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The Effects of Nuclear Electromagnetic Pulse (EMP) on Nuclear Power Plants

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THE EFFECTS OF NUCLEAR ELECTROMAGNETIC PULSE (EMP) ON NUCLEAR POWER PLANTS

P. R. Barnes
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FOREWORD

The EMP surge estimates given in this report are, in many cases, the upper bound for the actual surges that will be experienced in a nuclear power plant. These estimates were obtained by applying the maximum EMP coupling conditions to long cables (160 m) routed near the exterior wall which is illuminated by the incident EMP. These worst-case surges were used along with conservative assumptions to determine the effects of EMP on important plant systems. Therefore, the conclusions of this report are considered conservative and pessimistic.

GLOSSARY OF ACRONYMS

APRM	-	Average Power Range Monitor
BWR	-	Boiling-Water Reactor
CVCS	-	Chemical and Volume Control System
ECCS	-	Emergency Core Cooling System
EMP	-	Electromagnetic Pulse (generated by the detonation of a nuclear weapon)
ESF	-	Engineered Safety Features
HOB	-	Height of Burst
LPRM	-	Local Power Range Monitor
NIS	-	Nuclear Instrumentation System
POE	-	Point of Entry
PV	-	Process Variable
PWR	-	Pressurized-Water Reactor
RBM	-	Rod Block Monitor
RCIC	-	Reactor Core Isolation Cooling
RCS	-	Reactor-Coolant System
RHRS	-	Residual Heat Removal System
RPS	-	Reactor-Protection System
SIS	-	Safety Injection System
SSPS	-	Solid State Protection System

THE EFFECTS OF NUCLEAR ELECTROMAGNETIC PULSE (EMP ON NUCLEAR POWER PLANTS

P. R. Barnes
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ABSTRACT

The electromagnetic pulse (EMP) from a high-altitude nuclear detonation consists of a transient pulse of high intensity electromagnetic fields. These intense fields induce current and voltage transients in electrical conductors. Although most nuclear power plant cables are not directly exposed to these fields, the attenuated EMP fields that propagate into the plant will couple some EMP energy to these cables. This report predicts the probable effects of the EMP transients that could be induced in critical circuits of safety-related systems. It was found that the most likely consequence of EMP for nuclear plants is an unscheduled shutdown. EMP could prolong the shutdown period by the unnecessary actuation of certain safety systems. In general, EMP could be a nuisance to nuclear power plants, but it is not considered a serious threat to plant safety.

1. *INTRODUCTION*

1.1 Purpose and Content

Nuclear power plants are designed to minimize the probability of accidents which would damage the plant or endanger the community. Protection against accidents is normally provided by large safety factors in the design and use of redundant safety and instrumentation equipment. The redundant equipment provides protection against a single failure in the instrumentation and safety systems. This provides a large safety margin since the probability of a multiple failure involving two or more independent instrumentation channels or safety systems is considered to be extremely small. However, the probability of a multiple failure due to EMP was not considered in the original safety analysis. This probability is not necessarily small since all parts of the system may be subjected to the failure mechanisms at the same time.

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The purpose of this study is 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. Due to the limited scope of this effort and the complexity of the EMP power plant problem, zeroth or first-order estimates have been used to determine the EMP-induced transients and their probable effects on the plant. If warranted, a more in-depth analysis can be performed in a later study.

The second section of this report briefly describes some of the more important systems in light-water nuclear power plants. The third section covers the expected EMP surges and their probable effects on important plant systems. The latter sections cover the consequences of assumed worst-case EMP effects for nuclear plants.

1.2 High-Altitude EMP

The detonation of a nuclear weapon is accompanied by an EMP with a large portion of its energy within the radio frequency spectrum. The process by which EMP is generated is described in previous reports.[1,2,3] The electromagnetic fields radiated from nuclear detonations vary greatly with weapon yield and detonation location. A strong EMP is produced by both high- and low-altitude detonations. The EMP produced by a low-altitude detonation attenuates quickly with distance and is normally accompanied by the other nuclear weapon effects. High-altitude EMP is produced by a nuclear detonation at an altitude near or above 50 km. Due to the large area of the Compton-electron source current, high-altitude EMP can cover a large portion of the country which is completely free from the other nuclear weapon effects. Nearly all nuclear power plants will be subjected to high-altitute EMP due to its wide area of coverage. Typical areas of coverage for a megaton-range weapon detonated at a height of burst (HOB) of 100 km and 400 km are shown in Fig. 1.1. As shown, most of the United States can be covered by a single exoatmospheric burst.

The short duration EMP fields are very intense. The amplitude of the electric field pulse is on the order of 50 kV/m. The time history of EMP is characterized by a very short rise time of about 10 nanoseconds

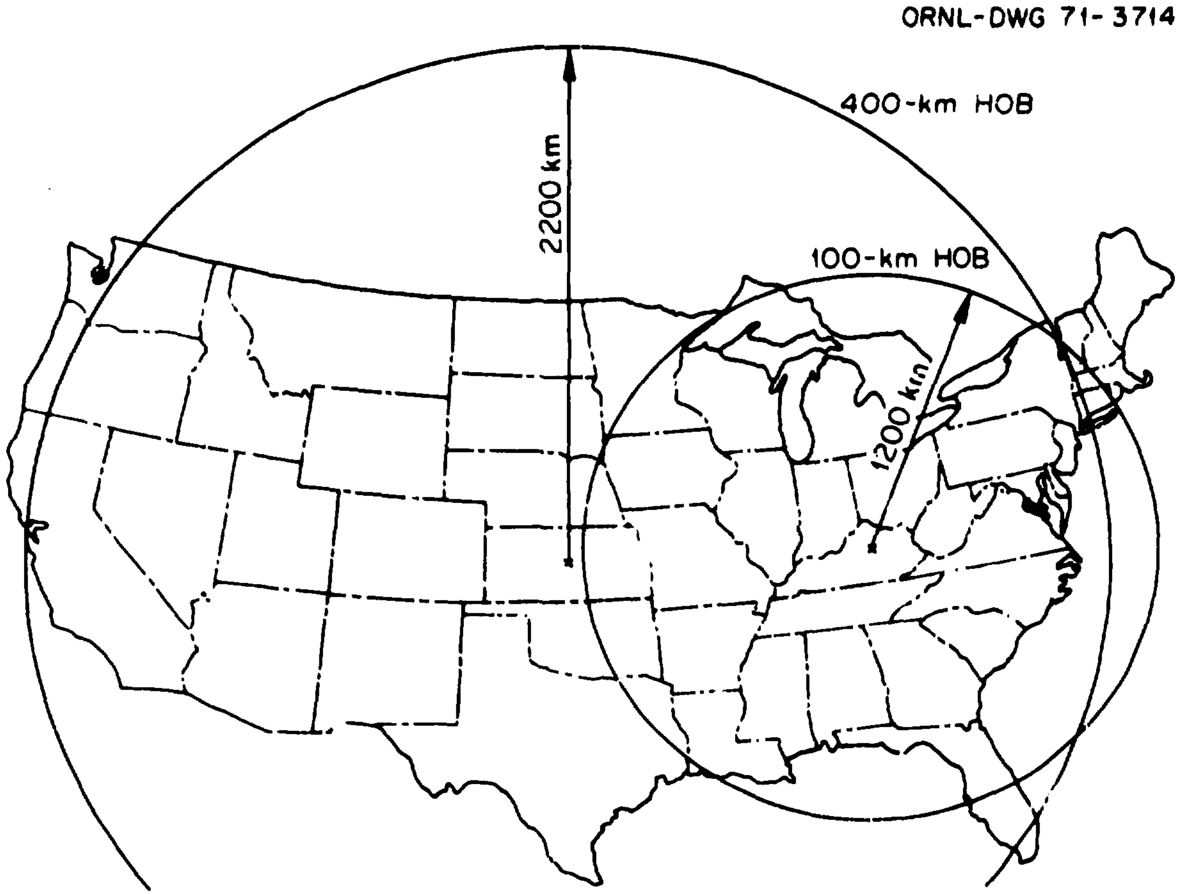

Fig. 1.1. Area of Coverage of EMP from High-Altitude Detonations.

(nsec) and an exponential-type decay with a time constant on the order of 200 nsec. A double exponential is often used to describe the EMP wave form. An example of a double exponential EMP wave form is shown in Fig. 1.2. The fast rise time implies a wide excitation bandwidth, and the high intensity implies significant energy content in a broad range of the electromagnetic spectrum.

1.3 The EMP Threat

Any conductor exposed to the EMP fields performs as an inadvertent antenna by receiving EMP energy. The EMP-induced electrical transients in conductors greater than 30 m (100 ft) long have large magnitudes comparable to near-average lightning surges. However, both the rise and decay times of EMP surges are much shorter than those of lightning surges. Many solid state components are especially vulnerable to these fast rising EMP surges. This is due to the significant energy at high frequencies. The fast rising surges also present special protection problems.

The instrumentation, control, and power lines of a nuclear power plant will have EMP surges induced in them. Even well shielded lines may pick up enough EMP noise to upset (change the state of) sensitive logic circuits. Also, cumulative effects of EMP surges may cause damage to electronic components which might survive a single pulse. Multiple failures due to damaged components or upset circuits may cause the plant protection systems to respond incorrectly. To examine this possibility, we shall focus our attention on the instrumentation, control, and safety systems of modern nuclear power plants.

2. MODERN NUCLEAR POWER PLANTS

2.1 Introduction

The basic elements of a modern nuclear power plant are shown in Fig. 2.1. The reactor is the source of heat energy which is transferred to the heat exchanger by the reactor-coolant systems (RCS). The reactor

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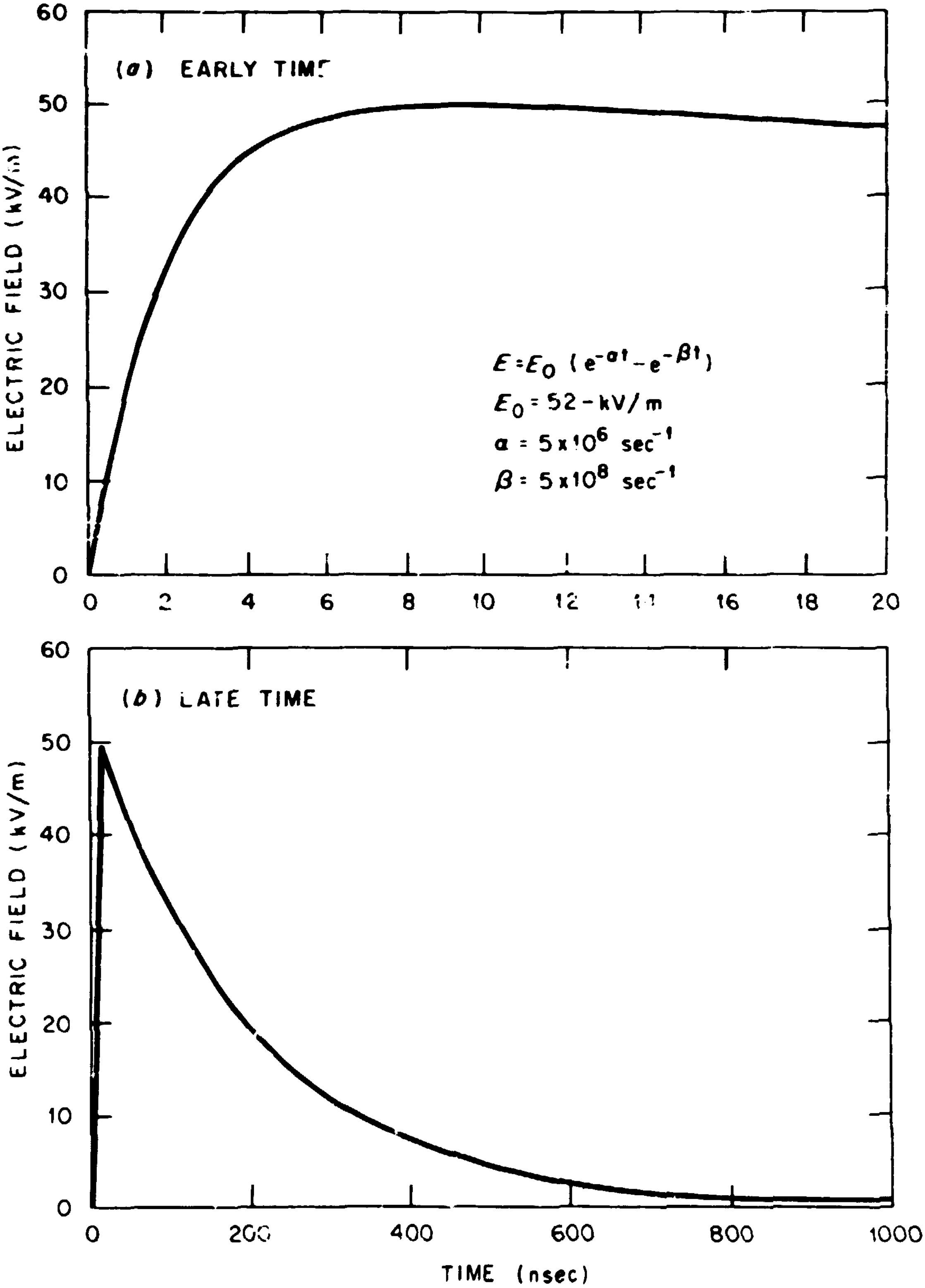

Fig. 1.2. Double Exponential Wave Form used to Represent the EMP Electric Field Time History.

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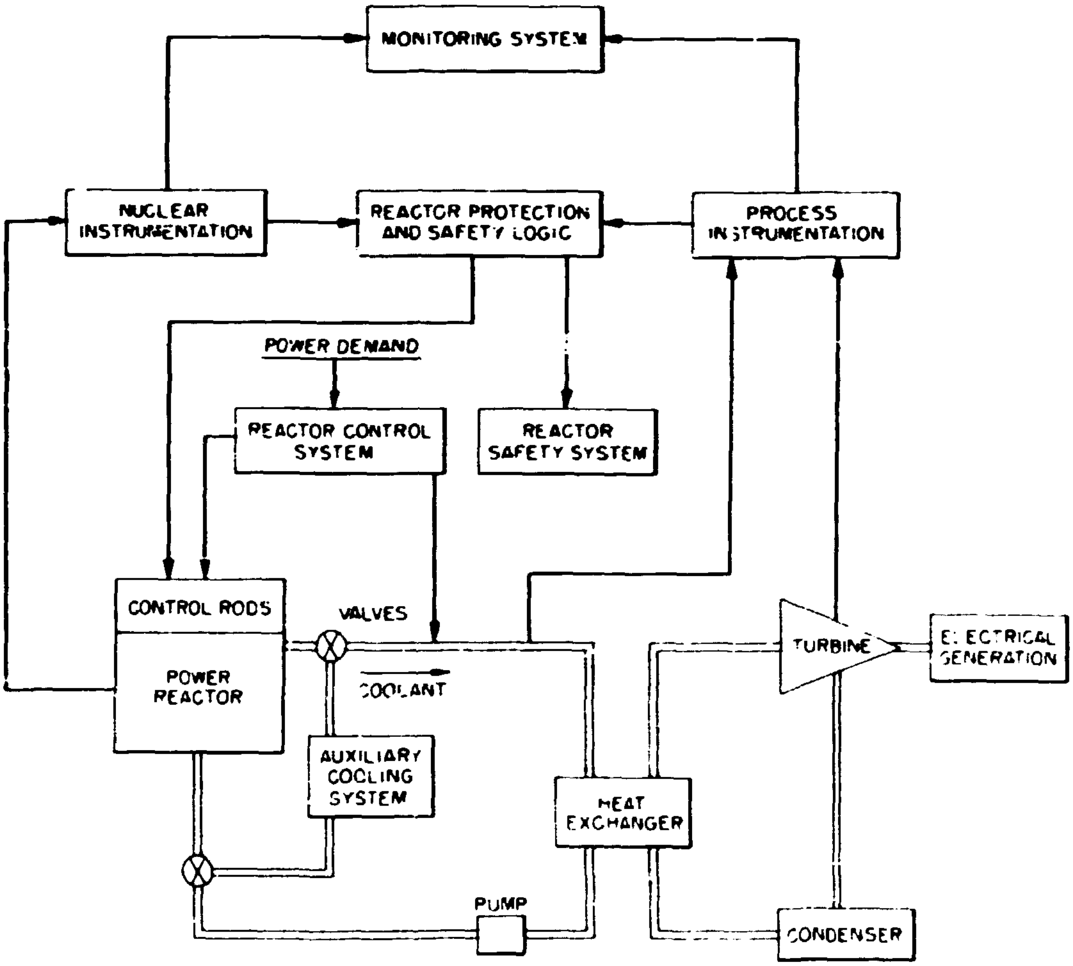


Fig. 2.1. Simplification Block Diagram of a Nuclear Power Plant.

coolant determines the reactor type; i.e., water is used in Pressurized-Water Reactors (PWR's), water and steam are used in Boiling-Water Reactors (BWR's), and gas is used in high-temperature, gas-cooled reactors. The heat exchanger serves to restrict the radioactivity to the reactor and the reactor-coolant system. The turbine, condenser, and electrical generator operate in a similar manner as those in coal- or oil-fired power plants.

Also shown in the diagram are the reactor control and safety systems. The reactor-control system can control the power output of the reactor by proper positioning of control rods located in the reactor core and by adjusting reactor-coolant parameters. The operator can monitor the plant operation by a monitoring system which receives inputs from the nuclear and process instrumentation systems among others. The nuclear instrumentation system monitors the neutron flux in the reactor, and the process instrumentation system monitors the temperature, pressure, and flow rate of the reactor coolant. The nuclear and process instrumentation systems are part of the reactor-protection system (RPS) which, if necessary, can scram (shut down) the reactor and initiate special reactor safety measures.

Not shown in Fig. 2.1 are the various essential electrical power systems. Control, instrument, and ac electrical power are all important for the safe operation of the plant. Most reactor safety systems also require electrical power. Since it is possible that normal power can be interrupted, backup power is normally provided for these systems.

The nuclear power plants now operating or under construction in the United States are PWR and BWR plants. We shall focus our attention on these two important nuclear plant types.

2.2 Pressurized-Water Reactors

Modern pressurized-water power reactors have two reactor-coolant loops separated by a heat exchanger as shown in Fig. 2.1.[4] The primary loop removes heat directly from the reactor. The secondary loop provides steam to drive the main turbines. In large reactors such as the 1200-MW(e) PWR used in the Sequoyah nuclear plant near Chattanooga, Tennessee, the primary loop system consists of four essentially identical coolant loops.[5] Pressurized water is circulated in each of the four loops from the reactor vessel to a steam generator (heat exchanger) by a 6000-hp coolant pump. A single pressurizer in one loop maintains the required coolant pressure for all four loops. Chemical control of the coolant is provided by the chemical- and volume-control system (CVCS). The CVCS also maintains the correct water level in the pressurizer and provides the required coolant pressure when the RCS is cold.

Magnetic-jack control-rod-drive mechanisms are used to position the PWR control rods. These drive mechanisms are located above the reactor vessel. During normal plant operation, the drive mechanisms hold in position the control rods that have been withdrawn from the core. If power to the magnetic jack is removed, either deliberately by a reactor trip or because of an accidental power loss, the control rods fall instantly by gravity into the core.[4]

Important safety-related PWR auxiliary systems are the residual heat removal system and the engineered safety features. The residual heat removal system (RHRS) consists of dual heat exchangers and pumps. The purpose of the RHRS is to remove heat from the core during plant shutdown. The RHRS is also part of the emergency core cooling system (ECCS) which has the function to supply cooling water to the reactor under accident conditions. The RHRS is normally activated about four hours after the control rods have been inserted into the core.

The engineered safety features (ESF's) include the safety injection system and the containment spray system among others. The safety injection system is part of the ECCS. It supplies borated water to the reactor to ensure that the reactor remains shut down after a loss-of-coolant accident.

2.3 Boiling Water Reactors

The core design of a BWR is such that the water coolant is allowed to boil in the active region of the system.[6] The steam is directly channeled to the turbine for electrical power generation. Thus, there are no secondary loops in a modern BWR steam supply system. Figure 2.2 shows a simplified schematic representing a direct-cycle, forced-circulation BWR with the major control systems incorporated.

Depending upon the power level of the reactor, the boiling rate can tend to compromise the effectiveness of the water moderator. Boiling bubbles are formed around the circumference of the fuel rods. As the concentration of bubbles increases, fewer neutrons are reflected back into the fuel rods to continue the chain reaction at its desired rate; thus, the reaction decreases with a subsequent decrease in the reactor power level. Because of this phenomenon, the modern boiling-water reactor incorporates jet pumps into the recirculation flow loop. The purpose of these pumps is to control the bubble concentration and thus control the available reactivity and hence the power without movement of the control rods. Approximately two-thirds of the recirculation flow in the reactor vessel is generated by these jet pumps. In practice, the power level may be altered as much as 25% by this technique.

The BWR control rods are mounted on the bottom of the reactor vessel and are positioned by hydraulically actuated piston-drive mechanisms. The drive mechanisms can position the control rods at increments over the entire core length. The drive mechanisms can also scram the reactor by driving all of the rods into the core. The scram signal overrides all other control signals to the drive mechanisms.

Important safety-related BWR auxiliary systems are the reactor core isolation cooling system (RCIC), the ECCS, and the RHRS. The RCIC supplies cooling water to the reactor in the event the vessel is isolated from the turbine steam line and from the feedwater flow. The BWR ECCS consists of high- and low-pressure core spray systems and the various modes of RHRS. The RHRS is made up of various subsystems including the low-pressure coolant injection system, suppression pool cooling system, and the shutdown cooling system. The shutdown cooling system removes low-level residual reactor heat. It is normally initiated about 20 hours after shutdown.

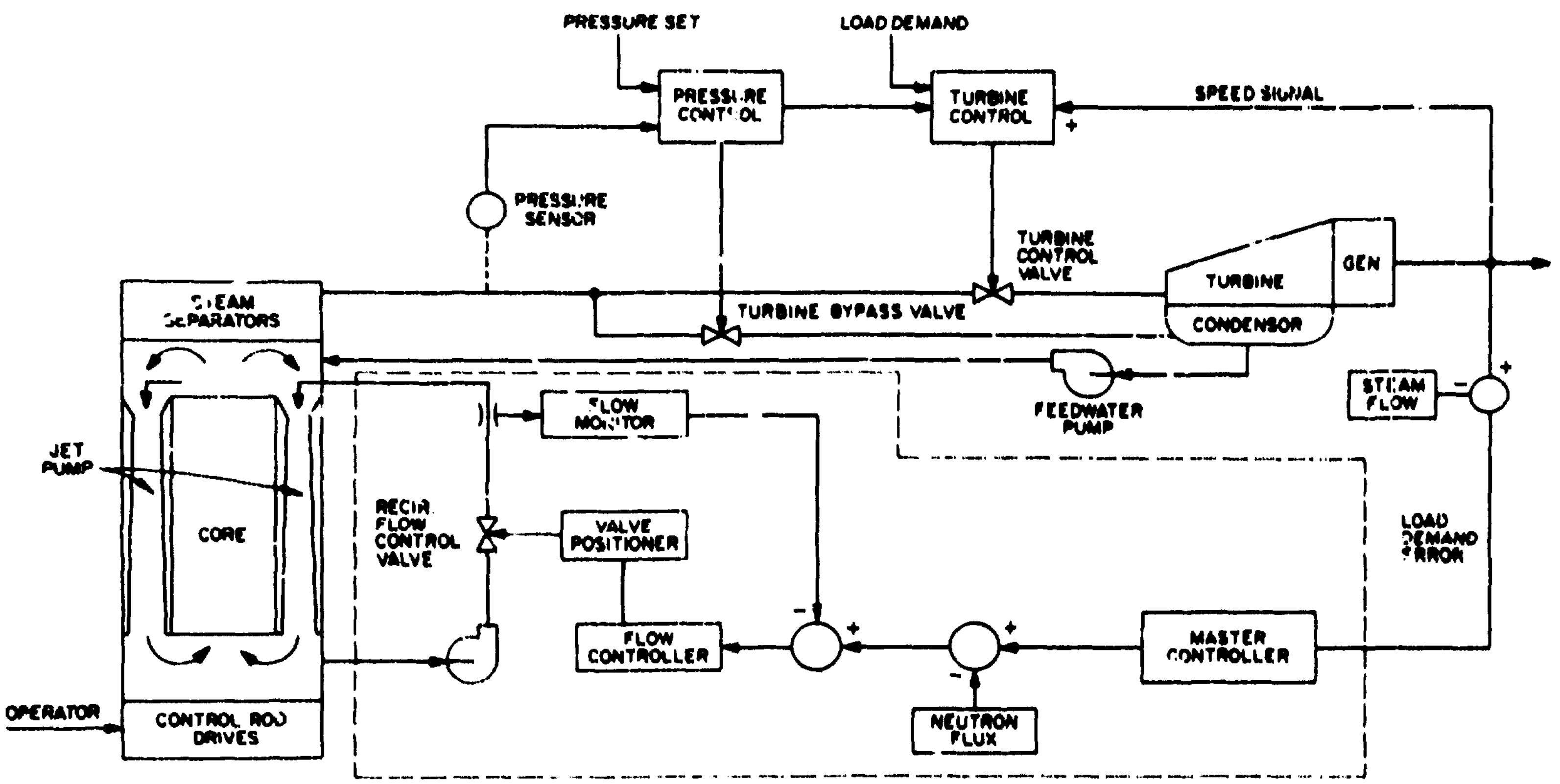


Fig. 2.2. Simplified Block Diagram of the Direct Cycle BWR with Major Control Systems.

2.4 Instrumentation and Controls

Modern nuclear power plants have sophisticated instrumentation and controls. Multiple instrumentation and control channels are used to prevent system failures due to a single malfunction. The nuclear instrumentation system (NIS) monitors the neutron flux, its spatial slope in the core, and its rate of change. The process instrumentation typically monitors the temperature, pressure, and flow rate of the primary and secondary coolant systems. Various spatial and time derivatives are also monitored by the process variable (PV) instrumentation.

The instrumentation systems normally employ low-level-current analog signal transmission from the sensors to the instrumentation racks. Industry standards for process instrumentation signal currents are 4-20 mA and 10-50 mA. Nuclear instrumentation signal currents are normally one or more milliamperes. The signal-current range used in Westinghouse PWR's is 0-4 mA.

Due to the low signal levels, sensor cables are generally well shielded against electromagnetic noise. The NIS cables may also be placed in conduit for electromagnetic noise suppression and physical protection.

The primary purpose of the instrumentation is to provide information for the RPS and for the operator. Digital information which indicates that the engineering design limits have been exceeded is provided to the RPS logic by bistables which change states when certain instrumented variables or their derivatives exceed or fall below preset values. This is normally accomplished by removing the voltage at the input of the RPS logic. If the RPS logic input is de-energized by a failure in the instrumentation system or the interruption of instrument power, a bistable trip signal is generated. Thus, the system is said to be fail-safe. The bistables that are typically used in nuclear power plant instrumentation return to their original state once the trigger signal is removed. An exception to this is the latching bistable which changes state and remains in the new state until the circuit is reset.

The control system controls reactor power, reactor coolant variables such as temperature, pressure, etc., and the turbine generator output. Reactor power is controlled by moving the control rods or adjusting coolant variables. The control system utilizes relatively high signal voltages on the order of 120 V or greater to activate rod, valve, and pump controls. Electrical noise is generally not a problem at these signal levels.

The operator is furnished with information on the plant status by the monitoring system. Positions of control rods, nuclear and process instrumentation variables, as well as many other variables, are monitored. Modern monitoring systems employ a computer to provide continuous plant status information.

2.5 Plant Electrical Power

The plant electrical power systems are the off-site auxiliary power, the nuclear-unit auxiliary power, emergency auxiliary power supplied by diesel-driven generators, and the inverter-charger battery supplies. The auxiliary power voltage is normally several kilovolts. (Typical auxiliary power voltages are 4000 volts or 6900 volts.) This voltage is used to power the large motors throughout the plant. Lower voltages such as 400 volts, 240 volts, and 120 volts are obtained from stepdown transformers to power small motors and other plant auxiliary loads.

The loss of the off-site auxiliary power will often scram (shut down) the reactor. The auxiliary systems essential to a safe shutdown are then transferred to the diesel generators. Important instrument and control power is maintained by the battery-inverter power supplies for several seconds until the diesel generators obtain the proper voltage.

3. EMP SYSTEMS ANALYSIS

3.1 Approach

The general approach for an EMP systems analysis is to (1) identify the important systems, (2) determine the points of entry (POE's) through which EMP energy can enter each system, (3) obtain quantitative estimates of the EMP surges at the POE's, and (4) determine the probable effects of these surges on each system. Due to the numerous systems and the complexity of a nuclear plant, a very detailed and exact analysis is beyond the scope of this effort. A more complete and thorough analysis should be performed at the conclusion of this study on those systems that appear to have EMP susceptibilities. This should presumably be done by the various systems' manufacturers.

The important systems of interest in nuclear power plants are those related to reactor and plant safety. These are the instrumentation systems, the reactor protection system, the reactor control system, the monitoring system, the residual and emergency heat removal systems, and essential electrical power systems.

The EMP energies which can couple to systems by the plant electrical ground system are minimized by installation practices which avoid ground loops in order to reduce electrical noise effects. The electromagnetic fields that can interact directly with the systems' electronics are greatly reduced by the attenuation afforded by the metal cases and grounded metal equipment racks. The most important EMP coupling mechanisms for most of the systems and equipment in the plant are the cables and wires that are connected to the systems.

The expected EMP surges on power plant cables have been investigated by a previous study.[7] These surges vary greatly and depend on the location, shielding levels, and length of each cable. Thus, the surges are dependent on parameters which can vary from plant to plant. We have assumed that the shielded cables are similar among plants of the same type. For cable lengths and locations, we have assumed realistic worst-case conditions. To obtain these parameters, the Sequoyah nuclear plant has been used as a model of a modern PWR plant, and the Browns Ferry nuclear plant in Alabama and the Hatch nuclear plant in Georgia have been used as modern BWR plants.

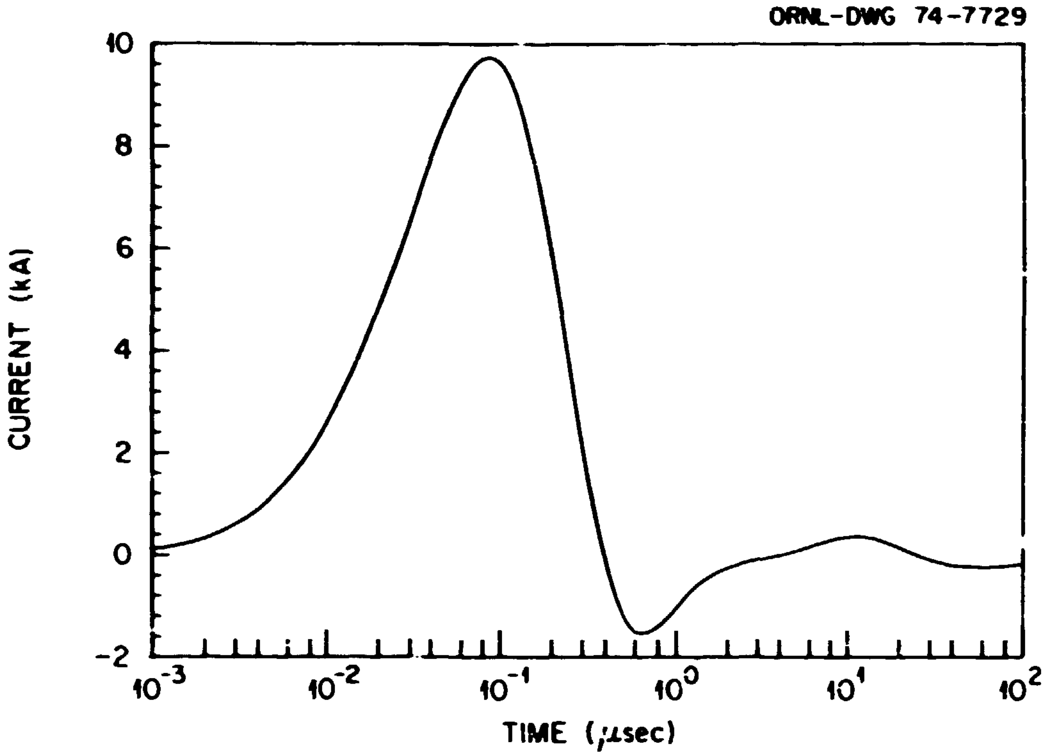
To evaluate the possible effects of EMP on the important systems, the peak EMP surge is compared with the normal operating level on each cable connected to the systems. If the surge peak is ten times greater than normal levels, then damage is possible and may occur. If the surge peak is equal to the setpoint of trigger circuits for a sufficient duration, then a logical upset or change-of-state may occur.

3.2 EMP Surges

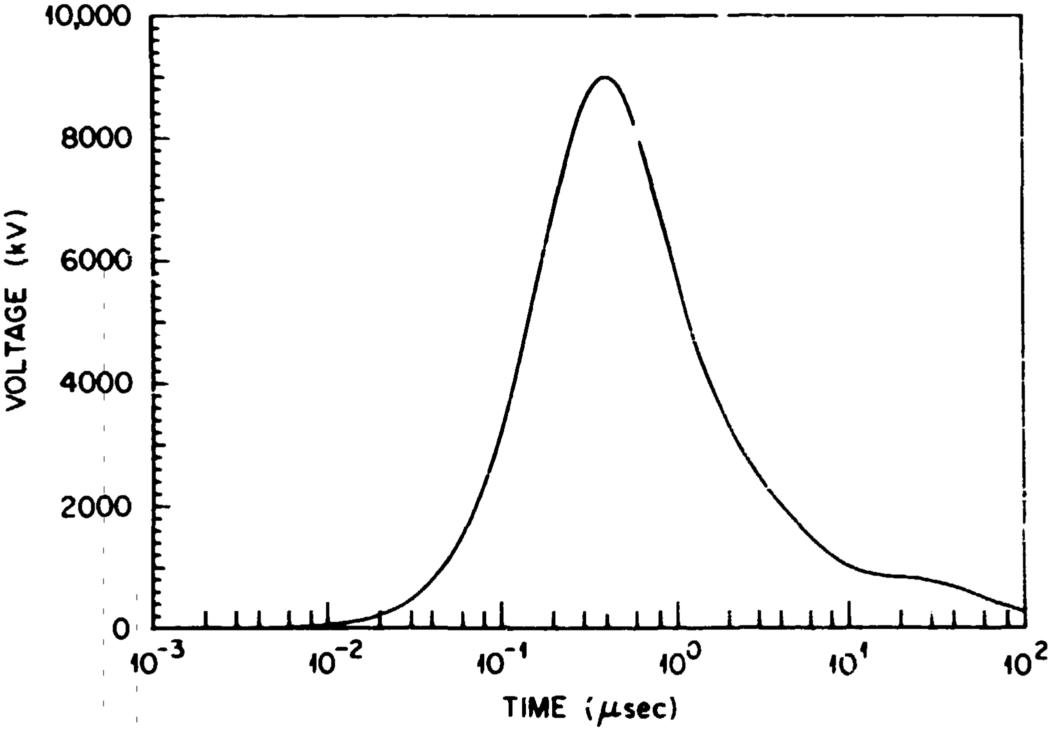
The EMP surges induced in electrical transmission lines and nuclear power plant cables have been considered in previous studies.[7, 8] The amplitudes of the induced surges depend on the EMP wave form, the length of cable or line, the orientation of the cable with respect to the incident EMP and the earth, and the level of electromagnetic shielding. For our analysis, we shall take the conservative approach by assuming worst-case EMP coupling conditions. Worst-case EMP coupling conditions are those that realistically maximize the EMP surges.

Electrical power transmission lines will collect large amounts of EMP energy due to their length. The EMP voltage surges will have peaks on the order of a megavolt with rise times on the order of a tenth of a microsecond. These surges will occur on all of the lines throughout the power grids. Flashovers on these lines and in the switchyards will likely initiate circuit breaker action to disconnect the preferred off-site plant power. Also, the entire power grid is likely to become unstable, if subjected to multiple EMP's, resulting in a power blackout.[9] Thus, EMP is likely to cause a loss of the preferred off-site plant power.

Realistic worst-case EMP surges on the off-site power lines at the plant transformer are shown in Fig. 3.1.[7] The voltage peak is over 9 MV. The transient decays to near 1 MV after 10 μsec. Most high-voltage transmission lines would probably flashover and significantly reduce the surge amplitude. However, if flashover does not occur, a portion of the surge will capacitively couple across the plant transformer. Typical transformers have a primary-to-secondary winding capacitance of several hundred picofarads and a secondary-to-earth capacitance of several nanofarads. The transformer appears as a capacitive voltage divider to the transients; and the voltage transients, coupled to an "open-circuit" secondary, have the same wave form as that in Fig. 3.1



(a) CURRENT SURGE



(b) VOLTAGE SURGE

Fig. 3.1. EMP Surges at the Plant Off-Site Power Transformer.

except that the amplitude is reduced by about a factor of five. The per-phase-load resistance of a nuclear plant is about one ohm. Thus, the time constant of the secondary winding capacitance and the one-ohm load is several nanoseconds.

The surge coupled to the secondary side of the plant power transformer will decay to near zero after 10 nsec. This short-duration pulse will not likely cause a flashover since air normally requires more time to ionize. The total energy dissipated by the one-ohm load is less than one kilojoule. This energy should not do any damage to the relatively high voltage and high-current power circuits.

The EMP surges induced in the numerous cables within the plant building have been considered in a previous study.[7] The types of cables considered were unshielded wires, coaxial and triaxial cables, and shielded twisted pairs. Long cables located near an exterior wall will collect more EMP energy than cables located elsewhere in the plant. Cables located in conduit or in cable trays collect less EMP energy than single cables. In Figs. 3.2 and 3.3, the EMP surges induced in an unshielded wire and a coaxial cable are shown for 160-m cables routed along an exterior wall. These surges may be considered as upper-bound or worst-case surges.

The EMP surges that will be induced in the various plant cables are shown in Table 3.1. Since the lengths of cables interconnecting the many plant systems vary from plant to plant, we shall assume that all cables are relatively long, near 160 m. This gives conservative results for the EMP surges listed in Table 3.1.

3.3 Plant Noise and Transient Protection

Many systems in a nuclear power plant are designed to operate correctly in an environment of electrical and electromagnetic transients. These transients are due to the many electromechanical relays, motors, and circuit switches in the plant. To ensure the operation of instrumentation, control, and safety equipment, a relatively high level of noise and transient protection is employed. Much of this protection provides a high level of inherent hardness against EMP surges.

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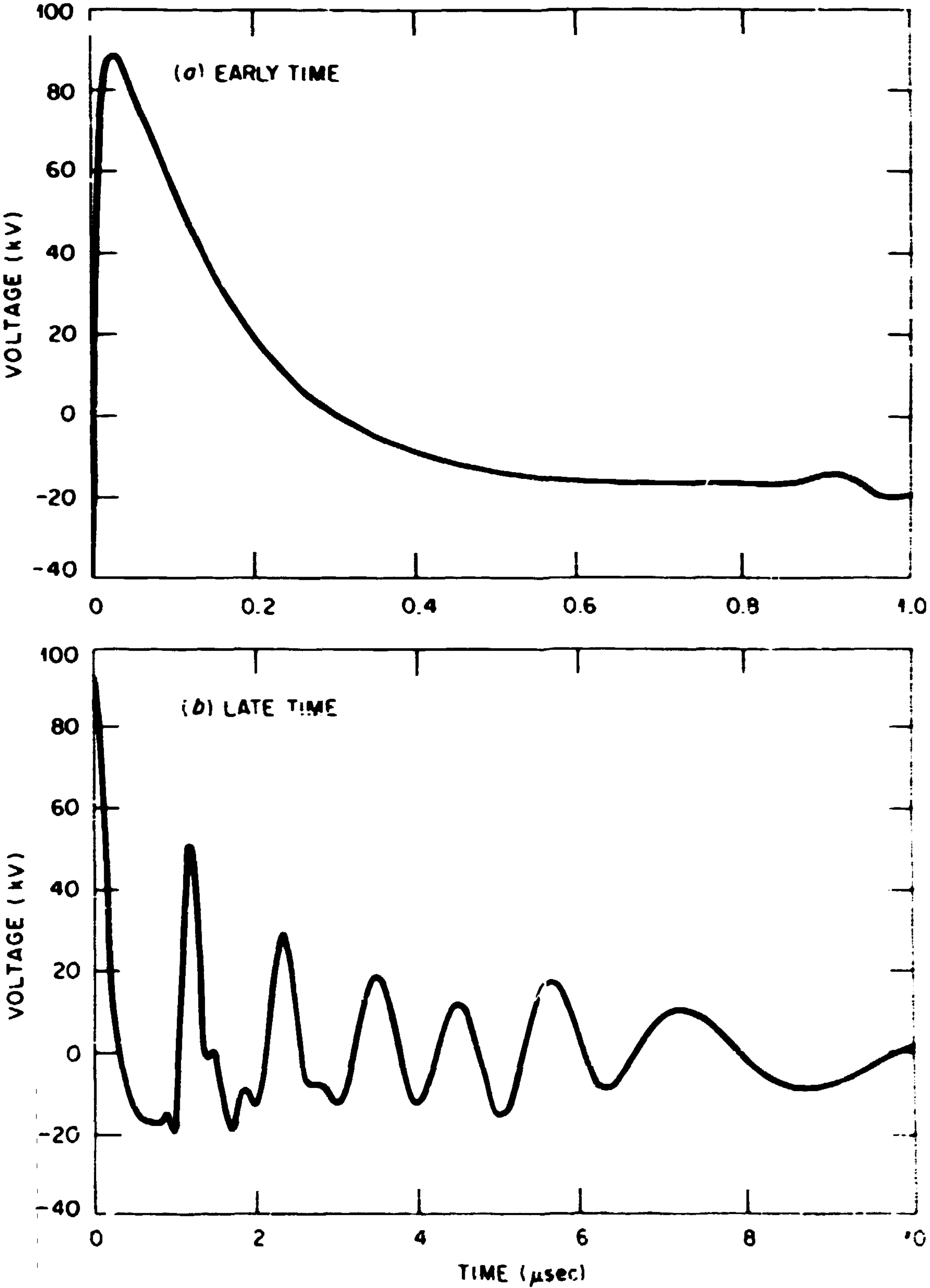

Fig. 3.2. The Open Circuit Voltage Induced on a 160-m Unshielded Line 10 m above the Earth by the Representative EMP.

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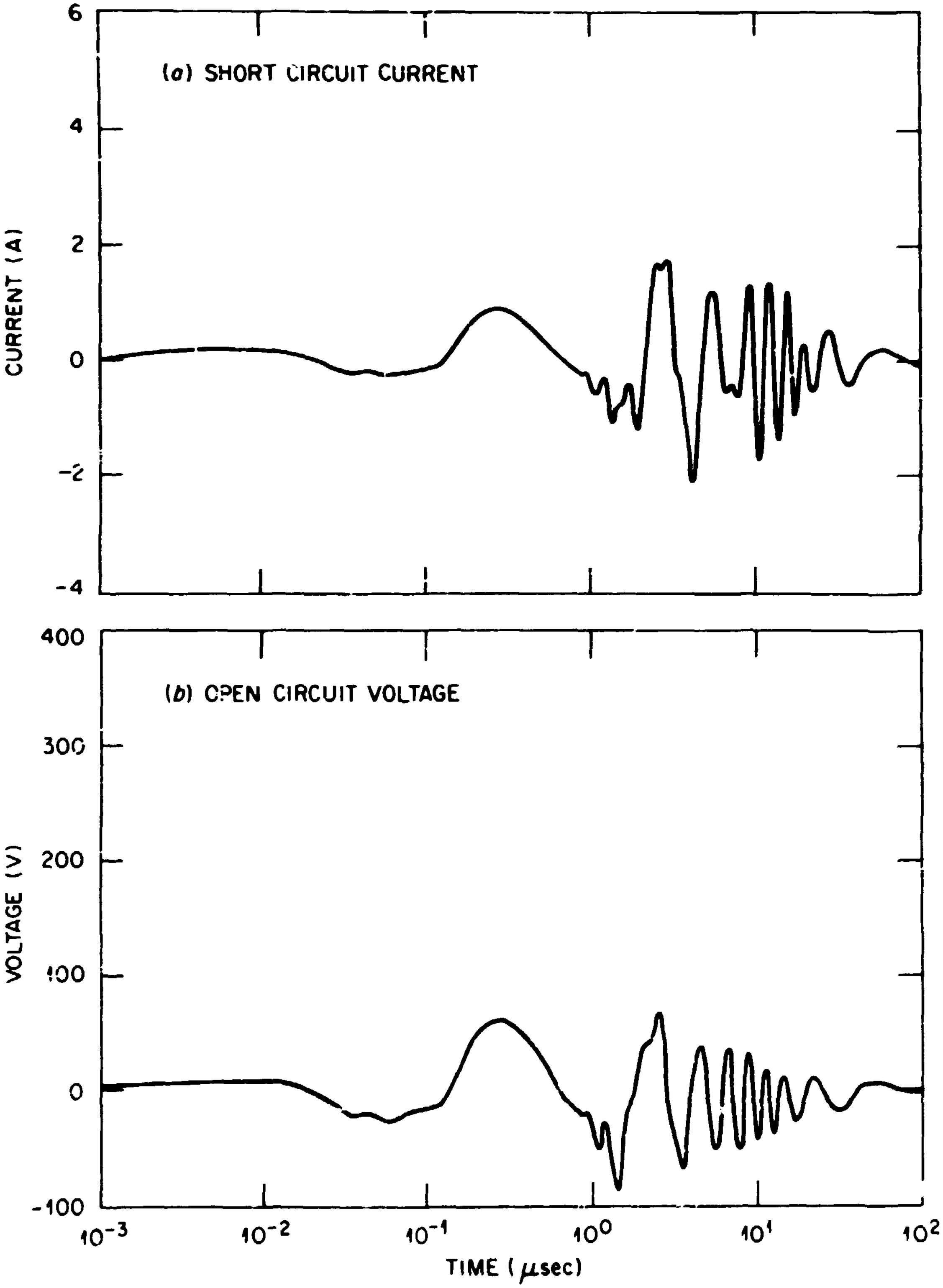


Fig. 3.3. Open Circuit Voltage Transient Induced in a 160-m Coaxial Cable Similar to RG-59B/u.

Table 3.1. EMP Cable Surges

Cable	Location	V_p	ROR	Duration	I_p
Unshielded Copper Wire	Near an External Wall	88 kV	7.12 kV/nsec	6.4 μsec	170 A
Unshielded Copper Wire	Near an External Wall in a Cable Tray	8.8 kV	710 V/nsec	50 μsec	17 A
RG-59B/U Coaxial Cable	Near an External Wall in a Cable Tray	8 kV	0.1 V/nsec	10 msec	0.22 A
Triaxial Cable	Near an External Wall in Conduit	37.5 μV	15.6 μV/nsec	10 msec	0.5 μA
Shielded Twisted Pair	Near an External Wall in a Cable Tray	0.8 V	10 mV/nsec	50 μsec	22 mA
Shielded Twisted Pair	Near an External Wall	8 V	100 mV/nsec	50 μsec	220 mA

V_p = Peak open circuit voltage

I_p = Peak short circuit current

ROR = Initial rate of rise from 10 to 90% of the open circuit voltage

Duration = Time required for the voltage surge to decrease to 10% of V_p

The noise and transient protection measures that are normally employed include one or more of the following: (1) shielded cables, (2) relatively high current and voltage signals, (3) relay isolation, (4) diode transient suppressors, (5) capacitive transient suppressors, (6) electrostatically shielded transformers, (7) isolation amplifiers, (8) filters to reject noise and transients, and (9) the response time required for actuation is long compared to most transients. Combinations of these protective measures such as shielding, diode transient suppressors, and relay isolation will provide excellent EMP protection.

The plant electrical power circuits are protected against lightning by arresters at the station transformer and by the inherent lightning shielding capabilities of the plant buildings. Power circuits are protected against fault currents by circuit breakers and differential relays. Surge suppressors are often installed on large motors to suppress line transients.

The noise and transient protection normally used in a nuclear plant have to be considered in the analysis of EMP surge effects on the instrumentation, control, and safety systems. Most of the protection measures employed provide adequate EMP protection. However, some lightning protective measures such as overhead ground wires and the shielding effects of the building may not provide effective EMP protection.

3.4 Instrumentation and Control Systems

The instrumentation and control systems consist of the process variable (PV) instrumentation, the nuclear instrumentation system (NIS), the rod control system (RCS), and the reactor protection system (RPS). There are, of course, other instrumentation and control systems associated with a nuclear power plant. However, we have selected only those systems related to reactor safety for the analysis. Other systems and their instrumentation and controls which are related to reactor safety will be covered later in this section.

3.4.1 PWR Instrumentation and Controls

The instrumentation, control, and protection systems associated with the Westinghouse PWR nuclear steam supply system consist of the NIS, PV instrumentation, the RCS, and the solid-state protection system (SSPS). The SSPS consists of two logic trains which perform the logic (decision making process) for the RPS. A simplified block diagram of the SSPS is shown in Fig. 3.4. The RPS is composed of the instrumentation that monitors the reactor parameters, the SSPS, and various protection functions.

The NIS receives inputs from the four detectors located at each quadrant of the reactor core. A simplified block diagram of the NIS is shown in Fig. 3.5. Detector signal current ranging from 0 to 4.1 mA is transmitted by triaxial RG-11/U cable to the NIS racks which are normally located in the control room. The detector cable is run in conduit the entire length from the containment to the control room. Due to the extensive amount of shielding afforded by the triaxial cable and the conduit, the maximum EMP-induced surge peak is only about 0.5 μA. This small current should have little effect on the system.

The NIS output cables are also shielded cables such as the twisted shielded pairs of wires used at the Sequoyah plant. Most of the input and output cables connected to the SSPS, PV instrumentation, and the RCS are also shielded cables such as shielded twisted pairs. These cables are normally placed in cable trays. The EMP transient voltage peak for a shielded twisted pair in a cable tray with several other cables is about 0.6 V. This low-voltage transient should have little or no effect on the instrumentation and control systems since the operational signals are much larger, ranging from 10 to 118 V.

A small amount of surge energy in each of the input and output lines will couple across the relays to the RCS control logic circuits. Will EMP cause the control rods to be withdrawn? This question has been raised by those concerned about reactor safety. It is unlikely that the EMP energy available could cause logical upsets (change of logic states) in the RCS logic. If we assume for the moment that such upsets do occur and that one or more rod clusters are accidentally

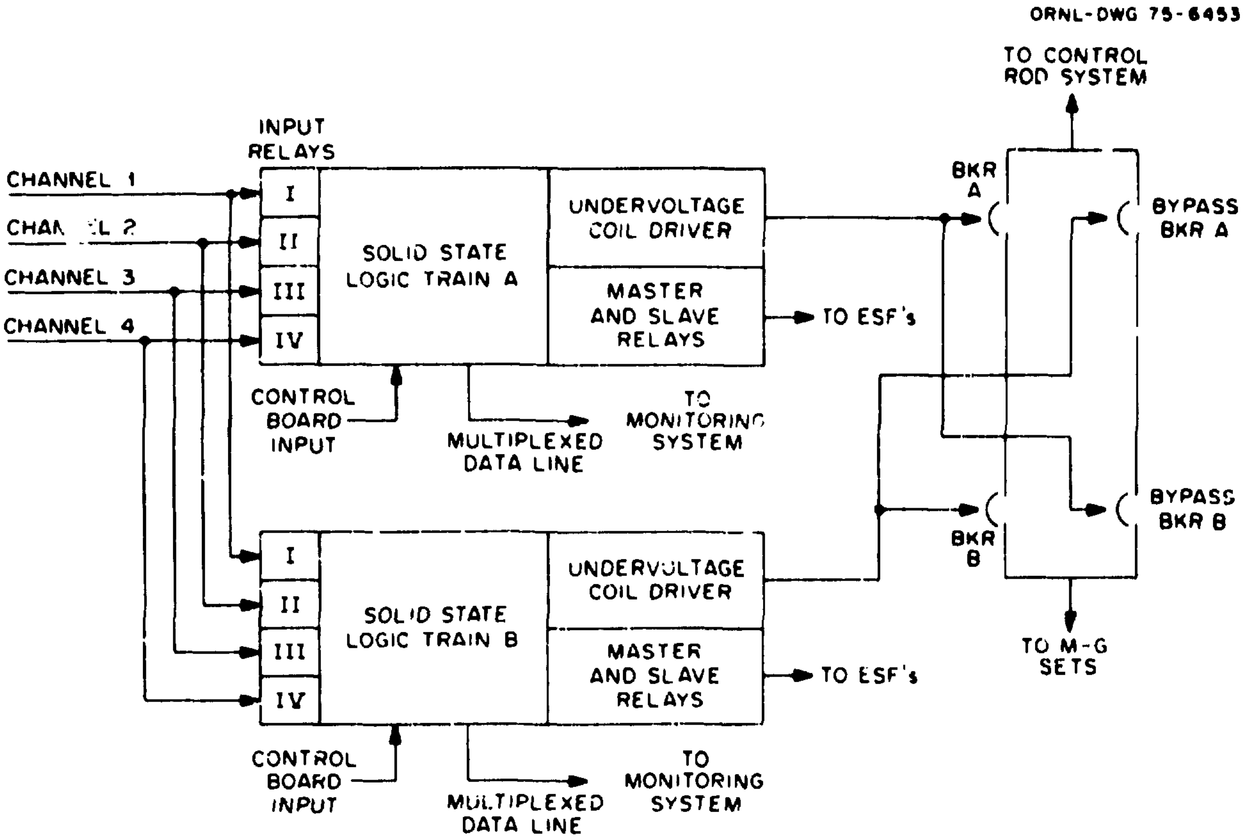


Fig. 3.4. Simplified Block Diagram of the Solid-State Protection System.

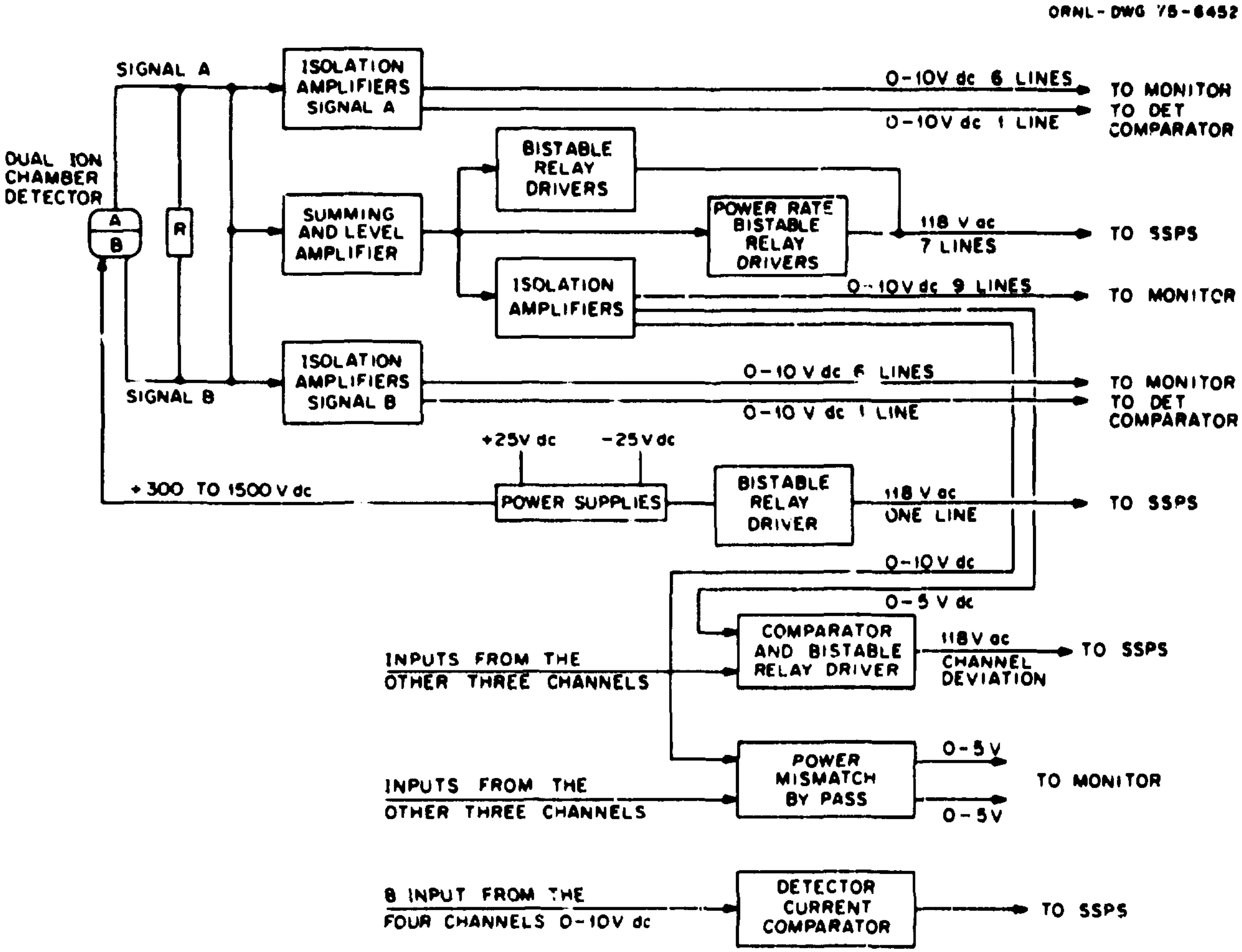


Fig. 3.5. Simplified Block Diagram of One Channel of the Four-Channel NIS.

withdrawn, the consequences to reactor safety are limited to very minor fuel damage, if any. Minor fuel damage would not release any radioactivity outside the RCS. During normal operations, most of the rods are fully withdrawn from the core, and rod withdrawal accidents result in only a minor excursion.[10] The RCS "failure-monitoring circuit" if operating correctly would block further rod withdrawals. If the reactor parameters did become abnormal, a reactor scram would result. Damages to the RCS would not prevent a scram since the shutdown rods are completely separate from the control rods and are not affected by the rod control system.

The various instrument and control equipment power supplies which are connected to the unshielded electrical power circuits will be subjected to EMP voltage transients with peaks that range from about 200 to 8800 volts. If these power supplies are not adequately protected, solid state components may be damaged. Such damages would likely result in a loss of voltage from the damaged power supply. Damaged components could, however, cause a regulated power unit to supply unregulated voltages, voltages that are either too large or too small for proper use by the equipment connected to the power supply.

The results of our analysis of the PWR instrumentation and controls are presented in Table 3.2. The important points of entry (POE's) for EMP energy are listed for each system. The peak EMP surge and the transient protection at each POE are also listed in the table along with the important circuit parameters and the probable EMP effects.

3.4.2 BWR Instrumentation and Controls

The important instrumentation, control, and protection systems associated with the General Electric BWR nuclear steam supply system consist of the neutron monitoring system, rod block monitor system (RBM), process variable instrumentation, and the RPS. The neutron monitoring system for use when the reactor is operating at power levels consists of the local power range monitor system (LPRM) and the average power range monitor system (APRM).

Table 3.2. EMP Effects on PWR Instrumentation and Controls

System	POE	EMP Transient Peak	Noise and Surge Protection	Line Voltage or Current	Electronic Components	Probable EMP Effects
NIS	Detector Cable	0.5 μA	Triaxial Cable in Conduit	0-4 mA	IC's, Diodes, and Transients	None
NIS	SSPS Cable	0.8 V	Electrostatically Shielded Transformer, Shielded Twisted Pair	118 Vac	Solid State Switch	None
NIS	Monitor Lines	0.8 V	Isolation Amplifiers	0-10 Vdc	Transistors	None
NIS	Electrical Power	8.8 kV	Electrostatically Shielded Transformer	118 Vac Instrument Power	Diodes, Transistors	None
PV	Detector Cable	22 mA	Shielded Twisted Pair Cable	10-50 mA	Transistors	None
PV	SSPS Cable	0.8 V	Shielded Twisted Pair Cable	120 Vac or 24 Vdc	Diodes, Transistors	None
PV	Monitor Lines	0.8 V	Shielded Twisted Pair Cable	118 Vac or 0-10 Vdc	Diodes, Transistors	None
PV	Unit Electrical Power	8.8 kV	Electrostatically Shielded Transformer	120 Vac	Solid State Circuitry	None
PV	Transmitter Power Supply	8.8 kV	Capacitor Differential Transient Protection	118 Vac	Diodes	Possible Loss of Power

Table 3.2. EMP Effects on PWR Instrumentation and Controls (cont'd)

System	POE	EMP Transient Peak	Noise and Surge Protection	Line Voltage or Current	Electronic Components	Probable EMP Effects
SSPS	Input Cables	0.8 V	Shielded Twisted Pair Cables, Relay Isolation, Diode Surge Protection	118 Vac	IC's	None
SSPS	Reactor Trip Cable	0.8 V	Shielded Cable	48 V	Transistors, Diodes	None
SSPS	ESF Lines	0.8 V	Relay Isolation, Shielded Twisted Pairs	48 V or 118 Vac	Transistors, Diodes	None
SSPS	Multiplexed Monitor Lines	0.8 V	Shielded Twisted Pair Cables, Signals Reset Periodically, Isolation Amplifiers	Several Volts	Solid State Circuitry	None
SSPS	Electrical Power	8.8 kV	No Protection	120 Vac	Diodes, Transistors	None
RCS	Control Lines	0.8 V	Relay Isolation, Shielded Cables	118 Vac	IC Logic	None
RCS	Monitoring Lines	0.8 V	Relay Isolation, Shielded Cables	0-10V or 118 V	Solid State Circuitry	None
RCS	Magnetic Jack Cables	40 V	Metal Cable Runs	260 V pulsed dc	SCR's	None
RCS	Electrical Power	40 V	MG Set Isolation, Metal Cable Runs	260 V	SCR's	None

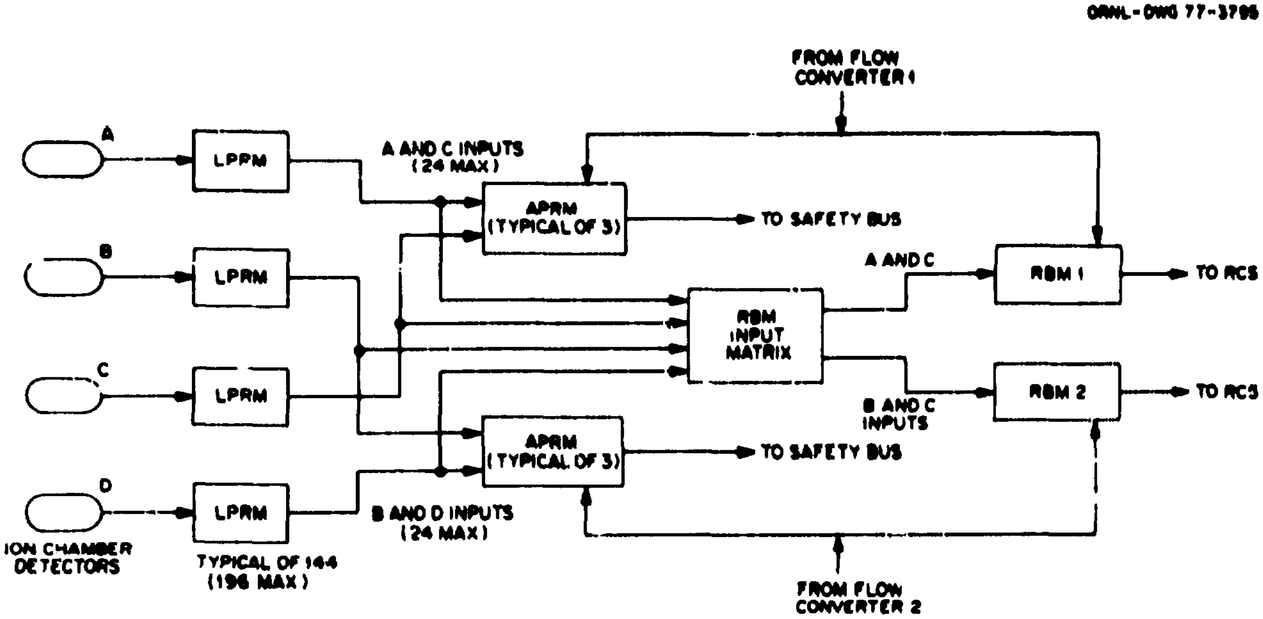
The LPRM system takes inputs from sensor cables connected to miniature ionization chambers distributed throughout the reactor core. The sensor cables are normally RG-59B/U coaxial cables. The LPRM system consists of amplifiers and readout equipment which are normally located in the control room. The APRM system averages the output signals from selected LPRM amplifiers. A block diagram of the neutron monitoring system is shown in Fig. 3.6. Also included in the figure is the RBM system.

The RBM consists of two channels, 1 and 2, which monitor the local neutron flux levels during the withdrawal of a selected control rod. If the monitored flux level exceeds preset limits, the RBM generates trip signals to actuate rod inhibit and annunciator circuits. The RBM receives inputs from the LPRM's, APRM's, and flow units. The flow units measure reactor recirculation flow.

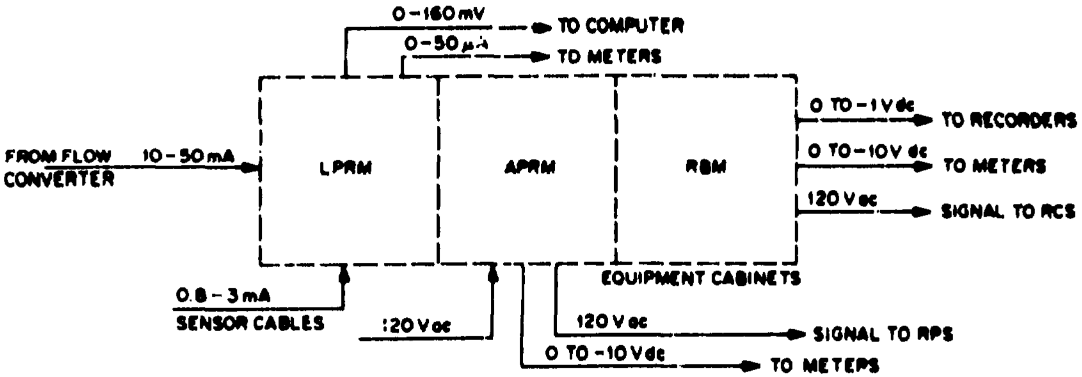
The LPRM, APRM, and RBM are normally arranged in adjacent cabinets. The primary points of entry of EMP energy for these systems are the cables entering the three cabinets as shown in Fig. 3.6(b). The NIS cables that transmit low level signals are either shielded coaxial or twisted pair cables. The EMP transients that would be induced in these cables have peak amplitudes which are on the same order of magnitude as the normal operating signals. These transients are not expected to have any effect on the NIS. The 120-V control and power circuits often employ unshielded cables. These circuits, however, have relay isolation and/or diode surge suppressors. Thus, again EMP surges are not expected to do any damage with the possible exception of the various system power supplies which have not been provided with transient protection.

The BWR reactor protection system used in current plants (BWR-4 and older plants) employs many relays in a four-channel, two-out-of-four logic protection system. A simplified diagram of the RPS is shown in Fig. 3.7. The RPS operates on a fail-safe basis; i.e., if power fails, a scram signal is generated and, if a relay fails, the most likely failure mode will cause a scram.

The motor-generator sets that provide power to the RPS will also provide isolation from EMP transients on the emergency power buses A



(a) POWER RANGE MONITOR BLOCK DIAGRAM



(b) POWER RANGE MONITOR SYSTEM AND EMP POE'S

Fig. 3.6. BWR Power Range Nuclear Instrumentation System.

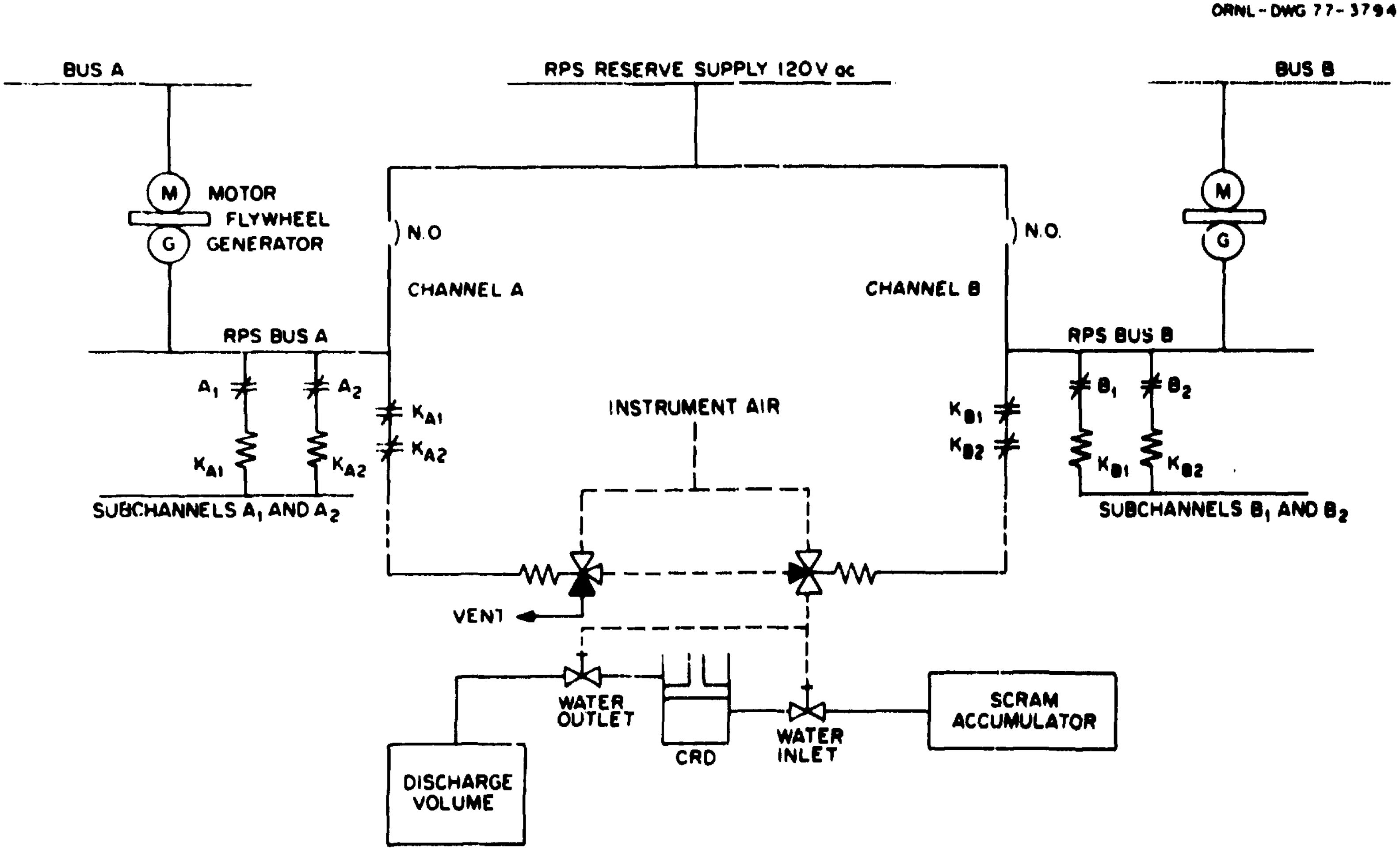


Fig. 3.7. Simplified Diagram for BWR RPS with One Input Variable (No. 1) Shown.

and B. EMP surges will be induced in the main channel circuits A and B. EMP surges will also be induced in the subchannel circuits. Mechanical relays are rather "hard" components which are not easily damaged by transients. Since the transients are not likely to have amplitudes ten times greater than the normal operating signal, no damage is expected. Level and pressure switches may experience sparkovers which would indicate that setpoints have been exceeded. Such sparkovers may cause an unnecessary scram.

The results of our analysis of the safety related BWR instrumentation and control systems are presented in Table 3.3. This table is similar to Table 3.2 for the PWR. The PV instrumentation is considered as input for the RPS in Table 3.3.

3.5 The Reactor Monitoring System

The reactor monitoring system is related to plant safety only through the actions of the operator. False information may be generated by EMP as a result of damages to some of the instrumentation power supplies. For the PWR SSPS, damages to the power supply may also result in false information being sent to the monitor computer. EMP transients induced on the 5-10 V multiple twisted pair shielded signal cables from the PWR SSPS, NIS, and the PV equipment will have peaks of less than 1 volt. These transients should have little or no effect on the monitoring system. Any logical upsets that might occur from EMP signal line transients would be quickly reset by the PWR monitoring system and would not be seen by the operator.

In the BWR monitoring system, the computer monitors inputs from the various nuclear auxiliary systems. Neutron flux, control rod position, process variables, and input variables to the RPS are monitored by the computer. These data are read periodically. EMP transients in the computer 160-mV input cables would likely cause logical upsets. However, these upsets would be reset after the transient was dissipated. It is possible, however, that false signals could be received by the computer as a result of damages to unprotected power supplies in the instrumentation and control systems.

Table 3.3. BWR Instrumentation and Control Systems

System	POE	EMP Surge Peak	Noise and Surge Protection	Line Voltage or Current	Electronic Components	Probable EMP Effects
NIS	RG-59B/U Sensor Cable in Conduit	8 μA	Shielding	0.8-3.0 mA	IC's	None
NIS	Flow Converter Sensor Cable	22 mA	Shielded Twisted Pair, Diode Surge Suppression	10-50 mA	IC's	None
NIS	Computer Input Circuits	800 mV	Shielded Twisted Pairs	150 mV	IC's	None
NIS	Meter and Recorder Inputs	220 V	Relay Isolation, Diode Spike Suppressors	0-50 μA or 0 to -10 V	Transistors	None
NIS (RBM)	RCS Inputs via Unshielded Multi-wire Cable	80 V	Short Cable Run to Adjacent Cabinet	120 Vac	Relays	None
NIS	RPS Inputs via Unshielded Multi-wire Cable	80 V	Short Cable Run to Adjacent Cabinet	120 Vac	Relays	None
NIS	Instrument Power Cable	8.8 kV	MG-Sets, Powerline Filters	120 Vac	Power Supply Transformers and Solid State Components	Possible Damage to Supplies, Loss of Power
RPS	Process Variable Inputs	22 mA	Shielded Twisted Pairs	10-50 mA	Mechanical and Solid State Relays	None

Table 3.3. BWR Instrumentation and Control Systems (cont'd)

System	POE	EMP Surge Peak	Noise and Surge Protection	Line Voltage or Current	Electronic Components	Probable EMP Effects
RPS	Main Steam Line Radiation Monitor Input	220 mA	RG-59B/U Shielded Coaxial Cable	10-50 mA	Solid State Relay	None
RPS	Eight Conductor Unshielded Cables used with Valve Controls and Pressure and Level Switches	1 kV	None	120 Vac	Relays	Pressure and Level Switches May Spark Over for One Half of a 60 Hz Cycle
RPS	RPS Power Bus	8.8 kV	MG-Sets, Spike Suppressor Filters	120 Vac	Relays	None
RPS	Cable to Scram Solenoid	0.76 V	Unshielded Cable in Conduit	120 Vac	Relays	None
RPS	Annunciator and Computer Inputs to the Remote Electronic Cabinet	80 V	Unshielded Cables Run in Conduit to Nearby Cabinet	120 Vac	Relays	None

False information as a result of EMP effects on the reactor monitoring system will be analyzed by the control room personnel. In most cases, the conclusion of the operator will be that one or more parameters are out of bounds. The operator may decide that a reactor shutdown is necessary and scram the reactor.

3.6 Plant Electrical Power

The plant electrical power systems are the off-site auxiliary power, the nuclear unit auxiliary power, emergency auxiliary power supplied by diesel-driven generators, and the inverter-charger battery power supply. The auxiliary power voltage is usually 4000 volts or 6900 volts. This voltage is used to power the large motors throughout the plant. Lower voltages such as 400 volts, 240 volts, and 120 volts are obtained from stepdown transformers to power small motors and other plant auxiliary loads.

The loss of the off-site auxiliary power will scram (shut down) the reactor. The auxiliary systems essential to a safe shutdown are transferred to the diesel generators. Essential instrument and control power is maintained by the battery-inverter power supply.

EMP may interrupt auxiliary power to the safety loads by interacting with the differential relays. Relatively low-level VHF fields have been found to cause false operation of a differential relay, apparently by interacting with the relay's control circuits.[11] Also, EMP transients in lower voltage branch circuits may cause flashovers and initiate breaker action to disconnect those circuits and interrupt auxiliary power to low-voltage loads.

EMP transients in the diesel control circuits may also interrupt auxiliary diesel-generator power. However, many plants have installed their diesel-generator control cables in conduit. The control circuits may also employ shielded cables. Such shielded diesel-generator control circuits are unlikely to be affected by EMP.

EMP transients in the auxiliary, control, and instrument power cables connected to the battery inverter-charger system could result in damage to the system components. Lightning damage does occur to inverter-charger systems at remote microwave relay sites even though they are protected by lightning arresters. Damage to the battery-charger control circuit may cause the charger to further damage itself and the batteries. However, damage to nuclear plant charger-inverter systems by EMP is considered unlikely since the most probable EMP current surges in the auxiliary, control, and instrument power cables are about two orders of magnitude smaller than an average lightning surge.

4. CONSEQUENCES, COUNTERMEASURES, AND CONCLUSIONS

4.1 EMP Events

In this section, we examine the consequences of EMP on nuclear power plants by postulating possible events due to EMP. One or more events lead to a consequence. Due to the limited scope of this study, the probabilities of events have not been computed. However, we consider consequences other than the false actuation of scram or of the engineered safety feature circuits only as very remote possibilities.

In considering the consequences of EMP, we assume that the plant is operating at full power, the operator is unaware of EMP effects, and no special EMP precautions have been implemented. The consequences discussed here are the most obvious and are not necessarily a complete set. They are presented in an approximate order of increasing significance. Since the more serious consequences require more events, we may surmise that they are less likely to occur than the less serious consequences.

4.2 A Reactor Scram

The most likely result of one or more EMP events is an unscheduled shutdown of the plant. A reactor scram signal may be generated by a loss of power from the various instrument or control power supplies due to EMP surge effects. A loss of off-site power due to a power blackout on the entire grid as a result of multiple EMP's will also cause a scram. A loss of power to the large motors due to circuit breakers or differential relays responding to EMP transients may also scram the reactor. The relatively large number of independent events caused by EMP that can possibly cause a scram makes it a likely possibility.

4.3 Actuation of Safety Systems

The false activation of safety systems is another possible consequence of EMP. For example, the loss of power to the pump motors in the PWR chemical and volume control system could result in a pressure drop in the primary loop. Over an extended time period, the pressure could drop low enough to actuate the safety injection system. Power could be lost for an extended period due to multiple EMP's. If a single EMP tripped the pump breakers, they would probably be quickly reset by the plant personnel. If, on the other hand, multiple EMP's continued to trip the breakers each time they were reset, the operator would probably conclude that major problems existed in the plant electrical system and discontinue the attempt to restore power.

4.4 Loss of Electrical Auxiliary Power

The loss of all auxiliary plant power is a possible consequence of multiple EMP's. Several EMP events are necessary to make this consequence possible. They are as follows. First, EMP scrams the reactor. Minutes later, an EMP-caused power grid blackout occurs, and off-site power is lost. The plant power circuits are then automatically transferred to the standby diesel generators. EMP-induced flashovers in the auxiliary power circuits result in large fault currents. Power trains A and B are then shut down by fault-current trips, and all auxiliary power is lost.

For the PWR, the steam-driven auxiliary feedwater pump could be employed, along with the natural circulation in the RCS, while the auxiliary power circuits are being examined. Without auxiliary power, the CVCS cannot maintain RCS pressure. If the auxiliary power is not restored before the RCS pressure falls below 650 psi, the accumulators would discharge 2000-ppm borated water into the RCS. Reactor startup would be delayed until the boron concentration was reduced. For the

BWR, the steam-driven main feedwater pumps, reactor core isolation cooling (RCIC) pumps, or other steam-driven pumps could be used to cool the reactor while the auxiliary circuits are being examined.

4.5 Loss of Instrument and Control Power

EMP surges in the auxiliary power circuits, the 120 Vac instrument circuits, and/or the control circuits could possibly damage the vital battery chargers and inverters. A complete loss of instrument and control power would scram the reactor and actuate most of the ESF systems. If the auxiliary power is available, ESF systems such as the PWR Safety Injection System (SIS), containment isolation system, and the auxiliary feedwater system would be activated.

EMP by itself is not, however, a serious threat to reactor safety, even in the unlikely event that all power, including control and instrument power systems, is lost due to multiple EMP's. Modern power reactors have steam-driven pumps that could be used to remove the residual heat from the reactor. The steam-driven cooling system would be used only temporarily until electrical power is restored.

The PWR auxiliary feedwater system can cool the reactor by supplying water to the steam generators. The residual heat in the primary loop would be removed to the steam generators by natural convection. Auxiliary feedwater control is normally accomplished by an air-operated control valve. If the air valves fail, manual operation can be used for control.[4] But without instrumentation the operator of the steam-driven auxiliary feedwater pump would not know the water level in the steam generators. It is possible, however, to know when the generators are full by observing the steam generator safety relief valves. Thus, plant personnel could observe the safety relief valves and stop the feedwater pump.

The BWR reactor core isolation cooling (RCIC) system has a steam-driven turbine pump that is driven by a portion of the decay heat steam from the reactor.[6] This system operates independently of auxiliary power, plant service air, or external cooling water systems. The turbine pumps can be manually controlled in conjunction with manually-operated valves to allow the RCIC system to cool the reactor.

4.6 Countermeasures

In considering EMP protection for nuclear power plants, it is important to ensure the safety of the public and the plant. It is not necessary to ensure the continued operation of the plant in an intense multiple EMP environment. To provide this kind of protection would be very difficult and costly. Although EMP alone is not a serious threat to nuclear safety, it is conceivable that EMP-caused component failures in safety-related systems could go undetected and cause those systems to function improperly in the event of a nuclear plant malfunction. The countermeasures proposed below will greatly reduce the probability of serious damage to nuclear plants without significantly increasing the cost of the plant. The recommended countermeasures are as follows:

1. All plants should be equipped with a nonelectrical cooling system that can temporarily remove residual heat from the reactor in the event that all auxiliary electrical power is lost. Operating procedures should be developed for the emergency operation of this system in the event that all electrical power including control and instrument power is lost.

2. In the event of an escalating international crisis, nuclear power plant operators should be informed about the effects of EMP. They should also be instructed to thoroughly test all of the reactor instrument, control, and safety systems, if a nuclear weapon is detonated at a high altitude within or near the continental U.S.

3. EMP transient protection should be provided for the emergency battery systems. Also, electrostatically shielded transformers should be employed whenever possible for transient protection of important power supplies. And fast responding lightning arresters should be provided for the off-site power bus at or near its entrance into the building.

4.7 Conclusions

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.

Countermeasures to minimize the effects of EMP have been recommended. Implementation of these recommendations would also increase the protection of the plant against damage by lightning, switching, and electromagnetic interference transients as well as general failures in electrical, control, and instrument power.

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