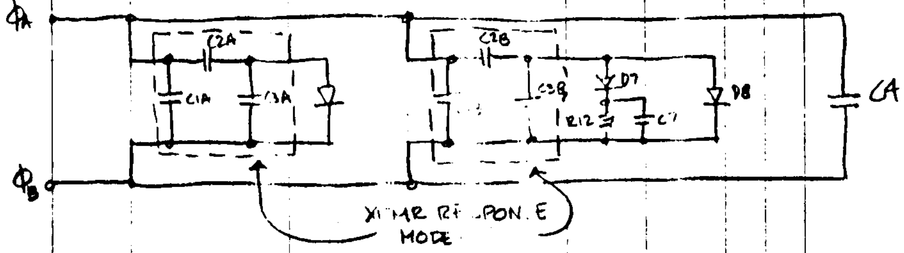
It should be noted that circuitry through T2 (see IDF-579) is eliminated from analysis because it contains no semiconductors.

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER **BOX:** – **ANALYST:** G. Rensner

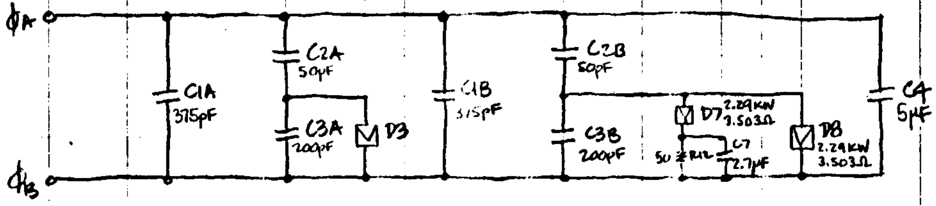
CONN.-PIN NO. TB1/1 **CALCULATION NO.** 28.2

A transformer response model may be integrated into the interface circuit for each of the transformers shown. The model used in this analysis is for power transformer (100–1000W) with Faraday shielding (as developed for B-52 hardening study).
The interface circuit becomes:



$C_{1A} = C_{1B} = 375\,pF$
$C_{2A} = C_{2B} = 50\,pF$
$C_{3A} = C_{3B} = 200\,pF$

This can be redrawn as:



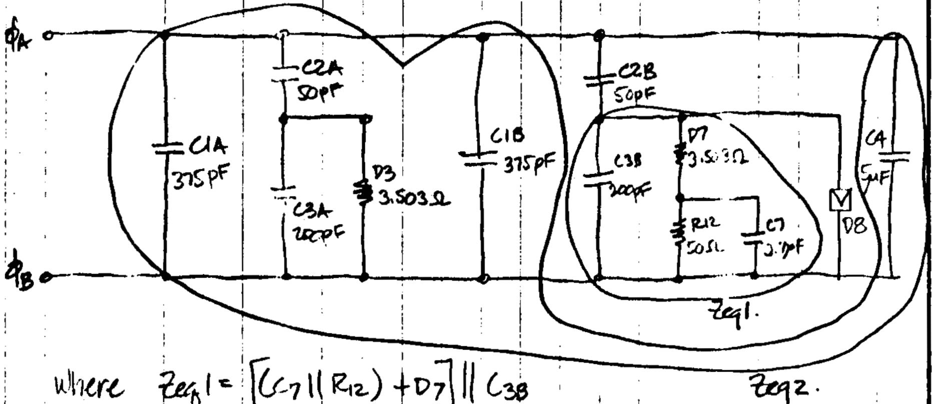
ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER **BOX:** — **ANALYST:** G. RENSNER

CONN.-PIN NO. TB1/1 **CALCULATION NO.** 28.3

I. Analyze D8.

The interface circuit is:



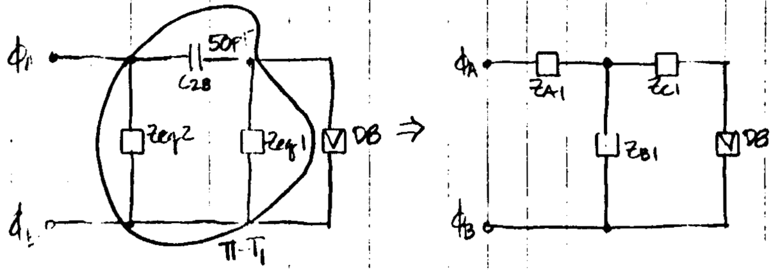
where $Z_{eq1} = [(C_7 \| R_{12}) + D_7] \| C_{3B}$

$= 3.502 - j7.436 \times 10^{-2}\,\Omega$

$Z_{eq2} = [(D3 \| C_{3A}) + C_{2A}] \| C_{1A} \| C_{1B} \| C_4$

$= 3.502 \times 10^{-10} - j3.183 \times 10^{-2}\,\Omega$

This reduces the circuit to:



$Z_{A1} = -3.502 \times 10^{-5} - j3.183 \times 10^{-2}\,\Omega$

$Z_{B1} = 3.502 \times 10^{-5} - j7.021 \times 10^{-7}\,\Omega$

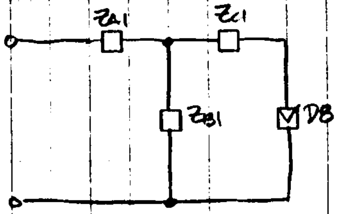
$Z_{C1} = 3.502 - j7.821 \times 10^{-2}\,\Omega$

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER **BOX:** — **ANALYST:** G. RENSNER

CONN.-PIN NO.: TB1/1 **CALCULATION NO.** 28.4

CALCULATION OF CIRCUIT FAILURE THRESHOLDS



RESULTS:

```
        1.       CKT

  1.000 06  FREQ
 -3.502-05  REZ1
 -3.183-02  IMZ1
  3.502-05  REZ2
 -7.821-07  IMZ2
  3.502 00  REZ3
 -7.821-02  IMZ3
  7.802 00    IF
293.475 00    VF
  2.290 03    PF

  9.158 06    IT
291.511 03    VT
  2.670 12    PT
```

$I_F = 7.802$ A.

$V_F = 293.475$ V.

$P_F = 2.290 \times 10^3$ W.

$Z_{A1} = -3.502 \times 10^{-5} - j3.183 \times 10^{-2}\ \Omega$

$Z_{B1} = 3.502 \times 10^{-5} - j\,7.821 \times 10^{-7}\ \Omega$

$Z_{C1} = 3.502 - j\,7.821 \times 10^{-2}\ \Omega$

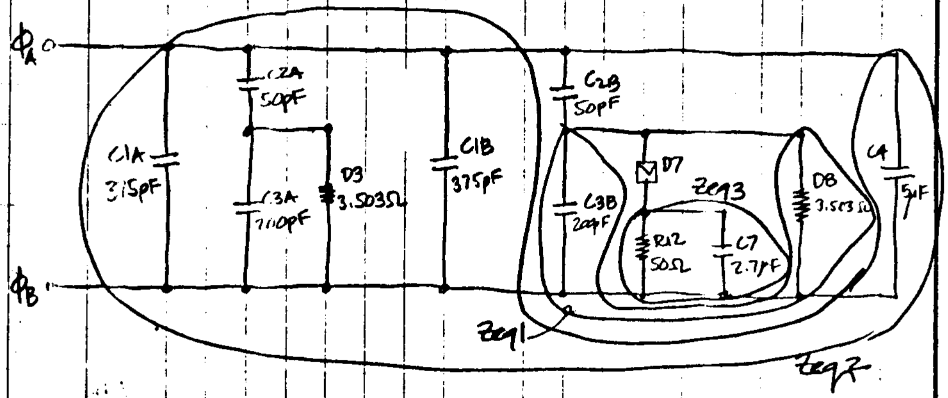
ANALYST WORKSHEET

SUBSYSTEM: Battery Charger **BOX:** — **ANALYST:** G. Rensler

CONN.-PIN NO: TB1/1 **CALCULATION NO.** 28.5

II. Analyze D7

The interface circuit is:

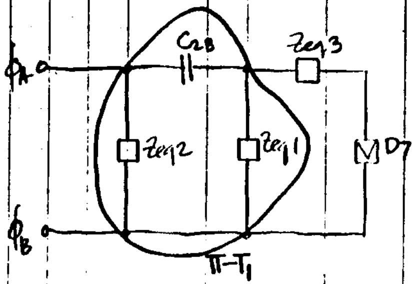


$Z_{eq1} = C_{3B} \| D_8 = 3.503 - j1.542\times10^{-2}\ \Omega$

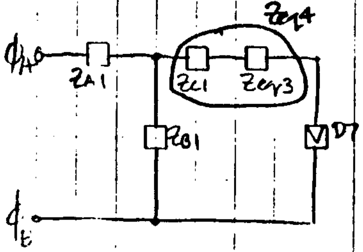
$Z_{eq2} = 3.502\times10^{-10} - j3.183\times10^{-2}\ \Omega$. (see p. 28.3)

$Z_{eq3} = R_{12} \| C_7 = 6.949\times10^{-5} - j5.895\times10^{-2}\ \Omega$

This yields:



⇒



$Z_{A1} = -3.503\times10^{-5} - j3.183\times10^{-2}\ \Omega$

$Z_{B1} = 3.503\times10^{-5} - j1.927\times10^{-7}\ \Omega$

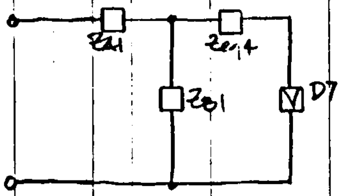
$Z_{C1} = 3.503 - j1.927\times10^{-2}\ \Omega$

$Z_{eq4} = 3.503 - j7.822\times10^{-2}\ \Omega$

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER
BOX: —
ANALYST: G. RENSNER
CONN.-PIN NO.: TB1/1
CALCULATION NO.: 28.6

CALCULATION OF CIRCIUT FAILURE THRESHOLDS



$I_F = 7.802$ A.
$V_F = 293.475$ V.
$P_F = 2.290 \times 10^{3}$ W.
$Z_{A1} = -3.503 \times 10^{-5} - j3.183 \times 10^{-2}\ \Omega.$
$Z_{B1} = 3.503 \times 10^{-5} - j1.927 \times 10^{-7}\ \Omega.$
$Z_{eq4} = 3.503 - j7.822 \times 10^{-2}\ \Omega.$

RESULTS:

```
          2.       CKT

     1.000 06 FREQ
    -3.503-05 REZ1
    -3.183-02 IMZ1
     3.503-05 REZ2
    -1.927-07 IMZ2
     3.503 00 REZ3
    -7.822-02 IMZ3
     7.802 00   IF
   293.475 00   VF
     2.290 03   PF

     9.158 06   IT
   291.498 03   VT
     2.670 12   PT
```

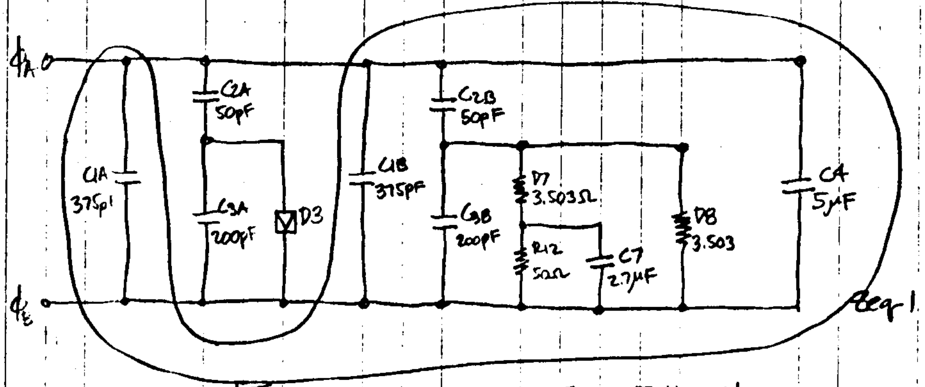
ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER **BOX:** — **ANALYST:** G. RENSNER

CONN.-PIN NO. TB1/1 **CALCULATION NO.** 28.7

III. Analyze D3.

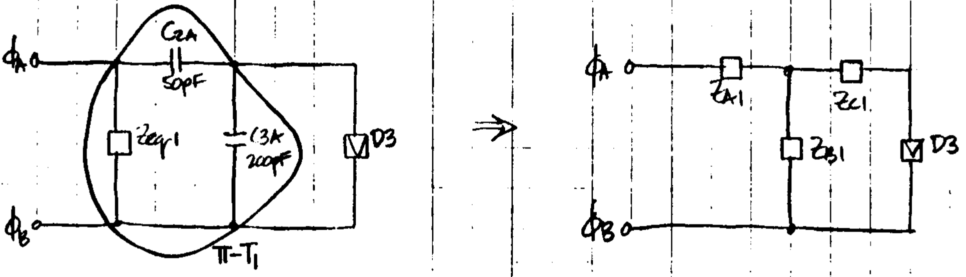
- The interface circuit is:



$$Z_{eq1} = \left[\left[\left[(C7 \parallel R12) + D_7\right] \parallel C_{3B} \parallel D_8\right] + C_{2B}\right] \parallel C4 \parallel C_{13} \parallel C_{1A}$$

$$Z_{eq1} = 1.751 \times 10^{-10} - j3.183 \times 10^{-2}\ \Omega$$

This gives:



$$Z_{A1} = 1.401 \times 10^{-10} - j2.546 \times 10^{-2}\ \Omega$$
$$Z_{B1} = 3.502 \times 10^{-11} - j6.366 \times 10^{-3}\ \Omega$$
$$Z_{C1} = -2.802 \times 10^{-11} - j6.366 \times 10^{2}\ \Omega$$

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER

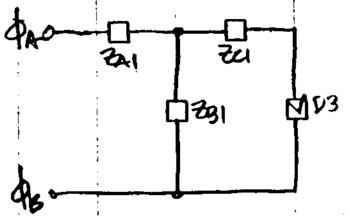
BOX: –

ANALYST: G. RENSNER

CONN.-PIN NO. TB1/1

CALCULATION NO. 28.8

CALCULATION OF CIRCUIT FAILURE THRESHOLDS



$I_P = 7.802 A.$

$V_F = 293,475 V.$

$P_F = 2.290 \times 10^3 W.$

$Z_{A1} = 1.401 \times 10^{-10} - j2.546 \times 10^{-7} \Omega$

$Z_{B1} = 3.502 \times 10^{-11} - j6.366 \times 10^{-3} \Omega$

$Z_{C1} = -2.802 \times 10^{-11} - j6.366 \times 10^{2} \Omega$

RESULTS:

```
        3.        CKT

     1.000 06  FREQ
     1.401-10  REZ1
    -2.546-02  IMZ1
     3.502-11  REZ2
    -6.366-03  IMZ2
    -2.802-11  REZ3
    -6.366 02  IMZ3
     7.802 00     IF
   293.475 00     VF
     2.290 03     PF

   781.569 03     IT
    24.874 03     VT
    19.441 09     PT
```

ANALYST WORKSHEET

SUBSYSTEM: BATTERY CHARGER **BOX:** — **ANALYST:** G. RENSNER

CONN.-PIN NO. TB1/1 **CALCULATION NO.** 28.9

A SUMMARY OF THE PIN THRESHOLD DATA SHOWS:

LOAD COMPONENT	I_T (A)	V_T (V)	P_T (W)
D8	9.158×10^6	2.915×10^5	2.670×10^{12}
D7	9.158×10^6	2.915×10^5	2.670×10^{12}
D3	7.816×10^5	2.487×10^4	1.944×10^{10}

This shows that the pin failure thresholds are determined by D3:

$I_T = 7.816 \times 10^5$ A
$V_T = 2.487 \times 10^4$ V.
$P_T = 1.944 \times 10^{10}$ W

Because of symmetry, ϕ_A/ϕ[illegible], & [illegible]/ϕ[illegible] analyses are identical to the analyses for ϕ_A/ϕ_B. Capacitors C3 & C5 are the same as C4 & thus the pin failure thresholds for these pins are as above for ϕ_A/ϕ_B.

APPENDIX E

REVIEWERS COMMENTS
AND
STUDY TEAM RESPONSES

Introduction

As indicated in the basic report, this study has been monitored since its inception by members of the NRC staff and a Research Review Panel convened by NRC for that purpose. In addition to their participation in periodic review meetings, each of the panel members was asked to review the report in draft form and provide comments. Interested NRC staff offices were also given an opportunity to review and comment. This appendix contains two sets of comments and documents the study team response to those comments. Part 1, Interim Report, contains those received prior to July 1, 1982, and Part 2, Final Report, contains those received between August 4 and October 31, 1982. The comments from the individual reviewers are presented first followed by those from the NRC staff. Each letter is followed by a response which indicates action taken to revise material or provides further justification of the study team position. In some instances the response may document discussions between the study team and the reviewer in an attempt to find an acceptable middle ground.

Part 1, Interim Report

Review Panel Comments. As of 1 July 1982, comments had been received from six members of the panel. Inputs were received from:

P. R. Barnes
Oak Ridge National Laboratory

J. C. Mark
Advisory Committee on Reactor Safeguards

R. W. Burton
University of Colorado at Colorado Springs

G. H. Baker
Defense Nuclear Agency

C. L. Longmire
Mission Research Corporation

H. C. Cabayan
Lawrence Livermore National Laboratory

There is a considerable range in the content of the review comments. Some reviewers have made very specific points addressing particular items of concern, while others are much broader in scope, and in some instances essentially a statement of philosophy.

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

May 7, 1982

Mr. Faust Rosa
Division of Systems Integration
Office of Nuclear Reactor Regulation
MS P-1030
Nuclear Regulatory Commission
Washington, DC 20555

Dear Faust:

I have reviewed the "rough draft" of the Sandia National Laboratory (SNL) report entitled "Interaction of Electromagnetic Pulse (EMP) with Commercial Nuclear Power Plant Systems" and have the following comments.

1. Reference No. 1 should be:

   P. R. Barnes, R. W. Manweiler, and R. R. Davis, "The Effects of Nuclear Electromagnetic Pulse (EMP) on Nuclear Power Plants," ORNL-5029, September 1977.

2. I did not find that the grounding systems and piping penetrations were addressed in any detail in the coupling analysis section. The influence of interior metal structures on the diffused fields were discussed.

3. Figures 6.24 and 6.25 have been constructed with only a few data points. The theoretical bases and references for these figures should be discussed.

4. In Section 7, a 1 MHz signal is used in the analysis of threshold predictions but in Section 8 the EMP induced transients are described as damped sinusoidal waveforms with resonant frequencies ramping from 0.5 - 5 MHz. The sensitivity of threshold level to resonant frequencies over the above range should be discussed.

5. Page 129. C1, C2, and C3 are not shown in Fig. 7.7a. It appears from the Appendix that these capacitances are associated with T1. This should be made clear.

6. Paragraph 7.5. Define "wire drives" (current and voltage surges on wires)?

7. Section 9, page 147. It should be noted that the Log-normal distribution with a zero mean is conservative since the mean usually is not zero.

8. Section 9, the meaning of survival confidence should be discussed.

9. The impact of different statistical approaches on the protection requirements in Section 9 should be discussed.

10. Page 8. EMP transients induced in the power grid that are important to the plant are those associated with the transmission lines and switchyard interconnections. Currents induced on the electrical distribution system are far away from the plant.

I hope these comments are helpful.

Sincerely,

Randy Barnes

Paul R. Barnes
Power Systems Technology Program

PRB:msn

cc: P. Bender, NRC
D. Ericson, SNL
W. Morris, NRC
T. Reddoch

RESPONSE TO COMMENTS OF P. R. BARNES

1. The reference list has been revised to include the more current citation suggested by the reviewer.

2. Grounding systems and piping penetrations are not "discussed" in detail in the report but they certainly are considered in the analyses. Our study found that the internal grounding philosophy and practice at the plant basically assure that all metal conducting media such as trays, support structures, equipment chassis and mechanical piping are connected together by the internal ground system. Transient current that would be conducted into the plan on mechanical piping would quickly disperse among divergent conducting paths. While the possibility of these transient currents coupling to critical equipment cannot be completely dismissed, no configurations were observed during the survey of the plant that would suggest such an occurrence. In general, in nuclear power plants mechanical piping is not routed near safety-related cabling because a piping mechanical failure could then damage vital electrical cabling. In addition, in the analyses as documented in Appendix A, although no current levels on underground piping are shown, the influence of buried piping on current sharing was considered in estimating currents on electrically related systems. The text in Section 5 has been revised to be more explicit regarding piping. Grounding systems do share the induced currents and this is indicated on the modeling diagrams. For example, see Figures A-3 and A-4 which show -6 dB attenuation of the bulk current due to the presence of ground cables which results in a reduced threat to the safety-related cables of interest.

3. It is agreed that the curves illustrated in Figures 6.23 and 6.24* have been constructed with only a few points. However, these were extracted from a complete set of swept CW response measurements over the frequency band 10 kHz to 100 MHz. Assessment of these functions does not indicate any significant discontinuity. (See Appendix 5, Reference 13). Some additional information has been provided in Section 6, which should clarify the basis for the curve shape reported. Essentially, all that is shown here is the attenuation, not shielding effectiveness, for the fields associated with the monopole (not plane wave). An attempt to deduce plane wave shielding effectiveness is developed in Section 6.5.3. Qualifications on the conclusions are also stated.

4. The 1 MHz signal was selected as a reasonable "average" or "median" value with which to do the threshold analyses. A

---

*These were Figures 6.24 and 6.25 in the draft report.

single value was used in order to keep the analyses tractable. The coupling data indicate that the center frequency of the interaction, or dominant resonances, usually lie in the 1-2 MHz range so the choice was appropriate. Furthermore, the circuit thresholds would increase at higher frequencies due to the correspondingly lower impedances of the shunt circuits. Individual component thresholds are proportional to the square of the frequency.

5. The capacitors C1, C2, and C3 are actually discrete capacitors in the original circuit, see figure on Page D-8. However, they do not need to be identified explicitly here for purposes of this discussion. The text has been revised to eliminate this reference to C1, C2, and C3.

6. In this context, "wire drives" does mean the currents or voltages induced as a result of EMP interaction with the plant. The text has been revised to make this point more precisely.

7. The reviewers point is well taken with respect to a zero mean being conservative. The comment becomes moot however because other concerns about, and constraints on, the threshold analysis have led to an extensive revision of Section 8 and the assessment of vulnerability.

8. In the context of the original draft, the reviewers concern is understood since the term "confidence" may have several meanings, and indeed has a number of standard interpretations in statistical treatments. However, as noted above, the revision of Section 8 obviates the need to further discuss "survival confidence."

9. The revised approach to the vulnerability assessment eliminates a need for a discussion of various statistical approaches in this particular study. It is understood that the viability and usefulness of several competing approaches are under continuous discussion in the EMP effects research community.

10. The study team agrees with the reviewers comment, however, other reviewers have argued that EMP transients from the grid should be considered. The text has been revised somewhat to address these other concerns and it is assumed that these revisions will adequately meet this reviewer's concerns.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

May 25, 1982

Mr. Faust Rosa, Chief
Instrumentation and Control Systems Branch
Division of Systems Integration
U. S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Mr. Rosa:

Subject: COMMENTS ON DRAFT SANDIA REPORT ON EMP

I have read through the report, along with the enclosures you sent out for comment. A few rather general observations follow:

1. It appears to me that the Report - though not yet fully complete nor through final editing -- will be a very good one. Because of its considerable length there may be a need for an Executive Summary.

2. At least some of the concerns raised by the commentators should (if possible) be clarified in the report, or discussed separately. I have particularly in mind:

   - Barnes' question concerning possible upset effects;

   - Cabayan's concerning validation of the current sharing assumptions; and

   - The question of whether Mensinger's preferred handling of the data (to the extent comparisons are possible) would change the general conclusions. (I understand that further discussions of some of these matters is planned.)

3. There is a need (recognized in the Draft) to be able to assess the extent to which the results for Watts Bar may be applicable to a few other different, but typical, plants.

4. As a general matter, I have supposed that the study was to assess the sensitivity of essential features of such plants; and to call attention to points which might seem to be unduly exposed, with the possibility of trying to remedy such undue sensitivity — rather than planning to "harden" the plant to be able to withstand all conceivable circumstances, including possible "end-of-tail" uncertainties. If this is indeed the intention, I think the present study will meet

such an objective. I wonder if, to some extent, some of the concerns raised in some of the comments may not go beyond this limited objective, and be more relevant to an objective of achieving an assured "hardening" -- as might well be appropriate for some military systems. As implied, I feel that that would go rather further than what I would consider appropriate here.

Sincerely,

C. Mark

J. Carson Mark
ACRS Member

cc: Philip Bender, ICSB
David Ericson, SNL

RESPONSE TO COMMENTS OF J. C. MARK

1. The study team concurs with Dr. Mark's concern over the length of the report and the possible need for an Executive Summary. Such a summary is now included as part of this report, although it appears as a separate volume.

2. The question of upset was not addressed in this present investigation. That is one of the conditions of the study which will be more clearly identified in the early sections of the report. It is not being dismissed as unimportant, but the investigation of upset will require significantly different analytical techniques. Questions regarding the current sharing assumptions are addressed elsewhere in direct response to Dr. Cabayan's comments. As mentioned in response to P. R. Barnes' comments, the revised approach to the vulnerability assessment essentially eliminates the disagreements over the Boeing approach as opposed to the broad based probabilistic approach favored by R. W. Mensing of LLNL. However, it is noted that in separate correspondence to NRC (Memo, EM82-0102, dated April 1, 1982, from R. W. Mensing to P. Bender) Mensing states:

   > W. Morris suggested I apply the probabilistic method to the Watts Bar data. Based on how the stress and threshold values were estimated and the random variation that could realistically be assumed, I do not believe that the overall conclusions would be any different. Any probability of failure, i.e., $P(SM < 0)$, would be extremely small."

3. The consideration of other, yet typical, plants is outlined in this expanded report. As indicated in Section 9, there are strong similarities plant to plant, however, there do exist differences in site layouts which can influence the interaction and response.

4. Dr. Mark has clearly stated the basic premise of this study. It was intended to "scope the problem" and come to some conclusions about reasonable actions if problems were identified. Several sections of the report have been rewritten to better state the objectives and constraints. Further, the conclusions have been restated to avoid any presumption of overall plant hardness based upon results reported here.

UNIVERSITY OF COLORADO AT COLORADO SPRINGS
COLORADO SPRINGS, COLORADO 80907

College of Engineering and Applied Science

April 30, 1982

John F. Ahearne
Commissioner
Nuclear Regulatory Commission
Washington, D.C. 20555

Dear John:

I have read the Policy Issue you sent me as well as the Sandia report. There is a great deal of very good work described in the Sandia report, but I am recently alarmed by the stream that runs through these latter stages of the effort that focus on the fact we are on schedule not that we did it right.

I call your attention to two letters from R. W. Mensing and H. S. Cabagan of Livermore to P. Bender of NRC dated 1 April (attached). Both of these letters raise a number of very good points. The most significant discussed in the Mensing letter which he recommends that vulnerability be predicted on a probabilistic rather than on worst case analysis. I agree completely, but Boeing resists and I believe this important issue will be ignored as the desire to get the final report completed on time becomes first priority.

Sincerely,

Robt W. Burton

ROBERT W. BURTON
Professor

RWB:rw

Attachments

"AT THE CENTER OF THE MICROELECTRONICS AND COMPUTER INDUSTRY IN THE ROCKY MOUNTAIN AREA"

RESPONSE TO COMMENTS OF R. W. BURTON

Professor Burton expresses concern that more attention is being given to arbitrary schedules than to proper conduct of the study. The study team does not believe this to be the case although it certainly has strived to complete the work in a reasonable length of time.

Professor Burton also believes that the vulnerability assessment should be done on a probabilistic basis rather than on a worst case basis. The study team would agree that given unlimited, or at least extensive, resources the problem could be treated probabilistically. However, given the available resources, including data availability, the study uses an engineering approach to gain some understanding of the EMP problem as it affects nuclear power plants As Dr. Mark has stated, the basic question was not, are such plants "hard to EMP" but rather, are there "undue sensitivities" which should be eliminated. In addition, the revisions to the vulnerability analyses which have arisen from other concerns should put to rest some of the differences on analytical approach.

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEFENSE NUCLEAR AGENCY
WASHINGTON, D.C. 20305

MAY 27 1982

RAEE

Mr. Faust Rosa/ICSB
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Faust:

I have recently reviewed SANDIA's draft interim report, Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems, and offer the following comments.

1. In general, the report represents a thorough review of the program to date. I do believe, however, that the report needs more detailed background information concerning the EMP threat and system effects (types of causes) as well as the national concerns that led to this study.

2. The objectives of the program are fairly well stated -- however, we need to make sure the reader understands that the work reported here only partially satisfies the stated objectives; e.g., the report should clearly state the limits of the present program, and what it was not designed to do.

3. In my mind, the program objectives and limitations might be stated as follows.

Objective: To identify any flagrant problems with the functional operation and circuit design of a representative nuclear power plant that would prevent the safe shutdown of the reactor following an exposure to the electromagnetic pulse from a high altitude nuclear detonation.

Limitations: To date, analysis has been constrained to identifying any possible permanent damage to plant electrical equipment necessary for safe shutdown. We have not, as yet, investigated possible transient upset of electrical equipment, such problems being difficult to predict in the absence of large scale, threat level testing. In addition the present study has been limited to local plant effects, not with EMP effects on overall power grid (including MHD, ripple outages, etc.).

4. The report conclusions must also be carefully worded. I think we can say that as a result of this effort we do not believe that component burnout from direct EMP induced currents

will occur in the plant's safe shutdown equipment. We cannot at this time completely rule out shutdown problems that may result from temporary upset of critical control equipment because EMP signals are in some cases expected to be comparable to normal operational signals.

5. The statement on page 154 that "no EMP protection is required for the plant," is not supported by what we've done here.

I have several other comments I will defer to subsequent discussions. I am concerned about the need for and the meaningfulness of the statistical treatment, however, we can take this up as a separate issue. My major concerns are contained in this letter.

Sincerely,

GEORGE H. BAKER
Project Officer
EMP Effects Division

CY FURN:
OSD (AE)
Bill Morris/CRBRP
Phil Bender/ICSB
Dave Ericson/Sandia

RESPONSE TO COMMENTS OF G. H. BAKER

1. Mr. Baker suggests that this report include more detailed background on the EMP. At least one other reviewer has also suggested that the description of EMP be modified. Some changes have been made in this material, however, it is not intended that this report be a primer on EMP and its effects. There is a wealth of information in the open literature if an individual reader cares to pursue it further.

2. Other reviewers have expressed similar concerns. That is, they have recommended that objectives, constraints, limitations, etc., be clearly stated not only in context, but explicitly in a separate section of the report. This has been done and this should enhance the usefulness of the material.

3. As noted, a number of suggestions have been made for ways to state the objectives and constraints. The wording suggested by Mr. Baker is similar in many respects to that suggested by others. It is assumed that the textual revisions noted in 2 above, as well as elsewhere, will adequately address Mr. Baker's concerns.

4. It is agreed that shutdown problems cannot be completely ruled out. It is certainly not the intent of the study team to suggest that. System upset has not been addressed in this study, and the conclusions of this expanded report have been written to be as precise as possible about the results and their application.

5. Although there is a strong feeling on the part of the study team that no special EMP protection is required, it is agreed that the flat statement, "no EMP protection is required for the plant," is probably too strong. Appropriate revisions have been made.

6. In his final paragraph (unnumbered), Mr. Baker expresses some concern about the need for, and meaningfulness of, statistical treatments in this study, although he does not define them. Similar points have been raised by others and as a result the treatment of the vulnerability analyses has been extensively revised. It is presumed that these revisions will also alleviate Mr. Baker's concern.

CLL-N-3

COMMENTS ON

THE ASSESSMENT OF THE WATTS BAR NUCLEAR PLANT FOR SUSCEPTIBILITY TO EMP INDUCED DAMAGE

June 1982

Conrad L. Longmire

MISSION RESEARCH CORPORATION
735 State Street, PO Drawer 719
Santa Barbara, California 93102

1. INTRODUCTION

A draft report, "Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems," March 1982, by David M. Ericson Jr., <u>et al</u>, summarizes the procedures and results of an investigation into the possibility that the EMP from high altitude nuclear explosions could cause sufficient damage to nuclear power plants to prevent a safe shutdown. A copy of this report was made available to me by the U.S. Nuclear Regulatory Commission. This note presents my comments on the investigation and the conclusions reached by the investigators.

2. PERSONAL BACKGROUND

Since the NRC may be unfamiliar with my background in EMP, the following summary may help the NRC decide what weight, if any, to place on my comments.

My experience in nuclear weapons and their effects, including EMP, extends over quite a few years. From 1949 to 1969 I worked in the Theoretical Division at Los Alamos, at first on the design of fission and fusion weapons, later on controller thermonuclear reactions, and in the 1960's on EMP and high altitude explosion phenomenology in general. In 1961 I assisted the planners of The Minuteman missile system in evaluating potential effects of EMP on their system. At that time there was little quantitative understanding of EMP. In a series of lectures at AFWL in 1963-'64, I developed the first comprehensive theory of the EMP near low-altitude bursts and from high-altitude burst (HEMP); these lectures were written up in Los Alamos reports LAMS-3072 and -3073. Later, I and my associates developed computational methods for predicting the EMP environments, based on that theory. These methods were implemented in computer codes at LASL, AFWL, and at Mission Research Corporation (under support from DNA), and environment information currently in use comes from these codes and the basic theory. At MRC since 1970, my associates and I have provided support to DNA, AFWL and other DoD agencies on environments and coupling of EMP into such systems as Minuteman and MX.

My connection with the Watts Bar assessment is a little unusual. Having learned of this study only after it was arranged, I called both DNA and the NRC, asking how I might participate. DNA agreed to pay my travel expenses, and NRC agreed that I could attend meetings of the advisory committee as a private citizen. Grateful for these accommodations, I have provided my time at no cost to the Government.

3. THE HEMP THREAT

It should be recognized that the HEMP threat posed for this study is incomplete, since it included only the early time (first microsecond) part driven by prompt gamma rays in their first interaction with the atmosphere. The EMP due to scattered prompt gammas, to gammas resulting from neutron interactions with the atmosphere, and that due to magnetohydrodynamic effects (MHD EMP) were not included. It is true that the early time EMP has the largest amplitude. However, the energy developed per unit area of earth surface and the electric impulse $\int Edt$ are not bounded by the early time EMP, but rather by the MHD EMP. Further, coupling effectiveness is generally strongly dependent on frequency or pulse length. For example, long power lines respond especialy well to the low-frequency content of the MHD EMP.

It would have been difficult, of course, to consider the whole EMP in a study with the limited scope of the present one. However, the statement in Section 2.3 of the draft report, to the effect that MHD EMP would not cause problems beyond the capabilities of the safety system, begs the question.

The explanation of the (early time) EMP in terms of synchrotron radiation in Section 2.1 is, if pursued in detail, more hindrance than help. A more apt analogy, which is also more akin to engineering experience, is that to a phased array of transverse current elements. While the explanation of the generation of HEMP is not at all critical to the report, there are several published papers dealing with that subject which could have been referenced if desired.

4. BRIEF DESCRIPTION OF STUDY

We shall not attempt to critique the report page by page, or even section by section. Instead we shall discuss what, in our view, can logically be concluded from the study and what cannot. This discussion requires a brief statement of what was done.

(A) For that part of the HEMP that arrives in the first microsecond, certain plausible entry points of EMP induced currents into the main reactor building were selected, namely, some unshielded wires that run (underground) from the main reactor building to other parts of the total facility.

(B) Estimates were made of the currents that would be carried by these wires at the points of entry. It is plausible that, on the average, the estimated amplitudes are conservatively high. A single plausible pulse shape was specified (2 MHz damped sine wave), which was later augmented by another shape having the same form as the assumed EMP (double exponential).

(C) Some plausible fault trees were hypothesized, and critical safety equipments identified for these fault trees.

(D) Plausible wire pathways from the points of entry to the identified critical equipments were selected.

(E) Estimates were made of signal attenuation along the selected pathways, using plausible rules-of-thumb for signal division at branch points.

(F) CW measurements at many frequencies were made of attenuation along selected pathways inside the building, and the results were used to calculate attenuation for the pulse shapes specified. We call these the measured attenuations.

(G) These measured attenuations were compared with the estimates made under (E). The average error was such that actual signal amplitude arriving at test points was 2.6 db higher than estimated. The largest error was 34.8 db in the same direction, which occurred at a point where the estimated signal was relatively small.

(H) Damage thresholds were estimated for a subset of the selected critical equipments which could plausibly be expected to be most sensitive. Estimates of the damage thresholds of semiconductor devices in these equipments were made theoretically by using known data and theoretical models. These damage thresholds were then extrapolated back through the circuitry to the interface pins of the equipment.

(I) The damage thresholds at the interface pins were compared with the EMP signal estimated to arrive at the pins, and found to be many tens of db higher than the estimated EMP signals. The smallest excess of damage threshold over estimated EMP signal was 45 db for the equipments examined.

(J) On the assumption that errors in estimated EMP signals have a log-normal distribution with standard deviation determined from the work under (E), (F) and (G), and that errors in damage threshold estimates have a log-normal distribution with standard deviation based on conclusions from previous equipment assessments, a statistical calculation was carried out yielding the result that all equipment items examined are expected to survive with confidence values greater than 99.5%.

(K) A search for inadvertent penetrations was conducted by moving a small CW transmitting antenna around the outside of the main building and observing the signal at 5 test points inside. No evidence of inadvertent penetrations was found. Some of the known penetrations showed up in these tests, but the report does not state whether all known penetrations showed up.

(L) Tests of the shielding effectiveness of the main building walls and roof were made by using small electric and magnetic dipole radiators just outside the building with sensors inside. Similar tests were also made with a vertical top-loaded radiator located farther away from the building so as to provide excitation somewhat closer to the plane wave character of HEMP. Shielding effectiveness was expected to be 30 db or more. The tests showed values as low as 10 db at 1 MHz, but it was argued that this low value was due to excitation of conductor penetrations. In addition, an anomalous decrease in shielding effectiveness at higher frequency (100 MHz) was attributed to apertures (doors) which would not be open in actual reactor operation.

5. POSSIBLE CONCLUSIONS

Lay readers of the report, and possibly some technical readers as well, are likely to agree with the conclusions stated in Section 10 of the report. In fact, such readers are apt to extrapolate, from what may appear to be understated conclusions, to the conclusion that the chance that HEMP may cause significant problems with reactors is negligible. For what appears to be highly professional tests and analyses found only wide gaps between EMP excitation levels and damage thresholds.

It is not the quality of these tests and analyses, for the most part, that I feel it necessary to challenge. Rather, it is the long chain of plausible but not provable assumptions that provide only a shaky foundation for the remaining fine-looking structure, and thus prevents the conclusions from having confidence levels anywhere near 99.5%. I think that with a sufficiently long chain of plausible assumptions one could reach almost any conclusion desired.

One aspect of the analysis leaves me thoroughly unconvinced. This is the model that has the EMP-induced current following the wire pathways guessed at, dividing down according to a rule-of-thumb at branch-out points. This doubt is not relieved by the fact that one such prediction was low by 34.8 db.

These prediction errors lead us to the least plausible of the assumptions, in my view. This is that the prediction errors, in db, have a normal distribution. It seems to me that prediction errors as large as 20 or 30 db indicate that some important physics has been missed. In this case, I doubt that any reliable statements about error distribution can be made. This would deny that quantitative calculations of survival probability have much meaning.

I am not saying that the tests and analyses carried out in the study have no value. They do tend to support the view that the facility studied is at least not riddled with susceptibilities to HEMP, and that any susceptibilities it might have should be easy to fix if one knew where they were. Unfortunately, this qualitative result falls short of what is desired.

I expect that others with experience in analyzing the effects of HEMP on systems would have doubts similar to those expressed above. While the assessment methods used in the study have been applied by the same groups for several other types of systems, they have not evoked the confidence of the EMP community at large. I found it surprising that members of this larger community were not invited to participate in this study. It could appear that the gentlest investigation possible was desired.

Reports of troubles with reactor control systems due to lightning and walkie-talkies tend to reinforce concerns over what EMP might do. Such incidents, if investigated thoroughly, could produce understanding that would be helpful in the analysis of EMP effects.

6. RECOMMENDATIONS

Without pretending to have evolved a plan guaranteed to solve the NRC's problem with respect to EMP, I list here some steps that seem to be necessary for progress with that problem.

(I) Include the long line coupling, especially of the MHD EMP, in the analysis of system response.

(II) Take a deeper technical approach to the coupling of EMP into the wiring and to the propagation of the induced currents through the wiring system. This seems necessary to reduce prediction errors and to acquire understanding of the <u>bounds</u> on signals arriving at critical points.

(III) Study the feasibility of introducing shielding, filtering and limiting for the elements of the safe-shut-down system sufficient to reduce the analysis problem for EMP respnse to a level such that high-confidence conclusions can be drawn.

(IV) Study the feasibility of performing threat level tests on reactors with the maximum degree of realism possible.

(V) Pursue vigorously evidence of electromagnetic interference with reactor control systems (lightning, walkie-talkies) for the purpose of understanding as well as fixing. In this, follow both scientific and engineering approaches, i.e., use the highest technical quality available.

RESPONSE TO COMMENTS OF C. L. LONGMIRE

Dr. Longmire's comments begin with a review of his credentials in the field of EMP analysis. The authors of the report are indeed familiar with Dr. Longmire's long and extensive involvement in the study of the nuclear electromagnetic pulse (EMP) and its effect upon U.S. weapon systems. His qualifications to review and comment on this study are not questioned. However, there are a number of comments by Dr. Longmire with which we disagree, these are discussed in the following paragraphs.

1. In Section 3 Dr. Longmire raises the question of magnetohydrodynamic EMP and the description of EMP phenomena. The discussion of MHD-EMP has been changed somewhat in the revised text. Although we concede that the very long transmission lines can be subjected to a substantial threat, we also believe that the signals will be in a time domain such that the normally installed protective devices will function and provide surge limiting if the signals are large enough. As noted in the report, this subject is being actively studied under a Department of Defense program. If the results of that study indicate that signals significantly exceeding those now estimated for the power grid feeds may exist, then the question would have to be readdressed. Note, however, that MHD-EMP signals would have to be orders of magnitude greater than those from the HEMP in order to pose a threat to safety system components in so far as permanent damage is concerned. Based upon some earlier discussions with Dr. Longmire, the HEMP description has been modified and some additional references included. We trust that these changes will alleviate some of Dr. Longmire's concern.

2. In Section 4 Dr. Longmire describes what he believes was done in the study. The chronology is correct, but there are some statements which are incorrect or reflect some misunderstanding of what was done.

    a. In paragraph (A) it is stated that, "certain plausible entry points of EMP induced currents into the main reactor building were selected, namely some unshielded wires." The implication left by the comment is that some wires were just selected from a cursory examination. In fact, the plant was studied extensively to understand as well as possible the potential points of signal penetration, and based upon the available data and on site inspections, the penetrations to significant safety equipment were identified. Furthermore, in the limited experimental program conducted at Watts Bar no previously unidentified penetrations were found.

    b. In paragraph (B) it is stated that, "A single plausible pulse shape was specified (2 MHz damped sine wave), which was later augmented by another shape having the same form as the assumed EMP (double exponential)." The reviewer has apparently confused the discussions of the confirmatory test program (see Section 6) with the prediction effort. In Section 5.2 (page 40 in the draft) it is stated,

> "With optimum incidence angles, the response to the commonly accepted high-altitude EMP wave form used here is a peak bulk current of 1000 to 2000 amps. The current time history is roughly double exponential in character....."

Also in Section 5.3 where the Verification Test Predictions are discussed reference is made to, "... a spectral content similar to that of the standard EMP double exponential pulse ...." That is, predictions were based upon a broad band pulse.

In the early discussions of the testing program (October 7- 8, 1981, meeting at Watts Bar) it was argued that a 2 MHz damped sine wave input could be used for the direct injection tests because it was believed that the interior currents, even with a double exponential drive on exterior cables, would be a damped sinusoid or sums of damped sinusoids. Because of resonances near 2 MHz the test data was subsequently reprocessed using the double exponential input, and this data was used in the prediction/ measurement comparison. As expected, even with the double exponential driving function, the interior currents do contain a mixture of damped sine waves. (See Figure 6.12 and page 101, et seq in Reference 13).

c. In paragraphs (A) through (E) the reviewer refers to "plausible entry points," "plausible fault trees," etc., the implication seems to be that our analysis was superficial. The authors can only respond that many hours were spent reviewing plant systems and design, equipment specifications, and layouts and that we believe that material goes far beyond "plausible" and indeed is very representative of what exists in the plant.

d. In paragraph (G) the errors associated with the predictions are discussed. Although the values cited are correct (2.6 dB is now 2.3 dB after some corrections) it should be recognized that there are two distinct data sets, current and voltage. The two groups are summarized individually in Tables 6.2 and 6.3. For the 27 current predictions versus measurement the average "error" is -1.7 dB with a standard deviation of 8.4 dB. For the 10 voltage predictions versus measurement the average error is 13.2 dB with a standard deviation of 13.1 dB. It is generally accepted that the voltage measurements are more difficult to accomplish, and therefore, agreement with predictions is more elusive.

e. In paragraph (J) Dr. Longmire indicates that the errors in estimated EMP signals have a log normal distribution. That statement is incorrect. The Boeing predictions are assumed to be represented by a Beta distribution (see Section 9.1, page 147 in the draft). This distribution is then folded together with the assumed log normal distribution on the thresholds to generate the survival confidence curves. (This treatment does not appear in the final Report.

f. In paragraph (L) the reviewer indicates that shielding effectiveness test values were as low as 10 dB at 1 MHz. Again there appears to be some misunderstanding. Figures 6.21, 6.23 and 6.24* show attenuation, not plane wave shielding effectiveness, of a transmitted signal as a function of frequency. In Section 6.5.3 arguments are presented relative to deducing some bounds on the plan wave SE from these attenuation measurements. Some revisions to the text have been made and we believe that they will clarify this point.

3. In section 5 Dr. Longmire deals with conclusions from the study. In the first paragraph on page 8 he refers to, "the long chain of plausible assumptions." The authors, as noted above, believe that the assumptions are more than "plausible," they are solid and reasonable. In the second paragraph he refers to, "wire pathways guessed at, dividing down according to a rule-of-thumb at branch out points." The pathways were not "guessed at," but arrived at after careful consideration and review of the plant design and extensive on-site examination. Unfortunately, we know of no way to relieve Dr. Longmire's concern at this point except to note that other facilities analyzed using these techniques, then modified when required by the analysis to increase hardening, did not fail when subsequently tested to a pulsed threat environment.

   Again, as stated in 2e above, the prediction errors were not assumed to have a normal distribution but a Beta distribution based upon prior work. As also stated above, those experienced with such testing have indicated that voltage measurements are very difficult to make with the DNA equipment and the lack of agreement in the voltage domain is not as of much concern as it would be in the

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*These were Figures 6.22, 6.24 and 6.25 in the draft report.

current domain. It is difficult to conceive of any approach with reasonable resources that could analyze a system as complex as a nuclear power plant and predict every point "exactly."

Dr. Longmire acknowledges that the tests and analyses do support the view that the facility studied is at least not riddled with susceptibilities to HEMP. He further asserts that "this qualitative result falls short of what is desired." We believe that such a conclusion is completely acceptable in the context of this study. This is clearly expressed in the alternative statement of the objective in Section 1.2.

> "An alternate expression of the objectives is that this study assesses the EMP sensitivity of essential features of selected safe shutdown systems of nuclear power plant in order to identify any points which may be unduly exposed or sensitive. Then where appropriate proposes remedies for such sensitivity. It is not the intent of this study to propose "hardening" against all conceivable circumstances."

Dr. Longmire's reluctance to accept such a conclusion may be predicated upon his long association with the U.S. military systems in which complete operation under the full spectrum of threats is required.

The authors cannot comment upon the selection and makeup of the NRC panel. Certainly we believe that the study team (Sandia, Boeing, IRT and Booz-Allen) are qualified to participate in this study.

There is a significant and vast difference between <u>tripping</u> of various individual alarms or sensors by a walkie-talkie and the <u>failure</u> or even upset of complete systems required for safe shutdown of a nuclear power plant. This study was not intended to address upset, as has been indicated on several occasions in response to other reviewers.

4. Dr. Longmire makes a number of recommendations regarding NRC study of EMP. The authors cannot speak for the NRC, but do offer the following observations.

   (I) We have not included long line coupling in the analyses for the reasons cited. If Dr. Longmire has some analyses or data which indicate our reasoning is incorrect, we would like to consider it.

(II) What "deeper technical approach" to coupling does the reviewer have in mind. There are literally thousands of individual cables in a nuclear power plant associated with safety-related systems.

(III) It is difficult to envision on what bases one could justify introducing into an already complex and expensive system, shielding and filtering for a possible EMP threat, especially when our analyses suggest signal levels generally well-below usual operating levels.

(IV) One could certainly examine the feasibility of threat level tests against a nuclear power plant. However, even if one could conceive of a suitable simulator, there are other considerations. Under present law, licensees are not required to cope with acts of war. Therefore, it is hard to see how any licensee could be asked to accept the economic penalties associated with making a plant available for such tests. Obviously, prudence would suggest that any plant being tested and instrumented be "off line." With replacement power costs running $500K to $1M per day, just shutting down a plant would be extremely expensive.

(V) As noted above, there is considerable difference between a walkie talkie in close proximity to a single instrument tripping it and control system failure. However, such considerations could well be studied with the upset question. Is the reviewer suggesting in his last statement that the present study team does not have acceptable quality? If so we obviously take exception to the statement.

Interdepartmental letterhead
Mail Station L- 156
Ext: 2-8871

June 9, 1982
EM82-0176

To: P. A. Bender

From: H. S. Cabayan

Subject: Review of Report Titled "Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems"

1. Page 1. Remove first sentence in second paragraph. It does not fit into the discussion. The only examples for assessment that are pertinent are those for large communication facilities. The last sentence in this paragraph should read, "Based upon these studies, some weapons systems ....".

   I suggest that the third paragraph read as follows, "At the present time, no nuclear EMP specs have been developed for commercial nuclear power plants. Furthermore, none of the existing plants have been designed with EMP in mind. The present study was undertaken to answer the following question: "Could a nuclear ....".

2. Page 2. I suggest that the scope of the Oak Ridge report be very briefly outlined and some of the shortcomings alluded to. This will help create some continuity and enhance the rationale for having performed the present work.

3. Page 3. '... we are also able to make some statements about our confidence in these estimates.' - this implies a subjective statement about a degree of belief or level of knowledge which is not inherent in Boeing's statements. This is the type of misinterpretations that were raised on several occasions.

4. Page 10. "Likewise, none of the others suggest peak fields (Eo) greater than the 50 kV/m cited." This is not quite true. Please check with George Baker to see if he fully agrees with the way this is stated.

5. Page 38. In two occasions, the work experience is used to justify certain features of coupling: the fanning and attenuation. I suggest that a footnote be added to alert the reader, tests that will be described later on in the report will try to validate these claims.

University of California
Lawrence Livermore National Laboratory

6. Page 30. Claims about 30 dB shielding don't quite agree with figures 6.24 and 6.25 where substantial amounts of energy (as I had previously speculated) diffuse inside the building at frequencies below 1 MHz. This raises serious concerns not just for NEMP but also as far as MHD-EMP is concerned. There is precipitous drop at the higher frequencies. This will also pose problems if the threat does include energies above 100 MHz! I urge the authors to seriously reconsider interpreting the shielding data. I agree that the shielding deep in the building is going to be high. However, there are cables in the outlying sections of the building where the shielding is low which will pick-up the energy and conductively carry it into those highly shielded regions.

7. Page 41. The middle paragraph talks about buried cables sharing the current. No tests have been done to provide evidence for this claim. Reference to previous test data (and possibly reproducing such data) should be provided to satisfy the reader. As I mentioned in an earlier memo, in cable bundles, an individual cable was found to carry twice as much current as the bulk cable!

8. Page 58. First paragraph, "... prior experience indicated that a damped sine wave with a dominant frequency in the 1-10 MHz frequency band is typical." This is weak. The experience may have been gained on other totally different facilities. The authors should state that this is just an assumption that cannot be supported with valid evidence.

9. Page 71. "Transfer function from Exterior to Interior" - the significance of this data point should be discussed. What does it mean in terms of double exponential type currents outside driving damped sinusoids inside.

10. Page 97. The authors should point out that certain agreements as far as fanning out and attenuation between prediction and test data can be obtained and yet peak amplitude predictions can still be off. There is a critical initial assumption in all this as to how much gets inside in the first place (note 7).

11. Page 100. Can the statement in the last paragraph be supported? I think it is very subjective at this point.

12. Page 123. Damage thresholds: the discussion of errors suggests that it is assumed that the threshold is a constant, i.e. not subject to random variation, and there is only an error in the predicted value (error sources in Table 7.7) - I believe this is a poor assumption. If, in fact, this is the way the analyses is done, i.e. a 'worst case' analyses, it should be stated somewhere in the report and not lead the reader to believe a probabilistic assessment was done.

13. Page 154. The stated 'confidence', 0. 995, is applicable only to a single component. There does not seem to be any systems discussions.

The results imply that all the components (i.e. those investigated) will not fail, (i.e. their safety margin is greater than 0) and thus the system will not fail. Two shortcomings of this method.

- The 'confidence', 0.995, applies to a single component not failing. What is the 'confidence' that all of the components, simultaneously subject to stresses from an EMP, will not fail? I believe it is less than 0.995. In Boeing's test of hypothesis language, one must consider simultaneous tests of hypotheses, e.g.

  $$H_1: SM_1 \leq 0 \qquad H_2: SM_2 \leq 0$$

  where SM_j refers to the safety margin of the jth component. If the tests are independent, and the probability of a Type I error on each test is 0.005, then the probability of a Type I error on at least one of the two tests is

  $$\begin{aligned} P(\text{at least one Type I error}) &= 1-\prod_{j=1}^{2}[1-P(\text{Type I error on jth test})] \\ &= 1-(.995)^2 \\ &= .01 \end{aligned}$$

  Consequence: Although ones 'confidence' in the SM>0 for any one component is 0.995, the 'confidence' in stating SM>0 for two components is 0.99. As the number of components increases, this 'confidence' goes down even further.

Thus, the question - what is the 'confidence' the system does not fail?

- With regard to a systems analysis, in complex systems with many components required for operation or safe shutdown, although each component may have a small probability of failure but the system could have a larger probability of failure. Of course, redundancy reduces the system probability. The point here is that Boeing's analysis does not take into consideration the effect of the system (i.e. interrelationship between components for system operation or shutdown) in assessing the risk of an EMP.

14. Page 102 - Section 7. The analysis for component damage thresholds is performed with the use of much experience and judgement gained in post military programs. The analysis has been very carefully qualified as to restrictions or constraints on what was done. This is highly commendable and should be encouraged throughout.

15. Page 123. Note specifically the statement "It was not possible to develop an error factor specifically for this present analysis because no test data was available."

16. Page 124. Note that sources of error are identified (Table 7-7). It is not made specifically clear why AABNCP Assessment Program is applicable? Are Circuits and devices quite similar?

17. Page 125. Note pertinent observations relative to limitations of study (also see page 132). It is pointed out that many types of components were omitted from the analysis on the assumption that semiconductor devices were most susceptable. Other components may possibly be located in a much more severe environment from EMP, however.

Cabayan

H. S. CABAYAN
Electronics Engineering Department

rc/5009R

RESPONSE TO COMMENTS OF H. S. CABAYAN

1. Dr. Cabayan suggests several changes in the introductory material. The second paragraph has been revised to place the emphasis upon the questions actually being addressed. The qualification "some" will be used. Revisions in the third paragraph also reflect the approach suggested by Dr. Cabayan.

2. The text has been revised to include a very brief discussion of the earlier Oak Ridge study. It is agreed that providing such a tie to the earlier efforts does place the entire question into better perspective.

3. The intent of Dr. Cabayan's comment is not clear. If it is a <u>subjective</u> statement of our confidence in the results, it is difficult to understand the argument that it is "<u>not</u> inherent." This study used techniques which have been employed elsewhere in Department of Defense sponsored studies. There exists a difference of opinion about the use of this approach as opposed to a more generalized probabilistic treatment. However, as noted in other responses, the latter approach requires resources that were not available and, even if done, is unlikely to change the conclusions. Similarly, as noted in other responses, when facilities have been analyzed using these techniques, and any required protection (based on the analysis) installed, subsequent tests have not produced failures in equipment which the technique said would be safe. Furthermore, concerns about the interpretation of the threshold data have led to a revision of the vulnerability analyses which does away with the "survival confidence" discussion. The revised treatment relies much more on engineering judgment and that is clearly spelled out.

4. The information upon which this conclusion is based was in fact provided by G. Baker of the Defense Nuclear Agency at the request of NRC. The question has been discussed with Baker and he accepts our position.

5. It is believed that techniques being discussed in Section 5.1 stand alone. However, there is no objection to adding a footnote that indicates that tests are described later which address these issues for Watts Bar. Such a footnote has been added.

6. It should be noted that in Section 5.2 it is stated, "Steel reinforced buildings of this type have exhibited magnetic field shielding effectiveness of 30 dB or more to frequencies ranging up to 75 MHz." That is, in Section 5.2 there is simply a statement of historical fact which was used by the analyst to guide his approach. (See also Reference 13 and "EMP Engineering Practices Handbook," NATO File #1460-2, October 1977.) It must be remembered that the analysis was

completed prior to any testing, and indeed, Dr. Cabayan was one of those who insisted that the analysis and tests be independent operations.

We believe that the limitations of magnetic and electric shielding effectiveness measurements (modified MIL-STD 285) are fully discussed in Section 6.5.3 of the report. Some rearrangement of the text may make the point clearer. The attenuation (not shielding effectiveness) given in Figures 6.23 and 6.24* are values associated with the monopole (which is not plane wave). An attempt to deduce plane wave SE numbers is developed in Section 6.5.3 (page 100 of the Draft Interim Report).

Energy in the EMP spectrum above 100 MHz is normally considered to be essentially zero for the standard double exponential threat. (See References 2 and 13). The minimal values for attenuation quoted, namely 30 dB, are at 100 kHz, below which less than 10 percent of the energy in the EMP spectrum exists (Reference 13). In general, the cables that lie near the exterior walls, are those cables which also run outside, so that they will already be "excited."

7. Testing programs using the TEMPS antenna have measured current distributions on buried communications cables at AUTOVON Switching Centers. The excursions from mean current value measured on the cables are typically bounded within a factor of two of the mean current value. The measurement quoted by the reviewer concerned aircraft cabling configurations, where high Q's and extremes of load impedance generally occur. The conductor and source topology for such cabling is not analogous to the long buried cables under consideration here. The effect as noted by the reviewer has not been observed in pulse testing of ground based communication facilities.

8. This paragraph was revised by the study team prior to receiving the reviewers comments. The revised text does not contain this reference.

9. Section 6.2.1 hs been rewritten to indicate that the response wave forms are expected to be damped sinusoids (or sums of several damped sinusoids) with resonant frequencies ranging from 500 kHz to 10 MHz. This is supported by the test results which show damped sine characteristics at the test points when the input wave form is the double exponential. (See Figures 6.5, 6.12 and page 101, et seq of Reference 13).

10. As indicated above (see 7) we believe that in these types of installations the induced signals are reasonably well understood and that the predictions are realistic.

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*These were Figures 6.24 and 6.25 in the draft report.

11. It is agreed that these comments are subjective. However, experience certainly indicates that shielding effectiveness is improved when apertures are eliminated. Therefore, the study team believes it reasonable to leave the paragraph as stated.

12. The threshold analysis does produce a single value. In the usual approach, testing is then done to establish the bounds or uncertainties on the predictions. Because there was no component testing in this present program, the experience from the AABANCP GFE Assessment Program (Reference 21) was used to provide some indication of the potential uncertainties in the predictions.

13. The question of "confidence" in the results and the conclusions drawn from the results is important in this study. The points raised by the reviewer are germane - given the approach reported in the Interim Report. However, as has been indicated elsewhere, the treatment of the vulnerability analyses has been revised extensively in the Final Report. This revised approach which relies more heavily upon engineering judgment rather than attempting to build a statistical case in the absence of adequate data. Such an approach does not resolve all the questions regarding confidence in results, etc. However, the authors believe that given the lack of quantitative data which exists for these equipments and systems, conclusions based upon engineering judgment are the only reasonable way to proceed.

14. The comment is noted. Material throughout the report was reviewed and some modifications have been made to accurately reflect the conditions of the analyses.

15. See response to 14 above.

16. The results of the AABNCP Assessment Program were used precisely because no test data was available here. The authors have attempted to indicate that the AABNCP experience provides some indication of what confidence might be obtained given a test program were conducted. Obviously, the quantification of error is required if one is attempting to establish the confidence levels numerically. Given the revised treatment of the overall vulnerability assessment this quantification becomes less critical.

17. Dr. Cabayan's concern is recognized. However, we believe that the revised treatment wherein the existence of other circuit phenomena at levels significantly lower than the estimated thresholds is used in the vulnerability assessment should resolve this concern.

NRC Staff Office Comments. As of 1 July 1982, comments had been received from six staff offices including:

- Office of Nuclear Regulatory Research
- Office of the Analysis and Evaluation of Operational Data
- Division of Licensing
- Division of Safety Technology
- Power Systems Branch, Division of Systems Integration

As noted earlier in introducing the comments of the Research Review Panel, there is considerable range in these comments from very technical to philosophical. Responses to the individual comments follow.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

May 14, 1982

MEMORANDUM FOR: Phillip A. Bender
Instrumentation & Control Systems Branch
Office of Nuclear Reactor Regulation

FROM: Andrew L. M. Hon
Instrumentation & Control Branch
Division of Facility Operations
Office of Nuclear Regulatory Research

SUBJECT: COMMENTS ON DRAFT INTERIM REPORT:
INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH
COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

Enclosed is a list of comments, as you requested, on the subject draft report. These comments are from reading the draft report only. I feel resolving them will increase the effectiveness of the report. I did not try to evaluate the methodology and the approach taken by Sandia.

Andrew L. M. Hon
ICB/DFO/RES

Enclosure: As stated.

cc: F. Rosa, NRR
Bill Morris, NRR.

COMMENTS ON THE SANDIA EMP DRAFT REPORT

1. PP 8 "The HEMP being a broad-based radio frequency signal ...". What is the expected range of the frequency and why 1MHz was used for damage analyses?

2. PP 80 Table 6.5 When noise level = signal level, one needs to justify validity of the result.

3. PP 98 Section 6.5.2 From the significant limitations of 5 test points and undetected penetrations, what is the conclusion? Is the data base complete or sufficient?

4. PP 102 "Only permanent damage failures were examined." How serious is the signal upset? If not, should be stated and justified.

5. PP 102-132 This chapter deals with component damage threshold analysis. The numbers presented in Table 7.2 seem very high (10^9 volt. 1.5×10^{18} Watt, etc). The text stated that the shunting capacitors in the circuits were supposed to absorb the high energy pulse and protect the components. Intuitively, one may think of the following concerns as he sees these large numbers:

   (a) Capacitor may indeed absorb the high energy pulse, but after the pulse is gone, the capacitor is charged up (Q=CV) and now it can discharge to the circuitry with nearly the same amount of voltage and energy.

   (b) Simply multiply V_t and I_t and call it P_t is questionable. $10^7 - 10^{18}$ Watt in 1 millisecond means a lot of energy ($U=0.5CV^2$) and heat.

   (c) Can the capacitors survive the high voltage? These may be simple-minded concerns. But, when such high numbers as claimed reference to actual test data and more clarification will definitely increase the readers' confidence.

6. PP 133 "Estimate of the damage threshold level for electromechanic-type devices is defined to be ten times of the operational voltage ..." How was ten selected? Any data from other studies to support it?

7. When one compares Chapters 7 and 8, it seems solid state circuitry has significantly higher damage threshold than electromechanic type devices. This seems to be different from the common belief that solid state devices are more susceptible to EMP. This needs to be clarified.

RESPONSE TO COMMENTS FROM OFFICE OF NUCLEAR REGULATORY RESEARCH

1. The frequency content of HEMP extends from essentially DC to about 150 MHz. The discussion of HEMP was revised to include this information. The 1 MHz level was selected as the frequency for threshold assessment because it represents a "reasonable" average for the predicted responses. Subsequent tests verify that this was a reasonable selection for the threshold predictions. (See also the response to Barnes' comment 4). Some revisions to the text were made in this regard in response to individual reviewers comments.

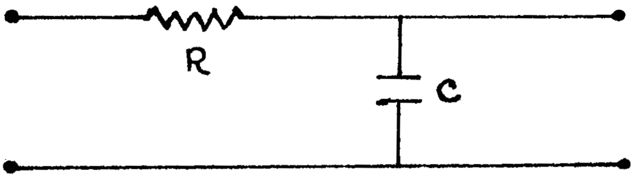
2. The reviewers concern is understood and the table and accompanying text have been revised to remove the ambiguity. In this test, when the signal level = noise level while the transmitter is being moved around the site, the conclusion is that there are no other penetrations driving the test point. The intent of the remarks was to indicate that when a signal above the noise level was observed, it was because the test point was being driven from another point on a previously identified source.

3. The authors recognize that five test points is a significant limitation on the effort. These tests are time consuming (approximately half a day per test point) and limitations of cost and time precluded our taking additional test data. Also, given the nature of controls on nuclear power plant design, the ease with which excitations at points other than the principal penetration were detected, and the experience gained just studying the site, the authors are convinced that inadvertent penetrations do not exist. It should also be recognized that these measurements are not intended to stand alone as a verification that no inadvertent penetrations exist, but to serve as a partial confirmation that "as built" drawings have been correctly interpreted. We believe that goal has been achieved. Nevertheless, it is acknowledged that completeness or sufficiency cannot be quantitatively specified.

4. This study was intended to examine damage only. This constraint, as well as other limits on the study have been more clearly defined in a separate section of the report. At this point, the authors cannot make any statement about signal upset except that it has not been studied here.

5. The concerns expressed here about the high threshold values are accepted and understood. As a result of internal reviews by the study team, this discussion has been revised to better define the conclusions which can be drawn. Certainly other phenomena, arc over, breakdown, etc., will occur before these very high levels are reached. What the analysis does say however, is that the inherent protection the solid state devices have by virtue of their location in the circuitry

means that solid state device failure is not the controlling mechanism and that other mechanisms must be considered. In addition, the following comments are offered in response to Mr. Hon's specific concerns. The majority of circuit protection provided through shunting capacitors encountered in this study is in the form of a low pass RC-filter (which is reasonable since we are dealing with a 60 Hz system). A general pictorial of an RC-filter is:



The nature of the capacitor at the high frequencies is to provide a very low impedance path to return/ground for the input current.

(a) Regardless of whether the capacitor is uncharged or fully charged at the instant the EMP pulse is incident on the input pin, there will be little additional charge (and thus voltage by $V = Q/C$) placed upon the capacitor. The voltage across the capacitor during charging due to EMP can be described by:

$$V_C = V_T(1 - e^{-t\rho/RC})$$

where V_C is the voltage across the capacitor, V_T is the EMP-induced terminal voltage, $t\rho$ is the EMP pulse width, and RC is the time constant of the circuit. For this study $t\rho << RC$ and thus we can approximate $e^{-t\rho/RC}$ as $(1 - t\rho/RC)$. This gives

$$V_C = V_T(1 - 1 + t\rho/RC) = V_T(t\rho/RC)$$

Since $t\rho/RC \ll 1$, this gives $V_C \ll V_T$. Thus, it is true that the capacitor will be charged slightly due to EMP, but the voltage induced across the capacitor will not be equal to the EMP-induced terminal voltage, V_T, and, in fact, is much, much less than V_T.

(b) For the same RC filter configuration in (a), the phase angle between the input voltage into the filter and the output voltage of the filter is described by the relation:

$$\phi = \tan^{-1} \frac{1}{\omega RC}$$

In this study, ωRC is on the order of 10^2. This implies that $\phi = \tan^{-1} 1/10^2 = 0.57^\circ$. That is, for a first order approximation, the voltage output of the filter is in phase with the voltage input into the filter. Because of this, the multiplying of I_T and V_T as an approximation of P_T is reasonable (i.e., I_T and V_T are roughly in phase).

From the response in (a), since V_C is "small", $U = 1/2\ CV^2$ is "small". Also, the duration of the pulse is microseconds, not milliseconds.

(c) Because of the nature of the action of a low pass filter, the impedance provided by the capacitor is very small at high frequencies. The energy dissipated across that small impedance, given by I^2Z, is therefore small. The piecepart thresholds for damage to the electrolytic capacitors are high (>10 KW). It is unlikely, then, that these components will be damaged.

Additionally, for circuit (pin) damage thresholds greater than 2-3 kV, other phenomena such as arcing or other dielectric breakdown will take place; i.e., the failure of the most sensitive semiconductor component is not the primary failure mode of the circuit. Thus, it is reasonable to expect that these capacitors will not be required to survive extremely high voltages. It should be noted that arcing may or may not constitute a circuit failure. To determine arcing thresholds analytically is intractable. The determination of these thresholds will require the support of an engineering test program.

6. The damage level for electromechanical devices of 10X operational voltage was predicated upon Boeing's experience in other facilities. We have confirmed in discussions with other experts in insulation phenomena that this is a conservative assumption.

7. Solid state devices, that is individual transistors, integrated circuits, etc., are more susceptible to EMP than electromechanical devices. What the analyses indicates is that when incorporated into a variety of circuitry, the "effective" damage threshold is much higher. That is, the pulse amplitude at the connector must be higher in order to drive the device to failure. Revisions to the text have been incorporated which should help clarify the situation.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 10 1982

MEMORANDUM FOR: Roger J. Mattson, Director
Division of Systems Integration
Office of Nuclear Reactor Regulation

FROM: Carlyle Michelson, Director
Office for Analysis and Evaluation
of Operational Data

SUBJECT: REVIEW OF DRAFT INTERIM REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

We have reviewed the subject draft interim report as requested by your memorandum dated April 12, 1982. The analyses and testing work performed for the report, within the limits of the scope of the study, is commendable. Based on our review, we have the following general comments to offer.

We believe that the limitations of and constraints imposed upon the study and their consequences should be emphasized more in the final report, perhaps even in a separate section. The limitations and constraints of particular importance are:

1. (Page 10 of the draft report)
   Magnetic-Hydrodynamic (MHD) EMP is not considered in the study because of the conclusion reached that protective devices would respond to isolate the plant and protect it from the large currents that may be developed due to (MHD) EMP.

2. (Page 102 of the draft report)
   The three early decisions and four constraints imposed on the study of threshold damage in order to keep the threshold effort tractable, viz;

   a. No attempt was made to predict damage thresholds for rotating machinery;

   b. Only selected components, representative of classes of equipment used in the safe shutdown systems, were analyzed;

   c. The damage threshold effort is analytical only.

   and

   a. Because semiconductor components are more susceptible to EMP induced failure than passive components, the analysis was restricted to include only semiconductors and to eliminate calculating circuit damage thresholds for passive device failures;

b. The circuit analysis was conducted at 1 mHz, no other frequencies were used to determine damage threshold;

c. On the equipment items analyzed, only those pins that serve as interfaces to "outside-world" connections were considered, all others, i.e., those that serve as interfaces internal to the box or equipment cabinet, were excluded from analyses;

d. Only permanent damage failures were examined, that is, signal upset was not considered in the study.

The consequences of the above limitations and constraints should also be addressed in the final report. For example, in not considering signal upsets due to EMP (item d), the consequences of such upsets causing plant transients and adverse control system and protection system interactions will not be included in the study.

If you should desire additional information or assistance, the AEOD contact is Matthew Chiramal.

Carlyle Michelson

Carlyle Michelson, Director
Office for Analysis and Evaluation
of Operational Data

cc: H. Denton, NRR
F. Rosa, NRR
P. Binder, NRR
B. Morris, NRR
M. Srinivasan, NRR

RESPONSE TO COMMENTS OF THE OFFICE FOR ANALYSIS AND EVALUATION OF OPERATIONAL DATA

The need to highlight the limits on the study is a point well taken and one with which the study team agrees. The revised report contains a separate section which emphasizes the constraints and limitations of the study. In addition, these points are reiterated within the report when it is germane to the subject being discussed.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 1 9 1982

MEMORANDUM FOR: Roger J. Mattson, Director
Division of Systems Integration

FROM: Darrell G. Eisenhut, Director
Division of Licensing

SUBJECT: REVIEW OF DRAFT INTERIM REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

In accordance with your memorandum of April 12, 1982, we have reviewed the subject report and offer for your consideration the comments presented in Enclosure 1.

Darrell G. Eisenhut, Director
Division of Licensing

CONTACT:
J. Calvo, X28563

Enclosure:
Comments

cc w/enclosure:
G. Lainas
F. Rosa
P. Bender
B. Morris
G. Holahan
J. Calvo

ENCLOSURE 1

COMMENTS ON
DRAFT INTERIM REPORT:
INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

This enclosure presents the comments from the Division of Licensing on the subject report:

1. Page 10 of the report states that the Deparment of Energy and Department of Defense are now addressing the potential effects of EMP on electric distribution systems in the U.S. If the results from that study do not confirm our assumptions, it may be necessary to re-examine the magnetic-hydrodynamic (MHD)-EMP question in relation to safe shutdown systems.

   In view of the fact that the same techniques that have been developed over the past decade to study military systems were also used to assess the vulnerability of components to EMP in commercial nuclear power plants, it would be highly beneficial if cognizant members of the Departments of Energy and Defense and NRC and their consultants compare notes on the approach, methodology, assumptions and results of the two studies in progress. We believe that this is consistent with providing the high quality review of the results of the EMP program that is essential to the resolution of this issue.

2. The summary of analytical predictions indicates that the estimated thresholds are well above anticipated EMP induced signal levels. No vulnerable areas, components or systems were identified for the Watts Bar Nuclear Plant which was selected as the example plant for this study. It was also indicated that the construction practice employed at the example plant provide a great deal of inherent electromagnetic shielding to the areas of the plant housing safety-related systems. Furthermore, due to the consistent use of continuously connected metal conduits and cable trays within the plant, internal cabling and the associated electrical equipment will be largely decoupled from the attenuated diffusion fields.

   We believe that the aforementioned construction practice and electrical design installation are followed in all nuclear power plants. Therefore, unless the current study identifies possible problem areas as a result of variations in design installation or configuration, we believe that there is no need to evaluate other plants pertaining to EMP-induced failures as suggested in the study.

3. Although there were no EMP-induced failures of the equipment selected for analyses, the EMP signal may induce currents on existing plant control circuits that may cause several systems to behave in a manner for which they have not been programmed. The study should determine if this is possible and whether the possible consequences are acceptable or not.

RESPONSE TO COMMENTS OF THE DIVISION OF LICENSING

1. The study team agrees with the observation that the various studies should be in contact, and in fact they are. It was not so stated in the report, except as noted in the reference list, but the same group from Boeing Aerospace Co. who participated in this study are conducting the DOD program. In addition, a number of the review panel members (C. Longmire, H. Cabayan, G. Baker) have been and are active participants in DOD sponsored research.

2. The study has already examined several other plants as part of the "generic extension" of this effort. That examination has indicated that although there are many and strong similarities in plant design, there are also differences which can influence the interaction/coupling process. Although it is agreed that not every plant must be examined, the potential problems outlined in Section 9 of the expanded report should not be ignored.

3. This reviewer is also addressing the question of signal upset and its consequences. As has been discussed elsewhere, upset is beyond the scope of this present investigation. This has been stated very clearly in the report.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

APR 28 1982

MEMORANDUM FOR: Roger J. Mattson, Director
Division of Systems Integration

FROM: Stephen H. Hanauer, Director
Division of Safety Technology

SUBJECT: REVIEW OF DRAFT INTERIM REPORT:
INTERACTION OF ELECTROMAGNETIC
PULSE (EMP) WITH COMMERCIAL NUCLEAR
POWER PLANT SYSTEMS

In your memorandum dated April 12, 1982, you requested staff review of the subject study report. The primary purpose of the study was to determine the vulnerability of selected safe shutdown systems of a specific nuclear power plant (Watts Bar) to EMP effects resulting from a high altitude nuclear detonation.

Based on our review of the Sandia study, which is to be expanded, we found the systematic engineering approach and results encouraging. We recommend that the following topics be considered in the expanded study.

1) Plants with a different type of containment structure (in particular the older plants) may be less effectively shielded. If EMP shielding effectiveness is reduced in these plants, a re-analysis of the effect of EMP on critical systems may be required.

2) Because solid state devices are more susceptible to EMP damage, other plants that use more solid state equipment may be more susceptible. The BWR/6 uses solid state components in the reactor protection system and the reactor manual control system, and is an example of the type of plant that might be considered in the expanded studies.

3) The study has not addressed systems upset, spurious or erroneous instrumentation signals, or computer print-out errors that might result from the EMP. Therefore, it is not clear that the chance of operator error, based on false instrument readings or induced process computer errors, in overriding automatic equipment operation would not be increased.

If you have any question concerning our review contact Robert Riggs of the Safety Program Evaluation Branch.

Stephen H Hanauer

Stephen H. Hanauer, Director
Division of Safety Technology

cc: E. Case
M. Ernst
W. Minners
F. Rosa
B. Morris
R. Riggs

RESPONSE TO COMMENTS OF THE DIVISION OF SAFETY TECHNOLOGY

1. Based upon experience in other programs, it is the opinion of the study team that any plants in which the buildings have double course rebar will have significant shielding against diffused fields. Furthermore, the strength of the driving signal on externally excited cables which are directly tied to safety related equipment suggests that even if diffused field coupling exists, it will be lower and therefore of less concern. Available date on the SEP plants has been reviewed and

2. The more modern designs such as those of the BWR 6 and NUPLEX 80 were examined as part of the generic extension. Our observations and conclusions therefore are reported in Sections 9&10 of the expanded report.

3. Mr. Hanauer is correct, upset has not been examined in this present study. Therefore, we cannot comment upon effects of signal upset on operator errors.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 12 1982

MEMORANDUM FOR: Faust Rosa, Chief
Instrumentation and Control Systems
Branch, DSI

FROM: M. Srinivasan, Chief
Power Systems Branch, DSI

SUBJECT: COMMENTS ON DRAFT REPORT "INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEM"

As requested, we have reviewed the subject report and make the following comments:

1. The electromagnetic pulse (EMP) described in the draft report exhibits characteristics similar to the lightning wave pulse. The differences between the two waves are that the EMP has a much steeper rise and an overall short wave duration. Also, the peak electric fields for the EMP wave are higher than the lightning type wave. In the 500 kv transmission line model, the EMP voltage wave will be limited by the discharge voltage of the lightning arrestor located on the 500 kv side of the main transformer. (The lightning arrestors are rated for impulse currents using a 8 x 20 microsecond current wave. The EMP wave is a $(5\text{-}10)\cdot10^{-3}$ x (.5-1) microsecond wave and it is questionable if the lighting arrestor can safely discharge this surge current). A typical lighting arrestor discharge voltage value (kv crest) at 15 ka surge current is approximately 930 kv. This 930 kv impulse wave (or wave of similar magnitude) will be injected into the plant electrical equipment via the main transformer. The wave attentuation through the transformer is limited by the expression $e^{-RX/Z}$. Since R is very small incomparison to Z of the transformer winding, minimum attentuation takes place in the transformer. Analysis should be provided to show the various impulse wave voltage magnitudes encountered at critical locations as this wave propagates into the plant electric system. (Similar analysis should also be included for the 161 kv offsite power grid.)

2. The study does not include discussion (or analysis) for EMP wave reflections which will occur at the open circuit points and cable splices or junctions. We believe consideration should be given to wave reflections to ensure that total peak values (due to doubling effect) do not exceed assumed voltage damage threshold values for the plant critical equipment.

Contact:
P. Gill
x27773

3. The failure modes discussed in the study are assumed to be an arc-over condition of the electrical equipment or device. However, many failures in the electrical system or apparatus are of incipient insulation failure due to very high transient overvoltages as a result of surge or lightning waves. Usually, these faults are pin-hole type puncture (high resistance fault) in the insulation system of electrical equipment.

4. The damage thresholds assumed in the study are 10 times the operating voltage for various voltage class equipment. The damage threshold voltage (withstand voltage) for short duration pulses are defined in terms of standard Basic Impulse Levels (BIL) for systems rated above 1000 volts. The systems below 1000 volts such as 480V and 208V do not have standard BIL ratings. The maximum power frequency one minute voltage withstand rating for systems below 1000 volts is only 2200 volts. It would be most appropriate if the assumed voltage threshold cited in the study for various system voltages were referenced to an industry standard.

5. It would be helpful if the backup data and calculations are included in the Appendix A for the 500 kv transmission model for the derivation of surge currents as shown in Figure A-2.

6. The damage threshold predictions for rotating machinery are not included in the study. We believe that this data should be included in order to evaluate the survivability of the rotating machinery under conditions of EMP surge.

7. The penetration of 161 kv overhead transmission lines to the plant electric equipment are not discussed in the study. It appears that penetration of 161 kv transmission lines are capable of producing bulk-current threats similar to 500 kv transmission lines penetration. Why is this penetration consideration not included in the study?

8. Refer to pages 3, 26, 32, 42 and 49 for typographical errors. Please see attached pages as marked for comments.

M. Srinivasan, Chief
Power Systems Branch
Division of Systems Integration

Attachment:
As stated

cc: See page 3

should be subjected to an EMP. This involves examining the plant in light of the potential interaction mechanisms, and based upon the configuration of the plant systems (that is, what loads are active, what circuits are open, where are cables routed, etc.) analyzing how signals could be induced and distributed. Concurrently, component damage thresholds were estimated. The components of the systems of concern were examined, and based upon circuit configurations and piece part characteristics, estimates made of the signal levels at the component interconnections which could cause failure of the component. These two sets of estimates were then than folded together to assess the vulnerability of the selected components. Using techniques which have been developed over the past decade studying military systems, we are also able to make some statements about our confidence in these estimates. Because nuclear plants, like many military systems are very complex, a modest experimental program was conducted to provide some verification of the estimates induced signal levels. These measurements were not intended to establish whether the example facility is or is not hard to EMP. Rather they serve to verify (or reject) conclusions reached about signal distribution and attenuation.
If vulnerabilities are defined, recommendations will be made for eliminating or reducing them, that is recommendations for hardening. Finally, the results will be extrapolated to other nuclear plants. This interim report describes the initial stages of this study and the results obtained for the example plant.

motor control centers (e.g., the Containment and Auxiliary Building Ventilation Board). The 480 V Shutdown Boards also provide power to the battery chargers and inverters and thus to the vital DC and AC boards.

The actual loads associated with each of the shutdown boards and subsequent load centers were established by a detailed examination of the one-lines for each board. Such a one-line is shown in Figure 4.3. This permitted us to define the loads, the control systems (AC or DC), the location os switches (control room, motor of control center, local). This information was combined with estimates of the length of cable runs interconnecting the load and the bus, a decision as to load status assuming the plant was a normal full power operation (normally energized, normally open, etc.), a decision as to load criticality, and the results tabulated as shown in Table 4.1. These tables were then used by the analysts to establish the points in the system at which predictions of EMP induced signals were to be made. The typical prediction points are summarized on Table 4.2.

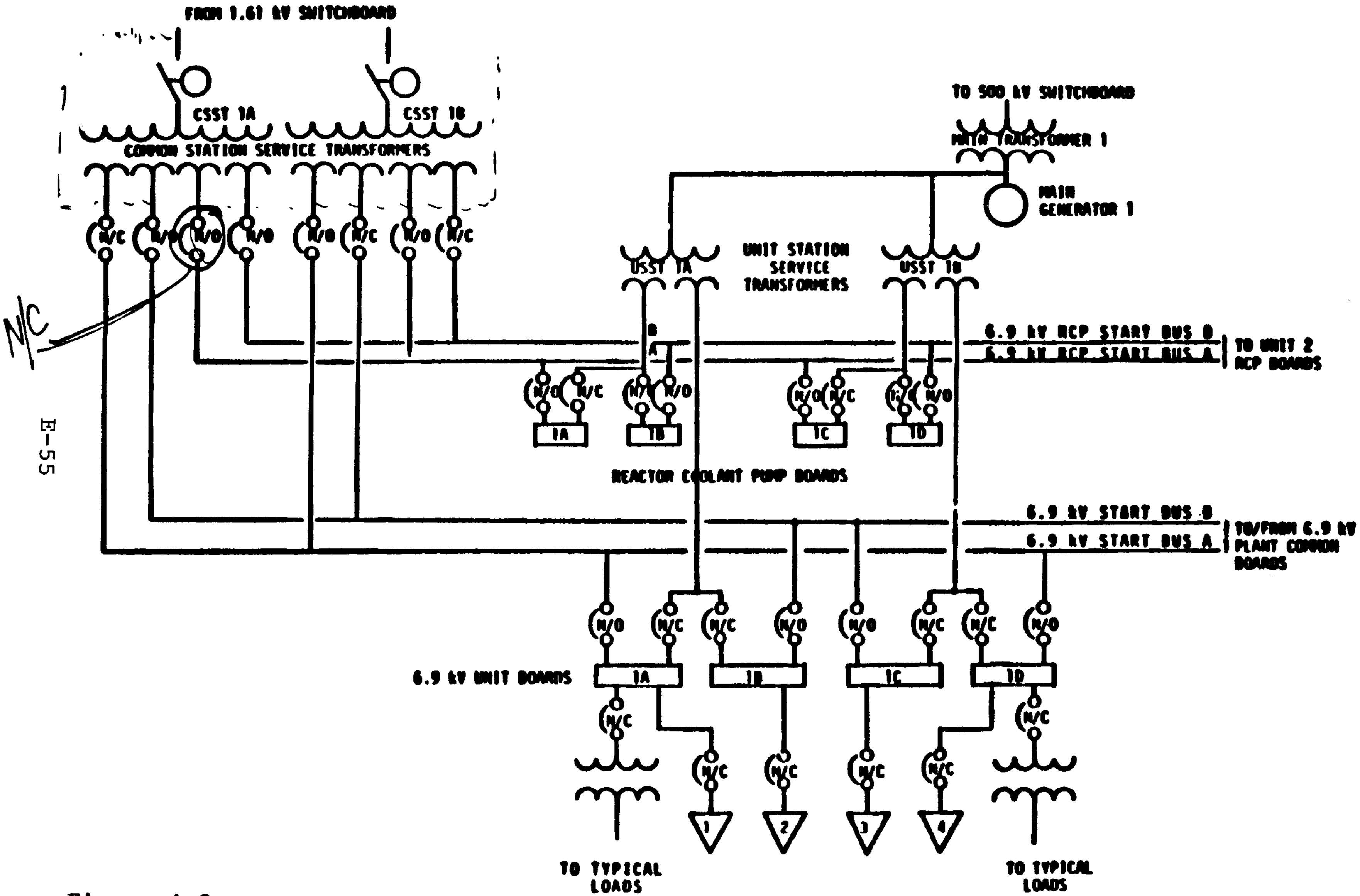


Figure 4.2. Simplified One-Line Diagram Watts Bar Nuclear Plant Electrical Power System.

How about 161KV overhead transmission lines
6.9KV Control boards. is that of not any Conce

composed of large numbers of individual cables, are discrete, readily identifiable and well controlled. At Watts Bar the following penetrations were investigated in detail for coupling potential to critical equipment and are depicted in Figure 5.2 by a simplified penetration connectivity diagram.

1) 500 kV overhead transmission lines to the Turbine Building
2) Buried conduit duct bank cables to the Intake Pumping Station
3) Buried conduit duct bank cables to the Diesel Generator Building
4) Buried conduit duct bank cables from the Diesel Generator Building to the Auxiliary Building
5) Buried conduit duct bank cables from the Intake Pumping Station to Auxiliary Building

The principal source of EMP energy coupled to critical circuits in the plant is current induced on cables in the external buried conduit systems which penetrate the buildings. The level of the current induced in these conduit systems can be estimated from that of the infinitely-long buried wire with an incident EMP in the form of a parallel-polarized plane wave of 50 kV/m amplitude. With optimum incidence angles, the response to the commonly accepted high-altitude EMP waveform used here is a peak bulk current of 1000 to 2000 amps. The current time history is roughly double-exponential in character, rising to a peak value in about 500 nanoseconds, and falling to half-peak value in tens of microseconds. Due to the finite length of the buried conduit systems, reflections

Same will true of 161KV system.

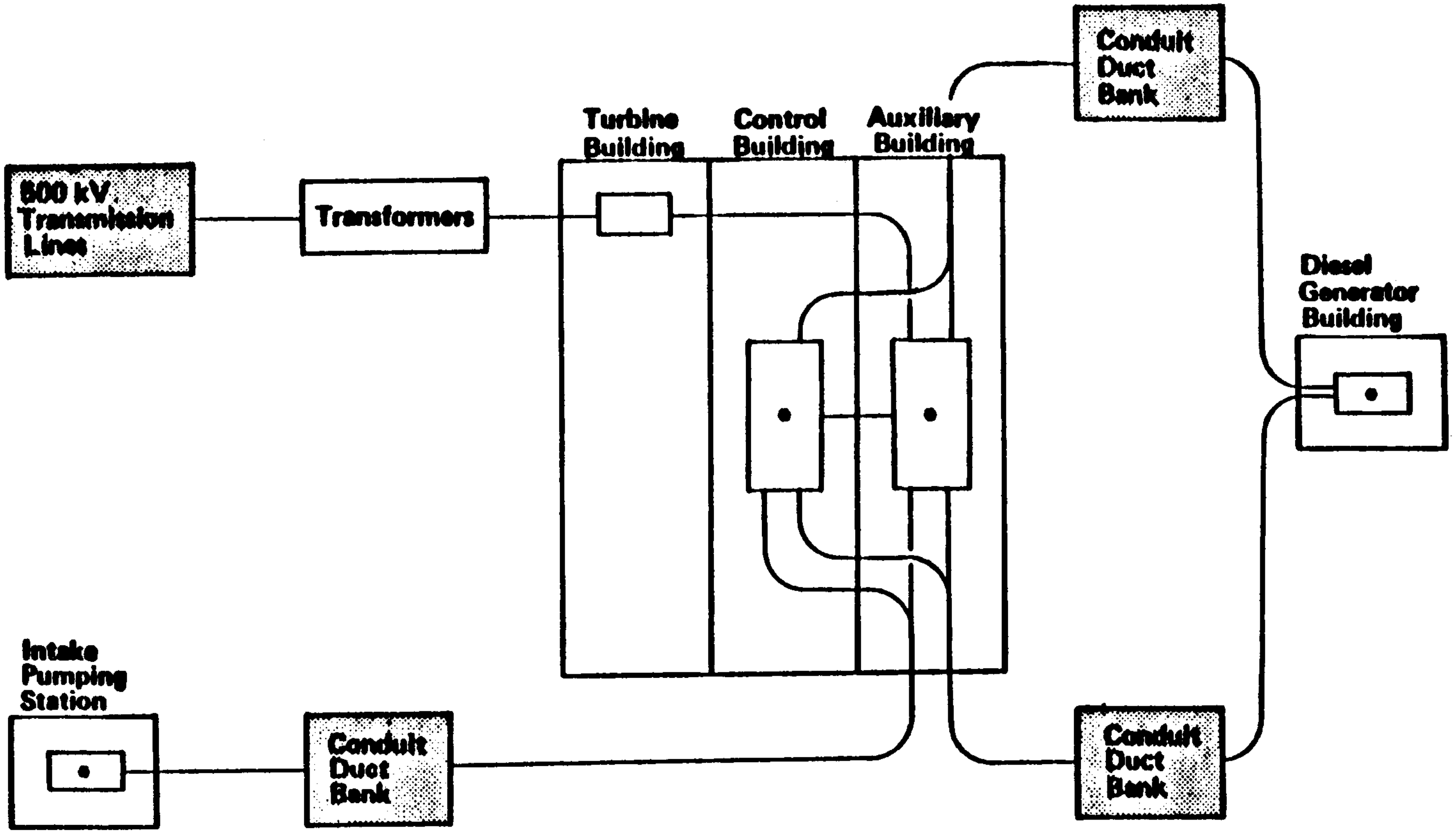
conductors attached to the bus. Therefore, as it propagates inward from a point of penetration the EMP energy tends to be dispersed throughout the interior cabling system, attenuated by ohmic loss, and distributed at bus distribution boards.

In general, only the first or second stages of fan-out distribution will experience a substantial EMP threat. This is the case for the penetration of the 500 kV transmission lines which are capable of producing a bulk current threat on the order of 10,000 to 20,000 amperes at the outputs of the plant main transformers. While this level of current appears formidable, it is attenuated by transformer losses, ohmic and cross-coupling losses, and distribution fan-out to the degree that only milliampere levels remain to threaten system critical equipment. This analysis appears in more detail in the 500 kV Transmission Line model shown in Appendix A.

Provide backup data for this statement
and calculation for [illegible]

5.3 EMP-Induced Signal Predictions

The predictions for the various portions of the safety related systems are detailed on the response model diagrams in Appendix A, and in Table ?. However, it is also convenient to summarize these preditions as shown in Figure 5.3. Here the responses have been grouped according to the nominal operational levels of the equipment involved. It is observed that except for the instrumentation the predicted voltages are much less than the nominal operating levels. Furthermore, a significant fraction of the higher predictions (circled points on Figure 5.3) are observed to occur on systems in the outlying structures. Although the analysis indicates numerous signals less than 1 volt, all such predictions have been summarized as one volt and in the subsequent vulnerability



● Critical Equipment Location

▨ Principal EMP Sources

Where is the 161kv Connectivity point?

Figure 5.2. Simplified Connectivity Diagram.

6.0 Verification Measurements

6.1 Introduction

Whenever a facility as complex as a communications terminal or a nuclear power plant is analyzed for EMP vulnerabilities, the question arises, "How good is the assessment?" Such concerns are frequently addressed, as least in part, by conducting experimental measurements. This program is no exception to that practice. However, it is impractical to subject a facility as large as a nuclear power plant to "threat level" simulation signals. On the other hand, it is possible to conduct a program of specialized verification measurements. Such tests were conducted at the Watts Bar Nuclear Plant and those measurements are discussed in detail in the following sections.

6.1.1 Direct Injection Tests. A test plan[5] was prepared and distributed to the NRC staff and the NRC Research Review Panel for this program to acquaint them with the test procedures and objectives, and to outline the impact of the tests on the facility operations. After review and subsequent discussions between the study team and the panel the test objective was finalized as follows:

> "The objective of this test is to conduct a series of CW direct injection measurements on a selected sample of those points for which predictions have been made. The results of these measurements will then be used to compute the amplitude of the induced signals at the selected points. A comparison of the measured and predicted values may then be made to check the assumptions and analytical techniques used in the assessment."

It should be noted that these tests will serve only to check the validity of the internal coupling models used and will not serve as a verification of the external to internal, i.e., incident field to facility penetration coupling mechanism.

7.0 Component Damage Threshold Analysis

7.1 Introduction

The electrical equipment used in a commercial nuclear power plant spans the range from large horsepower, heavy duty fluid pumping systems to solid state logic devices. In order to keep the damage threshold estimate effort tractable, a number of key decisions were made early in the study. One, no attempt was made to predict damage thresholds for rotating machinery. Why? Two, only selected components, representative of classes of equipment used in the safe shutdown systems, were analyzed. Three, the damage threshold effort is anlaytical only, there was no test program to verify threshold~~s~~ estimates.

In addition to the three decisions cited above, four additional constraints were imposed upon the damage threshold program: (1) Because semiconductor components are more susceptible to EMP included failure than passive components, the analysis was restricted to include only semiconductors and to eliminate calculating circuit damage thresholds for passive device failures; (2) The circuit analysis was conducted at 1 mHz, no other frequencies were used to determine damage threshold; (3) On the equipment items analyzed, only those pins that serve as interfaces to "outside-world" connections were considered, all others, i.e., those that serve as interfaces internal to the box or equipment cabinet, were excluded from analyses; (4) Only permanent damage failures were examined, that is, signal upset was not considered here.

Table 8.1. Watts Bar Nuclear Plant abbreviated assessment EMP predictions.

Critical Equipment	Interface	Operating Level	BIL Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Residual Heat Removal Pump	AC Input	6.9 kV	10X	1.4 V	94
Centrifugal Charging Pump	AC Input	6.9 kV	10X	12 V	75
Essential Raw Cooling Water Pump	AC Input	6.9 kV	10X	225 V	50
Aux Feedwater Pump	AC Input	6.9 kV	10X	4 V	85
Pressurizer Heater Transformer	AC Input	6.9 kV	10X	1.4 V	94
480 V Shutdown Transformer	AC Input	6.9 kV	10X	17 V	72
Diesel Generator	AC Output	6.9 kV	10X	346 V	46

Provide reference standard

Table 8.1. Watts Bar Nuclear Plant abbreviated assessment EMP predictions (Continued).

Critical Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Component Cooling System Pump	AC Input	480 V	10X	24 V	46
125 Vdc Vital Battery Charger	AC Input	480 V	25 kV	8.3 V	70
	DC Output	125 V	8.3 kA	0.2 A	92
120 Vac Vital Inverter	AC Input	480 V	1.8 kV	8.3 V	47
	DC Input	125 V	934 V	1.0 V	59
	AC Output	120 V	887 V	2.6 V	51
Aux, Control, and Service Air Compressor	AC Input	480 V	10X	16 V	50
Control Room Air Conditioner Compressor	AC Input	480 V	10X	16 V	50
Hydrogen Electric Recombiner Transformer	AC Input	480 V	10X	1.0 V	74
Hydrogen Detector System	AC Input	480 V	10X	1.0 V	74
RHR Pump Room Cooler Fan	AC Input	480 V	10X	1.0 V	74
Diesel Generator Lube Oil Circulating Pump	AC Input	480 V	10X	6.9 V	57

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Table 8.1. Watts Bar Nuclear Plant abbreviated assessment EMP predictions (Continued).

Critical Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
DG Water Heater	AC Input	480 V	10X	19 V	48
DG Battery Charger	AC Input	480 V	10X	19 V	48
DG Room Exhaust Fan	AC Input	480 V	10X	6.9 V	57
DG Day Tank Fuel Oil Transfer Pump	AC Input	480 V	10X	6.9 V	57
DG Heat Exchanger Supply Valve	AC Input	480 V	10X	6.9 V	57
DG Building Lighting Cabinet	AC Input	480 V	10X	19 V	48
AFW Pump Valve, Elec Hyd Actuator	AC Input	480 V	10X	1.8 V	69
AFW Pump, Lube Oil Pump	AC Input	480 V	10X	1.8 V	69
Boric Acid Tank Heater	AC Input	480 V	10X	1.2 V	72
Centrifugal Charging Pump, Aux Oil Pump	AC Input	480 V	10X	1.8 V	69
Charging Pump Minimum Flow Valve	AC Input	480 V	10X	1.8 V	69

Provide reference Standard

Table 8-1. Watts Bar Nuclear Plant abbreviated assessment EMP predictions (Continued).

Critical Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
RWST to RHR Pump Flow Control Valve	AC Input	480 V	10X	1.0 V	74
Charging Flow Isolation Valve	AC Input	480 V	10X	1.8 V	69
Seal Flow Isolation Valve	AC Input	480 V	10X	1.8 V	69
RHR Heat Exchanger to CVCS Charging Pump	AC Input	480 V	10X	1.2 V	72
RHR Pump Inlet Flow Control Valve	AC Input	480 V	10X	1.0 V	74
RCS Pressure Relief Flow Control Valve	AC Input	480 V	10X	1.0 V	74
RHR System Isolation Bypass Valve	AC Input	480 V	10X	1.0 V	74
AFW Pump Turbine Steam Supply	AC Input	480 V	10X	1.0 V	74
Steam Flow to AFW Pump Turbine Isolation Valve	AC Input	480 V	10X	1.0 V	74
Steam Generator Feedwater Isolation Valve	AC Input	480 V	10X	1.1 V	74
ERCW Header Isolation Valve	AC Input	480 V	10X	29 V	44

provide
reference
standard

Table 8-1. Watts Bar Nuclear Plant abbreviated assessment EMP predictions (Continued).

Critical Equipment	Interface	Operating Level	Damage Threshold	Peak Value EMP Response	Safety Margin (dB)
Component Cooling Heat Exchange Isolation Valve	AC Input	480 V	10X	1.0 V	74
Aux Building ERCW Header Isolation Valve	AC Input	480 V	10X	1.0 V	74
ERCW to Component Cooling Heat Exchanger	AC Input	480 V	10X	1.1 V	74
CCS Heat Exchange Outlet Valve	AC Input	480 V	10X	1.1 V	74
RHR Heat Exchange Header Inlet Valve	AC Input	480 V	10X	1.0 V	74
CCS Heat Exchange Inlet Isolation Valve	AC Input	480 V	10X	1.0 V	74
RHR Heat Exchange Return Header Isolation Valve	AC Input	480 V	10X	1.0 V	74
CCS Pump to CS Outlet Isolation Valve	AC Input	480 V	10X	1.0 V	74
RHR Heat Exchange Outlet Valve	AC Input	480 V	10X	1.0 V	74

Provide ref. Standard

RESPONSE TO COMMENTS ON THE POWER SYSTEMS BRANCH

1. The analysis reported here does not assume that in the HEMP case there is any limiting effect due to surge arrestors or similar devices. The analysis does use transformer attenuation (10 dB) based upon measurements for 25 KVA transformers. That is, the transformer provides a capacitive coupling with little attenuation and behaves like a band pass filter. Similar values were used by Barnes in the study reported in Reference 1.

   In this analysis we have not reported voltage values at intermediate points but have followed the current attenuation as the EMP induced signal flows inward.

   The 161 kV system (preferred offsite power) would be a source of signals comparable to those from the 500K system (normal offsite power). That is, it is an either/or situation because only one of these potential sources is connected to the safety-related systems at any given time. During normal operation the station auxiliary power needs are provided from the main generators. During startup and shutdown auxiliary power needs are met by the 161 kV system.

2. The text in Section 5.1 has been expanded to provide a more detailed explanation of the computations performed.

3. Although the report uses the term "arc over" in discussing equipment failure, in fact this has been interpreted to include dielectric breakdown, arc over, and other similar phenomena.

4. It should be recognized that the phenomena being studied here occur at frequencies well above power frequencies. In general, the higher the frequency (i.e., the shorter the pulse width) the better the insulation withstand capability. For those cables carrying power below 1 kV (480 VAC, 120 VAC and 125 VDC), the revised vulnerability estimates assume failure (conservatively) at 3X operating voltage.

5. As noted in Section 5 of the report, in the "abbreviated analysis" technique employed here, there is a strong dependence upon the experience and acquired skills of the analyst. The modeling diagrams are not intended to be detailed records of the analysis, however, the diagrams do indicate where and to what extent attenuation occurs. In this technique all of the calculational details are not documented.

6. There is no available data base for the failure of rotating machinery of the size found in power plants, nor are there any analytical models now available. Some models do exist for much smaller motors, etc., but they are not considered to be applicable here. In fact, it is usually found that manufacturers of such equipment do not know under what conditions their product will fail. They can, and do, certify as to the conditions under which the equipment will operate as designed. It seems that such commercial equipment is seldom tested to failure by the vendor, and certainly not under EMP threat conditions.

7. See Response No. 1 above.

Part 2, Final Report

Review Panel Comments. As of October 31, 1982, written comments had been received from three members of the panel:

P. R. Barnes
R. W. Burton
H. S. Cabayan

In Addition, verbal comments were received from J. C. Mark, most of which led to revised treatment of the material in Section 7.0. Comments were also received from G. H. Baker after the report had been submitted for publication. The letters of comment and study team responses follow.

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION
UNION CARBIDE
POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

August 30, 1982

Mr. Faust Rosa
Instrumentation and Control Systems Branch
Division of Systems Integration
Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Faust:

I have reviewed the draft report by Sandia National Laboratories (SNL) entitled "Interaction of Electromagnetic Pulse (EMP) with Commercial Nuclear Power Plant Systems." The report has been greatly improved by the changes and clarifications made by SNL. Much attention is still required to correct the many typographical errors, missing symbols, mis-spelled words, etc. I have made no attempt to address these minor problems. I do, however, have a few comments on the content of the report.

1. In the Executive Summary on page 15 and in Section 6, the overall predicted current responses are shown to be conservative by 1.7 dB, but in Table 6.1 a few predictions were too small by 10 to 15 dB. A 10 dB difference between prediction and measurement is often considered to be good agreement by most EMP test analysts. However, to the extent possible, the differences should be explained and a sensitivity analysis should be performed on those points that are likely to be underestimated by 10-15 dB to determine how it would affect the overall conclusion.

   The disagreement between voltage predictions and measurements is much greater; the voltage estimates are underestimated by an average of 13 dB with a few predictions too small by about 30 dB. The reasons that voltage measurements are difficult to measure should be explained and the importance of the voltage predictions in the assessment should be discussed.

   I feel that the lack of discussion on the few large differences between predictions and measurements and their significance is the major weakness of the report.

2. The discussion on the shielding effectiveness of the building and the demonstration that penetrations are identifiable is adequate. The test demonstrated that the shielding effectiveness and significant penetrations can be determined for nuclear plants with reasonable accuracy by the analyst. There will, however, be local "hot spots" near penetrations which showed up in the test.

3. On page 3 in the Introduction, the Oak Ridge National Laboratory (ORNL) study is discussed. In the ORNL study, the Sequoyah Nuclear plant which is similar to the Watts Bar plant was used as a model of a "modern" PWR plant. However, the Sequoyah plant used metal conduit for underground cables, thus the EMP induced surges on underground cables were not significant. Also, a very conservative shielding effectiveness for the building was used in the analysis. The similarities and differences between the ORNL and SNL studies are not made clear.

   On page 3 of Mr. Baskekas' memorandum, he states that he believes the staff's intent was to reflect the same conclusion reached by the earlier ORNL study. I have seen no evidence of this. As a consequence of the conservative upper-bound approximations used in the ORNL study, larger surgers were estimated for the 120 V ac and dc power circuits. The ORNL study recommended surge protection for the vital equipment as a precautionary measure and suggested that special actions and training on the part of the plant operator may be necessary. The preliminary conclusion of the SNL study is that the safety related systems examined will not be damaged. If the SNL study had resulted in EMP induced surge amplitudes that were near or larger than the threshold levels, the conclusion would be different. I have no reason to suspect that the NRC staff or SNL dictated the results of the analysis of threshold levels and EMP induced surges.

5. On page 99 the Agastat relays on the 480 V boards were assessed. The Agastat relays on the 6.9 kV boards may be subjected to much larger transients. Are the relays on the 6.9 kV boards necessary for a safe shutdown?

6. In Section 9 a very rough assessment on three additional plants is made to "scope-out" any potential EMP problems. Only modern plants were considered. What can be said about older plants?

7. In Section 10 the conclusions of this report are supported by the preceding sections. I agree with the recommendations.

8. In general, good responses have been made to reviewers' comments; even "abstract" comments have been handled reasonably well. Modifications and changes made in response to the comments have improved the report.

Sincerely,

Paul R Barnes

Paul R. Barnes
Electrical Systems Group
Energy Division

PRB:ds

cc: P. Bender, NRC
D. Ericson, SNL
W. Morris, NRC
T. Reddoch, ORNL

RESPONSE TO COMMENTS OF R. P. BARNES

1. We understand Dr. Barnes concern about the differences between some of the predictions and test data. A full sensitivity analysis is beyond the scope of this program. Also, it should be borne in mind that the purpose of these tests was only to provide additional confidence in the analytical technique. However, we have revised and augmented the text in Section 6 (and Section 8) in an attempt to better define the effect these uncertainties may have on the conclusion.

2. No comment required.

3. Dr. Barnes makes a good point. We have revised the wording in this section to better define the conditions of the Oak Ridge study. Similarly in other areas we have attempted to highlight the differences in the two plants.

4. We appreciate Dr. Barnes' support of the independence of this study. SNL and its associated subcontractors have exerted considerable effort to insure the objectivity of this work.

5. These relays are required for 6.9 kV load shedding and for sequencing loads back on the bus once the diesel generators are running. They were included in the assessment, see Table 8.1, Page 8-9.

6. This is a pertinent, although difficult, question. The older plants probably contain even fewer solid state components than the plants examined, and therefore have comparable or larger thresholds. However, as noted in Section 9, plant topology can influence induced-signal levels. Our opinion is that they will be essentially comparable but obviously that is a qualified opinion. We have not examined them.

7. We appreciate Dr. Barnes' support of this work as noted here and in Comment 8. We note that the position expressed here is diametrically opposed to that expressed by Mr. Basdekas in his comments.

UNIVERSITY OF COLORADO AT COLORADO SPRINGS
COLORADO SPRINGS, COLORADO 80907

College of Engineering and Applied Science

September 1, 1982

Mr. Faust Rosa
Division of System Integration
Office of Nuclear Reactor
  Regulation
Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Faust:

I have reviewed the Sandia report on EMP and found it thorough and well done. My only reservation is on p 31, item 6 of the Executive Summary, wherein I think that "unlikely" must be quantified into some probability useful to the commissioners and the public.

Sincerely,

Robert W. Burton
Professor

RWB:rw

"AT THE CENTER OF THE MICROELECTRONICS AND COMPUTER INDUSTRY IN THE ROCKY MOUNTAIN AREA"

RESPONSE TO COMMENTS OF R. W. BURTON

We recognize Dr. Burton's interest in further quantification. However, as we indicated, there is a strong element of engineering judgement involved here so that the qualitative expressions are more appropriate.

Interdepartmental letterhead

Mail Station L- 156

Ext: 2-8871

September 17, 1982
HS82-0012

To: P. A. Bender

From: H. S. Cabayan

Subject: Review of Reports on EMP Study

With the re-write of the introductory section including a good definition of the modest aims of the analysis and associated caveats, I am satisfied that the claims that are being made can be justified. I have still some minor reservations which I will briefly state below.

The approach used here has the following characteristics:

1. Only analytical results are in corporated into the assessment (even though test data were available).

2. The assessment performed at the component level may be justified for Watts Bar since the safety margins were quite high and no permanent damage was estimated at any of the components examined. In general, things may not work out this way. I should think a more sophisticated approach would be needed for plants that may be more borderline:

    A. An assessment methodology for both coupling and susceptibility incorporating analytical and test results.

    B. A vulnerability assessment methodology that is more system oriented and not component oriented.

I am sure the authors do not want to imply that the methodology used in this report is the most suitable under all circumstances; I am concerned that casual readers may come to that conclusion.

I will complete my inputs to you with some concrete suggestions to the executive summary.

1. Page 4, last paragraph: The MHDEMP will induce energy inside the plant directly through diffusion. Are they going to pose a problem? Are there normally protective devices for such low frequency transients inside the plant? Isn't it best just like in the case of upset to just say that MHDEMP has not been looked into.

2. Page 15--Section 6: The authors suggest that the large positive ratio X for the voltage is probably indicative of a systematic bias in the voltage measurement and procedure. Conrad Longmire in his comments has indicated that this large ratio may be due to a systematic bias in the analysis; i.e., some missing physics in the analysis. I believe that with the available data and information it is difficult to say which hypotheses is more liekly to be true.

   As it stands, the vulnerability assessment procedure used by the authors has made no use of the verification measurements. One recommendation the authors ought to make is for someone to re-examine the data, incorporate the measurement data and observe how that impacts the final assessment.

3. Page 31--Section 10: Two additional recommendations for further study should be made:

   A. A more complete systems analysis of a nuclear power plant should be considered so that the vulnerability of the system, rather than individual components, is assessed. This should consider interactions between components as well as the effect of other phenomena (e.g., arc over) on the operation.

   B. A probabilistic approach to vulnerability assessment should be considered. This analysis should recognize both the inherent randomness of the responses and failure thresholds of the equipment as well as the uncertainty in assessing the characteristics (e.g., nominal threshold plus its variation) of the responses and/or thresholds.

H. S. CABAYAN
Electronics Engineering Department

HSC/mas

Copy to:
G. Baker, DNA
D. Ericson, Sandia

RESPONSE TO COMMENTS OF H. S. CABAYAN

We appreciate Dr. Cabayan's support of our efforts. The additional revisions made in the text and presentation should further that support. Some specific responses to his numbered comments follow:

1. It would be inappropriate to include the test data in the vulnerability assessment because the tests were only intended to provide added confidence in the Boeing approach. Therefore, they were conducted on the plant "as is" and compared with predictions made for the same conditions. In contrast, the vulnerability assessment examined the plant in a normal operating mode.

2. We are not certain as to what Dr. Cabayan means by a more sophisticated approach. If one really believed that an EMP-related problem exists, then a more extensive analysis might be warranted. But, given the results here, that hardly seems appropriate.

We have reviewed the wording of the text to insure that the reader understands that other options exist.

Our responses to Dr. Cabayan's suggestions for the Executive Summary follow:

1. The discussion of MHD-EMP has been revised in the main report and the summary, this should resolve the concerns expressed.

2. The discussion of the differences between test and prediction has been expanded in the main report which may alleviate some of the concern. We do not believe that there is "some missing physics in the analysis." Again, we would remind Dr. Cabayan that the test program was not intended, nor designed, to verify hardness, only techniques. Nevertheless, the additional comments in Sections 6 and 8 do amplify the effects variations could have on the conclusions. In general, the safety margins are so large that uncertainties of a few tens of dB do not affect the conclusions.

3. Given the levels of EMP-induced response predicted for nuclear power plants it is not clear what would be accomplished by a "more complete systems analysis." Similarly, the available evidence suggests that there is no failure of safe shutdown. Therefore, it does not appear that a probabilistic approach would add significantly to our understanding of potential EMP effects on nuclear power plants.

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEFENSE NUCLEAR AGENCY
WASHINGTON, D.C. 20305

RAEE

DEC 10 1982

Mr. Faust Rosa
ATTN: ICSB
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dear Faust:

This letter transmits my comments on SANDIA's draft report, Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems. I would like to first state my belief that the effort has been a useful first look into the EMP susceptibility of safe shutdown equipment in a nuclear power plant subject to the limitations and constraints delineated in the executive summary. I do suggest some improvements and additions to the report which are outlined below. Several of my comments result from my having read concerns expressed by other reviewers in the Appendix E.

a. The report still needs a more complete introductory explanation of the national concerns that led to this work. The report states the objectives, but not why this particular set of objectives was chosen, and why the investigation was limited to certain safe shutdown systems at the outset. NRC should probably provide such background in a preface to the report as many important background events took place prior to Sandia's being on-board. It would be good to mention any previous experience with spurious electromagnetic effects, types and causes that added impetus to the need for this effort.

b. A brief explanation and pictorial layout of the operation of the safe shutdown system would be very useful for those unfamiliar with nuclear plants in general, or the shutdown process in particular. It's very difficult for the uninitiated reader to understand the shutdown process and equipment function from equipment lists and fault free logic diagrams. It's also not clear how man plays in the loop (if at all) such that human intervention could work around equipment malfunction. The human element was the subject of much discussion at our review meetings - it needs to be treated.

c. A description of the rationale used for screening penetrations and isolating the most important ones needs to be included. Two reviewers wondered why certain penetrations were not considered (Srinivasan and Barnes). In a telecon with Bill Morris subsequent to Sandia's draft interim report, I asked whether communication line penetrations had been considered. Bill thought so but was going to check. The C^3 lines are important penetrations, particularly where the human element is concerned. I don't see direct reference to these penetrations in the report. There should be a stated rationale.

d. In Section 6 I can't follow the reasoning leading to 32dB shielding effectiveness for the plant enclosure. Looks as if 17dB is the logical choice from Figure 6.23.

e. I agree with the conclusion that extrapolation of the Watts Bar results to other plants requires caution. The comparative analysis of plant geometry and penetrations is good, but should be carried one step further. One of the most positive and useful things we have learned in this study is the structural characteristics of plants that make them more or less transparent to EMP energy. These characteristics ought to be discussed in a dedicated section (2-3 pages) for the benefit of plant designers.

f. I have attached report pages where I made marginal notes.

I agree in general with the report's recommendations for further study. MHD effects should be considered in further baseline studies. The approach we take in addressing upset must be carefully considered and the nonpermanent EMP effects are somewhat different than permanent failures considered thus far.

(1) They are less easily detected by operators since equipment continues to function.

(2) They tend to be more widespread since required energy levels are lower.

(3) They may lead to self-induced equipment failures if normal processes or fail safe mechanisms are interrupted.

(4) They are less easily analyzed because their effects are intimately tied (particularly with digital equipment) to logic, switching, or operational status and interconnectivity of systems. The same extraneous pulse may or may not cause serious problems depending upon where it occurs in the operational cycle of the affected electronics. Upset presents a formidable modeling problem and probably will require heavy reliance on testing.

I apologize for the lateness of this input. I look forward to the publication of the work to date, and to discussion of follow-on efforts to investigate possible adverse EMP effects on nuclear power plants.

Sincerely,

George

Enclosure:
as stated w/d

GEORGE H. BAKER
Project Officer
EMP Effects Division

RESPONSES TO COMMENTS OF G. H. BAKER

As noted above, Mr. Baker's comments were received quite late and after the majority of the report had been submitted for approval and publication. However, the following limited responses are provided in order to be as comprehensive as is reasonably possible.

Mr. Baker suggests that more introductory explanations are needed. The study team can only report on what it has done. It would be inappropriate for us to comment in the report on earlier NRC staff actions and decisions.

We feel that it would be extremely impractical to provide a primer on nuclear power plant systems in this report. We remind Mr. Baker that this report is prepared for the nuclear power community and in that respect it is not for the "uninitiated reader."

We have noted in response to several reviewers that we looked for all penetrations which provided a signal path to equipment of interest. We do not understand Mr. Baker's statement that C^3 penetrations are important where the human element is concerned. Attention is also directed to the discussion of inadvertent penetrations in Section 6.

In response to other comments the discussion of plane wave shielding effectiveness, as inferred from insertion loss measurements, has been revised and expanded. We trust that will also resolve the concerns expressed here.

We believe that an adequate discussion of useful plant characteristics for EMP protection would require more than 2-3 pages and that it is more properly the subject of a separate effort.

The report pages with marginal comments have been reviewed. The comments there have either been addressed above or through revisions made in response to other reviewers.

NRC Staff Office Comments. As of October 31, 1982, written comments had been received from three staff offices including:

Division of Systems Integration (ISCB and PSB)
Office of Nuclear Regulatory Research

In addition, written comments were also received from D. Basdekas, Division of Facility Operations, RES. Individual comments and responses thereto follow.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OCT 0 4 1982

Mr. David M. Ericson, Jr.
Sandia National Laboratory
Nuclear Facility Analysis,
Division 4414
Albuquerque, New Mexico 87185

Dear Mr. Ericson:

SUBJECT: DSI COMMENTS ON THE SANDIA DRAFT FINAL REPORT, "INTERACTION OF ELECTROMAGNETIC PULSE WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS, SEPTEMBER, 1982"

The subject draft report has been reviewed by my staff. Comments from the Instrumentation and Control Systems Branch (ICSB) and the Power Systems Branch (PSB) are enclosed. Questions regarding these comments should be directed to the staff reviewer identified in the Enclosure.

In general, our comments are directed toward (1) a more direct correlation between the objectives and the results of the study, (2) close coupling between conclusions and the analyses performed, (3) a more lucid description of systems vulnerability, and (4) improved consistency within the report with less reliance on inference or experience in the nuclear or EMP areas for interpretation of the results. Some of our comments are in the form of recommended specific word changes. They have been framed in this manner only in order to effect an efficient feedback of our understanding of your results and to clarify the report. They should not be made if they can not be supported by the results of the study.

Our comment on the Executive Summary primarily concerns its organization. However, many of the comments on the main report apply and should be incorporated in a revised Executive Summary. We request that a revised draft of the Executive Summary be submitted for our review as soon as possible.

Sincerely,

Roger J. Mattson

Roger J. Mattson, Director
Division of Systems Integration
Office of Nuclear Reactor Regulation

Enclosure:
As stated

cc: R. Minogue
D. Eisenhut
S. Hanauer
C. Michelson
M. Srinivasan
T. Speis
E. Wenzinger
P. Gill
F. Rosa

ENCLOSURE

DSI COMMENTS ON DRAFT REPORT

"INTERACTION OF ELECTROMAGNETIC PULSE WITH COMMERCIAL NUCLEAR POWER PLANTS, SEPTEMBER 1982"

ICSB COMMENTS (CONTACT: F. ROSA):

1. Section 1.1 (Pg. 3): The second paragraph should not refer to a specific postulated nuclear attack situation. We suggest the paragraph be revised to read as follows to remove this problem and to add specifics in regard to the present regulations and the overall objective of the study:

   At the present time, commercial nuclear power plants have not been required to be provided with protection against EMP. The NRC Regulations (10 CFR 50.13) state that license applicants are not required to provide design features or other measures for the specific purpose of protection against the effects of (a) attacks and destructive acts including sabotage, directed at the facility by an enemy to the United States, whether a foreign government or other person, or (b) use or deployment of weapons incident to U.S. defense activities. Therefore, no protection against EMP has been required in nuclear power plant design. Given this situation, the present study was undertaken to address the question: "Could the effects of an EMP due to a high altitude nuclear weapon detonation (which produces no significant radiation or physical

> damage at ground level) adversely affect the safe shutdown capability of commercial nuclear power plants?" A sustained inability to shut down such plants could lead to significant public health effects or impair our national recovery capability in event of an actual nuclear attack. The limited objective of this study is to provide the Nuclear Regulatory Commission (NRC) with technical insights into the vulnerability of the plants to effects of EMP.

Additionally, the following paragraph should be added to Section 1.1 to address the potential threat to nuclear power plants from land-based EMP generators:

> The vulnerability of nuclear power plants to sabotage or terrorist acts employing land-based generators which are capable of producing EMP-like effects was considered early in the study. It was concluded that a serious threat of this type did not exist. This is discussed further in Section 2.4.

2. Section 1.2 (Pg. 4): This section should be revised as shown on the attached marked copy of Pg. 4 to more clearly define the scope and objectives of the study.
3. Section 1.4 (Pg. 6): The participation of the Defense Nuclear Agency (DNA) in the program should be cited as shown on the attached marked copy of Pg. 6.
4. Section 1.5 (Pg. 6, 7): The presentation of constraints and assumptions of the study is not complete and lacks balance. We recommend that Section 1.5 be revised to read as follows:

1.5 Study Constraints and Assumptions

Certain constraints and assumptions were adopted early in the work to keep the problem tractable. These bounding conditions are discussed in more detail where they appear in the report. However, they are assembled here because they affect the conduct of the study and the conclusions drawn, and so that they may be more readily identified by the reader.

1. The study is limited to those systems required for safe shutdown of the nuclear power plant. In addition, the study focused on particular systems and on components representative of classes of equipment. Detailed analysis of that equipment provides a basis for assessment of the vulnerability of the overall safe shutdown capability.
2. As explained in Section 2.3, the study is based on a "worst case" EMP threat situation. That is, it was assumed that the incident EMP threat embodied a bounding peak field intensity and an orientation relative to the plant systems such as to optimally excite every point of interaction, even though no single weapon could be targeted to do that to even one nuclear power plant.
3. The magnetohydrodynamic (MHD) EMP was not considered in the study for reasons cited in Section 2.3.
4. Permanent damage was the failure criterion used to assess system vulnerability in this study. That is, signal upset effects were not considered.

5. No attempt was made to estimate damage thresholds for rotating machinery. This was not deemed necessary because of considerations cited in Section 7.1.
6. The damage threshold calculations were analytical only, i.e., no supporting component test program was conducted as is traditionally done by the research community involved with EMP effects. However, the data base used included experimental data from previous programs, published threshold data, and data derived using empirical models and published electrical parameters.
7. Because semiconductor devices generally have been shown to be more susceptible to EMP induced failure than passive components, the failure threshold analysis focused upon those devices and excluded the passive components.
8. The failure threshold analysis was conducted at 1MHz, chosen as a median value for the predicted dominant responses. Coupling data subsequently developed (Figure 6.11) indicated that this was a reasonable choice.
9. Internal interfaces within individual modules or equipment cabinets were not included in the damage threshold analysis. That is, on equipment items analyzed, only those pins that serve as interfaces to the "outside world" were considered. More specifically, the threat parameter is traced from its source in the external circuitry to the module interface pin, the individual component damage threshold parameter is reflected back from the component through the module circuitry to the same interface pin, and the parameter values are then compared.

5. Section 2.0 (Pg. 11): The EMP threat due to the use of land-based non-nuclear generators were addressed and discussed. To reflect this, the following new subsection 2.4 should be added to Section 2.0:

   2.4 EMP Generators

   Land based generators capable of being transported by truck have been developed in connection with EMP vulnerability testing of military systems. These generators are capable of producing localized EMP-like effects. Concerns have been expressed regarding the vulnerability of commercial nuclear power plants to sabotage or terrorist acts employing such generators. This type of EMP threat was considered early in the study by the government and industry participants involved, including the Research Review Panel established to monitor the study and provide peer review of its results. It was concluded that a threat did not exist because of the difficulty of deploying and operating such equipment in the vicinity of a plant without being detected, and because the effects of this type of equipment are low level and highly localized. Therefore, no further analysis of this type of EMP threat was included in this study.

6. Section 4.1 (Pg. 23): Readability would be improved if the three essential functions were presented in tabular form (with no change in wording) rather than incorporated in the paragraph. Likewise for the systems required for safe shutdown in the second paragraph.

7. Section 5.1 (Pg. 35): Items 4 and 5 should be expanded to clearly define the calculations described. The expanded treatment should include an explanation of why "the open circuit voltage is a doubled voltage" when it is computed using the source impedence and short circuit current, as cited in the response to comment 2 of the Power Systems Branch on Pg. E66. Additionally, if this doubling of voltage is a significant conservatism in the analysis, this should be clearly stated; and consideration should be given to including it in Section 1.5 (see comment 4 above).

8. Section 5.1 (Pg. 36): In the third full paragraph, the parenthetical expression should be completed or corrected as appropriate, and one of the limits immediately following should be $I/N^{0.5}$ not I/N.

9. Section 5.2 (Pg. 39): It is noted from Figure 4.2 that there is one less transformer in series between the transmission grid and the shutdown buses when they are connected to the 161 KV system than when they are connected to the 500 KV system. Therefore, there is 10 dB less attenuation of the threat pulse originating on the transmission grid. A paragraph should be added to Section 5.2 to explicitly address this point and its effect on the results of the analysis, which was performed assuming the buses were connected to the 500 KV system. The percentage of the time the 161 KV connection is expected to be in effect should also be stated.

10. Section 5.2 and Appendix A (Pg. 38, 39, Figs. 5.1 and A-2): The first paragraph on Pg. 38 states that the peak bulk current threat is bounded between 1000 and 2000 amps. However, Figure 5.1 indicates a peak bulk current threat of 1000 amps. It is assumed that this value was used in the analysis. What is the basis for selecting 1000 amps? It is noted that in Fig. A-2 for the similar situation of the 500 KV transmission lines the bulk current threat is 15K amps and this value is the geometric mean of the bounding values of 10K to 20K amps given on Pg. 39. Section 5.2, Appendix A and the figures cited should be revised to clarify this point and for consistency.

11. Section 6.5.2 and Table 6.8 (Pg. 90, 91): The last paragraph in Section 6.5.2 and/or Table 6.8 should be expanded to indicate how the induced current varies with cable length and with the number of cables buried in parallel. Also, if there are conservatisms in the LOSSYIV code, they should be defined.

12. Section 7.3.2 (Pg. 104, 106, Table 7.3): The first sentence, which states that the equipment analyzed "--consists of 29 different part types as shown in Table 7.3," is not consistent with Table 7.3 which is titled, "Part Types Considered for Damage Thresholds", and lists either 23 or 27 items depending on how you define "part types." Also, one of these items is "motors" which were not analyzed (as stated in Section 7.1 and other prior sections), although they obviously were considered. Section 7.3.2 and/or Table 7.3 should be revised as appropriate for clarity and consistency.

13. Section 7.4.1 (Pg. 123,124): The paragraph which begins at the bottom of Pg. 124 with "The MUX assemblies---" and ends on Pg. 125 is very difficult to understand. I recommend that it be subdivided into three paragraphs with the third of these starting with the sentence on Pg. 125 which begins with "Even greater thresholds are determined---". Additionally, a circuit sketch should be provided (similar to that on Pg. 123) to provide a better understanding of the circuitry involved.

14. Section 8.0 (Pg. 126-140): This section is titled "Vulnerability Analysis For the Example Plant." Although this section very effectively presents the failure analyses performed and their results at the component level, it does not explicitly address the vulnerability of the plant safe shutdown systems, particularly the electrical, instrumentation and control systems. In our judgement, the results of the analyses performed as reported in Table 8.1 fully support explicit assessments regarding the survivability of these systems. We recommend that Section 8.0 be revised as follows to address these systems, and thus correlate directly with Section 4.0 which identifies the critical safe shutdown systems and functions.

a) The text should be divided into the following subsections:

8.1 Equipment Damage Threshold Analysis

(This section could be comprised of all except the last paragraph of the present Section 8.0.)

8.2 Electrical Power Systems Vulnerability

(This section should provide an assessment of the survivability of the following systems: (1) the AC power distribution systems from the switchyard down to the 120V level and with the 500 KV and the 161 KV sources both being addressed (see comment 9); (2) the 6.9 KV AC emergency power system including the diesel generators; (3) the 125V vital DC power system; and (4) the 120V AC vital instrumentation power system which is identified as the Uninterruptable Power System in Figure 7.2. The data in Figure 5.3, Table 8.1 and Appendix A indicate that the threat voltage peak at each voltage level 6.9KV and below in the AC and DC power systems does not exceed the operating voltage by a substantial margin. If this is the case, a positive statement of survivability is appropriate and should be made.)

8.3 Reactor Trip and Engineered Safeguards Actuation Systems Vulnerability

(The data in Table 8.1 support a positive statement of survivability).

8.4 Process Instrumentation Vulnerability

(The data in Table 8.1 support a positive statement of survivability).

8.5 Valve and Motor Controls Vulnerability

(The data in Table 8.1 support a positive statement of survivability).

8.6 Overall Safe Shutdown Vulnerability

(This section should integrate the assessments made above to arrive at an assessment of the overall safe shutdown capability).

b) The first paragraph on Pg. 127 of the present Section 8.0 should be expanded to provide the basis and/or references to support the statement that "a conservative estimate of the damage threshold level for electromechanical-type devices was defined to be ten times the operational voltage of the device interface." Additionally, the data in Table 8.1 indicate that the threat voltages at the device interfaces for this type of equipment are substantially lower than their operational voltage; therefore, a positive statement of survivability appears warranted.

c) The last paragraph in the present Section 8.0 (Pg. 128) should be revised to remove the implication conveyed by its first sentence that the analyses performed did not provide any basis for an assessment of systems survivability. It should then be incorporated in the above proposed Section 8.6.

d) Table 8.1 should be expanded to include the transformers (500/22.5 KV, 161/6.9 KV, 6.9 KV/480V, 480/120V) and the switchgear or distribution boards at each voltage level. It appears from Appendix A and from the existing data in Table 8.1 that this information is already available or can be readily calculated. It is recognized that some of this information can be inferred from what is already in the table, however, explicit inclusion is preferable.

e) Table 8.2 should be expanded to include the operating level voltages. This information should also be available and would provide a basis for assessing the vulnerability of this equipment.

15. Section 9.0 (Pg. 141): The use of the modifier "abbreviated" in the first sentence with reference to the analyses performed conveys a connotation of inadequacy. It is true that the analyses were limited in scope but they were also bounding and some confirmatory testing was performed. These attributes of the study are fully described in other sections of the report. Therefore, it is recommended that the word "abbreviated" be eliminated.

16. Section 9.0 (Pg. 164, 166, 170, 172, 173), Section 10.3 (item 3 on Pg. 185) and Section 10.4.3 (Pg. 186): The following statement (or a similar statement) appears in each of the above cited pages: "It is clear from the high magnitude of the calculated values that this is not the case; i.e., other phenomena such as arcing or other dielectric breakdown will occur before these levels are reached." This statement is true, however, it is subject to misinterpretation because it does not clearly correlate the probable occurrence

of these phenomena to a threat level approaching the calculated threshold level. We recommend that this statement, wherever it appears, be revised to clarify this point.

17. Section 9.3.2 (Pg. 173): The "(from Reference 1)" at the end of the second paragraph appears to be in error and should be checked.

18. Table 10.1 (Pg. 183): The 70V lower bound predicted damage threshold for the 125VDC/120 VAC equipment is less than the corresponding 100 V upper bound predicted EMP signal. We were unable to correlate this with any data on the example plant presented in Table 8.1 or elsewhere in the report. This item should be checked and corrected if necessary.

19. Section 10.3 (Pg. 184): We assume the use of the term "preliminary" in the second paragraph with reference to the conclusions reached is a carryover from the interim draft. It is not warranted in the final report and should be eliminated.

20. Section 10: A new subsection should be added following Section 10.3 which directly correlates the conclusions of the example plant analysis of Section 10.2, and the conclusions of the additional plant analysis of Section 10.3, to the objectives of the study cited in Section 1.2 (see comment 2).

21. Executive Summary: We recommend that the conclusions of the study be moved into Section 1.1, and that the entire Executive Summary be revised as necessary to accurately reflect the main report, including the changes which result from review comments.

22. We noted typographical and other errors or omissions which should be corrected on the following pages: 9, 31, 65, 68, 76, 89, 90, 92, 106, 107, 118, 122, 125, 126, 128, 147, 154, 161, 163, 164 and 181.

PSB COMMENTS (CONTACT: M. SRINIVASAN/P. GILL):

1. To clarify the scope of the study, we suggest that page 8, item 2 be revised to indicate that no attempt has been made to predict EMP damage threshold for cables, power and distribution transformers and other electrical apparatus and the basis for their exclusion.

2. The normal protective devices, as mentioned on page 11, second paragraph, should be clarified as to whether these are overvoltage, overcurrent or other type.

3. The expression I_{in}/n on page 36, third paragraph, line 7 should be corrected to read $I_{in}/\sqrt{n}$.

4. The estimate of the damage threshold level for electromechanical-type devices is assumed to be ten times the operational voltage in the study. We find this assumption to be arbitrary. The damage threshold levels for short-duration pulses is defined in the American National Standards Institutes (C92.1-1971 and C37.20-1974) in terms of Basic Impulse levels (BIL) for voltage systems above 1000 volts. We believe the damage threshold levels should be related to BIL so that the informed reader can easily make the transposition.

5. In Figure 4.2 (page 31), the 6.9 kV N/O secondary circuit breaker of CSST1A transformer feeding 6.9 kV, RCP start, Bus "A" should be shown as N/C.

6. The analysis in the study used a 10 dB loss through the various transformers for EMP signal propagation via the 500 kV transmission line connection point. As stated in your comments, this 10 dB loss was based upon measurements data obtained on a 25 KVA transformer. However, the transformers in the path of the EMP signal via the 500 kV connection point are significantly larger than the 25 KVA. The resistance values for the transformers above 6.9 kV is less than 0.5 percent and for transformer above 480 volts, it is less than 0.7 percent. The signal attentuation losses in these large transformers are significantly less than they are in a 25 KVA transformer. The assumed value of 10 dB loss should be revised to reflect a more realistic value of EMP signal attentuation through these large transformers as the EMP signal propagates via the 500 kV (or 161 kV) connection point.

7. It is not clear how the various EMP signal values have been determined in the modeling diagrams, such as the 500 kV connection point, without detail calculations. If these signal values are estimates based on the experience and acquired skills of the analyst (as stated in your comment no. 5), then this should be stated clearly in the study.

Because the Oak Ridge study did not attempt to analyze any particular plant in depth, some questions persist as to the applicability of the conclusions, and as to whether or not nuclear plants can be safely shutdown subsequent to an EMP interaction. Also, some of the newer operating plants and plants under construction use more electronic devices (semiconductors, transistors, integrated circuits, etc.) considered to be particularly susceptible to the currents and voltages which can be induced by an EMP interaction than do the older plants. Because of the resultant uncertainty about EMP effects on commercial nuclear power plant shutdown capability, this study was undertaken.

See Comment 2

1.2 Objectives

This program was established as a scoping study with ~~to address the question: "Could EMP cause failure of critical systems in nuclear power plants and is further study warranted?" Therefore, the study has~~ the following specific objectives:

1. Determine the vulnerability of the systems required for ~~selected~~ safe shutdown ~~systems~~ of a specific nuclear plant to ~~EMP~~ the effects of EMP.
2. Establish how any safe shutdown systems vulnerable to EMP may best be hardened against it.
3. Characterize to the extent possible, the effects of EMP on nuclear plants in general based upon the results for systems in the example plant.

An alternate expression of the objectives is that this study assesses the EMP sensitivity of essential features of selected safe shutdown systems on nuclear power plants in order to identify any points which may be unduly exposed or sensitive. Then, where appropriate, proposes remedies for such sensitivity. ~~It is not the intent of the study to propose "hardening" against all conceivable circumstances.~~

1.3 Study Approach

To accomplish these objectives, the program was structured as shown on Figure 1.1. First the systems of concern were identified and defined. Then estimates were made of the currents and voltages which might exist at key points (systems of concern) if the plant should be subjected to an EMP. This involves examining the plant in light of the potential interaction mechanisms, and based upon the configuration of the plant systems (that is, what loads are active, what circuits are open, where are cables routed, etc.) analyzing how signals could be induced and distributed. Concurrently, component damage thresholds were estimated. The components of the systems of concern were examined, and based upon circuit configurations and piecepart characteristics, estimates made of the signal levels at

Attachment

The Defense Nuclear Agency (DNA) of the DOD participate in the planning of the program and is represented in the Research Review Panel cited above.

the component interconnections which could cause failure of the component. These two sets of estimates were then compared to assess the vulnerability of the selected components. Because nuclear plants, like many military systems, are very complex, a modest experimental program was conducted to provide some verification of the estimated induced signal levels. These measurements were not intended to establish whether the example facility is or is not hard to EMP. Rather they serve to verify (or reject) conclusions reached about signal distribution and attenuation. If vulnerabilities are predicted, recommendations are made for eliminating or reducing them; that is, recommendations are made for hardening. Finally, the results are extrapolated to other nuclear plants. This report describes the study and reports the results and conclusions.

1.4 Study Organization

Any investigation of the potential effects of EMP on commercial nuclear power plants requires a broad range of expertise in nuclear plant systems and nuclear weapons effects. For this reason, a number of government and industry organizations are involved as shown in Figure 1.2. Overall program direction is the responsibility of the NRC Office of Nuclear Reactor Regulation. The program technical monitor is supported by other members of the NRC staff and a Research Review Panel comprised of nationally known authorities on nuclear systems and nuclear weapon effects. The day-to-day technical management has been handled by Sandia National Laboratories. In this capacity, Sandia provided the necessary nuclear systems analyses and the interfaces between the subcontractors conducting specific portions of the study. The EMP response and vulnerability analyses were prepared by Boeing Aerospace Co. using the techniques and expertise developed over a number of years in various programs done for the Department of Defense (DOD). The verification measurements were made by IRT Corporation, again using techniques, equipment, and expertise developed in various DOD programs. The damage threshold estimates were developed by Booz-Allen & Hamilton. Although similar work has been sponsored by the DOD, the equipment used in nuclear power plants contains components which are not included in current damage threshold data bases. This required Booz-Allen to do some extrapolation.

Subsequent sections of this report outline the boundary assumptions and constraints, the implementation of the approach, described above, and the results of the study.

1.5 Study Constraints and Assumptions

As with any analytical study certain constraints and assumptions were adopted early in the work to keep the problem tractable. These bounding conditions are discussed in more detail where they appear

See Comment 4

Attachment

RESPONSES TO COMMENTS FROM DIVISION OF SYSTEMS INTEGRATION

ICSB Comments (F. Rosa)

1. After review we agree with the comment and Section 1.1 has been revised to reflect the suggestions of the reviewer. The additional paragraph has been added to Section 1.1.

2. Some revisions to Section 1.2 have been made which we believe will satisfy the expressed concerns.

3. The participation by the Defense Nuclear Agency has been explicitly included in Section 1.4.

4. We agree that some rewording and reordering of the constraints and assumptions in Section 1.5 is appropriate. The revisions suggested have been included with minor wording changes prompted by other comments and our own view of the study.

5. Mr. Rosa is correct. The original Statement of Work on this program called for consideration of this subject, which was indeed handled precisely as described in the comment. Section 2.4 has been added to the report.

6. The requested revision in format has been accomplished.

7. The text has been expanded to provide a more detailed explanation of the computations involved. The comment on Page E66 has been revised to reflect this change.

8. Noted. Correction was made during in-house reviews.

9. Additional material has been inserted in Section 5.2 relating to the connection to the 161 kV system. Appropriate changes have also been included in Section 8 and Appendix A.

10. There was no intention to imply that a 15,000 ampere threat was derived from the range specified. Experience indicates that the threats to overhead lines are in this range, after the analysts had toured the site and examined the topology, a signal of 15000 amperes was selected as a reasonable estimate for this analysis. The test has been revised to remove the reference to a range of values.

11. Table 6.8 has been revised and extended to show the variation of induced current with depth of burial. A cable length of approximately 200 m is sufficient to reach a maximum value of the EMP-induced signal. Cable runs of concern exceed this length.

12. Other reviewers have had difficulty with the organization of Section 7. As a result, some rewrite and consolidation were performed and the points raised by Mr. Rosa were addressed at that time. The revised Section 7 should alleviate these concerns.

13. Section 7.4.1 has been revised to remove references to specific circuits/assemblies and reorganized to be more readable.

14. After careful review of these comments and reexamination of the results of the assessment, we agree with the need to reorganize Section 8.0. This was done and we believe that the revised version more adequately addresses the major results from the example plant. Information on the nominal power distribution system (Comment 14d) is also included.

15. It should be noted that the approach used by Boeing is officially titled "Abbreviated Coupling Analyses" because it does not rely upon large computer codes and analyses but draws more upon the skills of the analyst. Experience has shown that this is an effective and reasonable approach. However, to avoid any misunderstanding, the word "abbreviated" is deleted in this instance.

16. Other reviewers have made similar comments. Section 9 has been extensively reworked and revised and we believe Mr. Rosa's concerns have been adequately addressed.

17. Noted and corrected.

18. The 70V damage threshold appears in the output of the Basler 15V-10A power supply which supplies relays in the Solid State Protection System. This output cannot "see" a directly coupled EMP-induced signal from a penetration, therefore it is not tabulated in Table 8.1. To be consistent, the values reported in Table 10.1 should be 360 volts (3X nominal). Table 7.2 will still carry the 76 volt value because it is specifically labeled output. It should be noted that in Table 10.1 the ranges of threshold values and the range of EMP values are reported. There is no intent to imply that the limits correspond. For example, the 2 volt signal (V_R) may well appear in a circuit in which the threshold (V_T) is kilovolts.

19. Agreed. The qualifier "preliminary" has been eliminated.

20. Agreed. Based upon this comment and other discussions, the material in Section 10 has been reorganized. We believe this will resolve any concerns.

21. The Executive Summary has been revised to reflect the revisions made in the main report. However, the original order has been retained. Because this particular investigation has engendered considerable comment and interest, the authors believe it imperative that the "full flavor" of the report, especially the Executive Summary, be understood before the conclusions are assimilated. Placing the conclusions at the front of the study would guarantee that many readers would not consider carefully the objectives and constraints of the work.

22. Noted. These and other grammatical/typographical errors have been rectified during our internal reviews.

<u>PSB Comments (M. Srinwasan/P. Gill)</u>

1. The list of assumptions and constraints has been reworded and restructured in response to comments of other reviewers. It is indicated that damage thresholds for equipment cited were not calculated; however, it is also stated that estimates of these thresholds, based upon other considerations, e.g., Basic Impulse Levels, are used in the vulnerability analyses.

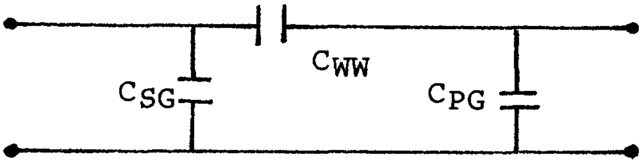
2. The discussion of MHD-EMP has been revised and expanded. We believe that this resolves (by elimination) the question as to the specific type of protective devices employed. It is probable of course that both overvoltage and overcurrent protection are provided.

3. Noted. Correction was made during in-house reviews.

4. It was indicated in the report that the assumption of damage thresholds was based upon experience in other analyses; therefore, we do not believe that it is arbitrary. An extensive review of the available standards for transformers and switch gear suggests that a conservative estimate of Basic Impulse Levels (BIL) for equipment operating in the 4 to 8 kV range is 60 kV. This value has been used in the vulnerability analysis (Section 8, Table 8.1) to estimate safety margins. Use of a 60 kV threshold in lieu of 10X the operational voltage results in only a slight reduction in predicted safety margin. Damage thresholds for system voltages 480 V and below have been revised to 3X operating voltage. All references to 10X have been deleted in Table 8.1 and the accompanying text. We have noted in pursuing this question of damage thresholds on major components (transformers, switchgear, etc.) that the standards do not specify (at least as we read them) what Basic Impulse Levels should be in a given application. Rather, they indicate ranges which are acceptable. Also, it must be recognized that the BIL is properly a survival value. That is, the transformer or switchgear can experience a surge of that magnitude and still function properly.

5. Noted. Correction has been made.

6. There seems to be some misunderstanding of the signal coupling mechanisms involved at the frequencies associated with the EMP-induced signals. Certainly the transformer inductive reactance will be large and as a result the transformer can be "modelled" as a network as illustrated below in which the signal couples capacitively. That is:



where C_{WW} is the winding to winding capacitance

C_{SG} is the secondary (500 kV side) of main XFMR)
to ground capacitance

C_{PG} is the primary (23 kV side) to ground capacitance

The amount of attenuation is thus a function of the actual values of C_{WW}, C_{PG}, and C_{SG}. Barnes (Reference 1) in his earlier study assumed current ratios of 5 (about 13 dB of attenuation) across the transformers. Based upon these considerations we believe 10 dB loss is a reasonable estimate.

7. We believe it is rather straightforwardly stated in Section 5 that signals following points of distribution can be estimated (bounded) by $1/N$ or $1/N^{0.5}$ where N is the number of conductors leaving the distribution point. Thus, if one examines Figure A-2, 500 kV Transmission Line Model, a 0.11A signal into the 6.9 kV Shutdown Board results in a 0.018A lowerbound signal out for six loads. For the upper limit, $0.98/\sqrt{6}$ yields a value of 0.40 ampere out. Section 5 also states explicitly that cable attenuation due to ohmic losses and cross-coupling effects are based upon experience and that 5-6 dB of attenuation per 100 feet of cable can be expected. This attenuation is shown on the model diagrams and was verified in the test program.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 2 4 1982

MEMORANDUM FOR: H. R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RES COMMENTS ON FINAL SANDIA DRAFT REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

Reference: Memorandum from Faust Rosa to Robert B. Minogue dated August 11, 1982, "Review of Draft Final Report"

As requested in the referenced memo, we have reviewed the subject report. Based on our review, we believe that the results reported are too preliminary in nature to provide conclusive results and that additional research is required.

For example, a limitation of this study, as stated on page 3 of the Executive Summary, and page 8 of the main report, is that the study does not evaluate upsets as a result of EMP. These upsets could possibly result in multiple malfunctions in systems important to safety and cause events which may jeopardize safety. Therefore, additional research is necessary to determine the effects of EMP-induced upsets. Other needs for additional research are discussed in the attached comments.

Regarding the specific conclusions stated in the report, our concerns are as follows:

(a) "(4) Damage thresholds for the components containing solid state devices examined are substantial. These thresholds are high enough that other phenomena (arc-overs for example) will occur before device failure."

This conclusion does not address the effects of arc-overs, which could themselves constitute a safety problem.

(b) "(5) Predicted EMP-induced signals at the critical equipment in the example plant are generally much less than nominal operating levels. But plant topology and cabling practice have a strong influence upon EMP-induced response. Example plant results can only be extrapolated to other plants with caution.

"(6) The likelihood that individual components examined will be failed is small. Therefore, it is unlikely that an EMP event will fail sufficient equipment so as to prevent safe shutdown."

These conclusions are premature if they are based on the work reported by Sandia alone. The basis for this belief are provided in the enclosed comments.

We recommend that the NRC not reach a general conclusion on the interaction of EMP with nuclear power plants' systems until the comments from all reviewers are satisfactorily resolved, including completing any additional research needed to resolve these comments.

We will be happy to provide further assistance or discuss our comments with you or your staff as needed.

Robert B Minogue

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: As stated

Contact: A. Hon, x35966.

cc: F. Rosa, NRR/ICSB —P-1030
P. Bender, NRR/ICSB
B. Morris, NRR/CRBRP
J. Vora, RES/EEB/DET
D. Basdekas, RES/ICB

ENCLOSURE

RES COMMENTS ON THE FINAL DRAFT SANDIA REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEEAR POWER PLANT SYSTEMS

1. The Objective and Scope of this Study

(a) The question this study addressed was stated as "Could EMP cause failure of critical systems in nuclear plants and is further study warranted?"

By looking at the constraints and assumptions of this study, especially in the stated contract that "only permanent damage failures were examined, signal upset effects were not considered in this study," it seems that the question was not fully answered. Since many systems and components can malfunction due to upset without themselves being permanently damaged, an unacceptable result of an EMP event may occur. Such events should be investigated and their effects determined before the question can be answered.

(b) The second objective stated on both page 1 of the Executive Summary and page 4 of the main report, is stated as "Establish how any safe shutdown systems vulnerable to EMP may best be hardened against it." The paragraph following restates the objectives in another way by saying "It is not the intent of this study to propose 'hardening' against any and all conceivable circumstances."

This apparent inconsistency needs to be resolved.

(c) The listing of "constraints and assumptions" on pages 1 and 2 of the Executive Summary and page 8 of the main report is quite appropriate. It would also be helpful to the reader to have a discussion in the Executive Summary of the potential significance of those "constraints and assumptions."

2. MFD-EMP Effects and Low-Frequency Response

The report (page 11 of the Executive Summary) assumed that normal protective devices would respond to isolate and protect the plant from Magneto-hydrodynamic (MHD). This conclusion has not been clearly substantiated by this study or any of the references cited in the report. We have some concern about this because:

(a) The protection devices for normal transmission grids and substations are designed for low frequency (50-60 Hz) over-voltage transients up to higher frequency lightening surges. The designs and the operating performance characteristics of surge arresters and power circuit breakers are optimized accordingly. These protection devices are not designed specifically to protect against very low frequency (much less than 50 Hz) MHD transients. Therefore, they should not be given credit for MHD protection before any evaluations.

(b) The voltage-time characteristic of an MHD signal should be included to help the reader to understand the significance of this very low frequency and whether it falls within the capability of low frequency (50-60Hz) protection devices.

(c) The report (page 11 of Executive Summary) implies that the system may not be vulnerable to very low frequency (approaching DC) signals. We feel that this conclusion may be premature. This nearly DC signal (which lasts up to hundreds of seconds) can alter the magnetic characteristics of the iron core of transformers, motors, relays, etc. (The MHD induced DC biases the iron core so that the normal AC may operate into the saturation region.) This may result in undesirable phenomena such as overheating and harmonic interference.

(d) The report indicated that DOE and DOD are currently studying the MHD problem.

The contractor should take this into account in drawing conclusions on the effectiveness of these devices or at least indicate the associated uncertainties.

3. Nuclear System Analysis

(a) The Abbreviated Analysis Technique used in this study (as we understand it) identifies and traces the cables between the critical equipments and the penetration of EMP energy.

However, when "non-critical" equipment is between the critical equipment and the penetration, it may not isolate the EMP. This indirect path should be evaluated as well. The event tree method can be a useful tool to identify all the possible paths.

(b) On page 10, first paragraph of the Executive Summary, and page 35, first paragraph of the main report, it is stated that "Cabling attached to critical equipment is traced to the most severe penetration of EMP energy which can drive it."

The words "most severe" appear only in the main report, not the Executive Summary. The two versions should be made consistent or the difference explained. If only the most severe penetration is traced, then the contractor should justify that the comulative effect of multiple paths of through "less severe" penetrations is not significant.

(c) On page 36 of the main report, it is stated that the input surge current is distributed among the individual conductors. Each conductor will only carry 1/N of the total input current for identical loads and $1/N^{3/4}$ for unidentical loads. This approximation is true for D.C.. But this may not be true for high frequency EMP signal. Because various loads may have different AC impedances and time constants, they may respond differently to high frequency AC inputs.

(d) On page 10, last full paragraph of the Executive Summary, it is stated that "diffused field strengths in the central regions of the plant are expected to be 50 dB or more below external incident fields." However, it is indicated in the first full paragraph on page 92 of the main report that the attenuation, depending on frequency and location, may be as low as 5 dB. The complete range of attenuation should be stated in the Executive Summary. The conclusions based on maximum and minimum as well as expected attenuations should also be stated in the Executive Summary and be supported by the main report.

(e) The discussion of grounding and ground cables presented on pages 37 and 38 of the main report does not include any mention of the fact that ground cables and other grounded metal structures and components can act as an antenna for high frequency EMP induced disturbances. The effects of this additional source of disturbance should be evaluated.

4. Verification Measurements

(a) In the summary of the comparison of measured and predicted responses, the statistical treatment of different test points seems unusual. The usefulness of estimating the mean and standard deviation of data from unrelated test points is not clear. These test points were measured at different locations of the plant. In this type of bounding calculations, the largest error should be used to define the uncertainty.

(b) In table 6.3 of the main report, the actually measured response is frequently larger than the predicted response by the model. But page 16 of the Executive Summary, last paragraph, says the analysis is concervative. This discrepancy needs to be resolved.

(c) In figure 6.21 of the main report, three points of magnetic and one point of electric field attenuation measurements are presented together.

It is not clear how the one point of electric field contributes to the overall conclusion of magnetic field attenuation. It is also not clear how any conclusion can be drawn from one point of electric field measurement.

5. Component Damage Threshold Analysis - Section 7.0

(a) From the system's point of view, the performance of rotating machines, in conjunction with the transmission grid system, must be considered in totality and evaluated together while studying an EMP response. For example, is it possible that an EMP event could isolate a transmission network (while carrying full load) at multiple locations simultaneously? If so, what would be the consequences and interactions between the power plant generators and the grid network? Should we be concerned with sub-synchronous and long-term dynamic voltage and frequency oscillations where voltages and frequencies are not under control?

(b) The analysis and measurement at Watts Bar were performed for non-operating plant at the end of its construction. How will the effects of typical temperature and humidity in operating reactors affect the damage thresholds?

(c) The damage threshold level for electromechanical devices such as transformers and rotating machines is defined rather arbitrarily as 10 times the operational voltage of the device interface. The basis for the 10 times estimate should be stated, such as the equipment specification, manufacturer's warranties, etc.

(d) In the Circuit Damage Threshold Analysis, as indicated on page 29 of the Executive Summary and other places of both the Executive Summary and the main report, the report suggests that "Other phenomena can, and probably will, occur in the circuitry before these thresholds are reached. Of course, the occurrence of such phenomena, arc-over, for example, does not necessarily mean that the component has been failed."

However, the report does not go on and state the possible effects of arc-over (a form of dielectric breakdown) on the system. Since arc-over can cause short circuit or current leakage, depending on where the arc-over occurs, other serious problems on the system can be created. Therefore, one can no longer casually say the component does not fail simply because arc-over occurs.

(e) Justification for the phrase in page 119 of the main report that "Component threshold will increase as the square of the frequency" should be provided.

(f) The conclusion on page 23 of the Executive Summary on Component Damage Threshold Analysis is based on the assumption that "all other circuit elements perform as designed."

The implication of this assumption should be explained. What if some of the other circuit elements do not perform as designed but are also affected by the EMP (i.e., common cause failure)?

6. Vulnerability Analysis for the Example Plant

(a) The conclusion of Vulnerability Analysis in page 24 of the Executive Summary says -

> "This analysis has only examined individual components of safe shutdown systems, not complete systems. However, if no component fails, the system does not fail. Conversely, if an individual component should fail, it does not follow that the system fails because of the redundancy within systems. Furthermore, safe shutdown in nuclear power plants is assured by a redundancy of safety related systems. Thus, the failure of a single component, or even several components, within one safety train does not preclude safe shutdown."

It seems in EMP analysis, the usual redundancy of safety systems should not receive credit. Because of identical designs in the redundant systems, the potential of common cause and common mode failure is likely to be quite high. Hence, no credit should be given for redundancy.

(b) The same concern on Sandia's treatment of arc-over as we stated in 5(d) applies to the Vulnerability Analysis.

7. Analysis of Additional Nuclear Power Plants for Vulnerability to EMP

(a) In the Palo Verde Analysis, some of the safety margins (SM) in Table 9.2 are negative. Does this mean this plant needs hardening?

(b) The basis for concluding that failures are not anticipated in the other plant designs evaluated is not convincing. Because there are many differences between Watts Bar and other plants, further analysis should be performed before conclusions can be made.

RESPONSE TO COMMENTS FROM OFFICE OF REGULATORY RESEARCH

1. (a) The reviewer appears to equate "failure" and "malfunction." As noted, this study addressed the question of failure of critical systems due to damage. We do not think that "failure" should be equated to "malfunction." We believe, based upon our analysis, that EMP-induced signals will not fail systems required for safe shutdown. Further, although we have not addressed the question specifically, given the predicted level of EMP-induced signals, their time domain characteristics, and the response characteristics of the instrumentation we have examined, we question whether these systems will even "see" the induced transients.

   (b) We don't believe these two statements are contradictory, however, because several other reviewers expressed a similar concern, the second statement has been deleted.

   (c) We believe that it would unduly expand the Executive Summary of such a discussion were included. This level of detail should remain in the Main Report.

2. The treatment of MHD-EMP has been revised and expanded. We believe this additional information will resolve the concerns expressed in these comments. It should also be noted that the DC component will not be propagated past the first transformer, therefore, motors and relays within the plant will not experience saturation effects.

3. (a) When cable paths are traced in this analysis, all cables in the penetration are accounted for and their share of the induced signals taken into account. Whenever distribution points are reached, all potential paths for current flow are examined. The reviewers concern about indirect paths is not clear. If signals on the most direct path are not large enough to cause problems, those on indirect paths, with increased numbers of distribution points and longer runs over which attenuation can occur are unlikely to cause problems.

   (b) It should be recalled that in this analysis, which is "worst case" from the EMP threat standpoint, it was assumed that every penetration was optimally driven, that is, the maximum coupling was presumed. Because some points of interest could receive an EMP-induced signal from several possible sources, only the largest disturbance was used in the vulnerability assessment. Bear in mind that in any actual encounter it would be impossible to provide optimum coupling at all penetrations. In fact, it is unlikely that the penetrations will be excited simultaneously. Furthermore, because of differing propagation paths, peak signals from multiple locations are very unlikely to arrive at the critical equipment at the same time. Two peak of 1.0 volt each out of phase by a few tens of microseconds will not produce as much stress as a single 2.0 volt pulse. Nevertheless, these two passages have been revised to remove any ambiguities.

(c) On Page 36 of the draft (now Page 5-2) it is stated that the EMP-induced signal on cables with non-identical loads is bounded by $1/N$ and $1/\sqrt{N}$, with the experience in EMP analysis supported by test data indicating that a reasonable value for the average peak value is $1/N^{3/4}$. It is agreed that varying AC loads may respond differently, but experience gained over many analyses indicates that the bounds, as cited, are acceptable for the EMP induced signals. This is further verified by the test results cited in Section 6.0.

(d) There appears to be some confusion here over insertion losses as measured with antenna systems and plane wave shielding effectiveness as deduced from these measurements. Section 6.5.3 has been revised and Section 6.5.4 added which should eliminate this confusion.

(e) The bulk current (approximately 1000 amperes) is induced on the entire duct bank including the associated ground cables. The sharing of the induced currents between signal and power cables and ground wires is discussed in Section 5. The ground system is not an additional, *independent* source.

4. (a,b) It should be recalled that the purpose of the verification tests was to provide additional confirmation of the Boeing analytical approach. Therefore, it is reasonable and appropriate to ask the question, "On the average, does the approach provide conservative estimates?" Therefore, even though the data comes from various locations, it is appropriate to find a mean value. Some individual predictions will be conservative some will not; but again, it is the overall result that is of interest. This approach has been used in numerous prior EMP vulnerability assessments.

(c) Other review comments have indicated, as noted above (3d), that some misunderstandings exist relative to plane wave shielding effectiveness and insertion loss measurements. Section 6.5.3 has been revised an Section 6.5.4 added which should eliminate the confusion.

5. (a) This program was not structured to examine effects of EMP on the entire grid. Some consideration of this question is contained in a study by Oak Ridge National Laboratory (ORNL- 4958, Power System EMP Protection, March 1975). In addition, the Defense Nuclear Agency now has an active program in this area (Reference 7) and it is our understanding that ORNL may be pursuing this question further in the near future.

(b) It is impossible to state conclusively what the effects of typical operating conditions will be. However, the semiconductor devices are sealed and experience suggests that there will be little or no effect from normal conditions. Obviously, humidity will affect the likelihood of arcover or breakdown, although the extent of that effect can't be stated "a priori."

(c) The 10 times operating voltage failure level was based upon experience in other analyses because there was no data available. As noted in responses to other comments, this approach has been revised to make the results reported in Section 8 even more conservative.

(d) Arcover and breakdown phenomena are not amenable to analyses. However, if EMP-induced currents are shorting to ground at terminals and external connections it is difficult to postulate failures. If arcs persist long enough (more than 1/2 cycle) and if the normal currents are large enough to cause power follow there may be associated damage. We believe that the required conditions do not exist for the components analyzed.

(e) There was a typographical error in the draft report. Obviously, based upon the relationships discussed in Section 7, the empirical evidence is that the damage threshold increases as $1/t^{1/2}$ where t is the pulse width. Therefore, the threshold increases as the square root of the frequency.

(f) Analysis indicates that circuit damage thresholds for the passive components (resistors, capacitors, etc.) are on the same order as those for the solid state devices. Therefore, the damage thresholds would be comparable.

6. We recognize the reservations expressed regarding redundancy. However, we believe that it is reasonable to take credit for redundancy for the following reasons. One, in an actual attack scenario it would be impossible to optimally excite all penetrations simultaneously. In fact, some penetrations might only receive minimal excitation due to orientation.

7. (a) Because the analysis at Palo Verde was not as complete as that at Watts Bar, the existence of some negative safety margins does not necessarily argue for hardening. As noted elsewhere, experience with EMP vulnerability analyses indicates that as more of the design detail is brought into play it tends to lower the estimates of EMP-induced signals.

(b) We agree that the analysis does not prove in a rigorous manner that failures are unlikely. However, as stated in the revised Section 10, it is the technical judgement of the study team, considering the analyses, the systems involved, and experience in other studies that failures are unlikely.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 16 1982

MEMORANDUM FOR: Roger J. Mattson, Director
Division of Systems Integration

FROM: Darrell G. Eisenhut, Director
Division of Licensing

SUBJECT: REVIEW OF DRAFT FINAL REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

As requested in Faust Rosa's memorandum of August 11, 1982, we have reviewed the subject matter and acknowledged that the draft final report was responsive to our comments submitted to you on May 19, 1982. We have no additional comments to offer on this subject.

Darrell G. Eisenhut, Director
Division of Licensing

Contact:
J. Calvo, X28563

cc: F. Rosa
P. Bender
B. Morris
G. Holahan
J. Calvo

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 08 1982

MEMORANDUM FOR: Philip A. Bender, Project Manager
Instrumentation and Control Systems Branch
Division of Systems Integration, NRR

FROM: Karl V. Seyfrit, Chief
Reactor Operations Analysis Branch
Office for Analysis and Evaluation
of Operational Data

SUBJECT: DRAFT FINAL REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH NUCLEAR COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

We have reviewed the subject draft final report as requested by your memorandum dated August 11, 1982. We note that our comments on the draft interim report have been addressed and incorporated in the final report. Based on our review, we have no further comments to offer.

If you should desire additional information, the AEOD contact is Matthew Chiramal or Karl V. Seyfrit.

Karl V. Seyfrit

Karl V. Seyfrit, Chief
Reactor Operations Analysis Branch
Office for Analysis and Evaluation
of Operational Data

cc: R. Mattson, NRR
B. Morris, CRBRP
F. Rosa, NRR ✓

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 9 1982

MEMORANDUM FOR: Phil Bender
Instrumentation & Control Systems Branch
Division of Systems Integration, NRR

FROM: Demetrios L. Basdekas
Instrumentation & Control Branch
Division of Facility Operations, RES

SUBJECT: REVIEW OF DRAFT FINAL REPORT: INTERACTION OF ELECTROMAGNETIC PULSE (EMP) WITH COMMERCIAL NUCLEAR POWER PLANT SYSTEMS

I have been requested(1) to review and comment on the subject report. My personal views on the issue of EMP vulnerability of nuclear power plants and related agency activities for addressing it, including an earlier draft of the subject report, are contained in a memorandum I prepared for the Commissioners on May 24, 1982(2). The comments contained in this memorandum are personal and not necessarily those of the Office of Nuclear Regulatory Research.

The subject report was prepared by Sandia Laboratories and its subcontractors as part of their fulfillment of contractual obligations in connection with a program plan and statement of work developed by the Office of Nuclear Reactor Regulation (NRR). These two documents are key to the work performed by the Sandia team, and therefore, I believe that they should be made part of the final report, possibly as an Appendix. Hence, comments relating to the NRR program plan apply directly to the work reported in the subject report, assuming that the work was in compliance with the NRR program plan.

I wish to take this opportunity to reiterate the comments contained in my memorandum to the Commissioners dated May 24, 1982.(2) They do apply to the current version of the subject report and NRR program plan and related policy issues. Because of time limitations I will only highlight those points that I consider to be of immediate and general applicability. They are the following:

1. There are inconsistent statements in the report regarding the objectives of the study. For example, the three objectives stated on page 1 of the Executive Summary and page 4 of the main report are apparently reneged in the paragraph that follows by having them "stated another way". What is "undue sensitivity"? If the study is not intended to propose hardening measures against "any and all conceivalbe circumstances" is it intended to propose hardening for some? If so, which ones and why those?

2. The listing of "constraints and assumptions" on pages 1 and 2 of the Executive Summary and page 8 of the main report is most appropriate. It would also be appropriate, and I believe, necessary to have a discussion of the significance of those "constraints and assumptions" regarding the validity of the conclusions reached in this study. For example, "Signal upset effects," not considered in this study can induce permanent damage by amplifying the effects of primary EMP induced disturbances (cascade effects). Hence, their exclusion leaves their study with very little meaning. As a matter of fact, I believe that had such statement of significance been offered by the Sandia team at the outset of the program, the agency would have been in a better position to decide to either modify the program or not undertake it.

3. On page 3, second paragraph of the Executive Summary, it is stated that "The systems of concern in an example plant were identified and defined." Considering that this is a key element in the program it would be appropriate to cite the rationale on which this "identification and definition" was based.

4. On page 4, third paragraph of the Executive Summary, it is stated that "this study uses a 'worst case' approach." If the intent of this statement is to suggest that the threat defined by the double exponential is the "worst case" one, it should be so stated clearly. Even if one were to accept this assumption, the word "approach" used in this statement implies that the "worst case" approach was taken throughout the study. Certainly, this is not the case.

5. On page 4, last paragraph of the Executive Summary and page 11, second paragraph of the main report it is stated that because MHD-EMP has significant low frequency components it was concluded that normal protective devices would respond to isolate and protect the plant. It would be appropriate to replace or specify "normal protective devices" with an identification of the specific devices referred to here. In any event, if the DOE and DOD are currently studying the problem, shouldn't we not take this into account in drawing conclusions on the effectiveness of these devices?

6. On page 8, second paragraph of the Executive Summary, the Reactor Protection System is listed as one of the "selected systems required for safe shutdown of a nuclear power plant." It would be appropriate to qualify the listing of the Reactor Protection System by stating that only its manual scram function was considered in the study, as it is alluded on page 23, second paragraph of the main report

7. On page 10, first paragraph of the Executive Summary, and page 35, first paragraph of the main report, it is stated that "Cabling attached to critical equipment is traced to the most severe penetration of EMP energy which can drive it." The words [most severe] appear only in the main report, not the Executive Summary. The two versions should be made consistent. But, in any event, the tracing of cabling to a penetration may involve paths that cannot possibly be identified by the methods of this study. This is a serious deficiency stemming from the "island" vs. "integral system" approach discussed in Reference 2, page 4, item 3. See also Section 6.5.2 on page 90 of the main report.

8. On page 10, second paragraph of the Executive Summary, and page 36, full paragraphs 2-4 of the main report, it is stated that the average cable current was estimated by In/N or $In/N^{3/4}$ assuming identical or non-identical loads respectively. Taking the average of currents tends to smear the calculated induced stresses on the respective components, and certainly not provide for a "worst case" approach in this respect. Dr. Longmire's comments on this assumption are of special interest.

9. On page 10, last full paragraph of the Executive Summary, it is stated that "diffused field strengths in the central regions of the plant are expected to be 50 dB or more below external incident fields." Assuming that this statement is true it is not complete and it certainly does not represent "worst case" conditions. It is indicated in the first full paragraph on page 92 of the main report that the attenuation, depending on frequency and location, may be as low as 5dB. A complete and realistic statement in the Executive Summary would be appropriate.

10. The discussion of grounding and ground cables presented on pages 37 and 38 of the main report does not include any mention of the fact that ground cables and other grounded metal structures and components can act as EMP induced disturbances. Their significance cannot be overstated for an EMP-like disturbance with a very wide frequency spectrum.

11. The last paragraph beginning on page 39 and continuing on page 40 of the main report, contains a portion starting with: "However, for the ...." It is inscrutable. Rewriting this portion appears necessary.

12. The diatribe on the analytical treatment of "threat" and "threat file" functions using fewer transforms presented in chapter 6.0 is pedagogically interesting, but what is the significance, for example, of average values of attenuation tabulated on page 78, Table 6.6 of the main report?

13. On page 15, first paragraph of the Executive Summary and page 46, first paragraph of the main report, it is stated that "It is impractical to subject a facility as large as a nuclear power plant to 'threat level' simulation signals." I do not dispute the large magnitude of the problem involved here, but the important question here is whether it is necessary. I agree with Dr. Longmire that as large scale testing as possible approaching "threat level" environments should be devised and performed at facilities that may be available for such testing. Decommissioned plants augmented with "state-of-the-art" components and systems offer an attractive vehicle for accomplishing this.

14. On page 16, last paragraph of the Executive Summary it is stated that "In Summary, the test program supports the EMP coupling analysis indicating that it is consistent and generally conservative." I agree that analysis and testing are consistent with one another. It should be pointed out, however, that they are consistently inadequate to reach the conclusions reached in the report. They both represent a miniscule and partial analog of the actual threat. They are very deficient in representing the interactive character of EMP and its effects, in conjunction with upset conditions, which are the primary damage mode of EMP induced disturbances.

15. It is not clear how applicable the data presented in Section 7.3.4 on page 119 of the main report are in this study. Some justification should be given for using them

16. In Section 7.4, page 119 of the main report it is stated that "circuit" parameters were evaluated at only one frequency (1 MHz)." The ensuing discussion is not convincing that the attendant limitations of the results may be safely discounted.

17. The conclusion on page 23 of the Executive Summary on Component Damage Threshold Analysis is based on the assumption that "all other curcuit elements perform as designed." It is not clear what the exact meaning and scope of this assumption is. The conclusion was also based on the assumption that "only those pins that serve as interfaces to "outside world" connections have been identified and considered. I believe it would be appropriate to define "outside world".

18. On page 24, fourth paragraph of the Executive Summary and page 128, first full paragraph of the main report it is stated that "This analysis has only examined individual components of safe shutdown systems, not complete systems". The discussion goes on to state that "the failure of a single component, or even several components, within one safety train does not preclude safe shutdown." I believe that the following points should be made respecting these statements:

(a) failures of many components (assuming common mode/common cause failures) cannot be restricted in one safety train.

(b) the above statements, as well as the entire program, are based on the supposition that, by ignoring upset conditions of signals and power on one hand, and process related disturbances (neutronic, thermohydrodynamic, etc.), on the other, the task is to "safely shutdown" the plant. Shut it down from where? What are the initial conditions? Are they those of steady state operation at a given power level? Is this a realistic expectation? How can "systems not-required for safety" such as control systems and their support systems be expected to behave? They may very well be outside "The island" defined by the program as "Safe Shutdown Systems" but their interactions with other plant systems both through electrical conductors, as well as through the plant processes they "share" should be expected to be substantial.

(c) Simultaneous stressing or damaging of individual components would likely have different effects on their respective systems, than if considered individually.

The above comments also apply to the last sentence of Chapter 9.0, page 181 of the main report, that, respecting the additional plants surveyed in the study "the possible loss of individual components in redundant systems does not preclude safe shutdown."

19. I agree with the statement made on page 27, third paragraph of the Executive Summary that "The EMP susceptibility of nuclear plant equipment in general cannot be determined from the data gathered during this study". I do not agree with the statement, however, that "the methods presented do provide a reasonable vehicle with which it may be determined whether very detailed in-depth studies should be conducted of each individual plant." I believe that the focus of future efforts should be the objective recommended in comment No. 9 above, namely, large scale, threat level testing. I do not agree with suggested continuation of effort along the same lines of approach in this study as outlined in Section 10.4 of the main report.

20. The six conclusions stated on page 31 of the Executive Summary cannot be supported by the study performed. Although some words have been changed to accommodate comments received as part of the preliminary draft report, the essence of the bottom line conclusion (No. 6) that "it is unlikely that an EMP event will fail sufficient equipment so as to prevent safe shutdown" remains the same as that stated in the preliminary draft of the report that "no EMP protection is required for the plant". These

statements are not supported by the study. To the contrary there is evidence strongly suggesting that if nuclear power plant hardness to EMP effects is needed as a matter of national policy, hardening measures will be needed to achieve this even for a single high-altitude explosion of the megaton class strategically placed. Examples of this evidence include operational experience with lightning and thunderstorm activity, use of "walkie-talkies" inside nuclear power plants, and data from defense programs on other systems.

21. I found no mention in the Executive Summary nor the main report of the related problem of EMP-like and EMI in general disturbances that may be generated by non-weapon sources. In SECY-81-641, November 5, 1981, the staff reported to the Commission that "Our preliminary conclusion is that a significant threat does not exist from non-nuclear generators because of the difficulty of deploying and operating such equipment in the vicinity of a plant without being detected, and because the effects of this type of equipment are low level and highly localized." This matter should be addressed in the report, and the staff's final conclusion, if any, on this matter should be stated in the Executive Summary and the main report along with its bases. The cited reasons for the staff's preliminary conclusion given above are not convincing. Also, they are not consistent with current state-of-the-art methods of generating and directing EM radiation of sufficient level to cause upset or damage to electronic/electrical systems and components used in nuclear power plants. The issue cannot be dismissed on the basis of the staff's above statement.

22. I concur with Dr. Longmire's comments contained in Appendix E, pages E-15-E23, dated June 1982.

Since EMP related technology involves highly specialized disciplines and NRC does not have all the requisite expertise in-house for an in-depth evaluation of this issue, including the Sandia Study, we should utilize the expertise in other Government agencies, particularly the Department of Defense. In order to assure the technical basis be soundly established for the Commission's policy decision, I recommend we proceed as follows:

1. Officially request the National Academy of Sciences and National Research Council to review the Sandia draft report on hand and all comments received, and report to the Commission as soon as practical. See also Enclosure 1 to Reference 2.

2. Request a similar review and comment from DOD, DOE, FEMA, and NASA.

3. Postpone the publication of the final Sandia report until items 1 and 2 above are completed, and revise the draft as needed, based on the resolutions of all comments received.

4. The NRC should coordinate the establishment of an Inter-Agency Task Force consisting of NRC, DOD, DOE and FEMA to formulate and recommend to the Commission a federal program under the primary financial sponsorship of NRC and DOD to study this issue and report on the results with recommendation as to how to deal with the EMP vulnerability of nuclear power plants. This key task is expected to take considerable effort, but with a leading active participation of DOD, it whould be completed expeditiously.

5. Integrate the EMP/lightning protection and Electromagnetic Interference (EMI) protection requirements so that future regulatory upgrading impact on the licensees can be minimized.

6. Organize technical seminars on EMP, lightning and EMI.

7. Arrange the exchange of technical personnel between DOD and NRC for training in nuclear reactor technology, and EMP technology respectively.

If I can be of any assistance, please contact me.

Demetrios L. Basdekas

Demetrios L. Basdekas
Instrumentation & Control Branch
Division of Facility Operations, RES

References:
1. Memorandum from E. C. Wenzinger to D. L. Basdekas, August 16, 1982

2. Memorandum from D. L. Basdekas to the Commissioners on the EMP Vulnerability of Nuclear Power Plants, May 24, 1982

cc: F. Rosa, NRR ✓
B. Morris, NRR
A. Hon, RES
D. Ericson, SNL

RESPONSE TO COMMENTS OF DEMETRIOS L. BASDEKAS

Several general comments are in order in response to Mr. Basdekas prior to addressing each of his more specific concerns. In other communications Mr. Basdekas has taken some rather strong positions regarding potential EMP vulnerabilities and the merit of the research program reported here. These prior positions are reflected in the tone of these comments. Mr. Basdekas also makes recommendations for actions which are clearly not the responsibility of the study team, these will be noted.

Our responses to Mr. Basdekas' comments, where appropriate follow below:

1. The study team does not agree that the objectives of the study are "reneged" by stating them another way. However, because of comments from several reviewers, the wording of the objectives has been carefully reviewed to eliminate any ambiguities.

2. Mr. Basdekas asserts, without support or an example, that upset can induce permanent damage by amplifying the effects of primary EMP disturbances, and to exclude upset leaves the study with little meaning. Obviously, we disagree, individual members of the study team (and the Research Review Panel) have considerable experience in the assessment of the EMP vulnerability of a variety of systems. In our opinion the conditions required for upset to induce permanent damage (for example, power follow) do not exist in the systems studied. It is implied here that Sandia "sold" this program to the staff and omitted key issues. In fact, the program was developed jointly by Sandia and NRR and the bounding conditions of the study have been continually emphasized.

3. Section 1 of the Executive Summary (Page 3) is an overview of the activities undertaken in the study, Section 4 describes the systems selected. Because a safe shutdown capability is a licensing condition, each Safety Analysis Report contains an identification of these systems for the particular plant. Therefore, it was not deemed necessary to discuss the rationale for these selections in any great detail.

4. Because this section is discussing the EMP phenomena, we did not believe there would be any confusion about the meaning of "worst case." However, to insure a clear understanding, some additional text has been added in the Executive Summary.

5. Several reviewers commented on the discussion of MHD-EMP. As a result both the Executive Summary and the Main Report have been revised with more discussion added to the latter. See also Response Number 2 to comments from the Office of Nuclear Regulatory Research (RES).

6. We agree and the Executive Summary has been modified to agree with Section 4.1 of the Main Report.

7. Some similar concerns were raised in Comment Number 3(b) from RES and revisions were made to the text. See also Response 3(b) to the comments from RES.

8. The report states that the cable currents are bounded by In/N and $In/\sqrt{N}$ and that $In/N^{3/4}$ is a reasonable estimate of the average peak value. We recognize that Dr. Longmire and Mr. Basdekas do not accept this approach. However, as noted in our earlier response to Dr. Longmire, the technique has been used successfully in many analyses and is an effective engineering tool. See also our response to RES Comment 3(c).

9. As noted in our response to RES Comment 3(d), the wording used apparently led to some confusion over insertion losses as measured with an antenna system and plane wave shielding effectiveness as deduced from those measurements. We believe the revisions to Section 6 will alleviate this problem. See also Response 3(d) to RES comments.

10. This comment was addressed in our response to RES Comment 3(e). The ground cables in the vicinity of the duct banks share the induced bulk current. They are not an additional, independent source.

11. This paragraph simply states that it was necessary to make some additional predictions of signal attenuation for the plant "as is" because that is the condition under which verification tests were conducted. Some wording has been reworked to alleviate Mr. Basdekas' concern, although no other reviewer indicated any problem with this passage.

12. The principal author takes strong exception to Section 6 being characterized as a "diatribe," particularly by Mr. Basdekas, given the volume of correspondence he has generated concerning this program. There may be more information provided than is absolutely necessary, however, it provides the reader with a more complete picture of the test techniques. The significance of the average attenuation values is discussed in Section 6.5. This section has been revised in some aspects to clarify that discussion.

13. The authors certainly recognize that there is a school of thought within the EMP research community which argues that only full scale tests provide the answers. Obviously, we do not agree, as large scale testing would make sense only if analyses indicated that EMP was likely to cause significant damage. Furthermore, Mr. Basdekas appears to discount the very real technical (and economic) problems associated

with such tests on a facility as large as a nuclear power plant, based upon his conviction that EMP is a problem. The authors simply cannot accept the suggestion that the "hybrid" that would result from augmenting a decommissioned plant with modern components is somehow representative of current generation nuclear power plants. On the contrary, it would truly be one of a kind.

14. The authors are at a loss as to how to respond to this comment. Again, Mr. Basdekas asserts, without support by example or analysis, that the work is inadequate to reach the conclusions. No other reviewers (many of whom have long experience in EMP research) have taken this position. It appears that because we did not examine upset, nothing we report will be acceptable to Mr. Basdekas; he believes there is a problem. We have conducted a detailed study, the results of which lead us to the judgement that damage is unlikely and that safe shutdown can be accomplished.

15. As noted, the data are not used directly because we do not have the appropriate uncertainty information from the coupling analysis to combine with it. However, it was included to provide additional indication of the generally conservative nature of the study.

16. Damage thresholds are not strong functions of frequency (threshold is proportional to $\sqrt{f}$) therefore the exact value is not critical so long as one reasonably models the situation which may exist. Based upon the data in Section 6, a 1 MHz signal is a reasonable representation of the damped sine which would exist as a result of EMP excitation.

17. This concern was also addressed in RES Comment 5(f) and our response thereto.

18. (a) Some similar concerns were addressed in the RES comments [6(a) and 7(b) in particular]. The common mode (common cause) concern is not unreasonable, if EMP-induced signals are large enough to stress the system. The evidence to date indicates they are not. Also, it must be reiterated that an actual single nuclear burst cannot achieve the excitation levels nor the simultaneity at all points as postulated in this study.

    (b) As noted in the study, three basic functions must be accomplished regardless of the initial conditions. The reactor must be maintained in a subcritical condition, coolant inventory must be maintained, and decay heat must be removed. We have identified the systems required to accomplish those functions and examined the components of those systems for possible

EMP effects. No damage is anticipated for the components in the example plant because all had substantial positive safety margins. The less detailed look at Palo Verde gave some negative safety margins on less critical portions of the systems. However, the overwhelming weight of evidence indicates that it is unlikely that EMP will cause any damage. We stand by our conclusions.

(c) The analyses indicate that the components will not be "stressed." EMP-induced signals are less than operating levels.

19. Again the full-scale test versus analysis and partial test philosophies are highlighted. The evidence does not support the need for large scale testing. The study team can only stand on its position, based upon this and other studies and the support it has received from the other reviewers.

20. The study team has no comment to Mr. Basdekas' position other than that we believe the conclusions are supported by the analyses. Mr. Basdekas seems to be suggesting that EMP would produce responses similar to those induced by lightning and hand-held radio transmissions. The frequency and energy characteristics of these signals are different and system response cannot be inferred from the "operational experience" cited. It should be noted that Mr. Basdekas appears to be alone in this flat rejection of the study.

21. The information on nonweapon sources has been reworked to some extent, however, the conclusion to eliminate it as a concern remains based upon the collective judgement of the study team and the Research Review Group. Mr. Basdekas frequently equates this report with NRC staff positions. It should be noted that the report documents and reflects the study team position, which may or may not be the NRR staff position.

22. Our response to Dr. Longmire's comments appear in Part 1 of this appendix.

Mr. Basdekas concludes his comments with a set of recommendations which are not the responsbility of the study team. However, there are several observations which are appropriate.

1. This study has had extensive peer review, in-house at the respective participants organizations, the Research Review Panel, interested participants, and the Nuclear Regulatory Commission.

2. The study team participants, Boeing Aerospace Company, IRT Corporation, and Booz-Allen & Hamilton in particular have a long history of involvement in DOD-sponsored EMP research, as do many of the Review Panel members. This is an excellent and more than adequate cross section of expertise in this area.

3. If a review were conducted by the National Academy of Sciences or the National Research Council, they would draw upon the same body of expertise available to Sandia to conduct the study. Neither organization has "resident" groups of experts. Representatives of the National Academy of Sciences have participated in the review meetings and have received copies of the draft reports.

Also, we note, with passing interest, that most of these recommendations are predicated upon the assumption that EMP is a problem. The evidence available supports the study team position that damage is unlikely to result from EMP. The recommendations put forth by Mr. Basdekas are not supported by the technical evidence and weight of technical judgement generated to date on this topic.

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This study examines the interaction of the electromagnetic pulse from a high altitude nuclear burst with commercial nuclear power plant systems. The potential vulnerability of systems required for safe shutdown of a specific nuclear power plant are explored. EMP signal coupling, induced plant response and component damage thresholds are established using techniques developed over several decades under Defense Nuclear Agency sponsorship. A limited test program was conducted to verify the coupling analysis technique as applied to a nuclear power plant. The results are extended, insofar as possible to other nuclear plants. Based upon the analysis, it was concluded that: (1) Diffuse fields inside Seismic Class I buildings are negligible; (2) EMP signal entry points are identifiable; (3) Interior signal attenuatio can be reasonably modeled; (4) Damage thresholds, even for equipment containing solid state components are high; (5) EMP induced signals at the critical equipment in the example plant are much less than nominal operating levels, but plant topology and cabling practice have a strong influence on responses; (6) The likelihood that individual components examined will fail is small; therefore, it is unlikely that an EMP event would fail sufficient equipment so as to prevent safe shutdown.

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