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Aging Assessment of Surge Protective Devices in Nuclear Power Plants

Prepared by
J. F. Davis, M. Subudhi, D. P. Carroll

Brookhaven National Laboratory

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Prepared by
J. F. Davis, M. Subudhi, Brookhaven National Laboratory
D. P. Carroll, University of Florida*

Brookhaven National Laboratory
Upton, NY 11973

J. E. Jackson, NRC Project Manager

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
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*University of Florida, Gainesville, FL

ABSTRACT

An assessment was performed to determine the effects of aging on the performance and availability of surge protective devices (SPDs), used in electrical power and control systems in nuclear power plants. Although SPDs have not been classified as safety-related, they are risk-important because they can minimize the initiating event frequencies associated with loss of offsite power and reactor trips. Conversely, their failure due to age might cause some of those initiating events, e.g., through short circuit failure modes, or by allowing deterioration of the safety-related component(s) they are protecting from overvoltages, perhaps preventing a reactor trip, from an open circuit failure mode. From the data evaluated during 1980-1994, it was found that failures of surge arresters and suppressors by short circuits were neither a significant risk nor safety concern, and there were no failures of surge suppressors preventing a reactor trip. Simulations, using the ElectroMagnetic Transients Program (EMTP) were performed to determine the adequacy of high voltage surge arresters.

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EXECUTIVE SUMMARY

This study is an aging assessment of the performance and availability of surge protective devices (SPDs), commonly called surge arresters and surge suppressors. These components are used extensively in electrical power and control systems in U.S. commercial nuclear power plants to protect systems and components from overvoltages caused by lightning and switching transients. Although SPDs have not been classified as safety-related, they are risk important because they can minimize the initiating event frequencies associated with loss of offsite power (LOOP) and reactor trip. Conversely, their failure due to age might be the cause of some of those initiating events, e.g., through short circuit failure modes, or by allowing more rapid deterioration of the safety-related component(s) they are protecting from overvoltages, perhaps preventing a reactor trip, from degradation or an open circuit failure mode.

This Phase 1 aging evaluation identified a paucity of data for nuclear plants for making age determinations for surge arresters in the high voltage range, 2.3 kV to 1,000 kV, that are found on transmission lines, switchyards, and feeder circuits, and for surge suppressors in the low voltage range 24 V to 1,000 V. The aging degradation modes associated with SPDs are well known from laboratory and some field testing, but their time-related in-service failure during operation is not well documented. In this project, 15 years of nuclear-plant SPD data, covering 1980-1994, were obtained from licensee event reports (LERs) and Nuclear Plant Reliability Data System (NPRDS) records, but upon evaluation, mechanisms and causes of failure could not be determined clearly. Functional failure modes for PRA initiating events could be determined; these included some physical failures of SPDs, but calendar life assessments were impractical.

Surge arresters are clamping devices, but surge suppressors can be clamping, crowbar, or isolator devices. Clamps have approximately constant voltage across them when conducting a surge current; crowbars change state from insulators to nearly perfect conductors during overvoltages; and, isolators offer large series impedance to common-mode voltages. In general, a short circuit is the predominant failure mode for arresters and suppressors, especially clamps and crowbars. For higher voltage surge arresters, a true open circuit would be rare, but partially open circuits, i.e., the arrester allows some portion of the overvoltage wave to pass downstream, are possible from in-service shattering or cracking of the arrester's conducting blocks or severe erosion of an arrester-gap (if used), or human-related errors, such as defects in manufacturing and errors in installation. For some types of low voltage suppressors, an open circuit is likely to promptly follow a short circuit.

If the suppressor or arrester fails as a short circuit, the circuit that is being protected will be taken out of service by a fuse or circuit breaker. If they fail as an open circuit or functionally, the components in the circuit are likely to be exposed to stress which may result in their failure. In general, normal wear for SPDs may be reduced to the combination of (1) the number of overvoltage pulses (which may not follow a simple linear repetitive pattern), including their magnitude and duration (which are both variables) it shunts to ground or attenuates for low-pass filters, and, (2) the environmental conditions under which they operate. It is apparent that assessing age for SPDs is not a simple matter of collecting data.

To identify the elements of a maintenance program for SPDs, some substantial knowledge of past performance and failure history is required. It is as important to know when to remove an SPD from service before it fails as it is to ensure it is properly coordinated in fulfilling its function. Regular frequency or surveillance testing of surge arresters varies from utility to utility, and at voltages inside the plant, suppressor testing schemes do not appear to be included in surveillance tests for those safety circuits in which they are installed, although it is likely the utility will test the suppressor when the fuse blows in the electronic circuit. Although SPDs are required to pass standards and performance tests for qualification, the practical problem is to determine the number of demands or overvoltage pulses, including their magnitude and duration, which the device sees in-service in order to determine age-related degradation.

The utility industry's ElectroMagnetic Transients Program (EMTP) was used to better understand the functional adequacy of placing surge arresters on the high voltage portion of a typical electrical power system used at nuclear power plants. Simulations included: (1) no arrester present at different bus voltage locations, and (2) partially open arresters present at different bus locations. The results showed that overvoltages from lightning, switching surges, and temporary overvoltages would propagate through transformers to lower voltages, with the highest instances of overvoltage occurring on the emergency buses due to their relatively low electrical loading.

Our review, covering 15 years, focussed on the performance of surge arresters during lightning-related losses of offsite power and reactor trip, and on that of surge suppressors during reactor trip from low voltage switching surges or electromagnetic interferences. The following are our results:

1. Lightning-Related Events (per reactor year)

- LOOPs and Partial LOOPs:	3.2 E-02
- Reactor Trips:	4.5 E-02

Contributions from Surge Arrester Failures, Shielding, Surge Suppressor Failures

- Surge Arrester Failures

- LOOPs and Partial LOOPs:	0.7 E-02
- Reactor Trips:	0.4 E-02

- Transmission Line Shielding

- LOOPs and Partial LOOPs:	1.8 E-02
- Reactor Trips:	0.9 E-02

- Building Shielding and Ground Potential Rise (GPR)

- LOOPs and Partial LOOPs:	0
- Reactor Trips:	1.6 E-02

2. Low Voltage Switching Events (per reactor year)

- Surge Suppressor Failures

- Reactor Trips:	0.2 E-02
- Prevention of Reactor Trip:	None Found.

The average U.S. nuclear industry-wide failure frequencies for LOOP and partial LOOP and reactor trip due to lightning are quite low by themselves and are not a risk nor a safety concern. The failure frequency for LOOP and partial-LOOP due to lightning is even lower after 30 minutes have elapsed since many faults are temporary. However, there were several plants that had higher incidences of losses of offsite power, and several different ones that had higher incidences of reactor trip. In fact 60 of the current 107 operating reactors did not have either a lightning-related loss of offsite power or a reactor trip due to lightning during the 15 year period.

The data base appears to identify most initiators of high-voltage arrester failure as occurring at older plants that used the gapped silicon carbide arrester. The industry recently completed significant research and development programs to enhance the capabilities of the mixed-oxide surge arrester, which now dominates the commercial market. As the older arresters are replaced, the use of mixed-oxide surge arresters should lower the failure rate of lightning arresters in-service and, consequently, reactor trips or losses of offsite power caused by short circuits in the arresters, principally due to their age. However, there is no consistent industry approach for determining the age of arresters in-service.

Flashovers of transmission line shielding appear to be the reason for the higher rate of losses of offsite power, assuming there was no premature actuation of relays. These types of faults tend to be temporary unless the breakers lock-out, or there is a physical failure of the shield wire. The failure of building shielding appears to be a small contributor to reactor trip, but it may be site-specific. Ground potential rise (GPR) appears to be one of the prominent pathway mechanisms for causing reactor protection system actuation.

At the low plant voltages, we found only three surge suppressor failures at power that resulted in reactor trip. There was no evidence that failures of surge suppressors would prevent a reactor trip from occurring when needed. In the 15 years, there was a high incidence of reactor protection system (RPS) actuations and half scrams reported for conditions at zero-power, e.g., shutdown, cold shutdown, refueling, just critical, and initial ascent to power, from low voltage switching surges or electromagnetic interference. Surge suppressors were being used extensively to divert and/or isolate these spikes and interferences (in conjunction with other preventive measures). We believe the use of surge suppressors will limit the number of zero-power reactor trips and would expect to see fewer LERs on this subject in the future.

The number of surge suppressors used in nuclear power plants is increasing. In some electronic circuits there may be all 3 categories of suppressors installed; clamps, crowbars, and isolators. These devices are in addition to those found in their power supply circuit, which if traced back to the source, may have several suppressors and several arresters. There are likely to be even more surge suppressors introduced in safety-related circuits in the future with the changeout of analog to digital instrumentation and control.

Our general conclusion from this study is that despite difficulties in using the LER and NPRDS data bases for obtaining age-related information, it would be inappropriate now to specifically modify them to include additional information on SPDs since their failure is not a safety or risk concern. However, better root-cause analysis would improve the quality of age-related data on SPDs, and a better pathway analysis would identify the best suppressors needed for protecting vital circuits. We believe an appropriate place to begin this increased vigilance is with the clamps, crowbars, and isolators used in safety-related digital instrumentation and control circuits.

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1. INTRODUCTION

This Phase 1 report discusses the aging of surge arresters and surge suppressors, commonly called surge protective devices (SPDs), and is being performed as part of the Nuclear Plant Aging Research (NPAR) Program, described in NUREG-1144 (Ref. 1.1). One of the many purposes of that program is to provide a technical basis for identifying and evaluating degradation caused by age. It is convenient to discuss surge arresters (synonymous with lightning arresters) as being applied in the transmission and distribution voltage range of 2.3 kV to 1000 kV, and surge suppressors as being applied in the distribution voltage range below 1000 VAC or below 1200 VDC. Both arresters and suppressors are considered surge protective devices. SPDs are components that are installed in electrical circuits to protect electrical equipment and systems from experiencing overvoltages over predetermined levels caused by electrical impulses. The commonest overvoltages arise from (1) lightning strikes, and (2) switching transients within the circuits. SPDs are preventive devices, diverting external source stressors that can cause downstream equipment failure or system upsets, and do so without interrupting the circuit, rather than mitigative devices, such as fuses and circuit breakers that clear downstream short circuits after they are initiated but do so by opening the circuit. SPDs prolong the life or normal wear of the components that they protect but can eventually fail or degrade. Their failure due to age may either cause a reactor trip or loss of offsite power from a short circuit failure mode, or the prevention of a reactor trip when needed from an open circuit failure mode. Therefore, surge protective devices must show a net benefit of extending the age of the components they protect against the consequence of their failure, which could be an internal short circuit or external open circuit.

Nuclear power plants not only produce electric power for the utility grid but also for internal use. For safe, reliable operation, a large number of safety- and non-safety-related electrical and instrumentation & control (I&C) equipment use this power for providing their design functions during normal and accident conditions. Any failures of this equipment are of major concern to both the utilities and the regulatory agency. One type of equipment failure is related to power quality problems caused by improper grounding and wiring, natural disruption like lightning, overvoltage (or swell), undervoltage (or sag), momentary interruptions, harmonic distortion, electrical noise, and other voltage surges, spikes, and impulses. One class of equipment, specifically the advanced electronic equipment that has brought reliable operation to control functions, is sensitive to these routine or non-routine power line disturbances. Some devices even create their own disturbances (Ref. 1.2).

Protective equipment including line conditioners, uninterruptible power supplies (UPSs), voltage regulators, motor-generator sets, filters, proper grounding and shielding, surge arresters, surge suppressors, ferroresonant transformers, and isolation transformers are used to ensure power quality. Which protective equipment is best suited and cost-effective for mitigating specific problems encountered by the safety- and non-safety-related equipment, depends largely on specific circumstances. Typically, electrical noise caused by improper wiring or grounding can be eliminated by using grounded shielding for cables, and a line conditioner or filter. Harmonic distortions caused by ferroresonance or nonlinear loads can be attenuated by using filters, static condensers or isolation transformers. Complete loss of power (lasting from several milliseconds to several hours) can be avoided by the presence of on-line UPSs, standby power supplies, or motor-generator sets. Surge arresters or surge suppressors play a vital role in protecting power plant equipment and transmission lines from high-voltage surges (or overvoltage conditions) caused by lightning, switching, and other phenomena.

Surge protective devices are on-line components used in both high- and low-voltage electrical distribution systems in a nuclear power plant and its power supply lines outside the switchyard, but are required to function only during abnormal overvoltage circumstances. A SPD's protection capability is not monitored on-line, and unless circumstances demand its function, an inability to respond may go undetected for some time. Therefore, failure of surge arresters and suppressors are found largely during scheduled periodic testing, or when problems with associated equipment are being resolved.

1.1 Objectives

The objectives of this study are to: (a) review the functions and designs of surge arresters and surge suppressors used for overvoltage protection of equipment in electrical systems needed for safe operation; (b) evaluate the impact of failure, malfunction, or degraded condition of SPDs on the overall safety and reliability of the plant; (c) review nuclear plant operating experience with these devices to characterize aging degradation and identify failures; and, (d) assess the existing technology for testing and monitoring the conditions of these devices during their service life.

1.2 Scope

The design and construction of surge arresters and surge suppressors are reviewed to identify age-sensitive components under normal and hostile environments. In addition, operational stressors are identified that can degrade or damage their functional capability. Information on operating experience of these components in nuclear power plants was obtained from reviewing licensee event reports (LERs) and Nuclear Plant Reliability Data System (NPRDS) records; with this data analyzed to understand the modes, causes, and mechanisms of SPD failure. Since surge protective devices protect other equipment from experiencing overvoltages, the impact of their failure or malfunction on the reliability of the protected equipment is an important design consideration; therefore, the data was further scrutinized to understand this effect.

To better appreciate the functional adequacy of surge arresters, a parametric study was performed using a transient model for a typical electrical system in a nuclear power plant by simulating lightning and switching surge phenomena both outside and inside the plant. The ElectroMagnetic Transients Program (EMTP) (Ref. 1.3) was used to model important loads inside a plant, including both safety and nonsafety equipment. Lightning surges are modeled by IEEE standard test functions which include a 10 kA, 8/20 μsec current pulse and a 1350 kV, 1.2/50 μsec voltage pulse. Switching surges are simulated by a 345 kV line energization and by line-to-ground faults internal to the plant distribution system.

The evaluation of testing and monitoring of degradation in surge protection devices was based on industry standards requirements, plant maintenance procedures, and several published techniques. Since SPDs functionally fail any time the circuit or equipment they are designed to protect from an overvoltage is damaged or upset, their degradation or inability to respond to overvoltages may go undetected until the next scheduled testing or maintenance. When an arrester or suppressor physically fail, it is generally a short circuit and the visible damage normally leaves no doubt that the unit is no longer functional.

Overvoltages attributed to lightning are diverse and include those caused by a direct strike, a lightning remnant (at high frequency) that was not diverted by an arrester passing through a transformer from high to low voltage, an induced voltage rise on a distribution line from a nearby strike, and a rise in station ground potential. In reviewing records for lightning caused failures or lightning suspected initiators, it is not always clear how the overvoltage occurred.

1.3 Organization of the Report

Section 2 gives background information on the design and construction of various types of surge protective devices, and their operating principles. Our analysis of reported failures of surge arresters and suppressors is reviewed in Section 3, and their associated modes, causes, and mechanisms is discussed. Section 4 presents the assessment of testing and monitoring activities to mitigate the age-related failures identified in Section 3. The results of the simulation study on various system conditions and surge arrester configurations are included in Section 5. Our summary and conclusions are given in Section 6. Appendices A and B include a tabulation of actual data on the failure of surge arresters and suppressors. Appendix C contains modelling data used for the EMTP simulations.

1.4 References

1.1 Vora, J. P. and Vagins, M., "Nuclear Plant Aging Research (NPAR) Program Plan," NUREG-1144, Rev. 2, 1991.

1.2 Douglas, J., "Solving Problems of Power Quality," EPRI Journal, December 1993.

1.3 Mauser, S. F. and McDermott, T. E., "Electromagnetic Transients Program (EMTP) Application Guide," EPRI EL-4650, November 1986.

2. SURGE PROTECTIVE DEVICES

This section contains: (1) background information on the types of overvoltages that surge protective devices (SPDs) must guard against; (2) a discussion of the design, construction, and operating principles of typical SPDs; and, (3) illustrations of SPD applications that are useful to nuclear power plants.

2.1 Background

2.1.1 Surge Protective Devices

Surge protective devices are used to protect against overvoltages in both the high and low voltage systems in nuclear power plants and in the plant's power supply lines outside the switchyard. Surge (or lightning) arresters protect against overvoltages caused by lightning surges, switching surges, and temporary overvoltages at the higher plant voltages; i.e., feeder through transmission voltages. Surge suppressors also protect against lightning surges and switching transients at the lower plant distribution voltages from 24 volts to 1000 volts. Overvoltages at high voltages can lead to (1) loss of offsite power (LOOP) with or without reactor trip, or (2) reactor trip without a LOOP, as discussed in Section 3. Overvoltages inside the plant may also result in reactor trips, but more frequently actuate engineered safety features, as also discussed in Section 3. Therefore, a major interest in surge protective devices is their ability to protect against overvoltages that can lead to (1) loss of offsite power and (2) challenges to the reactor protection system. Conversely, their failure due to age might be the cause of some of those initiating events, e.g., through short circuit failure modes, or allow a more rapid deterioration of the safety-related component(s) they are protecting from overvoltages, perhaps preventing a reactor trip, from degradation or an open circuit failure mode.

Surge protective devices have been evolving as nuclear plants were being built and operated. A major change in SPDs occurred with the introduction of the commercial metal-oxide surge arresters in the mid-1970s (Ref. 2.1). Nuclear plants built before 1976 used gapped silicon carbide surge arresters for their feeder, switchyard, and transmission lightning arresters. Subsequently, there has been some choice in selection, but today it is likely that only the metal-oxide surge arrester is available. By the early-1980s, the metal-oxide approach had been extended to distribution voltages with the advent of the metal-oxide varistor. (The usual acronym for the metal-oxide varistor is MOV. We do not use that acronym because of the potential confusion with motor-operated valve.) Other surge suppressor types also have been evolving over the past 10 years. To some extent, nuclear plants have been playing catch-up to the changes in surge protection devices. The need to properly apply SPDs becomes more important with the introduction of advanced reactors that use digital rather than analog instrumentation, and as more digital instruments replace analog instruments in current plants.

2.1.2 Insulation Withstand Voltage

The insulation of a system (e.g., electrical distribution system or equipment) must withstand the voltage applied throughout its service life under a variety of atmospheric and system conditions. To insure long-term integrity under anticipated service conditions, the insulation is designed to (dielectrically) withstand voltages higher than normal system operating voltages. However, transient overvoltages caused by lightning or switching are higher than insulation can be economically designed to withstand, and hence, surge arresters and surge suppressors are installed to divert surge voltage and its associated energy away from equipment it is designed to protect. Surge withstand capability is a fundamental concept in the design of electrical systems (Refs. 2.2, 2.3).

Figure 2.1 (Ref. 2.4) is typical of the arrester protection afforded to a high voltage transformer by a gapped silicon-carbide arrester. The transformer insulation has to withstand the impulses of lightning surges, switching surges, and temporary overvoltages. Its insulation strength is expressed in terms of the withstand voltage that it can resist without failing, and is commonly referred to as the basic impulse insulation level (BIL). The arrester discharge characteristic as a function of voltage (which may only be 20% higher than nominal voltage before it conducts) as a function of time in microseconds is shown below the insulation withstand curve. The difference between the curves is the level, or margin, of protection. There is some flexibility in specifying the level of protection in the actual design of transformer insulation and protection requirements of the arrester.

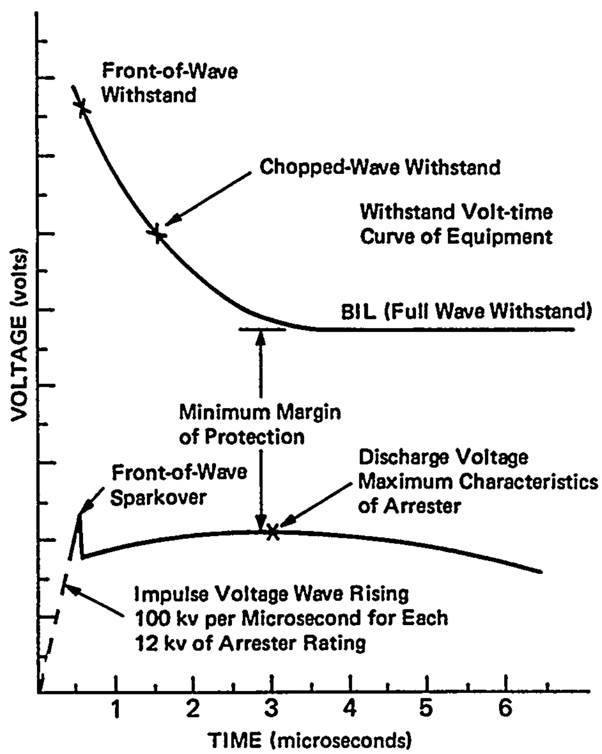


Figure 2.1 Typical transformer BIL vs. arrester operation

2.1.3 Overvoltages

Overvoltages of concern for plant transmission and distribution feeder voltages are (1) lightning surges, (2) switching surges, and (3) temporary overvoltages (TOVs). Lightning surges on power lines damp out on the order of microseconds, switching surges on the order of milliseconds, and temporary overvoltages, which usually have a lower magnitude, damp out between 2 cycles and 1.5 seconds (Ref. 2.5). TOVs occur more frequently, and their wear on the surge arrester must be considered in both specifying age requirements and guarding against excessive heating leading to rapid failure of the arrester. An EPRI study (Ref. 2.6) showed that 99% of lightning-induced surge voltages on distribution lines arise from nearby strikes. A utility study of distribution circuits found that the chances of an outage when shield wire type construction is used, which is for direct lightning strikes, is far more likely than when lightning arrester structures are substituted (Ref. 2.7). In addition, shield wire does not protect against switching surges and TOVs. Nuclear plants are more likely to be located in rural areas where the chances are high of lightning striking a transmission line in a thunderstorm. For feeder circuits, the chances of being directly hit are less because of the shielding afforded by nearby structures (Ref. 2.8). However, lightning striking structures, such as the containment, have resulted in plant trips from the lightning following a different pathway (discussed in Section 3).

Overvoltages at operating plant voltages less than 1200 VDC also can occur from lightning: switching of inductive loads such as relays, solenoids, and motors; propagation of surges through transformers; a showering arc from opening a switch; a fuse opening; and, electrostatic discharge (and also weapons-related surges which will not be discussed) (Ref. 2.9). A major change for nuclear plants is the replacement of analog by digital instrumentation. Modern electronic technology is producing smaller, faster semiconductor devices, particularly high-speed digital logic, microprocessors, and metal-oxide semiconductor memories for computers which are more vulnerable to overvoltages than earlier electronic circuits. Lightning is the most severe and unpredictable destroyer of electronic instrumentation. Although direct hits seldom occur, electromagnetic coupling is often sufficient to cause microchips to fail. Voltage spikes of only 40 volts can cause failure of some data and control line interfacing components. A solution is to strategically place protective devices within the equipment to reduce such failures (Ref. 2.10). A lightning bolt need not strike the feeder to cause damage; it can be caused by differences in the ground potential resulting from the lightning strike and subsequent flows of current setting up potential differences in segments of the ground structure. Conductors connected to various ground segments can experience a rise in potential (Ref. 2.11). There are more paths for lightning surges to reach loads than is generally believed. Multiple grounds at different potentials will prevent the primary arresters on the feeder transformer from protecting secondary circuits unless there is a secondary side suppressor and a suppressor at the load (Ref. 2.12).

Station Shielding

At nuclear plants, overhead shield wire, lightning masts, lightning rods, "air terminals", coursing conductors, and, in some cases, a lightning dissipation system may be used to protect the containment, auxiliary, and turbine buildings from direct strikes. If a strike to a containment lightning mast occurs, for example, the current is conducted to the grounding mat which will rise in potential (Ref. 2.13). If the ground mat is connected to the large quantity of interconnected (i.e., cadwelded) structural steel re-bar in the containment foundation or induces a voltage in the re-bar, a ground potential rise (GPR) can exist under the containment. This potential can induce overvoltages in cables, such as nuclear instrumentation cables, at the containment's lower elevations.

2.1.4 Lightning Overvoltages

The fundamental cause of lightning has been the subject of considerable research and is still not known. A current explanation is as follows: (1) a lightning-cloud forms by the upward drafts of warm moist air that subsequently condenses; (2) ice crystals form at colder altitudes that combine with water droplets to form ice balls (akin to hail); (3) subsequently, some ice crystals either collide or rub against the ice balls and produce opposite electric charges on themselves and the ice balls. The charged, lighter, ice crystals move up to the stratosphere and form the anvil head of a thunder cloud. The cloud can be 12 miles high and 15 miles across. (Most lightning strikes are internal in the cloud between the stratosphere ice crystals and the low altitude ice balls, called intracloud lightning). When lightning strikes an object outside of the cloud (i.e., cloud-to-ground lightning) it begins as follows: (1) lightning from the cloud forms a charged leader which works its way down towards the ground in jerky steps and branches; (2) little streamers from ground objects formed from the pull of the opposite attraction move upward toward the leader; (3) of the many possible connections, only one streamer will connect to the forward tip of the leader at a distance of 10 to 100 meters off the ground. The result is the apparent upward strike between streamer and leader. However, the lightning will continue to strike until each branch of the leader is discharged. This phenomenon is important in testing surge arresters for simulating the repetition of the strikes within the apparent single flash. Most often, a flash is composed of a number of individual strikes determined by the number of branches - typically three or four - separated by thousandths of a second. As many as 20 strikes, and as few as one strike, have been recorded in a single flash (Refs. 2.14, 2.15).

Overvoltages may be set up on overhead lines due to either direct or indirect lightning strikes. In a direct strike, the path of the lightning current is directly from the cloud to the equipment (e.g., an overhead power line). The voltage rises rapidly at the contact point and propagates as travelling waves in both directions from the point, raising the potential of the line to the voltage of the downward leader. This voltage will exceed the line-to-ground withstand voltage of the system insulation and, unless adequate overvoltage protection is provided, preferably in the form of an arrester, the voltage will establish a path from the line conductor to ground for the lightning strike by flashover. This completes the link between the cloud and the earth, releasing cloud energy in the form of surge current (Ref. 2.4).

In the indirect strike, the current path is to a nearby object, such as a tree. When the cloud comes over the line, the positive (or negative) charges it carries draw negative (or positive) charges from distant points and binds them in position under the cloud. The induced voltage on the line then is zero. If the cloud is assumed to discharge on the occurrence of the strike to the tree, the positive (or negative) charges of the cloud suddenly disappear, leaving the negative (or positive) charges on the line; their presence there implies a negative (or positive) voltage with respect to ground. The magnitude of this trapped charge depends on the initial cloud-to-ground gradient and the proximity of the strike relative to location of the line. The voltage induced on the line from the remote strike will propagate along as a travelling wave until dissipated by attenuation, leakage, insulation failure, or the arrester.

Direct lightning strikes to lines are of concern on lines of all voltage classes, as the voltage that may be set up is, in most instances, limited by the flashover of the path to ground. Protection at generating stations usually is a combination of overhead shield wire and surge arresters. The overhead ground shield wire is normally placed over the power conductors. If the shield wire is hit, lightning strike currents will primarily flow to ground through tower footings.

Indirect strikes produce relatively low voltages on lines, and are of particular concern for low-voltage lines supported on small insulators. They are of little importance on high-voltage lines whose insulators are designed to withstand hundreds of kilovolts without flashover.

Designing for protection against lightning requires a knowledge of the probability that lightning will strike a given location, and of the probability that a given strike will cause a certain level of damage or upset (Ref. 2.16). The number of thunderstorm days for the United States is shown in an isokeraunic contour map which was used in the past to estimate lightning intensity for designing surge arresters. Recently, however, actual ground strike densities or flash densities have been measured using the State University of New York at Albany lightning detection network (Ref. 2.17). These measurements give high confidence in establishing the probabilities of lightning strikes in a given area. Lightning production is a strong function of temperature and humidity; a hot humid summer will have more lightning storms than a cool summer. Hence, the number of challenges that lightning arresters see, and by inference, the challenges to a nuclear plant's reactor protection system from lightning, will be greater during a hot humid summer.

An EPRI sponsored research program is underway at the University of New Mexico to develop a laser-based system that could guide thunderbolts safely to the ground (Ref. 2.15). The technology ultimately may be able to discharge thunderclouds of their lightning at utility plants, airports, rocket launch sites, and other lightning sensitive locations, perhaps eliminating or minimizing the need for surge protective devices, shield wire, and lightning rods.

2.1.5 System Overvoltages

As discussed, switching surges and temporary overvoltages (TOVs), in addition to lightning, are of concern on plant transmission and feeder voltage lines. The causes of these overvoltages are mentioned below but no resulting problems were apparent from the data analyses of LER and NPRDS records. It appears to be difficult to ascribe causes of plant problems to overvoltages, other than lightning, that may have been initiated remotely from the plant switchyard. These overvoltages are potentially important because they can initiate a loss of offsite power or a reactor trip. The North American Electric Reliability Council publishes a review of selected electric system disturbances each year (Ref. 2.18) that may be useful in identifying external hazards such as those due to lightning, earthquakes, tornados, fires, and hurricanes. However, the majority of the transmission problems affecting power pool power flows relate to overvoltages brought about by faults and incorrect switching. While overvoltage data for other than lightning at transmission and feeder voltages is difficult to find, the data for the lower-voltage distribution circuit level for switching overvoltages is much better.

A switching transient will occur anytime a switch in a resistance, inductance, capacitance (RLC) circuit is opened or closed; this holds true for transmission lines, distribution feeders, and low- voltage circuits inside the plant. At the level of the transmission line, the opening of a circuit breaker or the untimely switching of a capacitor bank can cause overvoltage problems. In addition, there are TOVs, identified in Table 2.1, that also must be counteracted by SPDs (Refs. 2.5, 2.19).

At low voltages inside the plant, most of the system overvoltages (from other than lightning) either originate within the circuit containing the affected component or from an induced voltage from a spatially separate circuit or device. In addition, high-frequency transient surges can also transfer across a transformer due to transformer capacitances between the high and low voltage windings (Ref. 2.9).

Table 2.1 Summary of Important TOV Causes and Characteristics - Extra High Voltage Lines (Ref. 2.5)

Temporary Overvoltage Phenomena	Important Parameters	Overvoltage Magnitudes per unit (pu)	Typical Durations	Methods of Control
Fault Application	Fault Location System X0/X1 Ratio Fault Current Magnitude	1.0-1.4 pu	2-10 cycles	Usually not necessary
Load Rejection	Power Flow System Short Circuit MVA System Capacitance Machine Automatic Voltage Regulators	1.0-1.6 pu	Seconds	Switched Inductors Static Var Compensation Generator Controls
Line Energizing	Line Capacitance System Short Circuit MVA	1.0-1.2 pu	Seconds	Switched Inductors Static Var Compensation Generator Controls
Line Dropping/ Fault Clearing	Fault Conditions Line Capacitance Shunt-Reactors Breaker Opening Sequence	1.0-1.5 pu	<1 second	Shunt-Reactors Relaying Static Var Compensation
Reclosing	Line Capacitance Shunt-Reactors Trapped Charge Levels Fault Conditions	1.0-1.5 pu	Seconds	Shunt-Reactors Relaying Static Var Compensation
Transformer Energizing	System Short Circuit MVA Transformer Saturation Frequency Response System Voltage Level	1.0-1.5 pu	0-2 seconds	Switched Inductors Static Var Compensation Harmonic Filters Breaker Closing Res.
Parallel Line Resonance	Coupling Capacitance Shunt-Reactor Valves and Saturation Line Corona Losses	1.0-2.0 pu	Steady State	Neutral Inductors Switched Inductors
Uneven Breaker Poles	Circuit Capacitance Shunt-Reactor Valves and Saturation Line Corona Losses	1.0-2.0 pu	Steady State	Neutral Inductors Switched Inductors
Ferroresonance	Circuit Capacitance Transformer Saturation	1.0-1.5 pu	Steady State	Operating Procedures
Backfeeding	Transformer Characteristics Cable or Line Capacitance System Short Circuit MVA	1.0-2.0 pu	Seconds	Operating Procedures Shunt-Reactors

X0/X1 = Symmetrical components: Zero-Sequence-Reactance/Normal-Phase-Reactance

As mentioned earlier, typical causes of low voltage overvoltages for other than lightning are switching of inductive loads, such as relays, solenoids, and motors, a showering arc from opening a switch, a fuse opening, burnout of a tungsten lamp, and electrostatic discharge.

2.2 Design, Construction, and Operating Principles

This subsection describes the design and classes of surge protective devices (SPDs). In this study, SPDs were subdivided into surge arresters which cover the voltage range of 2.3 kV to 1000 kV, and surge suppressors covering the range ≤ 1000 VAC or ≤ 1200 VDC. SPDs may also be termed "clamps", "crowbars" and "isolators". A clamp has approximately constant voltage across it when conducting surge current. A crowbar is a device that changes state from an insulator to a nearly perfect conductor during an overstress. An isolator offers a large series impedance to common-mode voltages (i.e., the voltages that are not wanted but appear between two or more conductors and ground) (Ref. 2.9). Surge protective devices limit the surge voltages on equipment by discharging or diverting surge current, and prevent continued flow of what is called "follow current to ground". They can repeat these functions. ("Follow current" or "power current" or "power follow current" is current that passes through the surge protective device during and following the overvoltage).

Surge arresters, also known as lightning arresters, are devices that protect electrical equipment by limiting overvoltages from lightning strikes (Ref. 2.20). Ideally, a surge arrester is off-line under normal operation, switches on-line when the transient voltage is approximately 20% above normal value to ensure that it does not exceed this value regardless of the nature or source of the overvoltage, and switches off-line when the disturbance is past and normal voltage has been restored. The basic form of a surge arrester consists of a spark gap connected in series with a resistor (Figure 2.2). The gap is set at a sparkover value greater than the normal line voltage; hence, the gap is normally non-conducting. When an overvoltage occurs, the gap sparks over, and then the voltage across the arrester terminals is determined by the current flowing through resistance of the arrester.

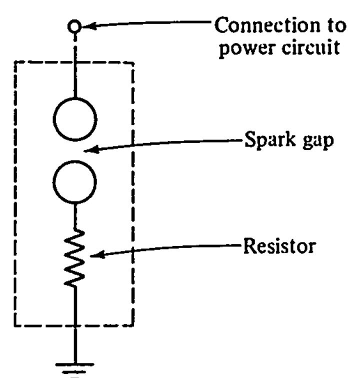


Figure 2.2 A basic surge arrester

The resistor limits the current flow, avoiding the effect of a short circuit. When the overvoltage condition has passed, the arc in the gap ceases, thus disconnecting the arrester from the circuit. If the arc does not go out, current continues to flow through the resistor, and both the resistor and the gap may be destroyed.

The ohmic value of the resistor is critical. If it is low, the voltage across it is low during the flow of transient current and the device protects effectively against overvoltage. However, the power follow current through the gap will be high and difficult to interrupt. Thus, with a linear resistor, severe transients will cause proportionately high voltages across the arrester's terminals. With a nonlinear resistor (resistance drops as voltage or current is increased), voltage across its terminals increases only slightly with an increase of the flow of transient current. Unlike a circuit breaker, the arcing contacts in an arrester are fixed in position, and presents a disadvantage for interrupting the arc. On the other hand, the nonlinear resistor allows a proportionately smaller current with normal voltage across the resistor. Hence, the power-frequency currents to be interrupted are much smaller than that of a circuit breaker.

2.2.1 Design, Construction, and Types of Surge Protective Devices

Figure 2.3 shows various components of a distribution-class gapped metal-oxide varistor surge arrester (Ref. 2.21). The arrester is structurally supported by the bracketed porcelain housing which also protects the internal parts from the atmosphere and acts as external insulation. Internally, valve arresters consist of a resistance-graded gap and valve material (the word "valve" is so named because it exhibits a valving action to the flow of system current; arresters using such valve blocks are called valve arresters). The resistance-graded gap provides a consistent sparkover characteristic from the various surge wavefronts it confronts and insulates the line from the ground under normal operating conditions. The valve material can carry high lightning-surge current with a resulting low discharge voltage; however, it offers high impedance to power-frequency follow current.

Surge arresters are subject to two voltage levels: the system operating voltage and the high-magnitude transient voltage. Elements of the arrester that primarily contend with these voltages are the gap and valve blocks. When conditions on the distribution system are normal, the gap element permits a minute grading current to pass to ground. Because of the relatively higher resistance across the gap, no voltage exists across the valve blocks.

Figure 2.4 shows a typical voltage-current (V-I) characteristic curve of a metal-oxide surge arrester (Ref. 2.22). At normal voltage, the arrester behaves like a simple resistor with a very small leakage current (less than 0.1 mA). At very high voltages, its response is dominated by the bulk resistance of the device. In between, it obeys the voltage-current relationship, $I=kV^{\alpha}$. The value of α characterizes the nonlinear V-I characteristic. An ordinary resistor would have $\alpha=1$. Mixed-oxide arresters have values of α between about 25 and 60, while silicon carbide arresters are around 4. A general rule, the greater the value of α, the better the arrester.

When a lightning strike produces a transient voltage surge on the line conductors, the air in the arrester gap becomes ionized. When the air's dielectric strength breaks down, the resistance of the gap drops to zero, the gap sparks over, the surge voltage is placed across the valve blocks, which exhibit low resistance at high voltage, allowing surge current to pass easily to ground.

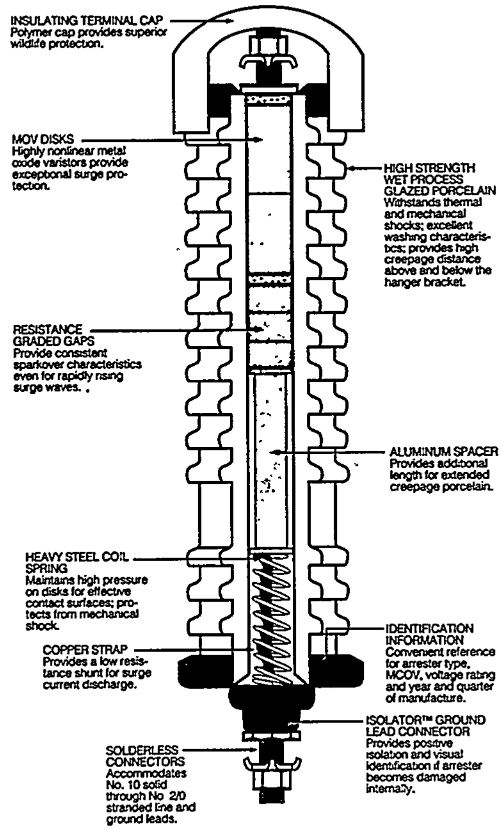


Figure 2.3 Design features of typical distribution-class surge arrester
(Permission to use copyrighted material granted by Cooper Power Systems)

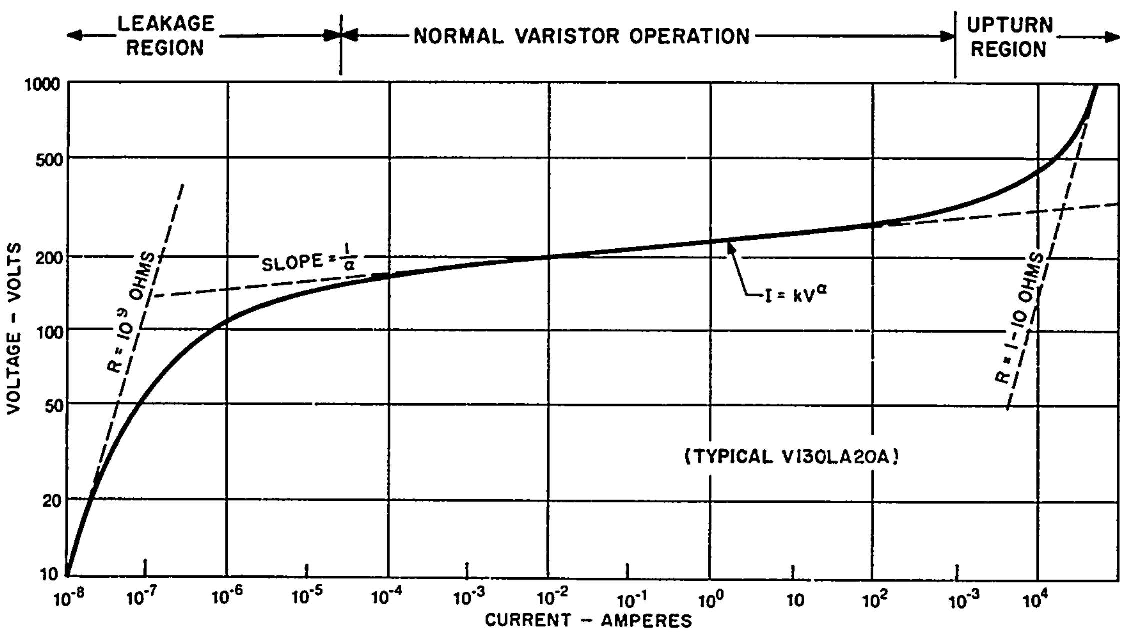


Figure 2.4 Typical V-I curve for metal-oxide arrester plotted on log-log scale
(Permission to use copyrighted material granted by HARRIS Corporation, 1995)

After the surge has passed, the voltage across the valve blocks drops to the system voltage, at which the valve blocks exhibit a high resistance. Power-frequency follow current through the arrester is reduced sufficiently by the valve blocks so that the gap recovers its insulating properties at the next current zero. Then, only the grading current passes through the arrester, and system voltage once again appears only across the gap, permitting the valve blocks to recover from heating effects of surge and power-frequency follow currents.

The lifetime of a varistor, whether a gapped silicon carbide or a gapless metal-oxide, is a function of the accumulated energy absorptions it was "pulsed" with before it fails its warranty. A plot of peak pulse current against impulse duration for a typical metal-oxide varistor is shown in Figure 2.5 (Refs. 2.22, 2.23). The model varistor shown can take a single peak pulse current of 80,000 A for 20 microseconds, or about 1000 pulses of 2,000 A for 20 microsecond impulses. Although the engineer has some latitude in determining the pulse lifetime for the calendar life of the varistor, the limiting requirement is likely to be the specification of lightning surges rather than switching transients.

2.2.2 High-Voltage-System Protection (Refs. 2.25 - 2.27)

Transmission lines entering and leaving the plant switchyard typically are protected against direct lightning strikes to the conductor by shield (overhead ground) wires, which are positioned to intercept strikes and direct them to ground via a metallic tower or pole. Similarly, overhead ground wires, metallic masts without ground wires, and lightning rods supported from the station structures are used for shielding buildings. The lightning ground structure and lightning arresters located adjacent to equipment complete the makeup of the plant's lightning protection system for voltages 2.3 kV to 1000 kV. The lightning arresters will be either silicon carbide nonlinear valve elements with active gaps, or metal (zinc) oxide valve elements that can withstand system voltage with series-gaps, shunt-gaps, or without gaps.

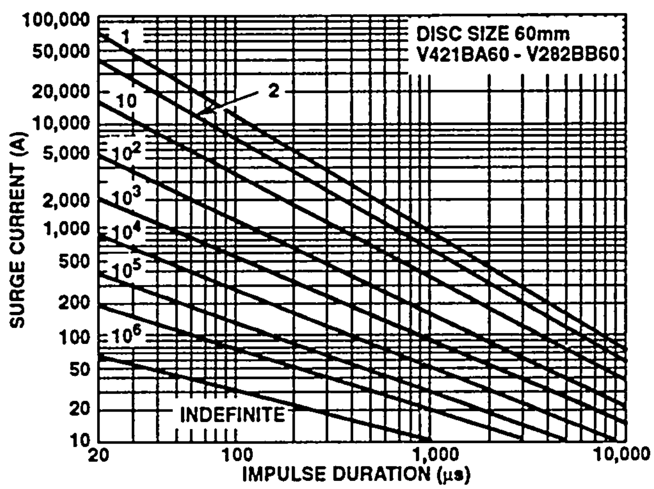


Figure 2.5 Pulse ratings for metal-oxide varistor plotted on log-log scale
(Permission to use copyrighted material granted by HARRIS Corporation, 1995)

The arresters must protect against switching surges and temporary overvoltages because the shield wires cannot. Switching surges are heavily damped oscillatory transients, which can be eliminated by an arrester that can successfully operate on successive peaks. Temporary overvoltages are also oscillatory overvoltages of relatively long duration that are undamped or only slightly damped but easily diverted by the arrester. A direct or indirect lightning strike to a power line will set up traveling waves which move along the line. Crest voltage will double when the wave arrives at the terminals of an open line switch or circuit breaker. Voltage approaching double occurs at line-terminating transformers. In general, an arrester should easily shunt twice the strike voltage.

As identified at the bottom of Table 2.2, only two types of surge arresters are found at nuclear power plants: (1) gapped silicon carbide surge arresters; and, (2) metal-oxide surge arresters. A typical station class arrester is shown in Figure 2.6 (Ref. 2.24).

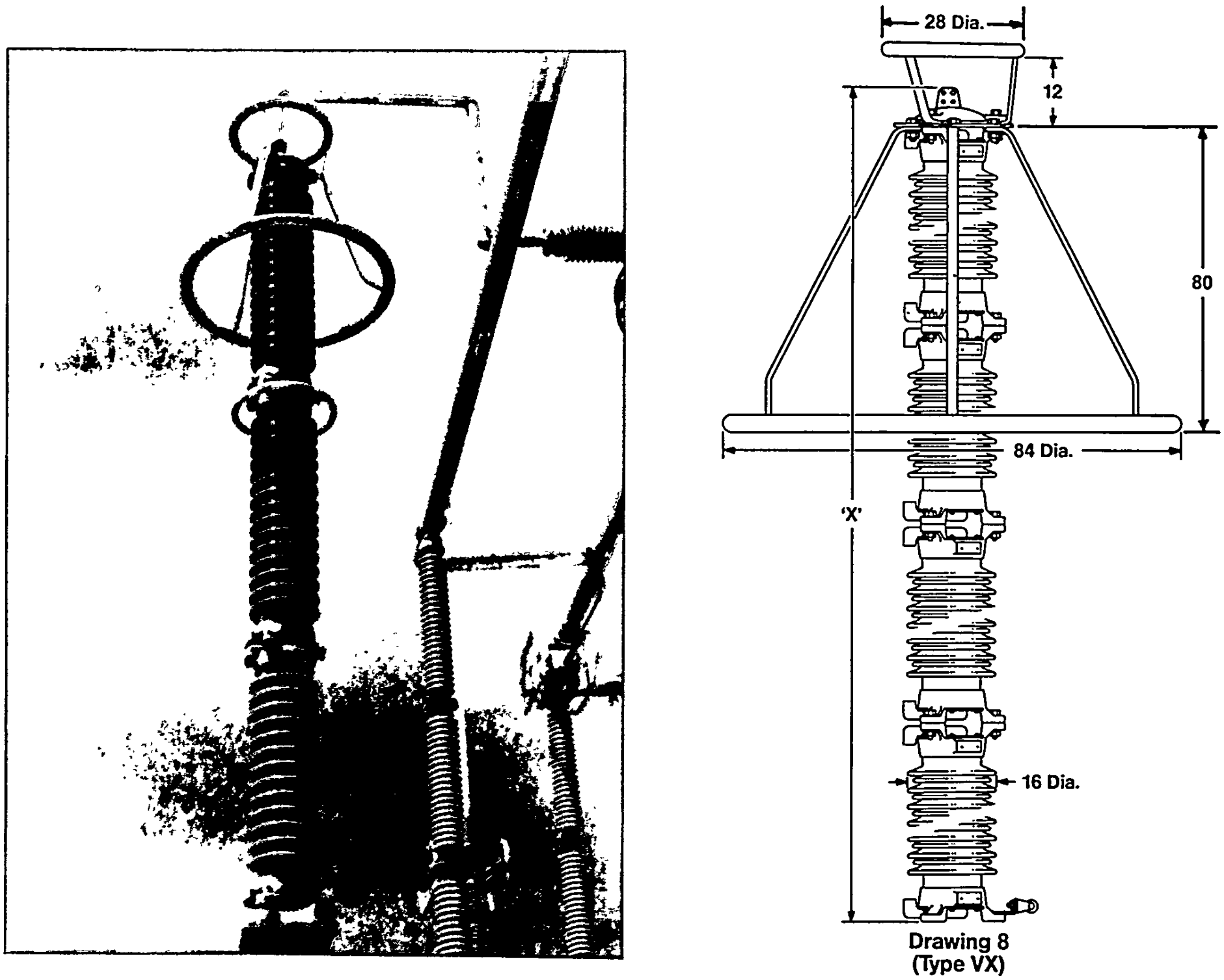


Figure 2.6 Typical porcelain-housed station class metal-oxide surge arrester
(Permission to use copyrighted material granted by Hubbell/The Ohio Brass Company)

Table 2.2

SURGE PROTECTIVE DEVICE COMPONENTS BY VOLTAGE CLASS (Derived from Ref. 2.9)

1. PLANT VOLTAGES: ≤1000 VOLTS AC OR ≤1200 VOLTS DC

<u>"CLAMPS"</u>

(Clamps have approximately constant voltage across them when conducting a surge current).

- METAL-OXIDE VARISTORS
- AVALANCHE DIODES OR AVALANCHE JUNCTION SEMICONDUCTORS
- SWITCHING AND RECTIFIER SILICON DIODES

<u>"CROWBARS"</u>

(Crowbars change state from insulators to nearly perfect conductors during overvoltages).

- GAS TUBES (or SEALED SPARK GAPS)
- AIR GAPS
- THYRISTORS - SILICON-CONTROLLED RECTIFIERS AND TRIACS

<u>"ISOLATORS"</u>

(Isolators offer large series impedances to common-mode voltages).

- OPTICAL ISOLATORS
- ISOLATION TRANSFORMERS
- COMMON-MODE FILTERS.

2. PLANT VOLTAGES: 2.3 KV TO 34.5 KV; TRANSMISSION VOLTAGES: 69 KV TO 230 KV; EXTRA HIGH VOLTAGE TRANSMISSION: 242 KV TO 1000 KV

- METAL-OXIDE SURGE ARRESTERS
- GAPPED SILICON CARBIDE SURGE ARRESTERS

Silicon Carbide arresters contain series gaps that protect valve elements from continuous power-frequency voltage and longtime overvoltage excursions (such as those caused by ferroresonant conditions). The series gap is the insulating means during normal voltage conditions. Besides keeping voltage across the valve elements below sparkover values, the gap performs an important secondary function of interrupting the power-frequency current that follows the transient current discharged by the arrester by not restriking on subsequent half-cycles of power-frequency voltage after the first follow-current zero. A silicon carbide surge arrester is a clamping device. These arresters are much less nonlinear than their counterpart, metal-oxide arresters, because of their lower α. The metal-oxide surge arrester is a relatively recent innovation (i.e., mid-1970s), so most lightning arresters in nuclear plant switchyards and feeder circuits are the gapped silicon carbide type. However, they are likely to be replaced by the metal-oxide arrester because of its dominance in the commercial market.

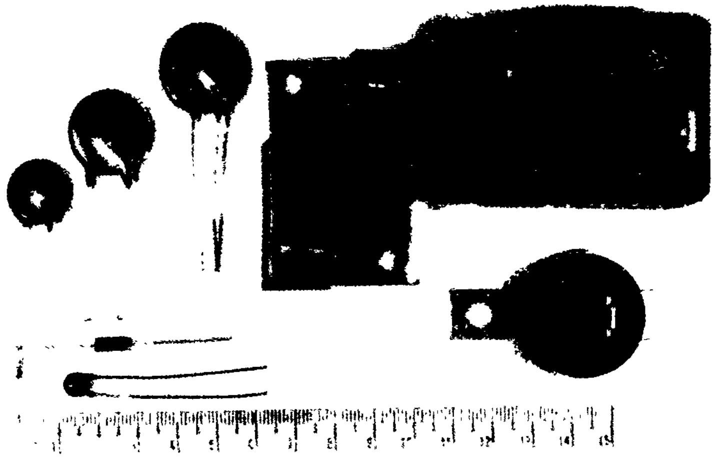
Metal-Oxide surge arresters are typically constructed without series or shunt gaps (but there are innovations with them); they rely, instead, on their valve elements to withstand the line voltage during normal operation. The valve elements start to conduct sharply at a precise voltage level and cease when the voltage drops below this level. A series gap is usually not required to insulate a metal-oxide arrester from ground because the arrester's valve elements permit only low leakage currents at operating voltages; nor is a series gap needed to interrupt power follow current that does not exist as long as the applied voltage is below the conduction voltage. This arrester maintains its protective characteristics provided it is not required to dissipate more energy than it can tolerate. The conduction voltage depends on temperature, decreasing as the temperature increases. [EPRI successfully sponsored a program that increased the energy absorption capabilities of metal-oxide valve blocks (Ref. 2.28).] The metal-oxide surge arrester is a clamping device which presently dominates the market. The concept has been adapted to low voltages with the metal-oxide varistor, as discussed below.

2.2.3 Low-Voltage Surge Protection (Refs. 2.9, 2.29)

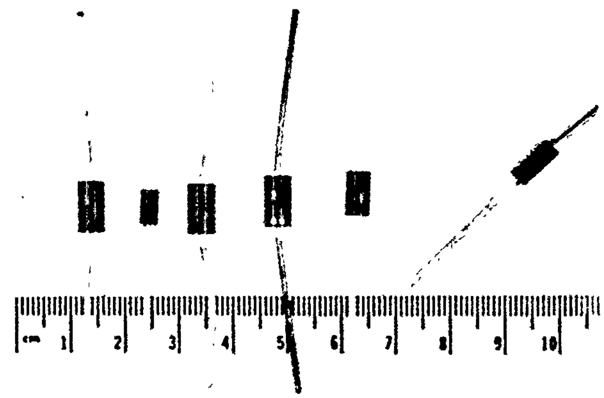
Table 2.2 shows that there are many types of surge suppressors in nuclear power plants; typical examples are shown in Figure 2.7 (Ref.2.9). In low-voltage surge protection there are two major categories of transient suppressors: (a) those that attenuate transients, thus preventing propagation into the sensitive circuits; and (b) those that divert transients away from sensitive loads to ground and so limit the residual voltages. The filter, generally of the low-pass type, attenuates the transient (high frequency) and allows the signal or power flow (low-frequency) to continue undisturbed. A filter is an example of an isolator device. Diverting a transient to ground is accomplished with a voltage-clamping device or with a crowbar type device. With the former, the circuit is unaffected by the presence of the device before and after the transient for any steady-state voltage below the clamping level; typical devices are metal-oxide varistors, avalanche diodes or avalanche junction semiconductors, switching and rectifier diodes (as shown in Table 2.2) and also silicon carbide varistors, reverse selenium rectifiers, and zener diodes. Crowbar-type devices involve a switching action, either the breakdown of a gas between electrodes or the turn-on of a thyristor. After switching on, they offer a very low impedance path which diverts the transient away from the parallel-connected load. Gas tubes (also called "spark gaps") are carbon-block protectors that belong to this type and have been widely used in the communication field where power-follow current is less of a problem than in power circuits. In some applications, a clamp and crowbar may be used to protect an electronic circuit, e.g., by combining a spark gap in series with a silicon carbide varistor to obtain a tight clamping voltage.

Gas tube, metal-oxide varistor, and avalanche junction semiconductor surge protective devices are used on systems with DC to 420 Hz frequency and voltages equal to or less than 1000 VAC or 1200

Metal-Oxide Surge Suppressors



Avalanche Diodes



Spark Gaps

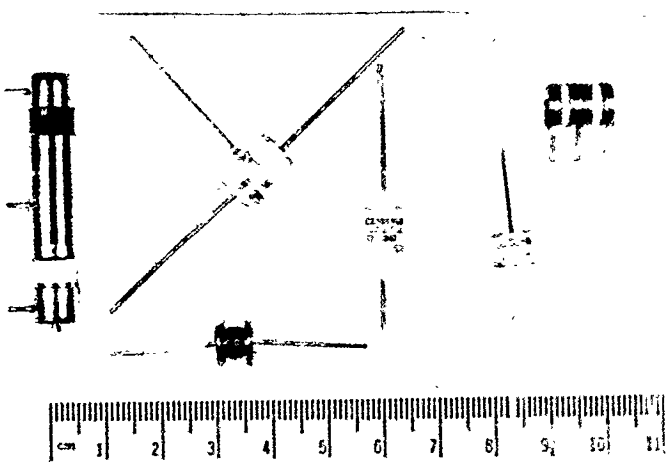


Figure 2.7 Typical surge suppressors
(From Protection of Electronic Circuits from Overvoltages, Ronald B. Standler, John Wiley & Sons, 1989 Reprinted by Permission of John Wiley & Sons, Inc.)

VDC. The metal-oxide varistors and avalanche junction semiconductor surge suppressors (which are clamps) simply limit the voltages, whereas the gas tube arresters (which are crowbars) exhibit steep negative-resistance characteristic clamp voltages well below their striking potentials. The current capability distinction between clamps and crowbars has important implications in circuit design. Crowbars cope with extremely high surge currents, while clamps are generally less well equipped to deal with them. But crowbars reflect a higher percentage of incident energy back into the circuit, while clamps dissipate more energy on the spot.

The following is a brief description of the suppressor devices identified in Table 2.2:

Air Gap surge protective devices can be used on systems with operating voltages equal or less than 600 V rms. They are designed to limit the voltages on balanced or unbalanced communication and signaling circuits. When the device's breakdown voltage is exceeded, its normal high impedance state changes to a low one to allow conduction of the surge discharge current. After this, the device interrupts the flow of system follow current and returns to its high impedance state.

Gas Tube surge suppressors consist of two or more metallic electrodes separated by gap(s) in a hermetically sealed envelope containing an inert gas or mixture of gases (e.g., argon, helium, hydrogen, and nitrogen), usually at less than atmospheric pressure, and they operate as a cold cathode discharge tube. Electrode spacing is maintained by ceramic, glass, or other insulating materials, which may form a part of the sealed envelope. An electrode may serve as either an anode or a cathode, depending on the polarity of the applied voltage. The electrodes are fitted with variety of terminations suitable for mounting on circuit boards, clip terminals, sockets, or for incorporation into a protector.

When the gap of a gas tube arrester is subjected to an increasing field intensity due to a voltage surge, it will break down at a voltage that is determined by its design and the rate of rise of the voltage surge. The faster the rate of rise of the surge wavefront, the higher the impulse breakdown voltage. Design factors include spacing between electrodes, type of gas used, gas pressure, electrode configuration, and surface coating. The DC breakdown voltage is a function only of the product of the gas pressure multiplied by the distance between the plate electrodes. Minute quantities of radioactive isotopes or conductive deposits on the inside wall of the gas tube arrester sometimes are used for stabilizing and reducing the breakdown voltage level. In the nonconducting state, the gas tube arrester has a very high resistance, (e.g., several thousand megohms), but once breakdown occurs, various operating states are possible, depending upon the external circuitry. As a result, a low-impedance state is obtained and the energy remaining in the disturbing transient is shunted and reflected away from the components to be protected. Gas tubes are usually used in AC applications.

Thyristors are silicon PNPN structures that are useful for switching very large currents. The two commonest types are the silicon-controlled rectifier (SCR) and the triac. The SCR can conduct in one direction and is used in DC circuits. The triac can conduct in both directions and is useful in AC applications. The SCR and triac each have two terminals that act as a switch, and a third terminal, called a gate, that turns on the device. The thyristor is designed to routinely tolerate abnormally large currents, such as motor starting and they are commonly found in motor controllers, battery chargers, and inverters. The thyristor requires several microseconds, which is relatively fast, to become fully conducting but it operates at a lower power dissipation and temperature for a given surge current. [There is a major innovation under development that uses thyristors as switching devices on transmission lines (Ref. 2.30).]

Metal-Oxide Varistors are related to the thyrite (i.e., silicon carbide) technology which dates back many years in the power industry, for suppressing transients on power lines. These surge protective devices became available at the low voltage level in the early 1980s. Their current voltage characteristics exhibit a higher order of nonlinearity than their thyrite predecessors, so they function much more effectively as voltage limiters or clamps. The metal-oxide varistor is formed by pressing and sintering zinc-oxide (ZnO) based powders into ceramic disks. Each ZnO grain acts as if it has a semi-conductor junction at the grain boundary. Since the nonlinear electrical behavior occurs at the boundary of each semiconducting ZnO grain, the varistor can be considered as a multi-junction device composed of many series and parallel connections of grain boundaries. The metal-oxide varistor is ubiquitous in its overvoltage application as a surge protective device for the electric power industry, covering the range from 10 volts to a million volts.

Avalanche Diodes or Avalanche Junction Semiconductor surge suppressors are wide-junction zener diodes that have the tightest clamping voltages and are widely used with voltage regulators. Other types of avalanche diodes that may be good for voltage regulation may not exhibit the surge capability necessary to satisfy the protective specification for a surge suppressor. These devices have a larger cross-sectional area, larger internal heat sinks, and exhibit a relatively high impedance at normal system voltages before and after the surge. They limit surge voltages on equipment by providing a low impedance to conduct the surge discharge current.

Switching and Rectifier Silicon Diodes are nonlinear, forward-biased semiconductor diodes that can be used for protection against transient overvoltages. Switching diodes can be applied in electronic circuits where the steady-state current is less than 0.50 A, and rectifier silicon diodes in circuits where the steady state current is greater than 0.50 A. A common arrangement is to have two diodes, connected in antiparallel, form a bipolar clamping circuit configuration, often called "silicon varistor", that provides low clamping voltages.

Optical Isolators are electronic components that contain a light source and a photodetector, with no electrical connection between the two. A light beam transfers information from the input to the output. A piece of transparent glass or plastic provides electrical insulation between the light source and the detector. The insulation typically can withstand a steady-state voltage of several kilovolts. The light source in nearly all modern optical isolators is an infrared light-emitting diode (LED), and the photodetector usually is a silicon phototransistor. Although the LED is an optical isolator, it generally requires protection from being driven into reverse breakdown by protective circuit elements of a spark gap and avalanche diode.

Isolation Transformers are magnetically coupled electronic isolators. The isolator may be either an analog or digital device, depending upon the input and output signals which it is designed to handle. Isolation transformers are most often used to block common-mode voltages in AC power applications. The common-mode voltage is eliminated by placing electrostatic shields between the primary and secondary windings that removes parasitic capacitance between the coils. (Isolation transformers are used in line conditioners to regulate steady-state voltages).

Common-Mode Filters are usually simple low-pass filters that attenuate high-frequency (i.e., 0.15 to 30 MHz) noise and transient overvoltages. However, a gas tube or a varistor generally is used in conjunction with them because the very large voltages and currents in severe transient overvoltages can overwhelm filters while the suppressor devices can conduct them away.

2.3 Applications of Surge Protective Devices

Specific applications for high voltage surge arresters in nuclear power plants include the protection of incoming and outgoing transmission lines, station, and feeder distribution systems. Station systems include the switchyard equipment, and perhaps, nearby transmission equipment such as capacitor banks, current-limiting reactors, autotransformers and gas-insulated substations. Switchyard equipment includes circuit breakers, transformers, switches, feeder circuits to plant buses, and any black-start gas turbines. Feeder distribution circuits include the generator, large motors, and diesel generators and ancillary switchgear.

Recent papers focused on the responses of metal-oxide surge arresters to switching surges and temporary overvoltages (Refs. 2.26, 2.31, 2.32). A potential application is the use of metal-oxide surge arresters at each end of a transmission line being switched, as in an offsite power-bus transfer operation, as a means of controlling the switching surge (Refs. 2.32, 2.33). Other recent papers deal with the question of adding mixed-oxide surge arresters on the generator breaker side of the main transformer and electric motor protection using a combination of surge capacitors and metal-oxide arresters (Refs. 2.34, 2.35).

There is an SPD transition region going from surge arrester to surge suppressor, i.e., the transformer high-voltage side of the feeder distribution to the low-voltage-side distribution circuits. The overvoltage protection discussed in literature suggests that a surge arrester should be mounted on the high voltage side (i.e., 2.3 kV or greater) of the transformer, and a surge suppressor (usually a varistor) connected on the transformer's secondary side and another secondary varistor located downstream at the distribution panel (Refs. 2.36-2.38). However, surge protective devices, not necessarily varistors, are also needed between the distribution circuit voltage and the load, and must be coordinated back to the high voltage side of the transformer (Refs. 2.39-2.45).

Inside the plant there are likely to be many low-voltage surge suppressors integrated into power supply circuits and various I&C circuits which control the functions of safety systems. Voltage spikes in the plant's power supplies, inverters, voltage regulators, battery chargers, adjustable speed drives, relays, line conditioners, uninterruptible power supply system, isolation devices, and control transformers are evident from the operating experience data. The low-voltage surge suppressors are used for electrical protection with a wide voltage range, from very low voltage in micro-electronics (of about 10 volts) to higher voltage (of up to 600 volts) in distribution circuits. Suppressors also have a wide application in the telecommunication field and are used to protect components and equipment in signal processing, communication, data computation, and other I&C applications in power plants. These devices are often small enough to be parts of an integrated circuit in some I&C applications.

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3. OPERATING EXPERIENCE

The goal of our review of operating experience review was to determine the causes of the functional and physical failures of surge protective devices (SPDs). Functional failures usually will result in system upsets and could cause a reactor trip or a LOOP without any physical damage to the arrester, suppressor, or any of the system components. However, a reactor trip could occur without any physical damage to the arrester or suppressor but with physical damage to a component in the system. Arrester failures do occur in service due to either age or from a lightning strike or switching surge that causes excessive overheating. Arresters that physically fail can initiate a LOOP or a reactor trip. It is possible that failures of suppressors could cause a reactor trip. This study found that there is very little published data on failures of arresters or suppressors.

IEEE 500 does not address either arresters or suppressors, and neither does the generating availability data system (GADS) data base of the North American Electric Reliability Council. Utilities test arresters, as discussed in Section 4, to determine if there are any out-of-specification parameters (which certainly are age-related) and, if so, make a decision whether the arrester should be removed from service. However, this information is not publicly available. EPRI performed a 3- year study to characterize lightning-caused surges and damage on 15 kV class distribution systems (Ref. 3.1). There are many industry papers dealing with arresters, including standards testing and pulse testing, but only two articles were found which referred to failure data for suppressors (Refs. 3.2, 3.3). There was one recognized industry source found on surge-suppressor failures in military aircraft but this source had few SPD types and the populations were small and time in service was short (Ref. 3.4).

The approach used for reviewing operating experience for this aging study (as well as previous aging studies) is to start with the Licensee Event Reports (LERs) by accessing the Sequence Coding and Search System (SCSS) (Ref. 3.5), and, the Nuclear Plant Reliability Data System (NPRDS) (Ref. 3.6). To completely review SPD operating failures (i.e., operating failures and those discovered during routine maintenance), it was necessary to examine both data bases. The NPRDS does not use arresters or suppressors as components in its data base, and although the SCSS does code "lightning arrester" and "surge protection package", there was little in these categories. Therefore, it was necessary to search the narratives in LERs and NPRDS records by using key words such as "arrester", "suppressor", "lightning", "voltage spike", "voltage surge", and "varistor". Over 2000 LERs and several hundred NPRDS records were reviewed, and the results of this evaluation are discussed next.

3.1 Arresters

Lightning strikes are a significant concern for electric utilities being the single greatest cause of service interruptions. In 1987, 654 of the Tennessee Valley Authority's (TVA's) 1,109 transmission line outages (59%) were attributed to lightning (Ref. 3.7). The following excerpt is from LER 457 89-004: "... At approximately 2000 hours, 9/7/89 a severe thunderstorm was in the area of Braidwood Station. A video recorder had been set up to monitor the effects of atmospheric events. From 2029 to 2036 sixty-three lightning flashes were recorded by the camera. Four of these lightning strikes hit station structures. The Unit 2 aux. building vent stack was struck twice. The Braidwood Station switchyard was struck. At 2031:44 the Unit 2 containment was struck...." Lightning arresters have the formidable task of protecting equipment in the presence of repetitive energy strikes.

3.1.1 EPRI Lightning Study

The EPRI failure data for the 3-year study of the 15 kV distribution system is contained in several references (Refs. 3.1, 3.8, 3.9). About 100 years of discharge current and voltage monitoring from 1,309 lightning surges was obtained for metal-oxide surge arresters. There were no reported failures; however, the arresters were relatively new. For lightning-caused failures of transformers protected by gapped silicon carbide arresters, the functional failure rate (which includes transformer damage and fuse cutout) is 6.8 E-03 per transformer year. Circuit breaker operation that was not protected by gapped silicon carbide arresters amounted to about 2.9 E-03 per transformer year. If these failure probabilities are combined, we surmise that the functional failure rate of a distribution line protected by gapped silicon carbide surge arresters that contains a circuit breaker and transformer is about 1.0 E-02 per transformer year, while the corresponding functional failure rate for a mixed oxide surge arrester is unknown. The EPRI study brings up questions about the protection philosophy of distribution surge arresters: 1) Should the criterion be that the surge arrester will completely protect against the lightning strike by shunting away the pulses so that neither a circuit breaker is required to open nor is a transformer fuse cutout required to be open?; or, 2) Should the surge arrester protect enough to prevent damage to components but allow the circuit breaker to open at a reduced current requirement and allow the transformer fuse cutout to operate but shunt enough current to increase the fuse's age? The assumption made in this analysis was to use the first criterion.

3.1.2 LER and NPRDS Evaluation

In Appendix A, Tables A.1 through A.7, there are 201 events obtained from LERs and NPRDS records from 1980 to 1994 that are related to lightning; Figure 3.1 summarizes this information. Of the 201 events, there were: (a) 10 losses of all offsite power (LOOP) and 3 of which caused reactor trips; (b) 35 partial losses of offsite power with 10 resulting in reactor trips; (c) 50 reactor trips without prior loss of offsite power; and, (d) 106 engineered safety-feature actuations or technical specification reporting requirements for failures (usually environmentally related), or component failures or upsets not requiring an LER report. Sixty-three reactor trips were attributable to lightning from 1980 till the end of 1994 and 45 complete and partial losses of offsite power. The distributions are shown in Figures 3.2 and 3.3. Figure 3.4 overlays the reactor trips that occurred concurrently with losses of offsite power using the combined totals of complete and partial LOOPs. During the 15 year period, 1980 to 1994, there was a 30% chance the reactor would trip given a complete LOOP, and a 29% chance that the reactor would trip given a partial LOOP. Hence, there is about a 30% chance the reactor would trip given any type of LOOP caused by lightning. (Other weather-related correlations may be different).

Not all nuclear plants are equally affected by lightning storms; those in high flash density areas of the country are challenged more frequently. In addition, there may be some deficiency in the lightning protection system used at different reactor sites. The data in Appendix A shows that about 75% of the nuclear plants reported lightning-related events between 1980 and 1994. However, only 36 plants had lightning-caused reactor trips as shown in Table 3.1, and only 28 had lightning-caused LOOPs or partial LOOPs, as shown in Table 3.2. Of the 107 current operating reactors, only 47 have experienced a LOOP, partial LOOP or reactor trip from lightning strikes during this period. Using an industry-wide average may be inappropriate. Several plants appear prone to LOOPs or partial LOOPs, and others appear more prone to reactor trips from lightning.

The components usually involved in loss of offsite power events are the circuit breakers protecting the transmission lines, along with their associated transformers, and either offsite power buses transferring

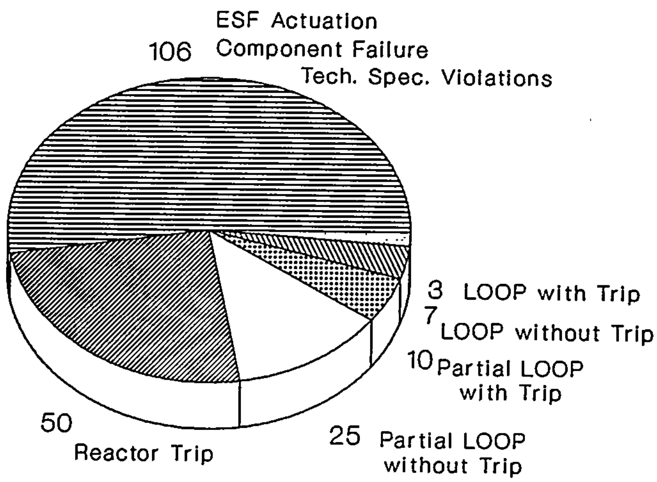

Figure 3.1 Effect of lightning strikes on nuclear power plants LERS and NPRDS: 1980-1994

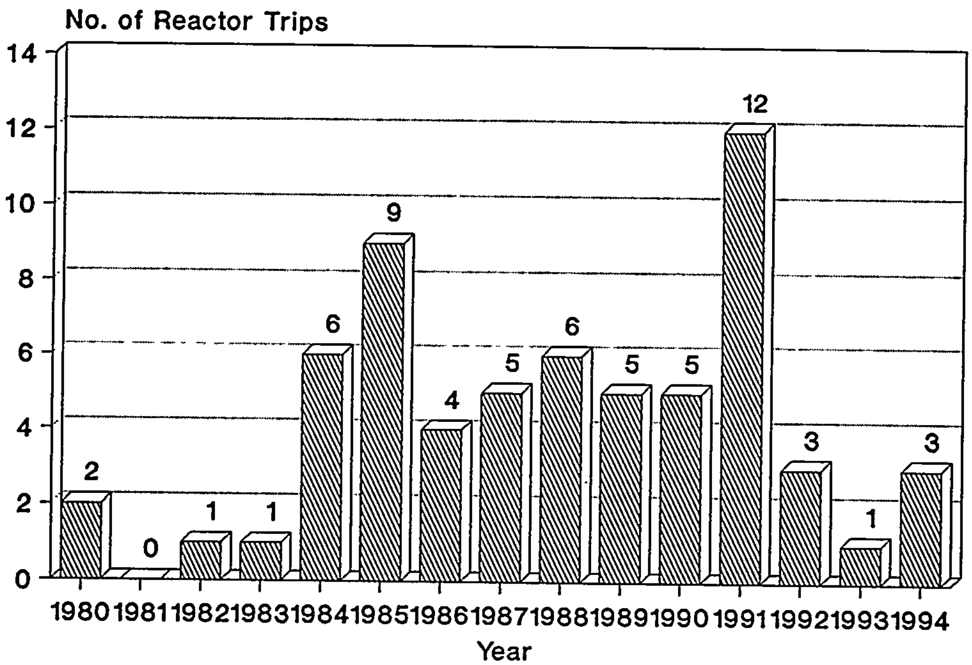

Figure 3.2 Lightning caused reactor trips (1980-1994)

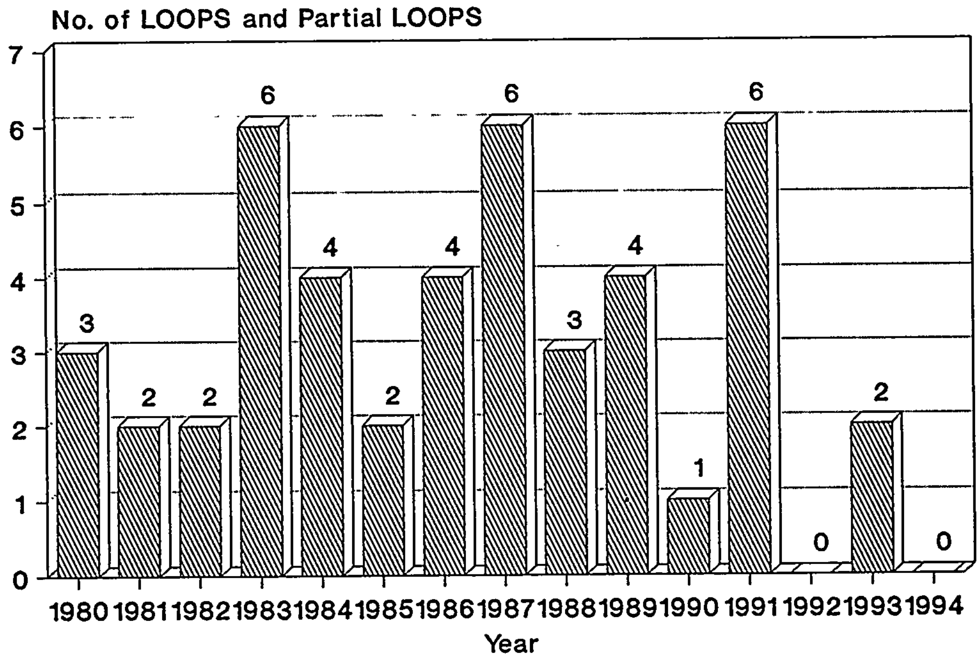

Figure 3.3 Lightning caused losses of offsite power (1980-1994)

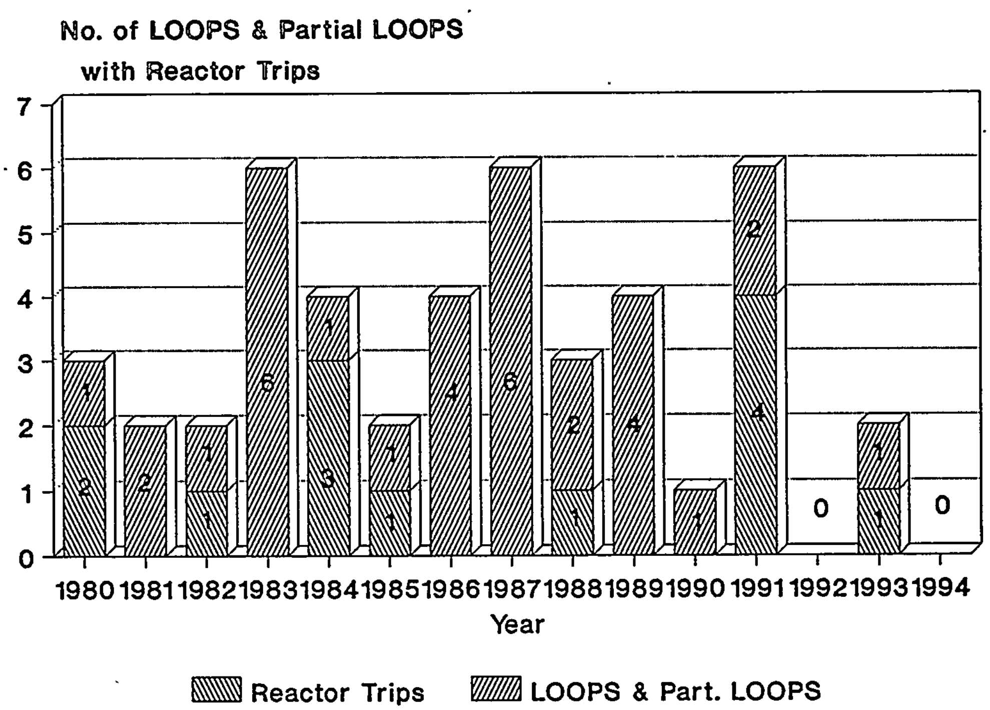

Figure 3.4 Coincident reactor trips with losses of offsite power

Table 3.1 - Lightning Caused Reactor Trips by Plant

Docket	Number of Reactor Trips	Reactor Years (1980-1994)	Frequency (Trips/RY)	Comments
456	4	7.6	0.53	Installing lightning dissipation array system. (1 event occurred during shutdown but Sister Unit tripped as well).
416	6	12.5	0.48	Installing lightning dissipation array system.
457	3	7.0	0.43	Lightning protection system is being modified.
454	4	10.2	0.39	Lightning protection system is being modified.
029	4	12.2	0.33	
530	2	7.8	0.26	In 1 event, Unit 1 also tripped.
445	1	4.8	0.21	
364	3	14.2	0.21	
272	3	15.0	0.20	Lightning arrester damaged in 1 event.
387	2	12.4	0.16	
250	2	15.0	0.13	Similar events.
263	2	15.0	0.13	
278	2	15.0	0.13	In 1 event, lightning was initiator but block switch failed.
301	2	15.0	0.13	Lightning arrester damaged in one event.
313	2	15.0	0.13	
424	1	7.9	0.13	
455	1	8.1	0.12	In startup at time of event.
458	1	9.3	0.11	
382	1	10.0	0.10	

Table 3.1 (Cont'd)

Docket	Number of Reactor Trips	Reactor Years (1980-1994)	Frequency (Trips/RY)	Comments
528	1	10.0	0.10	Unit 3 also tripped.
388	1	10.8	0.09	
220	1	15.0	0.07	Unit was in shutdown.
247	1	15.0	0.07	
254	1	15.0	0.07	Lightning initiator but ground relay failed.
261	1	15.0	0.07	Lightning arrester failed.
271	1	15.0	0.07	
277	1	15.0	0.07	
293	1	15.0	0.07	
302	1	15.0	0.07	
304	1	15.0	0.07	Containment lightning rods struck.
306	1	15.0	0.07	
324	1	15.0	0.07	In refueling at time of event.
325	1	15.0	0.07	
346	1	15.0	0.07	
348	1	15.0	0.07	
368	1	15.0	0.07	
Mean	63	459.8	0.14	Averaged over above events.
Industry Mean	63	1409.4	0.04	Averaged over all U.S. operating nuclear plants, 1980-1994.

Table 3.2 - Lightning Caused LOOP & Partial LOOP by Plant

Docket	LOOPs (L) or Partial LOOPs (PL), with Reactor Trip (W/T)	Reactor Years (1980-1994)	Frequency (LOOPs/RY)	Comments
387	7 PL, 2 W/T	12.4	0.56	2 events, without trip, caused by lightning arrester failure in construction substation.
298	4 PL	15.0	0.27	2 events related to cycling of breakers.
029	1 L, 1 W/T 2 PL, 1 W/T	12.2	0.25	
302	1 L 2 PL, 1 W/T	15.0	0.20	
499	1 PL	6.0	0.17	In low power physics testing at time.
395	2 PL	12.3	0.16	
277	2 PL	15.0	0.13	1 event occurred at refueling.
293	2 PL, 1 W/T	15.0	0.13	1 event, without trip, occurred at cold shutdown.
309	2 L	15.0	0.13	
456	1 PL, 1 W/T	7.6	0.13	
529	1 L	9.0	0.11	
382	1 L	10.0	0.10	Plant in mode 5.
416	1 PL	12.5	0.08	Occurred at 0% power.
213	1 PL	15.0	0.07	
220	1 L	15.0	0.07	
247	1 L, 1 W/T	15.0	0.07	

Table 3.2 (Cont'd)

Docket	LOOPs (L) or Partial LOOPs (PL), with Reactor Trip (W/T)	Reactor Years (1980-1994)	Frequency (LOOPs/RY)	Comments
263	1 PL, 1 W/T	15.0	0.07	
272	1 PL, 1 W/T	15.0	0.07	
278	1 PL, 1 W/T	15.0	0.07	
280	1 PL	15.0	0.07	Occurred at cold shutdown.
286	1 L	15.0	0.07	
306	1 L, 1 W/T	15.0	0.07	
315	1 PL	15.0	0.07	
324	1 PL	15.0	0.07	In refueling with no fuel incore.
328	1 PL	13.5	0.07	
331	1 PL	15.0	0.07	
333	1 PL	15.0	0.07	
348	1 PL, 1 W/T	15.0	0.07	
Mean	45 L & PL, 13 W/T	380.5	0.12	Averaged over above events.
Industry Mean	45	1409.4	0.03	Averaged over all U.S. operating nuclear plants, 1980-1994.

or emergency diesel generators starting and, perhaps, loading. Also involved were the shielding structures for buildings and shield wire at the switchyard station. In some cases, the reactors tripped. The lightning strikes initiating these events are usually (electrically) close-in to the plant and likely to strike the offsite power transmission lines or equipment in the switchyard. All of the 45 events in Table 3.2 were initiated at high voltage.

The components/systems involved in reactor trips without the loss of offsite power can have a different pathway, as shown by the 50 events in Appendix A Tables A.5 and A.6. Of these events, 18 were high-voltage related and the remaining 32 were low-voltage (i.e., <1000 V) related; these latter require some discussion. Eight of those events were related to lightning striking buildings, such as the containment (6) and the common turbine building (2). Where the lightning strikes occurred for the other 23 events was less specific, which is understandable because plants normally are not equipped with instruments to locate lightning strikes. Of the 32 events, 23 involved reactor protection systems such as control-rod drive mechanisms or power supplies, average power range monitor trip circuits, and nuclear instrument channels. In addition, 6 other events affected RPS input circuits. In general, lightning appears to have induced overvoltages at the lower elevations of the containment for most of these low plant voltage reactor trips.

Possible explanations given by licensees for these occurrences include: (a) a rise in ground potential from a lightning strike hitting the containment or a lightning rod array and being conducted into the building's ground mat where the potential rises, or a local strike that directly enters the ground mat with the same result, and (b) a lightning cloud passing over the station producing a ground potential rise and subsequent electromagnetic interference (EMI) coupling with the nuclear instrument cables causing voltage spikes that result in a trip. Other explanations in literature include: (1) passage of a lightning remnant (usually high frequency) through high voltage and low voltage transformers that was not shunted to ground by arresters (Ref. 3.11), and (2) rise in ground potential produced by lightning currents that were actually shunted by lightning arresters but entered the ground mat (Ref. 3.12). If there is a rise in ground potential in the grounding mat (from any of these mechanisms) and the mat is connected to the building's structural re-bar, the voltage will be conducted under the building, inducing voltages in cables at the containment's lower elevations. The generic result is that the induced voltage surge actually de-energizes the control-rod-drive power supplies momentarily. (A typical corrective action is to install surge suppressors in the DC control-rod power circuits and line conditioners in the AC system). For the 32 low voltage reactor trip events, 8 were classified as a failure of building shielding, 14 were considered caused by a rise in ground potential, and for the remaining 10, it was difficult to determine the most likely pathway.

At the high voltages, tripping of offsite power lines or grid undervoltages imply faults caused by lightning strikes. Unless there is a fault, there is no compelling reason for the protective relays to actuate a breaker trip for a strike on a phase conductor or an induced overvoltage from a nearby ground strike. For these cases, the arrester ensures that the withstand voltage of equipment damage is well within limits. If the arrester fails as a short circuit, the breaker will trip. Of the 45 LOOPs and partial LOOPs, 23 were classified as fault-related, 10 were physical failures of arresters, 2 were related to failures of the shield wire, 6 were arrester functional failures (although some components being protected were hit directly), and 4 were due to other causes.

Of the 31 reactor trips initiated on high voltage lines, 12 were classified as fault-related, 4 were undervoltages, 1 was related to the failure of a shield wire, 6 were physical failures of arresters, 8 were arrester functional failures (although there appeared to be some direct equipment hits) and 4 were due to other causes. Placing shield wire failures in the fault category and reclassifying these as transmission line shielding-related allows the following tabulation of results in terms of failures per reactor year over the 15 year period on an industry-wide basis (of 1409.4 reactor years):

High Voltage (Lightning Induced)	LOOP Events	LOOP Freq.	Reactor Trip Events	Reactor Trip Freq.
Physical Failure of Arresters	10	0.7 E-02	6	0.4 E-02
Functional Failure of Arresters	6	0.4 E-02	8	0.6 E-02
Transmission Line Shielding Failure	25	1.8 E-02	13	0.9 E-02
Other Cause	4	0.3 E-02	4	0.3 E-02
Total	**45**	**3.2 E-02**	**31**	**2.2 E-02**
Low Voltage (Lightning Induced)				
Building Shielding Failure	N/A	N/A	8	0.6 E-02
Ground Potential Rise	N/A	N/A	14	1.0 E-02
Indeterminate Pathway	N/A	N/A	10	0.7 E-02
Total	**N/A**	**N/A**	**32**	**2.3 E-02**
Totals	**45**	**3.2 E-02**	**63**	**4.5 E-02**

The tabulated data in Appendix A is sufficient to characterize the initiating event frequency for lightning in a PRA, but provides no insights on aging mechanisms for lightning arresters. In addition, this data does not identify whether the arrester is a gapped silicon carbide or a metal-oxide arrester, although it is more likely to be the former since the metal-oxide arrester was not introduced until the mid-1970s. The 12 arrester failures in Tables A.1 through A.5 and the 5 arrester failures in Table A.7 may have been end-of-life failures, and therefore, age-related. However, the LER and NPRDS records do not dwell on the failure mechanisms of lightning arresters, and treat them as fuses without identifying the engineering information. In addition, it is difficult to determine from these data bases high voltage switching surges and temporary overvoltages.

3.1.3 Other Evaluations

The Nuclear Safety Analysis Center (NSAC) provides annual reports on the losses of offsite power in U.S. nuclear plants (Ref. 3.10). Lightning caused LOOPs and partial LOOPs is one portion of all the external events that are evaluated. Some events identified are in addition to those documented in LER reports. NSAC also may clarify LER information in its data base by direct contact with the utility. We used the NSAC reports as cross checks in establishing the tabulated information. NSAC categorizes LOOPs and partial LOOPs, many of which last less than 30 minutes. Table 3.3 is a re-tabulation of the LOOPs and partial LOOPs of Table 3.2 after 30 minutes have expired. Unfortunately, in 10 of these

Table 3.3 - Lightning Caused LOOP & Partial LOOP Lasting More than 30 Minutes by Plant

Docket	LOOPs (L) or Partial LOOPs (PL), with Reactor Trip (W/T)	Reactor Years (1980-1994)	Frequency (LOOPs/RY)	Comments
387	6 PL, 1 W/T	12.4	0.48	2 events, without trip, caused by failure of lightning arrester in construction substation. Outage time not stated but likely to be greater than 30 minutes. Transmission line outage time not stated for other 4 events but likely to be of very short duration since faults were momentary.
499	1 PL	6.0	0.17	In low power physics testing at time. Offsite power to Unit 2 startup transformer lost and switchover to Unit 1 startup transformer occurred 32 minutes later. Unit 2 startup transformer outage time not stated but a lightning arrester had failed.
395	2 PL	12.3	0.16	
298	2 PL	15.0	0.13	Lightning arresters failed in one event.
302	1 L 1 PL	15.0	0.13	One event occurred at 0% power.
456	1 PL, 1 W/T	7.6	0.13	
529	1 L	9.0	0.11	
382	1 L	10.0	0.10	Plant in mode 5.
029	1 PL	12.2	0.08	
416	1 PL	12.5	0.08	Occurred at 0% power. Transmission line outage time not stated.
277	1 PL	15.0	0.07	Event occurred at refueling.
293	1 PL	15.0	0.07	Event occurred at cold shutdown.
309	1 L	15.0	0.07	Lightning arrester failure.

Table 3.3 (Cont'd)

Docket	LOOPs (L) or Partial LOOPs (PL), with Reactor Trip (W/T)	Reactor Years (1980-1994)	Frequency (LOOPs/RY)	Comments
213	1 PL	15.0	0.07	
247	1 L, 1 W/T	15.0	0.07	Shield wire failure.
263	1 PL, 1 W/T	15.0	0.07	Transmission line outage time not stated for supply that had insulator failure but Station has 3 sources of offsite power and successful bus transfer was made in 5 seconds.
272	1 PL, 1 W/T	15.0	0.07	Transmission line outage time not stated. Lightning arrester damage.
278	1 PL, 1 W/T	15.0	0.07	Transmission line outage time not stated. Manual closure of startup breaker by operator.
280	1 PL	15.0	0.07	Occurred at cold shutdown. Lightning arrester failed.
286	1 L	15.0	0.07	Shield wire failure.
306	1 L, 1 W/T	15.0	0.07	
315	1 PL	15.0	0.07	
328	1 PL	13.5	0.07	
348	1 PL, 1 W/T	15.0	0.07	Lightning arrester failure.
Mean	32 L & PL, 8 W/T	320.5	0.10	Averaged over above events.
Industry Mean	32	1409.4	0.02	Averaged over all U.S. operating nuclear plants, 1980-1994.

events the utilities did not supply in their LER submittal the transmission line outage time, so Table 3.3 will have to be revised. In general, a partial LOOP caused by an arrester failure is likely to last more than 30 minutes because the predominant failure mode is a short circuit, and replacement of the arrester is necessary.

The NRC evaluated lightning-related events using an LER data base for the years 1980 to 1991 (Ref. 3.13) and came to the following conclusions:

(1) The most significant impact on plant operations that may be caused by lightning is from the effects of local strikes, i.e., strikes that hit buildings or local structures, which result in ground potential rise.

(2) It appears from the LER reports that the pathway of high-frequency remnants remaining after arrester operation at high voltages and then capacitively coupled through transformers to lower voltages does not cause significant misoperation of, or damage to equipment.

(3) Damage or misoperation of equipment resulting from local strikes does not appear to create a significant risk to plant safety.

3.2 Suppressors

Surge suppressors are surge protective devices (SPDs) used with many low voltage components and systems such as relays, power supplies, inverters, voltage regulators, battery chargers, uninterruptible power supplies, line conditioners, circuit breaker coils, adjustable speed drives, digital and signal circuits. Their variety was discussed in Section 2. When reviewing the LERs and NPRDS narratives, it is not always clear when a surge suppressor is identified as failed (in addition to the component that failed) whether it is a metal-oxide varistor, avalanche diode, thyristor diode, sealed spark gap, or filter. In addition, in some failure narratives, pieces of a suppressor may be identified, but they lack sufficient detail to be distinguished from the normal operating portion of the circuit. Since neither the SCSS nor NPRDS adequately treat surge protective devices as components, it is difficult to establish either a failure or an age data-base. The only reference found that included some failure data on surge protective devices was the Griffiss Air Force Base Reliability Analysis Center's "Nonelectronic Reliability Data Base", 1991 edition (Ref. 3.4) with the following information:

FAILURES PER MILLION HOURS

SURGE ARRESTER		SPARK GAP	ARRESTER TUBE
9.26 (Airborne Env.)	3.15	0.05	(Benign Env.)

Birrell and Standler (Ref. 3.2) state that General Electric has sold more than 300,000 secondary arresters (called suppressors in this report) rated for 650 V service that contain metal-oxide varistors since their introduction in 1984, and, there have been fewer than 60 reported failures including misapplication by the user. This information gives a very low failure rate of 4 E-05 per year. The 1993 paper by Lai and Martzloff (Ref. 3.3) indicates that millions of small suppressors have been installed within equipment, or as plug-in devices, and have only sporadic and anecdotal reports of problems.

In this study, two approaches were taken to determine whether a data base on surge protective device aging/failures could be developed from LER and NPRDS records. The first approach attempted to identify component failures due to overvoltage switching surges, taking the position that a surge protective device could have prevented them (whether or not it was in the circuit to begin with). This approach was abandoned because components eventually fail due to age despite a suppressor's ability to shunt or filter overvoltages during switching surges. The second approach was to use a key word search and subsequently evaluate the sample of about 2000 LERs and several hundred NPRDS records for: (a) surge suppressor failures, and (b) proposed corrective actions that included adding surge suppressors to electrical circuits. The ideas in this approach were to (1) simply identify surge suppressors that had failed in-service and obtain any age-related information from the data records, and (2) identify problems that arose subsequent to the plant commencing operation where surge suppressors could be used as part of the solutions. Although this second approach did not give an aging data base, due to the problems discussed throughout this Section, it identified the relative risk importance of surge protective devices.

In addition to searching on key words such as "suppressor", other searches included "electromagnetic interference", "radio interference", and "electrostatic discharge" when accessing SCSS and NPRDS. After assembling all the records, they were reviewed to find those that clearly dealt with either a suppressor failure or the use of a surge protective device as a corrective measure. In Appendix B, Table B.1, 41 suppressor failures are identified, while Table B.2, which deals with proposed corrective actions, shows 45 uses for surge suppressors for plant problems. Three (3) of the 41 suppressor failures caused reactor trip at power. However, there were no suppressor failures identified that would have prevented a reactor trip from occurring, if a trip was required. Table 3.4 is a condensed summary of some common corrective actions using surge protective devices. (Additional details are given in Appendix B).

Some nuclear plants may be located in areas of the United States where lightning is not a serious concern. However, all plants have to deal with low voltage switching surges, voltage spikes, and noise spikes from operating equipment. The number of reactor trips and half scrams identified in the LERs at cold shutdown, shutdown, just critical, and initial ascent, are legion. The number of spurious signals generated by radiation monitors that actuate engineered safety features at any power level also is large. The solutions to these overvoltages that cause zero-power reactor trips and ESF actuations include: (1) applying surge protective devices; (2) considering the spatial layout of equipment and cable runs to avoid inducing electromagnetic interference (EMI); (3) having adequate equipment grounding; and, (4) protecting against a rise in ground potential level from lightning.

Although three suppressor failures were identified as causing reactor trips at power, their function is to prevent other devices from malfunctioning or degrading as a result of overvoltages. For example, in addition to protecting power supplies to the control rod drive, suppressors can extend the life of inverters by reducing their degradation from overvoltages, and thus increase the age at which an inverter failure could cause a reactor trip. Other important equipment to be protected includes power supplies for RPS channels, inverter sections of uninterruptible power supplies, battery chargers, controllers, voltage regulators, and digital circuits. Some electronic circuits may have all 3 categories of suppressors installed; crowbars, clamps, and isolators. To be effective, the age or calendar life of the suppressor should be known. It is difficult to determine age-related failures of suppressors from the LER and NPRDS data bases. If a suppressor fails as a short circuit, the fuse in the electronic circuit should blow. However, it would be too conservative to equate the life of a fuse to the life of a suppressor because other failures of components in the circuit could cause the fuse to blow. If the fuse does blow, it is always worthwhile to test the suppressor(s).

Table 3.4 - Summary of Common Corrective Actions

Phenomena	Component Failure or Upset	Typical Corrective Action
Lightning remnant or lightning overvoltage strikes power supplies of control rod drive system (CRDS).	Electrical surge either shuts down or de-energizes the CRDS power supplies.	(1) Add surge suppressors to input power supplies of CRDS. (2) Add time delay to rod drive cabinet overvoltage protection device.
Rod control system pulse to analog DC stepper motor noise.	Intermediate range channel received high startup rate.	Noise suppression devices of diodes and resistance-capacitor filters.
Opening of DC motor operated valve caused electromagnetic interference.	Intermediate range channel received spurious hi-hi signal.	Installed metal oxide varistor in motor valve circuitry.
Relay actuations external to neutron monitoring system produced noise.	Intermediate range channel tripped on hi-hi neutron flux.	Installed noise suppression circuitry in IRM circuits.
Source range monitor drive relays were chattering during withdrawal causing noise.	Intermediate range channels gave RPS actuation.	SRM/IRM drive relays are now installed with arc suppression.
De-energizing scram relays induced voltage.	Intermediate range channel spiked upscale and tripped.	Metal oxide varistors installed across coils of associated scram relays.
Electrical noise generated in annunciator cabinet, or by reset push buttons.	High startup rates on nuclear instrumentation channels.	Suppressor diode installed across the auxiliary relay coils.
Noise spike on radiation monitor.	Containment ventilation system isolated, or control room ventilation isolated and emergency ventilation initiated.	(1) Add time delay relay circuitry to containment ventilation actuation circuitry, and, (2) add surge suppression devices or capacitor filtering or resistor-capacitor filters to radiation monitor circuits.
Surveillance testing of sample flow switches caused electromagnetic interference.	Process radiation monitor initiated isolation of control room ventilation.	Install arc suppressors in the flow switch circuits to prevent high radiation trips from EMI induced spikes on radiation monitors.

3.3 Stressors

The aging characteristics are discussed below for the metal-oxide varistor (because of its present widespread use in industry) and the gapped silicon carbide arrester (because it is likely to be found in many nuclear plant switchyards). Succinct summaries of age-related failure mechanisms for the other surge protection devices listed in Table 3.5 also are presented.

3.3.1 Metal-Oxide Surge Arrester

The application of metal-oxide surge arrester/suppressor (Ref. 3.14 to 3.19) spans the complete range of overvoltage protection. At transmission and station voltages, it is referred to as a metal-oxide surge arrester, while at plant distribution voltages, it is known by the more generic name of metal-oxide varistor. Varistors are fabricated by a ceramic sintering process that produces a structure comprised of conductive metal-oxide (usually Zinc Oxide) grains surrounded by electrically insulating barriers composed of other metallic elements. Varistors are inherently multijunction grain-boundary devices and any transient surge energy absorbed is distributed between the many ZnO intergrannular barrier heterojunctions. In station class arresters, the ceramic blocks (or disks) are stacked and connected to electrodes. The cross-sectional area of the valve blocks is approximately proportional to the energy the disk must dissipate in a high energy operation, and the length of the block is approximately proportional to its voltage rating. The failure mechanisms are somewhat complex.

Microcracking of the blocks can occur from sudden joule heating. Subsequent strikes may tend to concentrate in such areas. At higher energy densities, this failure mechanism can become catastrophic with the blocks splitting apart from localized overheating, resulting in mechanical/ dielectric puncture or shattering. In present-day arrester designs, this is the onset of a major failure mechanism that is generally referred to as thermal runaway. A punctured pathway will at first cause degradation by changing the resistance of the blocks; high in the puncture-space but lower on the grain boundary edges surrounding the puncture. Additional strikes will concentrate in the puncture pathway with the resistances of the grain boundary edges continuing to decrease making it more difficult to dissipate heat. Eventually, the arrester fails by flashover along the path, i.e., a short circuit failure, while the degradation phase exhibits an increase in internal "trickle" current but no loss in protection.

If the blocks shattered or were severely cracked by a high energy strike, the grain boundary orientations will change. Although the damaged arrester may flashover with the next lightning strike, its conduction characteristics, clamping voltage, volt-ampere characteristic and other properties will have changed. Hence, when the next lightning strike flashes-over, a portion of the strike energy will pass downstream because of changes in the clamping voltage and conduction characteristics of the arrester. The damaged arrester has become a partially open circuit, i.e., it is not shunting as much energy to ground as it did when intact. Similarly, an arrester that failed as a short circuit from thermal runaway, that was cleared by a reclosing circuit breaker, may also appear as a partially open circuit to the next strike (provided the arrester short disappeared).

Although thermal runaway can happen under normal and contaminated conditions, it is likely to be an end of life phenomena also because the ZnO grain boundary properties deteriorate with time, or age such that the grain boundary resistance decreases allowing greater heat production. Pressure relief devices are installed in arrester housings to relieve the heat and atmosphere produced by catastrophic events such as thermal runaway. Other arrester failure mechanisms include: (1) installation error in which the blocks were improperly matched in a stack; (2) collar failure from electrical corona stress

Table 3.5 Failure Modes, Causes, and Effects for Surge Arresters and Suppressors

Component	Failure Mode	Failure Cause	Aging	Failure Effect
Metal- Oxide Varistor	a) Short Circuit b) Degradation c) High Clamping Voltage	Age, Thermal runaway, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y Y N P P P	a) Resistance 100Ω at 1 Vdc b) Voltage ⟨90% of pretest c) Clamping voltage ⟩120% of pretest
Avalanche Diode	a) Short Circuit b) Degradation c) High Clamping Voltage d) Open Circuit	Age, High current, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y Y N P P P	a) Resistance ⟨1Ω at 0.1V dc b) High stand-by current c) Clamping voltage ⟩120% of pretest d) Breakdown voltage ⟩150% of pretest V
Switching and Rectifier Silicon Diodes	a) Degradation	Age, Surge currents, High reverse current, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y P P Y Y N P P P	a) Decrease in reverse-breakdown voltage
Gas Tube Electrodes	a) Short Circuit b) Low Breakdown Voltage c) High Breakdown Voltage d) Low Insulation Resistance e) DC Holdover	Age, Follow current, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y P Y Y N P P P	a) Loss of vacuum b) DC breakdown voltage less than design c) DC or impulse breakdown voltage less than design d) Insulation resistance ⟨1 MΩ e) Time for follow-current turnoff greater than design

Table 3.5 (Cont'd)

Component	Failure Mode	Failure Cause	Aging	Failure Effect
Air-Gap Protection Devices	a) Short Circuit b) Low Breakdown Voltage c) High Breakdown Voltage d) Low Insulation Resistance	Age, Conducting surges, Electrode gap degradation, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y P Y Y N P P P	a) Loss of electrode gap b) DC breakdown voltage ⟨design (180 v @10 mA) c) DC or impulse breakdown voltage greater than design d) Insulation resistance ⟨1 MΩ
Thyristors	a) Degradation	Age, Conducting surges, Thermal degradation, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y Y Y N P P P	Gate trigger or Holding current greater than design
Optical Isolators	a) Degradation	Age, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y N P P P	a) Decrease in LED brightness
Isolation trans-formers	a) Degradation	Age, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y N P P P	a) Degradation of electro-static shield dielectric strength; or degradation of insulation resistance
Common Mode Filters	a) Degradation	Age, Irradiation hardening, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y N P P P	a) Dielectric breakdown in capacitors; insulation breakdown and inductor arcing

Table 3.5 (Cont'd)

Component	Failure Mode	Failure Cause	Aging	Failure Effect
Metal-Oxide Surge Arresters	a) Short Circuit b) Degradation	Age, Thermal runaway, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y Y N P P P	a) Circuit breaker trip b) Increased leakage current to ground
Gapped Silicon-Carbide Surge Arresters	a) Short Circuit b) Degradation	Age, Environmental degradation, Material defect, Insulation degradation, Degraded connections, Defective circuit.	Y Y N P P P	a) Circuit breaker trip b) Loss of housing tightness; spark-gap wear; or degraded element resistance from wear

caused by strikes (or normal-service aging); and, (3) manufacturing and assembly defects; of these, only the second would be considered an aging mechanism. Publications suggest that the predominate failure mode for metal-oxide surge arresters is a short circuit, but an open circuit mode cannot be ruled out entirely. IEEE Standards C62.11-1987 and C62.22-1991 (the standard and application guide, respectively) do not specifically identify any failure modes.

Environmental conditions may also cause failures. Partial discharge inside the arrester's housing may be caused by the difference between the voltage distribution in the internal blocks and a non-uniform voltage distribution in the external housing from pollution, such as adhering salt layers. Another mechanism related to severe polluting conditions is a rise in temperature from uneven voltage distribution created by surface leakage currents that could reach a certain temperature limit above which the arrester is not thermally stable. In addition, moisture inside the housing over a long period under ionizing potential may chemically react with the ZnO. The introduction of polymer housings and rigorous standards testing have tended to minimize these particular failures. However, external failure (flashover) of the arrester's housing may occur from the combined effect of accumulation of contaminants on the arrester, and conditions of wet snow, frost, light rain, or fog.

Age for a metal-oxide arrester is strongly related to the number of overvoltage pulses and their duration that it will shunt to ground during its use. A pulse rating is the number of isolated pulses that an arrester can absorb until its specification rating is reached. Reference 3.20 illustrates pulse rating with several examples. One example shows that a varistor can absorb 5000 pulses of 100 ampere peak and 100 microsecond duration overvoltages, but can absorb only one pulse of 100 ampere peak and 1000 microsecond duration. Therefore, the age of an installed varistor is likely to be nonlinear and dependent on the application. Another aging process which increases the trickle current is an increase in nominal voltage above the maximum continuous operating voltage rating of the arrester.

3.3.2 Low Voltage Metal-Oxide Varistors (Ref. 3.21)

The modes of failure of metal-oxide surge arresters and suppressors (or metal-oxide varistors) are similar. If the increase in energy deposition of the varistor proceeds more rapidly than the varistor can dissipate heat to the environment, its temperature will increase until it is destroyed by the thermal runaway mechanism; this mechanism causes a short circuit, which appears to be the dominate failure mode. If an under-sized varistor is used in an application, and a large surge current passes through it, it could literally explode from the short circuit current and become an open circuit. Similar to the arrester, a varistor could shatter or severely crack from high energy deposition. The varistor is likely to flashover with a power follow arc established between the electrodes during the next strike but its material properties will have changed and it would appear as a partially open circuit. It is difficult to identify a pure open circuit failure mode for metal-oxide varistors and metal-oxide surge arresters for other than human-error-related events. However, some small-diameter varistors, which initially fail as a short circuit, are likely to promptly fail as an open circuit, owing to the passage of large continuous currents.

IEEE Standard C62.33-1982 identifies three failure modes:

- Short Circuit - Varistor resistance is permanently reduced to 100 Ω at 1 VDC.
- Degradation - Varistor voltage < 90% of pre-test voltage.
- High clamping voltage - Clamping voltage > 120% of pre-test clamping voltage.

3.3.3 Gapped Silicon Carbide Surge Arresters and Varistors

The gapped silicon carbide surge arrester preceded the metal-oxide surge arrester and is more likely to be found in nuclear plant switchyards since the metal-oxide varistor at high voltage was not marketed until the mid-1970s. That situation is also true at plant distribution voltages where silicon carbide varistors in series with an air gap were likely installed since metal-oxide varistors were not marketed at those voltages until the early 1980s. In general, the major causes of failure relate to flashover from ambient environment intrusion into the housing, and voltage stresses causing wear of the spark gap and valve element resistance. Significant wear of the spark gap can cause an open circuit. (A similar open circuit failure mode is possible with gapped metal-oxide surge arresters).

Nonlinear valve blocks made of silicon carbide and a high-temperature bonding system were used extensively in station arresters over a long period before the introduction of metal-oxide arresters. The voltage across these blocks was roughly proportional to current within the range of 3 to 6, depending on the grain of the silicon carbide and its bonding and firing. Most of the changes to the product were made to improve its discharge capability because protective levels on switching surge waves were too high for many of these operations to occur. The volt-ampere characteristic of this class of surge arresters is much more linear than metal-oxide units. To prevent steady-state conduction, a spark gap is connected in series to form the arrester. However, when used in low voltage distribution circuits, a series spark gap may produce a relatively large remnant of overvoltage that propagates downstream from the varistor, and consequently, is unsuitable as the sole device for protecting electronic systems.

In the earlier designs, arrester failures caused by external contaminants, such as salt or industrial pollutants, began to appear with a frequency sufficient to cause alarm to the designers. Several measures were implemented including increasing the arrester's grading current, modifying sparkover circuitry, and increasing the creep lengths of the housing. It was found that using a single housing instead of multiple ones reduced the effect of external contaminations to some degree by eliminating paths for transfer of external leakage current to the interior of the arrester through the metal and fittings of the multiple housings.

3.3.4 Other Surge Protection Devices

- **Avalanche Diode or Avalanche Junction Semiconductor**

For avalanche diodes or avalanche junction semiconductors, aging is a change in the silicon material properties due to conducting surges while in-service. IEEE (Ref. 3.22) identifies: (1) a degradation failure-mode in which the standby current is greater than the maximum specified; (2) a short circuit failure-mode in which the device is permanently shorted with a resistance of less than 1 ohm at 0.1 VDC; (3) an open circuit failure-mode in which the breakdown voltage is greater than 150% of the pre-test value at an applied test current; and, (4) a high clamping voltage failure-mode in which the clamping voltage is greater than 120% of the pre-test value.

- **Switching and Rectifier Silicon Diodes**

The concern about these diodes is that there will be an increase in reverse voltage (or high reverse current) that can cause rapid failure. Diodes usually fail by short circuit. Silicon diodes do not exhibit as much degradation of electrical parameters after prolonged service compared to gas tubes or varistors.

- **Gas Tubes (or Sealed Spark Gaps)**

Gas tube electrodes, especially the cathode, are depleted with surge current operation. The glass or ceramic tube seal may leak which will change their conduction characteristics. Large internal pressure can be generated by a combination of a degraded electrode and conducting gas at high temperature which can shatter the tube. Sealed spark gaps may have a higher ratio of peak fault current to available rms current than varistors. Because of the possibility of sustained power follow current after conduction, spark gaps alone are usually not directly connected across AC supply terminals nor DC supply buses greater than about 20 V. A current-limiting device must be inserted in series between the spark and source of the follow current.

- **Air Gap Surge-Protective Devices**

The air gap electrodes will erode with use, and thereby increase the distance between electrodes; this widening means that a larger voltage is needed to conduct a surge. In addition, debris may be generated within the gap during ignition and conduction, and settle on the electrodes causing erratic conduction. In addition to a short circuit failure, the IEEE identifies: (1) a low DC breakdown voltage, (2) a high DC breakdown voltage, and, (3) a low insulation resistance of less than 1 MΩ.

- **Thyristors - Silicon Controlled Rectifiers and Triacs**

Surge currents eventually will degrade thyristor material properties but the PNPN structure makes its lifetime relatively longer than other crowbars. Degradation failure modes include an increasing gate trigger current or increasing holding current. Its predominant failure mode is a short circuit.

• **Optical Isolators**

The light source in nearly all modern optical isolators is an infrared light-emitting diode (LED), and failure mechanisms for LEDs include a loss of brightness and a high reverse voltage. A protective circuit of a spark gap and avalanche diode is normally used with a LED.

• **Isolation Transformers**

Failure mechanisms of isolation transformers include degradation of dielectric strength, and loss of insulation resistance of the electrostatic shields between the primary and secondary windings.

• **Common-Mode Filters**

Degradation failure mechanisms include dielectric breakdown of capacitors and insulation breakdown and arcing in the filter inductors. As stated previously, a gas tube or a varistor is usually used with the filter because the voltages and currents in severe transient overvoltages can overwhelm filters while the suppressor device can conduct them away.

3.4 Analysis of Failure Modes, Effects, and Causes

As a supplement to the operating data review, an analysis of Failure Mode, Effect, and Cause (FMECA) (Table 3.5) was made for each of the primary types of surge arresters and suppressors. Each FMECA included the following items:

a) Failure Mode: The basic manner(s) which a surge arrester or suppressor may fail or cease to perform as designed. The failure modes for these components were consistent with those used in industry standards (e.g., IEEE).

b) Failure Cause: The particular type of degradation mechanisms which may cause the surge arrester or suppressor to fail.

c) Failure Effect: The effect upon the operating and design characteristics of the component due to its degradation or failure.

d) Aging: A subjective assessment on the effect of aging upon the individual causes of failure. In some instances, the cause of failure may, or may not be due to aging, and these were classified as potentially aging (P).

Since the primary function of these components is to protect electrical devices from electrical surges, it is essential that they are maintained so that they function as designed when required. An important facet in assuring this is to understand the various aging failure mechanisms, and to be able to detect these before component failure.

The majority of the possible failure causes are, or potentially are, age related. Environmental degradation, due to the adverse affects of temperature, humidity, dirt, and radiation, also is a significant cause of their failure. A review of the failure effects for surge arresters and suppressors indicates that changes in one, or more, of the operating characteristics may be indicative of failure. Monitoring of these characteristics periodically may assure the operability of these components.

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4. INSPECTION, SURVEILLANCE, MONITORING, AND MAINTENANCE

4.1 Surveillance Testing of Arresters

Discussions with several electrical utilities suggested that they do not have formal surveillance programs for testing surge arresters, and in fact, they are only tested when the utility has reason to believe they may be faltering. An electric utility consultant indicated that some of its clients may test arresters at a 3-, 5- or 10-year frequency. Historically, the gapped silicon carbide surge arrester, and to the extent it was specified for the metal-oxide surge arrester, was supplied with a counter and monitor. The monitor gives a long-term indication of the arrester's internal working condition and its external cleanliness. The discharge counter provides data on system conditions by recording the number of voltage surges on the circuit on which it is installed. The reliability of counter/monitor devices on arresters has been questioned, however, because of frequent problems such as no readings of leakage/grading current flowing from the arrester base to ground, erratic current readings, or suspected failure. Appalachian Power Company (Ref. 4.1) described a new diagnostic approach for increasing the dependability of the counter/monitor. The method consists of using a portable kit to test the counter/monitor devices before they are installed and periodically thereafter when routine insulation testing is performed. However, not all utilities use such a scheme.

Many utilities today use the "dielectric-loss (or watts loss)" method (Ref. 4.2) which compares a benchmark reading of dielectric loss in terms of watts lost when the arrester was new and then compares that with the presently tested value. Either an increase or decrease in watts loss can indicate aging of the arrester material, provided that other factors such as internal or external contamination are not causing the changes. Therefore, the dielectric loss method can be effective in detecting defective arresters, provided that the analyses separate the effects of contamination from that of aging. The following are examples of conditions found in the field, reported in Reference 4.2:

- Higher-than-Normal Losses

1. Contamination by moisture and/or dirt or dust deposits on the inside surfaces of the porcelain housing, or on the outside surfaces of sealed-tap housings.
2. Corroded gaps.
3. Deposits of aluminum salts apparently caused by the interaction between moisture and products resulting from corona.
4. Cracked porcelain.

- Lower-than-Normal Losses

1. Broken shunting resistors.
2. Broken pre-ionizing elements.
3. Mis-assembly.
4. Poor contact and open circuit between elements.

EPRI recently evaluated various testing methods for metal-oxide varistor arresters (Ref. 4.3). At the end of 1992, EPRI was in the process of confirming its hypothesis that the only reliable method for evaluating the in-place failure of a metal-oxide varistor arrester in the field, e.g., a cracked block in a stack, was to observe its characteristics during conduction from a surge voltage, such as a 10kA impulse test, which could be monitored on-line for each varistor in-service. If a block is cracked, it will flashover at this impulse level. Lower impulse levels will not cause a flashover, even though the block is cracked. Other testing methods evaluated by EPRI included:

(1) Harmonic Analysis of Leakage/Conduction Currents.

A significant increase in (the fifth) harmonic current without a corresponding increase in bus voltage can indicate (a) a change in the conduction characteristics of the metal-oxide, and, (b) unbalanced voltage distributions caused by layers of pollution on the outside shell, or moisture inside the shell or on the block collars. Age corresponds to (a) and internal contamination to (b).

(2) Increased Radio Interference/Partial Discharge Production

If radio noise can be tested simply, it is likely that fragmented blocks inside an arrester's column might be creating the noise. However, the lack of radio noise does not necessarily mean that the column is undamaged. Some crack configurations may not produce detectable noise.

(3) Unbalanced Current/Energy Monitoring of Parallel Columns.

The EPRI program also evaluated parallel columns of stacked blocks of metal-oxide varistors, such as those used for protecting capacitor banks. By far the most feasible way to detect unbalanced operation of parallel columns was to compare the currents through the columns. The approach recommended is to separately compare the currents and the integral of the currents of every varistor column using Rogowski coils to determine the unit current and having a monitoring scheme that determines the change in energy per unit time.

(4) Field Tests of Varistors with Portable Equipment.

In one method, a known voltage is applied to a varistor column to collect a current signature which then is kept in a digital data base. At intervals of perhaps once per year, the varistor is again tested with the same equipment and the signature compared with the previous one. This scheme can provide information on aging, and possibly, major changes in the block's characteristics. Another method uses a portable impulse generator that can attain higher crest currents than a 60 Hz test and, with other things being equal, is the preferable technique.

4.2 Surveillance Testing of Suppressors

The surveillance testing of surge suppressors in safety-related systems or components is not identified in plant technical specifications. Therefore, if the surge suppressors are to be tested, it would be done in accordance with plant procedures. Test procedures may be developed from manufacturers' application catalogs. The types of information needed for initial benchmark testing are, for a metal-oxide varistor: nominal varistor voltage, maximum clamping voltage, standby current, capacitance as a function of frequency, pulse rating, power dissipation rating, continuous voltage rating, and continuous power dissipation (Ref 4.4). The suppressor would be tested in the laboratory using relatively simple circuits and inexpensive equipment.

Vendors of test equipment have published guidance on testing surge suppressors (Refs. 4.5, 4.6) and there are technical papers (e.g., Ref. 4.7) that use standards as a basis for performing in-situ tests of SPDs in panel units or plug-in units. A nuclear plant likely uses several hundred surge suppressors but it is unknown how frequently they are tested; possibly, they are only tested on circuits that failed or have a pattern of failure because testing all of them, in addition to normal surveillance testing, would create a timing bottleneck. The fallback position for preventing failure would be to ensure that qualification testing, using the IEEE standards (Ref. 4.8) and Underwriters Laboratories, Inc. performance standards, was performed on the suppressors before installation, and that they were appropriately coordinated with other upstream suppressors and arresters.

4.3 Synopsis of Arrester and Suppressor Testing

There does not appear to be any uniform approach taken by the utilities for testing surge arresters. Testing frequency could be based on some surveillance interval or on an as-needed basis, as determined by the utility. The testing could make use of the counter/monitors for older arrester designs, or use the dielectric-loss method, or perhaps, adapt some of the recently developed EPRI testing schemes. What is still missing are data bases on failure for the surge arresters which include their wear-and age-related failure rate.

There is no formal requirement for testing surge suppressors at a regular frequency. Consider an example where there are a large number of switching transients at lower voltages and the protecting suppressor will receive many pulses to divert. Some time after installation, some kind of testing (or indication of the number and strengths of prior pulses that the suppressor successfully diverted) would be necessary to predict how many more it could take before it failed due to age. Alternatively, it may be practical, for some applications, to develop a disturbance detector circuit (Ref. 4.8) that can count the pulses and trigger a digital waveform recorder, thus giving the information needed for an aging calculation, and then removing the suppressor before it fails.

4.3 References

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5. EMTP SIMULATION OF SURGE ARRESTER OPERATION

To evaluate the potential effects of aging degradation of SPDs, several simulations were performed using the Electromagnetic Transients Program (EMTP). These simulations used various system and arrester configurations and conditions. This Section gives a brief overview of the EMTP program, provides details on the analysis which considered lightning strikes and switching surges as transient initiators, and summarizes the results of these simulations.

5.1 Electromagnetic Transients Program (EMTP) (Ref. 5.1)

EMTP is recognized by the power industry as the only digital simulation program specifically designed to analyze power-system transients. It has a structure and library of component models well-suited for various types of investigations. This program initially was developed by the Bonneville Power Administration (BPA) in the late 1960s to study the effect of lightning surges on high voltage transmission lines. It has been used to analyze high-frequency phenomena (e.g., switching surges) and low-frequency phenomena (e.g., subsynchronous problems). EMTP usage generally falls into two main categories: system design, and analysis of operating problems. System design includes areas such as insulation coordination, specification of equipment ratings, protective device specifications, relay and control system design, and harmonic filter selection. Operating problems include system outages, equipment failures, harmonics and resonance, fault analysis, and voltage instability. The EMTP contains SPD models (i.e., arc gaps and zinc-oxide surge arresters), and numerous power-system models suitable for the detailed simulation of electrical distribution systems.

Since its initial development at the BPA, on-going efforts have modified and improved the original version (i.e., increased the number of modelling modules and specific applications, and improved the output capability). These improvements were made by EPRI and a Canadian/American (CAN/AM) User Group. The EPRI version, developed by the EMTP Development Coordinating Group, is referred to as the DCG version, and the CAN/AM version is known as the Alternate Transients Program (ATP). The DCG version is available to EPRI members, while the ATP version is available, royalty free, in the United States and Canada through the CAN/AM User Group. Both can be used on PCs. The ATP version was used for this SPD analysis.

5.2 EMTP Simulation Models and Results

Figure 5.1 is a simplified EMTP simulation model used in the surge arrester operation studies (Ref. 5.2), and represents the essential features of both safety and non-safety related systems. The normal operating system configuration includes the normal station-service transformer which feeds the non-safety related network, and the reserve station-transformer feeding the safety-related emergency system. Both the normal and reserve transformers were modelled in full three-phase winding detail, including losses, leakage reactance, winding capacitance, and magnetic saturation. Though the two systems are not coupled; the potential for coupling is provided at the transmission level in the offsite power system.

For the non-safety related system, the normal station-service transformer feeds the 13.8 kV buses B001 and B003. Bus B003 supplies two 12,000 HP pump motors, a static equivalent of several other motors, and a static equivalent of several 600 V loads connected through the 13.8 kV/600 V delta-wye transformers. The 12,000 HP motors are modelled in full transient detail as three-phase rotating machines, including losses, magnetizing current, and rotor/load inertia. Bus B003 also feeds two 4.16 kV buses (Bus B013 and B015) through a delta-wye transformer. These buses are loaded with static

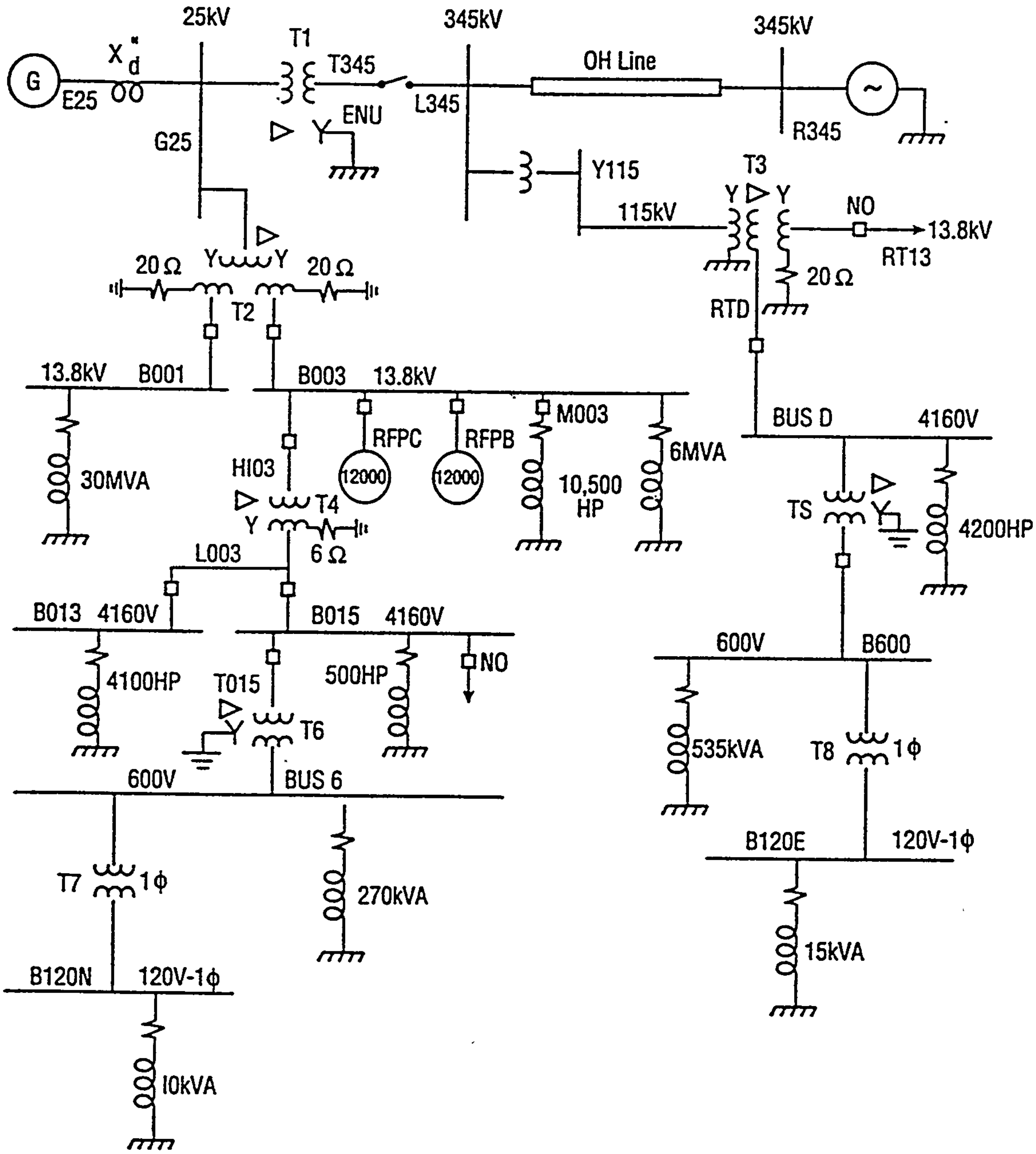

Figure 5.1 EMTP simulation model

equivalents of several additional motors, and Bus B015 also feeds a 600 V bus (BUS6) through another delta-wye transformer. In turn, BUS6 supplies a 270 kVA static equivalent load, and feeds a 120/240 V bus (B120N) through a single-phase transformer, which supplies power to fire protection panels and miscellaneous control circuits.

For the emergency system, the reserve station transformer 4.16 kV winding supplies the Division II main bus (BUSD). This bus, in turn, feeds several 600 V buses and distribution panels, which are represented by the equivalent bus B600. B600 feeds a static equivalent 535 kVA load, and supplies a 120 V bus (B120E) through a 25 kVA single-phase transformer. Bus B120A is an emergency relay supply panel. Specific model data for the simulation is included in Appendix C.

For this simulation, the system was assumed to be initially operating approximately at rated voltage on all buses, with approximately 1 per-unit (p.u.) real power flowing on the 345 kV transmission line out of the station. Four surges (2 lightning pulses and 2 switching surges) were modelled. The lightning surges used were a 10 kA 8/20 μsec current pulse applied to node T345 (Fig. 5.1), and a 1350 kV 1.2/50 μsec. voltage pulse applied at the center of the transmission line; these energies are equivalent to standard IEEE tests. One switching surge was induced by closing in the transmission line on the sending end, with the remote system disconnected. The second type of switching surge was produced by line-to-ground faults internal to the plant distribution system.

Table 5.1 summarizes the results for all the buses in the plant upon applying both lightning pulses at bus T345. The nominal system voltages and typical basic impulse insulation level (BIL) of the various voltage classes are also shown. The per-unit (p.u.) values are based upon peak line-to-neutral system voltages shown for each bus. Without the surge arresters, overvoltages range from 1.97 to greater than 200 p.u. Conversely, with surge arresters, the overvoltages are reduced to a maximum of 2 p.u. Without surge arresters, the overvoltages tend to be greatest on the emergency bus, probably due to the light loading which provides less natural damping to the lightning surge, though it also depends upon the various high-frequency circuit oscillations which are excited by the transient. This finding implies that the emergency system may be more prone to failure or stress on the lower voltage arresters, if an arrester open-circuit failure were to occur at the transmission level. The overvoltages on buses B120N and E demonstrate the ease with which the lightning surge propagates to the low voltage circuits.

Table 5.2 also summarizes the results obtained when a 1350 kV 1.2/50 μsec. lightning voltage pulse (Lightning surge 2) is applied at the center of the 345 kV transmission line. Without surge arresters, the overvoltages range from approximately 2 to 14 p.u; only bus RT13 is in danger of flashover without the protection of an arrester. With surge arresters, all overvoltages are reduced to acceptable levels. Again, the overvoltages (without arresters) are greatest on the emergency buses, and the lightning surge penetrates well into the low voltage circuits.

Table 5.2 summarizes the peak arrester currents and associated energy absorbed by each arrester during these lightning transients. Zero values indicate arresters which did not conduct. The arrester's current and energy values, compared to the manufacturer's specified maximum values, show that no arrester was under any significant stress. There is considerably greater activity in the arresters at the lower voltage levels than for the 8/20 μsec. pulse, which passes more easily through the various transformer-coupling capacitances. However, compared to the manufacturer's specified maximum values, again no arrester was found to be under any particular stress. Tables 5.3 and 5.4 give the results of the transients caused by switching surges. The first surge (Table 5.3) is caused by closing in the 345 kV

Table 5.1 Effects of Lightning Surge on Arresters

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER				SURGE WITH ARRESTER			
	L-L	L-G	kV	p.u.	kV		p.u.		kV		p.u.	
					Surge 1[a]	Surge 2[b]	Surge 1[a]	Surge 2[b]	Surge 1[a]	Surge 2[b]	Surge 1[a]	Surge 2[b]
T345	345	199.2	1550	5.5	2064.7	1082.8	7.33	3.84	576.88	579.3	2.05	2.06
G25	25	14.43	150	7.35	157.44	108.2	7.71	5.3	38.38	38.81	1.88	1.90
B001	13.8	7.967	75~95	6.7~8.4	22.23	21.93	1.97	1.95	13.21	17.64	1.17	1.57
B003	13.8	7.967	75~95	6.7~8.4	69.87	35.64	6.2	3.16	18.03	18.57	1.60	1.65
B015	4.16	2.4	~60	17.7	43.3	27.66	12.75	8.14	6.23	5.98	1.83	1.76
BUS6	0.6	0.346			4.67	3.11	9.53	6.35	0.926	0.803	1.89	1.64
B120N	0.12	0.12			1.58	0.962	9.31	5.67	0.169	0.258	1.00	1.53
Y115	115	66.4	550	5.86	498.9	387.4	5.31	4.13	168.77	186.7	1.80	1.99
RT13	13.8	7.967	75~95	7.35	114.2	96.72	10.13	8.58	18.26	18.82	1.62	1.67
BUSD	4.16	2.4	~60	17.7	69.86	49.38	20.57	14.54	6.09	6.33	1.79	1.86
B600	0.6	0.346			4.57	5.19	9.33	10.6	0.766	0.867	1.56	1.70
B120E	0.12	0.12			1.526	1.27	9.0	7.48	0.246	0.283	1.44	1.67

Notes:
a.) Lightning Surge 1: 10kA, 8/20 μsec. current pulse.
b.) Lightning Surge 2: 1350kV, 1.2/50 μsec. voltage pulse.

Table 5.2 Surge Arrester Energy Capability and Discharge Current for 10 kA, 8/20 μsec Lightning Current Pulse, and for 1350kV, 1.2/50 μsec Voltage Pulse

BUS	kJ/kV (of MCOV)			kA		
	Manufacturer data	EMTP simulation		Manufacturer data	EMTP simulation	
		Surge 1[a]	Surge 2[b]		Surge 1[a]	Surge 2[b]
T345	8.9	0.51	0.45	40 ~ 65	9.15	2.87
G25	4.9	0.007	0.064	40 ~ 65	2.10	0.813
B001	4.9	0.0	0.0	40 ~ 65	0.0	0.0
B003	4.9	0.0	0.005	40 ~ 65	0.0	0.21
B015	4.9	0.0	0.007	40 ~ 65	0.0	0.072
BUS6		0.0	0.004		0.0	0.027
B120N		0.0	0.0		0.0	0.003
Y115	8.9	0.003	0.0256	40 ~ 65	0.04	0.244
RT13	4.9	0.008	0.04	40 ~ 65	0.45	0.31
BUSD	4.9	0.008	0.06	40 ~ 65	0.45	0.416
B600		0.0	0.044		0.022	0.284
B120E		0.0	0.007		0.002	0.044

Notes:
a.) Lightning Surge 1: 10kA, 8/20 μsec. current pulse.
b.) Lightning Surge 2: 1350kV, 1.2/50 μsec. voltage pulse.

Table 5.3 Switching Surge for 345 kV Line Energization

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER		SURGE WITH ARRESTER	
	L-L	L-G	kV	p.u.	kV	p.u.	kV	p.u.
T345	345	199.2	1550	5.5	567.9	2.02	455.6	1.62
G25	25	14.43	150	7.35	43.91	2.15	29.95	1.47
B001	13.8	7.967	75~95	6.7~8.4	14.5	1.3	13.1	1.16
B003	13.8	7.967	75~95	6.7~8.4	17.63	1.56	16.09	1.43
B015	4.16	2.4	~60	17.7	9.6	2.83	4.54	1.34
BUS6	0.6	0.346			1.14	2.33	0.619	1.26
B120N	0.12	0.12			0.312	1.84	0.222	1.31
Y115	115	66.4	550	5.86	167.3	1.78	141.3	1.51
RT13	13.8	7.967	75~95	6.7~8.4	31.03	2.75	16.0	1.42
BUSD	4.16	2.4	~60	17.7	11.01	3.24	5.07	1.49
B600	0.6	0.346			2.74	5.60	0.72	1.47
B120E	0.12	0.12			0.834	4.91	0.225	1.33

Table 5.4 Internal Switching Surge for Line-to-Ground Faults

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER		SURGE WITH ARRESTER	
	L-L	L-G	kV	p.u.	kV	p.u.	kV	p.u.
Internal Switching Surge for Line-to-Ground Fault at B003A								
B003	13.8	7.967	75~95	6.7~8.4	18.78	1.67	17.5	1.55
B015	4.16	2.4	~60	17.7	4.58	1.35	4.05	1.19
BUS6	0.6	0.346			0.549	1.12	0.528	1.08
B120N	0.12	0.12			0.187	1.10	0.178	1.04
Internal Switching Surge for Line-to-Ground Fault at BUSDA								
BUSD	4.16	2.4	~60	17.7	8.23	2.42	5.66	1.67
B600	0.6	0.346			2.05	4.19	0.626	1.28
B120E	0.12	0.12			0.65	3.83	0.193	1.14

transmission line, and the second (Tables 5.4) by a line-to-ground fault at Bus B003A and BUSDA. In these cases, the overvoltages without surge arresters range up to 5.6 p.u.. With surge arresters, none exceed 1.67 p.u., and when compared to the manufacturer's recommendation, there are no problems.

5.3 Arrester Aging and Failure

Metal-oxide surge arresters are susceptible to aging, both due to continuous operating loads, and transients (i.e., lightning strikes, switching surges). Recent EPRI studies (Ref. 5.2) indicate that proper care needs to be exercised in sizing arresters for use at high ambient temperatures.

Due to the operating characteristics of arresters, degradation will not substantially affect the steady-state or transient response of the electrical power system. The steady-state arrester current or trickle current will be very small (e.g., milliamps), and the slight decrease in threshold voltage will have negligible effects on transient overvoltages. Therefore, the main effect of aging is the increasing probability of a short-circuit failure with time from the thermal runaway mechanism (discussed in Section 3.3.1). Simulating the short-circuit failure of an arrester using the EMTP program is not a fruitful endeavor because the circuit breakers will open, giving no insights on the need for arrester operation. Rather, the approach is to identify whether the arresters are located on the appropriate buses as protective devices, and whether they fulfill their function of protecting the basic impulse insulation level of the electrical power system. (As previously discussed in Sections 3.3.1 and 3.3.3, there are conditions where partial open circuits are possible due to cracking or shattering of arrester blocks, or severe erosion of gaps).

Simulations were performed which failed arresters as partially open circuits. Various combinations of single and multiple arrester failures were modelled to examine the effect on the distribution system at various voltage levels. To simulate the worst-case scenario for a bus with satisfactory arresters, it was further assumed that flashover did not occur at the buses with the failed arresters, even though the transient voltage may exceed the typical BIL design level for that voltage class. The results of these simulations will be highlighted in this Section.

Table 5.5 summarizes the results where a single arrester failure in the normal system mode is assumed, and a 10 kA 8/20 μsec. pulse is applied at Bus T345. Except for the unprotected bus (T345), the results are similar to those given in Table 5.1 which assumed that there were no failures of arresters. Overvoltages at protected buses again were held to 2 p.u. or less. Similarly, the arrester current and energy values, compared with the values obtained previously (Table 5.2), were not unduly large, though there was increased activity with higher peak currents and energy levels in arresters downstream of the failed one. Although the lower voltage arresters are challenged, the protection afforded by these are suitable, even with the loss of one of them.

Similar acceptable results were obtained when a 1350 kV, 1.2/50 μsec. lightning voltage pulse is applied at the center of the 345 kV transmission line. With a similar failed arrester assumed, overvoltages at protected buses are held to 2.3 p.u. or less. Similarly, though there was increased activity with higher peak currents and energy levels in arresters downstream, no arrester was under any stress. Table 5.6 summarizes the results obtained for transient operation at various voltage levels, when the 345 kV transmission line was energized at the crest of phase A with the receiving end open. Again, all the buses were held to less than 2 p.u., even the unprotected bus T345. This was apparently due to

Table 5.5 Lightning Surge with 10 KA, 8/20 μsec Current Pulse Arrester Failure at Bus T345

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER		SURGE WITH ARRESTER	
	L-L	L-G	kV	p.u.	kV	p.u.	kV	p.u.
T345	345	199.2	1550	5.5	2064.7	7.33	2026.1	7.19
G25	25	14.43	150	7.35	157.44	7.71	38.62	1.89
B001	13.8	7.967	75~95	6.7~8.4	22.23	1.97	19.7	1.75
B003	13.8	7.967	75~95	6.7~8.4	69.87	6.2	17.09	1.52
B015	4.16	2.4	~60	17.7	43.3	12.75	5.70	1.68
BUS6	0.6	0.346			4.67	9.53	0.76	1.55
B120N	0.12	0.12			1.58	9.31	0.25	1.48
Y115	115	66.4	550	5.86	498.9	5.31	193.2	2.06
RT13	13.8	7.967	75~95	6.7~8.4	114.2	10.13	18.38	1.63
BUSD	4.16	2.4	~60	17.7	69.86	20.57	6.12	1.80
B600	0.6	0.346			4.57	9.33	0.858	1.75
B120E	0.12	0.12			1.526	9.0	0.273	1.61

Table 5.6 Switching Surge for 345 kV Line Energization Arrester Failure at Bus T345

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER		SURGE WITH ARRESTER	
	L-L	L-G	kV	p.u.	kV	p.u.	kV	p.u.
T345	345	199.2	1550	5.5	567.9	2.02	497.2	1.77
G25	25	14.43	150	7.35	43.91	2.15	30.9	1.51
B001	13.8	7.967	75~95	6.7~8.4	14.5	1.3	13.6	1.21
B003	13.8	7.967	75~95	6.7~8.4	17.63	1.56	16.8	1.49
B015	4.16	2.4	~60	17.7	9.6	2.83	4.53	1.33
BUS6	0.6	0.346			1.14	2.33	0.657	1.34
B120N	0.12	0.12			0.312	1.84	0.222	1.31
Y115	115	66.4	550	5.86	167.3	1.78	148.0	1.58
RT13	13.8	7.967	75~95	6.7~8.4	31.03	2.75	16.25	1.44

Table 5.6 (Cont'd)

BUS	SYSTEM VOLTAGE (kV)		BIL		SURGE WITHOUT ARRESTER		SURGE WITH ARRESTER	
	L-L	L-G	kV	p.u.	kV	p.u.	kV	p.u.
BUSD	4.16	2.4	~60	17.7	11.01	3.24	5.07	1.49
B600	0.6	0.346			2.74	5.60	0.739	1.51
B120E	0.12	0.12			0.834	4.91	0.229	1.35

spill over into the secondary arrester at bus G25, which effectively limited the switching on the high voltage side. The current and energy absorbed by each arrester during this switching transient also was within acceptable limits.

Numerous simulation runs were performed for various system conditions and arrester configurations. Without arrester protection, direct lightning strikes on the transmission line resulted in transient overvoltages greater than 20 p.u. on some buses; then, flashover could have occurred. With arrester protection, overvoltages were reduced to less that 2 p.u. All the studies demonstrated that lightning surges at the high voltage transmission level could easily propagate into low voltage circuits, even through several layers of transformers, highlighting the need for a well-maintained arrester to protect the most sensitive low-voltage circuits. Without arresters, the overvoltages tended to be highest on the emergency buses; this was attributed to the relative light loading which provided less damping to the lightning surge, although it also depended on the various high-frequency circuit oscillations that were excited by the transient. This result implies that the emergency system may be more prone to failure or stress on the lower voltage arresters, if arrester failure were to occur at the transmission level. However, regardless of the lightning surge, no arrester exhibited any stress.

The simulated switching surges generally produced lower overvoltage stress on the various buses which were easily controlled to less than 2 p.u. by the metal-oxide arresters. The switching surges produced more sustained arrester activity, especially on the emergency buses. Energy dissipation by the arresters at these buses for the duration of the surge were noticeably higher than for the lightning surges, but the dissipation levels were still well within manufacturer's specifications.

Simulation studies were also performed for several combinations of single and multiple arrester failures to determine the effect on the distribution system. For all cases, the general effect was that the failed arresters at the high voltage levels tended to divert most of the energy to the lower voltage buses, challenging these components. Although the remaining protection system was acceptable, with energy dissipation levels well within manufacturers specifications, the added burden at the lower voltage buses may result in their shorten lifetime. Again, the energy system tended to be more sensitive to arrester failure, particularly if the failure occurred at the 115 kV reserve supply bus.

5.4 References

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6. SUMMARY AND CONCLUSIONS

Surge protective devices (SPDs) are essential components needed for preserving the (overvoltage) surge withstand capability of electrical power and control circuits. Despite their importance, SPDs are not given their due in nuclear plant applications. The safety philosophy behind the design and application of SPDs appears equivalent to that of a passive safety device, and is analogous to a relief valve that diverts the overflow but does not interrupt the steady flow portion in pipe flow. (In this same sense, a circuit breaker would be analogous to a safety valve which completely interrupts flow). Surge protective devices if properly applied and maintained should do the following:

(1) Eliminate lightning strikes as a source of reactor trips and losses of offsite power.
(2) Eliminate internal sources of reactor trips and actuations of engineered safety features from overvoltages caused by switching.
(3) In the worst case, prevent damage or failure to the buses.

Surge arresters and surge suppressors are preventive devices, limiting external source stressors that can cause failure or upset of downstream equipment, and do so without interrupting the circuit, rather than mitigative devices such as fuses and circuit breakers that are used for clearing downstream short circuits after they are initiated but do so by opening the circuit. SPDs also prolong the life or normal wear of the components that they protect. Although SPDs have not been classified as safety-related, they are risk important because they can minimize the initiating event frequencies associated with loss of offsite power (LOOP) and reactor trip. Conversely, their failure due to age might be the cause of some of those initiating events, e.g., through short circuit failure modes, or allow a more rapid deterioration of safety-related component(s) they are protecting from overvoltages, perhaps preventing a reactor trip, from degradation or an open circuit failure mode. Therefore, the SPD must show a net benefit of extending the age of the components it protects against the consequence of its failure. For nuclear power plants, surge arresters are connected to the transmission system coming into or leaving the site at the switchyard, on the feeder circuits, and at the generator and large motors. Surge suppressors are located downstream on the distribution circuits, and again, either inside the chassis or outside the chassis of electronic equipment.

Surge arresters and surge suppressors will eventually degrade or fail. If they fail as a short circuit, the circuit that they protect will be taken out of service by fuses or circuit breakers. If they fail as an open circuit or functionally, the components in the circuit are likely to be exposed to stress which may result in failure. In general, normal wear for a surge protective device may be reduced to the combination of (1) the number of overvoltage pulses (which may not follow a simple linear repetitive pattern), including their magnitude and duration (which are both variables) it shunts to ground, and, (2) the environmental conditions under which it operates. It is apparent that the determination of age for SPDs is not a simple matter of collecting data.

To identify the elements of a maintenance program for SPDs, some substantial knowledge of past performance and failure history is required. There also is no apparent, nor recommended, surveillance test program for arresters and suppressors in nuclear power plants. It is as important to know when to remove an SPD from service before it fails, as it is to ensure it is properly coordinated in fulfilling its function.

6.1 Lightning and Overvoltage Protection Components

- Surge Arresters

Over the 15 years from 1980-1994, there were 12 physical failures of arresters that resulted in a loss of offsite power or reactor trip. The combined partial and complete LOOP initiator frequency is about 7 E-03 per reactor year, which is quite small for an initiator, and consequently, is not a significant risk or safety concern. Similarly, the reactor trip frequency of 4 E-03 is quite small, and not a risk nor safety concern. The data base appears to identify most of these instances as occurring at older plants that used the gapped silicon-carbide arrester. The industry recently completed significant research and development programs to enhance the capabilities of the mixed-oxide surge arrester. Today's station-class and distribution-class arresters offer a substantial improvement in performance over the older gapped silicon-carbide arresters that were used in pre-1976 nuclear plant switchyards. Testing these arresters using the IEEE standards gives confidence that they are qualified to perform their function. Using mixed-oxide surge arresters should lower the failure rate of lightning arresters in-service and, consequently, reactor trips or losses of offsite power caused by short circuits in the arresters, principally due to age. An unequivocal endorsement can not be made because there does not appear to be a consistent industry approach for determining the age of arresters in-service.

- Building and Transmission Line Shielding

Local strikes to buildings, or in the vicinity of buildings or to the grounded lightning protection shielding scheme may contribute to 50% of all reactor trips that occur from the subsequent production of a ground potential rise inducing overvoltages on low-voltage RPS protection circuits or from some circuitous pathway through the building structural steel. Building lightning-shielding includes lightning rods, masts, "air terminals", coursing conductors, dissipation arrays, and grounding of ground mats. In addition, about 50% of the high-voltage circuit breaker trips causing either reactor trip or a loss of offsite power were due to faults (other than those from arresters' failure). Assuming that there is no premature actuation of relays, the implication is that the two-shield-wire configuration on the transmission lines entering and leaving the site are not adequately diverting direct lightning strikes through tower grounds, and flashovers are occurring. Building lightning-shielding failures and ground potential rise (GPR) from local strikes in the plant vicinity are significant contributors to low voltage reactor trips. However, the combined initiator frequency of 1.6 E-02 per reactor year is neither a risk nor a safety concern.

- Surge Suppressors

This study only found three surge suppressor failures at power that resulted in a reactor trip; others may not have been uncovered, and there may be some cases in which a suppressor could have prevented a reactor trip, e.g., from an inverter failure, if the suppressor had not failed first. Nevertheless, the direct evidence of suppressor failure resulting in reactor trip is small over the 15 years and therefore, it is not a safety concern as an initiator. In addition, there was no data found that could link a suppressor failure to the prevention of a reactor trip. There are likely to be more surge suppressors introduced in safety-related circuits in the future with the changeout of analog to digital instrumentation and control. Surge suppressors have been applied in nuclear plants as possible panaceas for overvoltages, voltage surges, and voltage spikes that have occurred on low voltage equipment including power supplies in the reactor protection system. This study concurs with that industry approach, and a reduction in the number of LERs submitted for zero-power RPS actuations should become apparent in the future.

6.2 Problems in Data Base Interpretation

In the case of surge protective devices, which are not safety-related, the information contained in the LER and NPRDS data bases is insufficient for making aging determinations and also poses some difficulty in determining proximate causes (i.e., pathways) for reactor trips and losses of offsite power. In addition, nuclear plants are not normally instrumented for determining the location of lightning strikes nor the pathways for lightning strikes, high voltage switching surges, and high voltage temporary overvoltages. At the low voltage end, the problem is one of sorting through many records that may specifically identify a suppressor without giving appropriate engineering and calendar data. The LER and NPRDS data records that were reviewed did not identify failures of surge protective device due to age, except a few which stated that they were worn. Since neither the SCSS nor NPRDS adequately treat surge protective devices as components, it was essentially impractical to develop an aging data base for this study.

The content of the LER text does not lend itself to a clear-cut determination of the lightning pathway for low voltage RPS actuations, and inferences have to be drawn. A pathway commonly suggested in the literature is that a high-frequency remnant remaining after the arrester's operation is capacitively coupled through transformers to lower voltages. This pathway can be simulated using the ElectroMagnetic Transients Program (EMTP). However, it is virtually impractical to identify this type of pathway from the text of LER reports without a lot of supposition. On the contrary, the mechanism of rise in ground potential following a local strike to a structure or nearby ground can be easily inferred as the source of an induced voltage rise on RPS circuits. Although we lean toward ground potential rise as a more prevalent pathway, it may be better if an I & C application considers suppressors for both mechanisms to cover all cases.

Despite our difficulties in using the data bases for this work, it would be inappropriate to specifically modify them to include additional information on SPDs since their failure is not a safety concern. However, better root-cause analysis would improve the quality of age-related data on SPDs, and a better pathway analysis would identify the most appropriate suppressors needed for protecting vital circuits.

6.3 Testing SPDs

At transmission and feeder voltages, tests for gapped silicon carbide arresters and metal-oxide surge arresters are available. In addition, there may be other field test methods being developed for the metal-oxide surge arresters. However, there are utilities that only test on an as-needed basis. Similarly, at plant distribution voltages, it does not appear that testing schemes that are available have been factored into system surveillance testing, although it is likely the utility will test the suppressor when the fuse blows in the electronic circuit. The lack of in-service testing requires that a great deal of faith is placed in standards testing for SPD qualification. However, even with such an assurance of meeting its promise, the major concern about the device is the number of demands or pulses including their magnitude and duration placed on it, which will dominate the aging rate. Age can not be determined because that information also is missing.

6.4 Results of EMTP Simulations

The following specific conclusions from the EMTP evaluation of a typical nuclear power plant electrical supply and transmission system are drawn:

(a) Without arresters, or with cracked or fractured arresters offering a partial open circuit on the 345 kV and 115 kV buses, the overvoltages were propagated to their highest per unit value on the emergency buses.

(b) Switching surges produced more sustained (i.e., repetitive) arrester activity at the safety-related buses.

In all cases studied, the general effect was that arresters that did not shunt all of the lightning pulse or overvoltage to ground tended to divert the remaining surge energy to the lower voltage buses, which caused the arresters at these locations to work harder. Although the remaining protection system seemed quite robust, with energy dissipation levels well within manufacturer's specifications, the added burden at the lower voltage buses would probably shorten the lifetime of arresters at these locations. In particular, the emergency system tended to be more sensitive to lightning remnants if the partially open arrester circuit occurred at either of the 115 kV reserve supply buses.

APPENDIX A

LIGHTNING ARRESTER (or LIGHTNING PROTECTION SYSTEM)

TABULATED DATA BASE

A.1 Lightning - LOOP - Unit Stayed On-Line

A.2 Lightning - LOOP - Reactor Trip

A.3 Lightning - Partial LOOP - Unit Stayed On-Line

A.4 Lightning - Partial LOOP - Reactor Trip

A.5 Lightning Induced Component Failure or Upset- Reactor Trip

A.6 Lightning Initiator - Protective Device Fails Function-Reactor Trip

A.7 Lightning Induced Component Failure or Upset-Reporting Requirement/Other ESF/Actuation /Tech Spec

Table A.1 Lightning - LOOP - Unit Stayed On-Line

Docket	Date	LER No.	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
220	08/31/93	93-007	Both 115 kV Lines	Offsite Power	EDGs started.	12 Seconds for one line. 39 seconds for second line. (Ref. A.1)	Concurrent lightning strikes took out both offsite feeds. Momentarily lost one recirculation pump reducing power to 87%. Auto-reclosing of breaker allowed one line to be re-energized. LOOP lasted 12 seconds. Partial LOOP lasted 39 seconds.
286	06/30/80	80-006	System transmission tower shield wire failed and took out 4 Station feeders and 138 kV to this Unit.	Offsite Power	EDGs started and loaded.	1 Hour and 45 minutes. (Ref. A.1)	Unit stayed on-line but Sister Unit (Docket 247) tripped. Unit auxiliary transformer supplied additional AC power.
302	06/16/81	81-033	All AC power from loss of startup transformer, upset of lightning arrester system, EDG-B failure.	Offsite Power	EDG-A energized one "ES" bus, fossil plant the other.	4 Hours and 56 minutes.	Lightning strike to startup transformer caused loss of all AC. The B diesel generator failed, but offsite power from the fossil plant startup transformer was manually connected to energize the B safeguards bus. (Ref. A.1). Cause attributed to lightning arrester system failure.

Table A.1 (Cont'd)

Docket	Date	LER No.	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
309	04/25/83	83-014	115 kV Lines (with One in Maintenance)	Offsite Power	EDGs started and were operable but did not load.	4 hours.	Lightning caused trip of one offsite source while other offsite source was in maintenance. Unit reduced power but supplied its own loads. **Lightning arresters replaced.**
309	07/02/83	83-025	115 kV Lines (with One in Maintenance)	Offsite Power	EDGs started and were operable but did not load.	4 minutes.	A lightning strike opened an offsite breaker while the other offsite line was out for maintenance. As above, Unit supplied its own loads.
382	12/12/85	85-054	All Offsite Power	Offsite Power	EDGs started and loaded.	33 minutes (Ref. A.1)	Lightning strike caused loss of all offsite power. Reactor was at 0%, Mode 5. Several breaker operations and additional faults and misoperation of some relaying. Corrective action included changing various relay settings.

Table A.1 (Cont'd)

Docket	Date	LER No.	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
529	01/03/89	89-001	All Offsite Power	Offsite Power	EDGs started and loaded.	About 21 hours for one offsite source.	Lightning caused flashover of ESF transformer. The ESF transformer bushings had a reduced withstand voltage from contamination of mineral deposits and mist from cooling towers.

Table A.2 Lightning - LOOP - Reactor Trip

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
029	06/15/91	91-002	88%	Lightning arrester destroyed on station startup transformer.	Offsite Power	EDGs started and loaded.	24 Minutes for one line.	More than 1/2 days.	Subsequent to **lightning arrester failure** an insulator flashed over onto 115 kV disconnect switch. Shutdown sequence complicated by inadvertent safety injection.
247	06/03/80	80-006	100%	System transmission tower shield wire failed and took out 4 Station feeders.	Offsite Power	Not stated.	1 Hour and 45 minutes (Ref. A.1)	Not stated.	Operator tripped turbine and substation signal tripped generator, reactor trip. Natural circulation used to maintain safe shutdown. Sister Unit (Docket 286) did not trip.

Table A.2 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
306	07/15/80	80-020	100%	One offsite line tripped, one offsite line degraded at 80%.	Offsite Power	EDGs started and loaded.	1 hour and 2 minutes for one source. 2 Hours and 41 minutes for other.	About 5 hours.	Lightning tripped several substation breakers which caused a Unit 2 generator trip and subsequent reactor trip. Loss of one offsite power line actually occurred 8 minutes later with lockout of a transformer. Other offsite source was degraded. (Unit 1 in cold shutdown).

Table A.3 Lightning - Partial LOOP - Unit Stayed On-Line

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
029	05/23/83	83-019	100%	115 kV Line	Offsite Power	No	One hour.	Initial power reduction. Loss of 115 kV line continuity.
213	07/30/83	83-014	100%	115 kV Line	Offsite Power	Auto transfer of loads to other source.	About one day.	Plant remained at 100% throughout.
277	07/10/87	87-012	0%	Startup Feed Breaker, Bus Transfer, Unit Aux Buses, PCI Isolations	Offsite Power, Emergency Power, Primary Containment Isolation.	Fast transfer of emergency buses, de-energizing Unit aux buses, some PCI isolations.	About 3 1/2 hours.	Lightning struck 220 kV line and tripped a startup feed breaker which initiated fast bus transfer. Both Units auxiliary buses were de-energized and some PCI isolations occurred. Unit 2 was in refueling and Unit 3 was shutdown at the time.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
277	09/16/90	90-027	80%	Startup Feed Breaker, Bus Transfer, Reactor Water Cleanup Isolation, SBGT Initiation	Offsite Power, Emergency Power, RWCU Isolation, SBGT Initiation	Fast transfer of emergency buses	About 15 minutes.	Somewhat similar to above event. Lightning struck Sister Unit startup feed breaker which initiated a fast transfer. Other Unit was shutdown at time but also experienced a RWCU isolation.
280	04/06/89	89-010	0%	500 kV Line in Switchyard	Offsite Power	One EDG started and loaded.	2 hours & 17 minutes. Both Units were in cold shutdown.	**Lightning arrester failure** initiated event. Auto-transformer locked-out, an RHR pump was de-energized as were radiation monitors.
293	08/02/83	83-045	0%	345 kV Offsite Power	Offsite Power	EDGs started and loaded.	Not stated. Unit in cold shutdown at time.	Lightning struck 345 kV line and startup transformer locked-out. The secondary offsite power source (23 kV) was available.
298	08/12/86	86-015	94%	69 kV Breakers	Offsite Power	EDGs started but did not load, twice in 4 hours.	Not stated but likely in re-closing time of breakers.	During lightning storm the 69 kV offsite feed cycled twice in 4 hour period.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
328	08/15/88	88-034	98%	Meterology Tower Instruments, Unit Circulating Water Pumps, 161 kV to 500 kV Switchyard Intertie, 6.9 kV Buses	Environmental Monitoring, Circulating Water, Offsite power, 6.9 kV Class 1E	All 4 EDGs started and loaded.	41 minutes (Ref. A.2).	Lightning strikes caused damage to Met. Tower instruments and tripping of circulating water pumps. Event complicated by Inadvertent Tripping of Switchyard Tie, and Flashover of 6.9 kV Start Bus (Ref. A.2).
331	08/07/91	91-008	100%	2 Offsite Switchyard Breakers	Offsite Power	EDGs started but did not load.	Not stated but likely in re-closing time of breakers.	During electrical storm 2 offsite power switchyard breakers cycled automatically.
333	07/06/82	82-033	Not Stated	115 kV Offsite Line	Offsite Power	No, other line and Unit power still available.	4 minutes.	Lightning struck one of two 115 kV reserve power lines causing supply breaker to open.
387	08/01/86	86-028	100%	230 kV Line to Unit 1 Startup Transformer Bus 10	Offsite Power	Bus Transfer from Bus 10 to Bus 20.	Not stated.	Lightning struck 230 kV line feeding Unit 1 startup transformer and opened breaker.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
387	03/06/87	87-007	100%	Lightning Arrester Failure in Construction Substation Off 230 kV. Unit 2 Startup Transformer	Offsite Power	Bus Transfer Realignment, Numerous ESF Actuations	Not stated.	**Lightning arrester failure** was initiator. Both Units remained on-line. Unit 1 exceeded its licensed power level.
387	04/21/87	87-015	100%	Same as Above	Same as Above	Same as Above	Same as Above	**Lightning arrester failure** in different phase than above. Remaining lightning arresters changed-out.
387	05/31/87	87-020	100%	230 kV Line to Startup Transformer Feeding Bus 10	Offsite Power	Bus 10 Transfer to Bus 20, Numerous ESF Actuations	Not stated.	Lightning strike on 230 kV system de-energized Unit 1 startup transformer. Both Units stayed on-line.
387	07/16/87	88-014	100%	230 kV Line to Startup Transformer Feeding Bus 10	Offsite Power	Bus 10 Transfer to Bus 20, Numerous ESF Actuations	Not stated.	Lightning strike on 230 kV system de-energized Unit 1 startup transformer. Both Units stayed on-line. (Same as above).

Table A.4 Lightning - Partial LOOP - Reactor Trip

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
029	06/29/82	82-029	100%	115 kV Line -	Offsite Power	RPS	11 Minutes	11 Minutes	Loss of flow scram occurred after lightning struck 115 kV line.
263	08/25/91	91-019	100%	115 kV Line, Station Reserve Transformer Lockout	Offsite Power	Several engineered safety systems actuated.	Not stated.	Not stated.	Station reserve transformer locked-out after insulator failed from lightning strike but auxiliary reserve transformer picked-up offsite power after 5 seconds. (There are 3 sources of offsite power available).

Table A.4 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
272	06/16/91	91-024	100%	Generator Step-Up Transformer, Unit 1 - 4 kV Auxiliary Transformer, 1 of 2 (each) Startup Transformers for Unit 1 & Unit 2	Offsite Power, Generator Surge Protection	RPS, bus transfer to remaining offsite power sources. (EDGs did not need to start).	Not stated.	About 8 days.	**Lightning damaged arrester** on 500 kV phase B main transf. resulting in Unit 1 trip & loss of 4 kV auxiliary tranf. Four seconds later, coast-down current from generator caused breaker flashover protection to activate which opened adjacent 500 kV breakers, resulting in deenergizing 1 of 2 startup transf. in each Unit. (Authors' note: Generator surge arresters should have prevented flashover).

Table A.4 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
278	07/11/84	85-018	100%	Cross-Tie Substation Breakers, Unit Startup Bus Supply Breaker	Offsite Power	Emergency Bus Fast Transfer, Group II/III Isolations, Manual RCIC Control of Water Level.	Not stated.	Not stated.	Lightning apparently struck North and South substations' cross-tie opening breakers and Unit startup supply breaker also tripped. Event complicated by spurious closure of one MSIV.
293	09/10/93	93-022	100%	345 kV Preferred Offsite Source, 345 kV Air Circuit Breaker (ACB)	Offsite Power	One EDG Auto-Started and Loaded, Other EDG was in Test Mode and Stayed On-Stream, 3 Main Steam Relief Valves Opened.	10 minutes (Ref. A.1)	About 44 hours.	Lightning struck one of the 345 kV air circuit breakers and another strike caused load rejection. NOTE: Surge suppression circuit replaced in ACB. (Same event given in Table B.1).

Table A.4 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
302	02/28/84	NSAC-182	74%	230 kV Preferred Offsite Source to SUT	Offsite Power	RPS Trip, Offsite power recovered in 5 seconds.	5 seconds	Not stated.	**Lightning arrester failed** on one of three fossil units serving as preferred offsite source causing loss of power for 5 seconds. Reactor tripped but startup transformer power was available after 5 seconds.
348	08/19/91	91-009	100%	Lightning Arrester, 1B Startup transformer (SUT), 2 RCPs	Offsite Power, 4.16 kV Buses B and C	Train B EDG started and loaded.	17 hours and 17 minutes.	About 40 hours.	Lightning struck SUT 1B and **lightning arrester failed** on Phase 2. 2 RCPs also tripped.
387	06/13/84	84-028	100%	230 kV Line Off Unit 1 Startup Transformer (SUT)	Offsite Power	Unit 1: RPS Trip, HVAC Isolation, SBGT Initiation, Safety Systems Functioned. Unit 2: RPS "A"	Not stated.	Not stated.	Lightning strike caused isolation of 230 kV Unit 1 SUT. Unit 1 eventually scrammed on reactor vessel level.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
298	09/18/86	86-020	72%	69 kV Breakers	Offsite Power	EDGs started but did not load, twice in 9 hours.	Not stated but likely in re-closing time of breakers.	Basically, same type of event as above.
298	07/07/87	87-017	100%	69 kV Line	Offsite Power	EDGs started.	4 hours.	Plant remained at 100% during the event. Some **lightning arresters damaged.**
298	08/06/87	87-018	100%	69 kV Line	Offsite Power	EDGs started.	55 minutes.	Event similar to above. No arresters reported damaged but lightning protection study of 69 kV is continuing.
302	06/29/89	89-025	0%	Normal 230 kV Offsite Source	Offsite Power	One EDG started and loaded. Other EDG was in maintenance. Second offsite power source aligned to emergency bus in 2 minutes.	1 hour and 22 minutes.	Believe lightning caused trip of 230 kV offsite line. Reactor was in hot shutdown at the time. Reactor cooled by natural circulation.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
315	09/30/81	81-049	Not Stated	Alternate Reserve Source 69 kV	Offsite Power	None, the normal and preferred 345 kV sources supplied onsite and offsite power to emergency buses.	10 hours and 8 minutes.	Believe lightning storm caused failure of jumper of one phase of 69 kV which took out the alternate reserve source.
324	10/05/91	91-016	0%	230 kV Offsite Distribution Line	Offsite Power	RPS Bus B De-energized Causing Some PCIs and SBGT Initiation.	Not stated.	Lightning caused phase to Ground fault on 230 kV line. Unit was In refueling with all fuel removed. One diesel was in maintenance and other in test at time of event. RPS power loss was 4 seconds.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
395	06/03/83	83-074	Mode 1	Normal 115 kV Line, Engineered Safety Feature Load Sequencer, EDG "A"	Offsite Power	Train A Vital Bus Sources Lost. (Offsite power breaker reclosed But load sequencer locked-out supply breakers).	1 hour and 10 minutes.	Lightning struck 115 kV normal power feed breaker which tripped. Event complicated by tripping of EDG "A" which was under full load test at time. The licensee was to evaluate additional surge suppression circuitry to protect D/G circuitry.
395	07/14/86	86-012	100%	Normal 115 kV Line	Offsite Power	EDG "A" started and loaded. Service water pump "A" did not start.	1.5 hours.	Lightning struck 115 kV normal power which tripped on 07/24/86. Power was also lost to 2 drywell chillers, and service water pump did not auto-start due to bad relay.
416	05/03/84	84-027	0%	115 kV Line	Offsite Power	Div. 1 and Div. 3 EDGs started and loaded. Aux. Bldg. Div. 1 isolation.	Not stated.	Lightning caused loss of 115 kV source. Normal power to buses supplied by paralleling 500 kV offsite source.

Table A.3 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Remarks
499	03/20/89	89-005	0%	Standby Transformer and 2 ESF Buses	Offsite Power	2 EDGs started and loaded.	Not stated.	During a thunderstorm a standby transformer lightning arrester failed. Unit was in low power physics testing at time. Moisture intrusion believed cause of failure.

Table A.4 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Transm. Line Outage Time	Unit Outage Time	Remarks
387	07/03/84	84-029	100%	230 kV Line Off Unit 1 Startup Transformer (SUT)	Offsite Power	Unit 1: RPS Trip, HVAC Isolation, SBGT Initiation, Safety Systems Functioned. Unit 2: RPS "A"	12 seconds (Ref. A.1).	Not stated.	Event essentially same as above but plant response a little different. Lightning strike caused isolation of 230 kV SUT. Unit 1 eventually scrammed on reactor vessel level.
456	10/18/88	88-022 NSAC-182	100%	System Relaying, Reactor and Generator Controls	Offsite Power	RPS Trip, Aux. Transf. Breakers Opened	1 hour and 35 minutes.	Not stated.	Lightning storms damaged or upset relays on 345 kV system causing Unit 1 generator/reactor trip and loss of preferred offsite source.

Table A.5 Lightning Induced Component Failure or Upset - Reactor Trip

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
029	06/14/83	83-022	100%	115 kV Line Undervoltage	Offsite Power	RPS	Short duration.	Lightning strike on 115 kV line in close proximity to switchyard.
029	06/01/86	86-004	100%	Heater drain tank level control power supply	Feedwater	All automatic safety systems functioned.	About 2 days.	Severe lightning storm caused surge on 120 VAC M-G set distribution panel that initiated loss of HDT level control which caused trip of boiler feed pumps and loss of feedwater. Heater drain tank level control power supply was damaged.
220	06/25/88	88-015	0%	115 kV Line undervoltage	Offsite Power	RPS, MSIV scram bypass valve	N/A	Unit was in shutdown. Lightning strike on 115 kV line caused low RPS voltage and subsequent de-energizing of low condenser vacuum and main steam isolation valve closure bypass relay.
250	07/21/85	85-019	100%	Pressurizer Pressure Protection Comparators	Reactor Protection System	RPS	Not stated.	Lightning strike believed cause of spurious signal generated by pressurizer protection comparators that caused pressurizer low pressure reactor trip.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
250	08/13/86	86-032	53%	Pressurizer Pressure Protection Comparators	Reactor Protection System	RPS	About 15 hours.	Event similar to above. Lightning strike believed cause of spurious signal generated by pressurizer protection comparators that caused pressurizer low pressure reactor trip.
261	02/27/85	85-009	100%	Main Transformer Phase C Lightning Arrester	Electrical Power System	RPS	Not stated.	**Lightning arrester failed** but LER does not identify lightning being present at the time of failure.
263	06/04/94	94-004	100%	Offgas Recombiner System, Condenser Vacuum	Main Steam (Condenser), Offgas Monitoring	RPS	Not stated.	Electrical storm caused loss of offgas recombiner which caused loss of condenser vacuum and reactor scram. Subsequent storm caused upscale trip of fuel pool monitor which caused containment isolation. Equipment was repaired.
271	06/15/91	91-014	100%	345 kV Switchyard Bus (Portion), 345 kV Air Trip Breakers	Electrical Power Transmission	RPS	About 112 hours.	Lightning struck phase B of 345 kV North switchyard bus and opened all 345 kV air trip breakers. Event complicated by shorted transistor in carrier current protective relaying.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
272	06/02/87	87-007	100%	500 kV Transmission Line (Momentary Loss)	Electrical Power Transmission	RPS	Not stated but probably short.	Lightning caused momentary loss of 500 kV but temporary "cross trip scheme" was in place for electrical stability concerns which probably made trip more likely.
272	07/14/94	94-011	100%	Circulating Water System 4 kV breaker trip	Electrical Power System	RPS (manual trip)	Not stated.	Lightning induced voltage drop of 500 kV line caused undervoltage on 4 kV bus that tripped all circulating water pumps. Operator manually tripped reactor. An undervoltage time delay relay is to be installed to prevent future occurrences.
277	07/17/92	92-012	95%	Group II/III PCI.	Primary Contain. Isolation	Group II/III isolations occurred.	Not stated.	During thunderstorm the main generator output breaker tripped. Two drywell chillers also lost power.
301	12/31/85	85-005	90%	Station Class Lightning Arrester, Non-Vital 4.16 kV Bus Transfer Failure	Electrical Power System	ESF Actuations	Not stated.	**Lightning arrester failure** caused trip. Event complicated by lack of needed time delay in synchro-verifier relay to assure bus transfer. Power was lost to RCPs, Main Feed, Condensate, and Circulating Water Pumps. Some MSIV damage.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
301	08/16/87	87-002	100%	345 kV Line to Unit Transformer, Non-Vital 4.16 kV Bus Transfer Failure	Electrical Power System	ESF Actuations.	Not stated.	Lightning struck 345 kV transformer causing lockout. Sequence of event same as above. Synchro-verifier relay dropped-out. (NPRDS report) No damage to MSIVs.
304	06/26/86	86-016	68%	5 RCS Hot Leg Resistance Temperature Detectors (RTDs)	Reactor Protection System	Reactor Trip on Overtemp. Delta T	Not stated.	Lightning struck 1 or more containment lightning rods and followed a path of containment liner to ground via electrical cable penetrations. Current induced in cables damaged 5 RTDs.
313	04/08/86	86-004	82%	Turbine Electro-Hydraulic Control and Power Supply	Main Steam	Emergency Feedwater Addition. Trip on High RCS Pressure.	Not stated.	Lightning surge apparently fed into one of the turbine EHC power supplies and caused rapid load reduction closing turbine governor valves. Lightning strike observed in switchyard prior to trip.
313	04/11/94	94-002	100%	Emergency Feedwater Initiation & Control Sys. Power Supply, MSIVs	EFIC, Main Steam Isolation Valves	RPS Trip on High RCS Pressure.	About 3 days and 4 hours.	Lightning struck in vicinity of reactor building causing loss of power to two channels of the Emergency Feedwater Initiation and Control (EFIC) system which initiated actuation of MSIV closure.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
325	09/10/84	84-025	99%	Reactor Main Steam Line High Radiation Monitors	RPS	PCI Group I, HPCI and RCIC Start with No Injection, 2 SRVs Opened	About one day.	Lightning struck common turbine building structure and common switchyard inducing electrical impulses into instrumentation.
324	09/10/84	Same as Above	0%	Average Power Range Monitor	RPS	RPS	N/A, reactor in refueling.	Same as above.
346	08/21/87	87-010	100%	Low Grid Voltage, Turbine-Generator Bearing	Grid Disturbance	RPS	About 2 days.	Lightning caused temporary grid disturbance of 3 and 1/2 cycles. Event complicated by trip originating from turbine vibration and poor main steam response.
364	03/27/84	84-004	100%	Primary and Secondary 25 Volt DC Power Supplies to All 4 Cabinets	25 Volt DC System Powered from AC, and Backup Supply Powered from M-G Sets	RPS	Not stated.	Severe lightning caused voltage surge on 25 volt DC supply cabinets. The NPRDS record for this event believes capacitive coupling caused overvoltage protection devices to trip backup supply. Line conditioners to AC system were added to prevent future occurrence.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
364	07/15/85	85-010	99%	Primary and Secondary Power Supplies to 2 Cabinets, All RCPs, Fast Bus Transfer	Primary and Secondary 25 Volt DC Power Supplies, Auxiliary and Startup Transformer Buses	RPS, Fast Dead Bus Transfer	(25 Minutes to get power to RCPs). About 2 day outage.	Severe thunderstorm caused voltage surge on RPS power supplies (as above). Event complicated by generator trip occurring before fast dead bus transfer and thus preventing transfer of RCPs power to startup transformer from auxiliary transformer.
364	08/06/91	91-005	100%	Control Rod Drive Mechanism Cables, One or More RPS Power Cabinets	RPS Power Supplies	RPS	About 28 hours.	Lightning induced transient produced overvoltage on CRDM cables which de-energized power supplies. No damage to rod control system.
368	08/05/85	85-016	100%	Erroneous RCS Parameters, 2 Channels CPC	RPS, Emergency Feedwater	RPS, EFW	Not stated.	Postulated that lightning strike caused erroneous parameters to be input to core protection channels. EFW control valve failed open subsequent to trip.
382	08/25/90	90-012	100%	230 kV Switchyard Circuit Breaker	Plant Electrical Output	RPS	Not stated.	Lightning strike destroyed switchyard circuit breaker. Rapid load reduction with trip on high pressurizer pressure. Event complicated by failure of steam bypass control system. Trip on high pressurizer pressure.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
388	10/05/85	85-025	100%	Main Generator Output 500 kV Breakers, Breaker Failure Logic	500 kV System	RPS on fast valve closure, 2 SRVs actuated.	About 34 hours.	Lightning strike caused phase to ground fault on 500 kV system. Event complicated by breaker failure relay logic which ensured trip. (Relay failure unrelated to lightning).
416	08/15/88	88-012	100%	Average Power Range Monitors (APRM) Channels	RPS	RPS	Not stated.	Lightning strikes in site vicinity believed to have caused APRM channels to spike and give high neutron flux signal. Surge conducted thru grounding mat.
416	07/22/89	89-010	100%	Average Power Range Monitors (APRM) Channels, RCIC Logic	RPS, RCIC	RPS, RCIC	Not stated.	Lightning storm passed over plant and caused APRM channels to spike and give high neutron flux signal. RCIC also initiated. Lightning dissipation array system to be installed.
416	11/07/89	89-016	100%	APRM Channels, RCIC, HPCS Low Water Level Channels	RPS, RCIC, HPCS	RPS, RCIC, HPCS	Not stated.	Lightning strike in vicinity of site caused APRM channels to spike and give high neutron flux signal. RCIC initiated but did not inject. HPCS had 2 low level channel trips. Lightning dissipation system to be installed on vulnerable structures.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
416	08/10/91	91-010	100%	APRM Channels, HPCS Low Level Channels	RPS, HPCS	RPS, HPCS	Not stated.	Severe thunderstorm in vicinity of site caused high flux signal from APRMs. HPCS had 2 low level trips.
416	11/19/91	91-012	100%	APRM Div. 2 Channels	RPS	RPS	Not stated.	Severe lightning caused high flux signal from Div. 2 APRMs. With Div. 1 RPS in maintenance surveillance a reactor trip occurred. It appears that the effect of the lightning surge was to de-energize the APRM power supply which would subsequently energize.
416	06/06/92	92-010	5%	APRM Actuation Signal to RPS	RPS	RPS	Not stated.	It is believed that an electrical storm in the vicinity of the plant caused electromagnetic interference coupling into the APRM system generating the scram signal.
424	07/31/88	88-025	16%	Control Rod Drive Mechanism Power Supplies	CRDS	RPS, Main Feedwater Isolation, Aux Feedwater Initiation.	304 hours	Lightning struck containment bldg. and electrical surge shutdown output of CRDMs power supplies. Installed surge suppressors in rod control power circuits.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
445	09/08/90	90-028	38%	Control Rod Drive System Power Supplies	CRDS	RPS	Not stated.	Lightning strike believed to have caused surge de-energizing CRDS power supplies. Corrective action was to add surge suppressors to input supply to rod drive power supplies.
454	07/13/85	85-068	11%	Control Rod Drive System Power Supplies, Some Train B Instruments	CRDS, ESF Train B	RPS	Not stated.	Lightning strike in vicinity of station induced a voltage transient in station ground causing 2 rod drive power supplies to fail resulting in reactor scram. Believe the most likely strike route was the containment building steel to containment cable penetrations to the power supplies. Corrective action was to modify containment lightning protection.
454	07/29/87	87-017	98%	Control Rod Drive System Power Supplies on 07/29/87 and 07/31/87	CRDS	RPS	Not stated.	Lightning strikes are the suspected cause deenergizing power supplies resulting in 2 trips, 2 days apart. A modification was being made to ground scheme as a corrective action.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
454	08/19/90	90-011	78%	9 Rod Drive Power Cabinet Overvoltage Protection Devices	CRDS	RPS	Not stated.	Severe lightning induced voltage surge that activated 9 out of 10 overvoltage protection devices in rod drive power cabinets. Rod drive system is to be further modified with a new power supply model.
455	06/14/92	92-004	0%	Source Range High Flux Channel Spike	Source Range Instrumentation	RPS	Not stated but probable short duration.	Lightning storm caused source range channel to spike to its trip setpoint. Unit was in startup with shutdown banks withdrawn at time of event.
456	10/17/88	88-023	0%	Unit 1: Erratic Over Temp Delta T and Over Pressure Delta T Had Coincidence. Unit 2: Reactor Vessel Level Indicating System; Rod Drive Power Supplies	CRDS, RVLIS	RPS	Not stated.	Lightning storm caused voltage transient in Station ground that actuated overvoltage protection for rod drive power supplies in both Units. Unit 1 was shutdown but actuated a trip. Unit 2 (Docket 457) also tripped. In addition Unit 2 lost RVLIS and its computer memory.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
456	07/18/89	89-006	86%	Both Units' Rod Drive Control Cards Overvoltage Protectors	CRDS	RPS	Not stated.	Lightning induced voltage transients actuated a number of overvoltage protectors in each Unit's rod drive power supplies. Both Units tripped.
456	06/08/90	90-008	100%	Overvoltage Protectors in 3 Rod Drive Cabinets	CRDS	RPS	Not stated.	Lightning struck Unit 1 containment causing voltage transient in Station ground system that actuated the overvoltage protectors.
457	09/07/89	89-004	90%	All 10 Rod Drive Cabinet Overvoltage Protection Devices Actuated	CRDS	RPS, Turbine Trip, Feedwater Isolation, Aux Feedwater Start	Not stated.	Lightning struck the Unit 2 containment and actuated all rod drive power cabinet overvoltage devices. New corrective action was the addition of a time delay to the protection devices. Other measures are being evaluated.
458	12/31/85	85-063	21%	Turbine Generator Power Load Imbalance	Turbine Generator	RPS	Not stated.	Lightning strike on 500 kV transmission Line in combination with a previously failed pressure transducer caused power load imbalance.

Table A.5 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
528	10/27/91	91-010	100%	Main Turbine Control System Fast Closure	Main Turbine Control, Steam Bypass Control, Core Protection Calculator	RPS, Safety Injection Actuation System, Containment Isolation Actuation	Not stated.	Lightning strike initiated a grid fault which caused the main turbine control system to fast close which set subsequent sequence into motion to RPS trip. Both Units 1 and 3 tripped.
530	11/14/91	91-008	100%	Main Transformer Phase A, Control Element Assembly Deviation	Electrical Power, CPCS	RPS	Not stated.	Lightning struck phase A of the main transformer and caused generator trip, turbine trip, and reactor power cutback. Reactor may not have tripped but there was a 9.5 inch deviation in control rod groups. Consequently, the reactor tripped on low DNBR.

Table A.6 Lightning Initiator - Protective Device Fails Function - Reactor Trip

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Unit Outage Time	Remarks
254	03/10/90	90-004	98%	Negative Sequence (Ground) Relay	Transmission	All safety features actuations functioned.	Not stated.	Time overcurrent negative sequence relay did not function properly following lightning strike to transmission line that caused fault.
278	07/07/91	91-010	97%	Block Switch	Main Generator Position Indication Relays.	Group II/III Primary Containment Isolations.	Not stated.	Block switch in circuit to relays was grounded and failed to block false signal.

Table A.7 Lightning Induced Component Failure or Upset - ESF Actuation/Technical Specification Reporting Requirement/Other

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
272	06/08/80	80-031	100%	Main Steam Pressure Transmitters. 7 were Struck and 2 Failed.	Main Steam	Safety injection occurred for 4 minutes.	Lightning struck south penetration area. Similar event in 1977 but power was reduced with no safety injection that time.
313	05/17/87	87-002	67%	Turbine Electro-Hydraulic Control Comparator Card	Main Steam	Emergency Feedwater Actuated.	Lightning apparently damaged comparator card at 67% power. Upon insertion of new card the turbine tripped without reactor trip (which had been bypassed). Insertion of card created a voltage spike which caused turbine trip. Reactor stabilized at 38% power.
269	09/03/80	80-028	57%	High Pressure Service Water Pump Auto-Initiate Function.	Service Water System	Manual makeup still available.	Lightning remnant caused failure of auto-initiate function. Cable protected by arrester operation. **Lightning arresters replaced.**
261	08/24/85	85-018	98%	Axial Power Distribution Monitoring System Channel	APDMS	Technical Specification Report	Lightning damaged process computer that analyzes APDMS Data.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
322	09/15/90	90-008	0%	Multiple Components Affected	RBSVS, RWCU, RPS, Air Compressors, Security System	ESFs of RBSVS Initiation, Isolation of RWCU, Loss of Station Air, RPS Bus B Tripped.	Lightning strike during severe thunderstorm caused multiple ESF actuations.
325	06/09/93	93-003	0%	RPS Bus A, ESFs and Isolations	RPS	ESF Actuations	Lightning strike on grid caused voltage spike with subsequent trip of RPS channel A.
353	08/13/94	94-008	99%	"A" M/G Set Scoop Tube Positioner	Power Output Increase	Technical Specification Report	Storm tripped 500 kV transmission line causing the "A" motor generator set scoop tube positioner to increase speed causing increased reactor flow and subsequent reactivity increase.
397	05/12/88	88-013	0%	RPS Loss of Power	Offsite Power	RPS Half-Scram, Numerous ESFs	Lightning strikes caused phase to ground faults on 230 kV system.
255	08/26/86	86-028	0%	Safeguards Buses Potential Transformers Fuses	Emergency Power System	EDGs started and were loaded.	Fuses opened when lightning struck. Plant in cold shutdown at time.
259	08/10/80	80-059	73%	Unit 3's 4 kV Bus-Tie Board	Electrical Power System	N/A	Cooling tower transformer tripped following lightning strike on 161 kV line which caused loss of 4 kV board.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
219	06/01/88	88-010	100%	Automatic Transfer Switch	Standby Gas Treatment and Reactor Building Ventilation	Manual actuation of SBGT system.	Lightning caused electrical transfer switch to change to alternate power supply. Operator manually initiated SBGT system in anticipation of automatic initiation.
271	07/20/94	94-009	100%	Bus Transfer of 120/240 Vital VAC from Motor-Generator Power Source to Alternate Source.	Bus Transfer Affected: PCIS, SBGT, Reactor Bldg. Ventilation, Electronic Pressure Regulator, Feedwater Regulation Valves, and M-G Set Scoop Tubes.	Some primary containment isolations, initiation of standby gas treatment, lockups of feedwater regulation valves and scoop tube, shutdown of electronic pressure regulator.	Lightning apparently failed vital AC transfer switch. Reactor did not Scram. Corrective action was to evaluate the addition of lightning surge suppression devices.
298	05/26/87	87-016	0%	69 kV Grid, Diesel Generators	Emergency Power System	EDGs started but did not load.	Lightning caused momentary undervoltage on 69 kV emergency transformer. Reactor was in startup mode but subcritical at the time.
331	07/07/92	92-011	100%	Emergency Buses Undervoltage	Offsite Grid Disturbance	EDGs started but did not load.	Electrical storm caused grid disturbance.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
344	09/07/90	90-037	100%	Turbine Load Reduction, Plant Startup Transformer Undervoltage	Offsite Grid Disturbance	EDGs started but did not load.	Lightning strike 125 miles away caused transmission disturbance. Unit initially reduced load but did not trip.
344	07/24/91	91-026	0%	Plant Startup Transformer Undervoltage	Offsite Grid Disturbance	EDG A started but did not load.	Lightning storm caused grid disturbance.
344	05/31/93	93-003	0%	Plant Startup Transformer Undervoltage	Offsite Grid Disturbance	EDG A started but did not load.	Lightning storm caused grid disturbance. Plant permanently shutdown.
346	01/27/81	81-008	Not Stated	Lightning Arrester	13.8 kV Startup Transformer Bus A	Fast transfer of bus.	**Lightning arrester failed.** Weather was wet and snowy.
369	05/23/84	84-017	50%	Class 1E Bus Undervoltage	Grid Disturbance	EDGs started but did not load.	Lightning storm in service area caused momentary grid disturbance. Blackout signal cleared in 1 second but diesels started. Time delay being investigated.
370	02/28/85	85-005	0%	Train B Switchgear Undervoltage	Grid Disturbance	Train B EDG started but did not load.	Electrical storm caused voltage dip on Train B bus. Unit was in refueling at time. Time delay being investigated to screen spurious signals.
395	07/02/91	91-003	99%	Vital Bus Undervoltage	Offsite Power	EDG "A" started but did not load.	Thunderstorm caused momentary fault on offsite power source. Fault cleared in less than 2.25 seconds.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
397	09/07/90	90-024	92%	Vital Bus Undervoltage	500 kV Grid Disturbance	EDG DG-2 started but did not load.	Electrical storm caused 550 kV grid disturbances.
413	05/15/85	85-034	0%	Vital Bus Undervoltage	Grid Disturbance	EDGs started but did not load.	Lightning storm caused momentary grid disturbance.
445	06/09/91	91-019	100%	Safeguards Buses Undervoltage	345 kV Grid Disturbance	Bus transfer to alternate supply, blackout sequencers operated	Lightning strike on preferred 345 kV line momentarily lost power from lightning strike. Time between opening and re-closing breaker sufficient to activate bus transfer.
445	07/28/91	91-021	100%	Same as above.	Same as above.	Same as above.	Same as above.
499	04/04/95	95-004	100%	Digital Rod Position Indication System, Automatic Transfer Switch	Digital Rod Position Indication System	Technical Specification Report	Electrical storm caused power perturbations to I & C power distribution panel that feeds Digital Rod Protection Control System. Automatic switch attempted to transfer to different voltage regulator transformer but failed.
219	06/21/86	86-012	0%	RPS Relays	Primary and Secondary Isolation, Standby Gas Treatment.	Isolation systems isolated and SBGT system initiated.	Lightning surge from 34.5 kV distribution line outside plant caused Vital AC Panel 1 to transfer to alternate power supply causing relays to de-energize. Happened three times that day.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
219	07/29/86	86-017	0%	RPS Relays	Primary and Secondary Isolation, Standby Gas Treatment.	Isolation systems isolated and SBGT system initiated.	Lightning surge from 34.5 and 230 kV distribution lines outside plant caused Vital AC Panel 1 to transfer to alternate power supply causing relays to de-energize. Happened twice (7/29 and 7/30).
219	07/31/87	87-027	0%	RPS Relays	Primary and Secondary Isolation, Standby Gas Treatment.	Isolation systems isolated and SBGT system initiated.	Lightning surge from 34.5 kV distribution line outside plant caused Vital AC Panel 1 to transfer to alternate power supply causing relays to de-energize. Happened three times.
219	04/22/86	87-030, Rev. 1	0%	Lightning Arrester (failure), RPS Relays (de-energize)	Primary and Secondary Isolation, Standby Gas Treatment	Isolation systems isolated and SBGT system initiated.	**Lightning arrester failed** but LER does not state there was lightning at the time. Voltage transient caused by arrester caused Vital AC Panel 1 to transfer to alternate power supply causing relays to de-energize.
219	01/01/93	93-001	0%	Lightning Arrester (failure), Reactor Bldg. Radiation Monitor.	Standby Gas Treatment and Reactor Building Ventilation	Reactor building ventilation system isolated and SBGT system initiated.	**Lightning arrester failed** which caused power perturbations resulting in radiation monitor in Reactor Building initiating ventilation isolation and initiation of SBGT.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
254	07/29/87	87-014	99%	Chlorine Analyzer	Toxic Gas Analyzer System	Control Room Ventilation Isolated.	Lightning struck 345 kV line and caused power perturbations.
254	06/26/90	90-013	100%	PCI Valve	Reactor Recirculation Sampling System	Isolated outboard sampling valve.	Believe lightning surge caused voltage fluctuation and subsequent valve closure.
254	03/22/91	91-008	0%	Reactor Bldg. Vent Fans, Control Room Vents, RPS 1/2 Scram	Ventilation Systems, RPS	Isolated Reactor Bldg. and control room vents.	Lightning struck in transmission line substation.
254	02/14/92	92-006	0%	Feeder Line Trip, Unit 1 Annunciators, Control Room Ventilation Dampers.	Annunciation, Control Room Ventilation	Isolated control room ventilation.	Lightning struck feeder in 345 kV switchyard. Fuses needed replacement in annunciators.
263	06/05/84	84-022	0%	Spent Fuel Pool Radiation Monitor Channel B Fuse	Radiation Monitoring, Standby Gas Treatment, Reactor Bldg. Ventilation	Isolated Reactor Bldg. ventilation and initiated SBGT system.	Lightning surge believed to cause overvoltage on 24 VDC which blew fuse.
265	05/20/87	87-007	90%	480 VAC Supply to Reactor Water Cleanup Isolation Valves.	Group III Isolation	Isolated RWCU system.	Lightning actually struck Met. Tower but backfed surge created bus overvoltage causing circuit breaker to trip. There was also other damage.
321	07/02/86	86-028	100%	Primary Containment Isolation Valves for High Ambient Temp., Reactor Water Cleanup System	Primary Containment Isolation	RWCU Isolated.	Lightning strike caused actuation of the primary containment isolation valves for the reactor water cleanup system.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
322	09/09/85	85-040	1%	Electrical Bus Undervoltage	Reactor Bldg. Standby Ventilation System, Control Room Air Conditioning	Reactor Bldg. Normal Ventilation Tripped, RBSVS and CRAC Initiated	Lightning strikes on 138 kV system caused 8 kV drop in transmission system which was reflected into lower voltage systems.
322	07/27/86	86-030	0%	Electrical Bus Undervoltage Spikes	Reactor Bldg. Standby Ventilation System, Control Room Air Conditioning	Reactor Bldg. Normal Ventilation Tripped, RBSVS and CRAC Initiated	Lightning strikes on 138 kV grid causes undervoltage spikes at lower voltages. Happened twice: 07/27/86 and 08/11/86.
331	06/17/84	84-020	57%	A Standby Filter Unit	Control Room Air Conditioning	CRAC Actuations	Thunderstorms may have caused CRAC actuations 4 times in 3 days.
388	05/31/85	85-020	0%	Voltage Transient	Tie-Line Between 230 kV and 500 kV Switchyards	Control room emergency outside air supply, SBGT initiations	Lightning strike to or near 230 kV and 550 kV switchyards tie-line.
410	08/15/89	89-021	96%	Standby Gas Treatment Radiation Monitor	Standby Gas Treatment (SBGT)	Group 9 isolation of primary containment vent and purge valve and SBGT initiation.	Lightning strike to main stack tower caused power interruption to radiation monitor and false signal from its microprocessor.
410	11/30/89	89-039	90%	Same as above.	Same as above.	Same as above.	Same as above.
410	01/18/91	91-001	0%	Same as above.	Same as above.	Same as above.	Same as above.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
412	09/06/90	90-011	0%	Containment Radiation Monitor	Containment Isolation	Containment purge isolation.	Lightning strike caused spike to radiation monitor. Plant initiating refueling at time.
416	06/25/91	91-006	100%	Reactor Water Cleanup Div. 2 Isolation Valves Temperature Switch	RWCU Leak Detection System	Isolation of RWCU	Lightning strike on 500 kV transmission line caused voltage spike affecting Riley temperature switch.
424	06/19/94	94-004	100%	Control Room Emergency Filtration System heaters in Units 1 and 2, Heaters Power Supply	Control Room Emergency Filtration System	Technical Specification Report	Thunderstorm caused fault in plant switchyard that caused the Control Room Emergency Filtration System heaters' control relays to deenergize in both Units. Event complicated by failure of relays to reset.
454	09/21/86	86-026	79%	Containment Bldg. Fuel Handling Radiation Monitor and Control Room Air Intake Radiation Monitor Undervoltages	Containment Ventilation Isolation and Main Control Room Ventilation	ESF Actuations	Lightning struck 138 kV offsite source which caused grid perturbation and undervoltage
454	08/26/88	88-006	98%	Fuel Handling Bldg. Radiation Monitor Undervoltage	Fuel Handling Isolation and Charcoal Filter Systems	ESF Actuation	Electrical distribution disturbance caused by static line which had been severely damaged by lightning in the past fell on transmission line and tripped distribution breakers initiating transient.
454	08/03/89	89-007	99%	Process Radiation Monitors Undervoltage	Main Control Room Ventilation Recirculation	ESF Actuation	Lightning struck a transmission line which tripped but initiated a voltage transient.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
454	05/05/91	91-002	100%	Process Radiation Monitors Undervoltage	Main Control Room Ventilation System	ESF Actuation	Grid disturbance during thunderstorm caused voltage transient. (Seismic monitoring had temporary failure).
455	04/10/92	92-002	0%, Mode 6	Some Radiation Monitors had Undervoltage	Containment Isolation Valves	ESF Actuation	Lightning created voltage transient that caused enough radiation monitors to produce containment isolation signal.
456	03/26/91	91-005	0%	Control Room Outside Intake Radiation Monitors Undervoltage	Main Control Room Ventilation	ESF Actuation	Lightning strike produced momentary loss of voltage. Corrective action on lightning strikes includes grounding system modifications and lightning dissipation for ventilation stacks.
457	11/15/88	88-027	0%	Containment Fuel Incident Monitor Power Failure	Unit 2 Train B Containment Isolation	ESF Actuation	Lightning on 345 kV system momentarily opened line 0103 which feeds system auxiliary transformer to motor control centers feeding the radiation monitors. This failed power to the fuel incident monitor.
457	08/26/92	92-005	100%	Containment Fuel Handling Incident Area Radiation Monitor	Unit 2 Train B Containment Isolation	ESF Actuation	Believe lightning strike induced a noise spike into the containment fuel handling incident area radiation monitor causing the Train B containment ventilation isolation signal.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
458	08/05/87	87-016	91%	Annulus Mixing and SBGT Initiations	SBGT	ESF Actuation	Lightning struck light pole in parking lot and auto-starts of annulus mixing and SBGT systems occurred.
458	04/06/94	94-005	98%	Actuations of SBGT, Isolations in Fuel and Aux Bldgs. Ventilation Systems	SBGT, Fuel and Auxiliary Buildings Ventilation	ESF Actuation	Shield wire fell on 230 kV transmission line during lightning storm which caused voltage transient.
482	08/06/85	85-055	92%	Control Bldg. Ventilation Radiation Monitor Isolation Signal	Control Room Ventilation System	ESF Actuation	Nearby lightning strike caused voltage fluctuation on radiation monitor.
482	10/09/85	85-071	0%	Control Bldg. HVAC Radiation Monitor	Control Room Ventilation Isolation System	ESF Actuation	Nearby lightning strike caused voltage fluctuation on radiation monitor.
528	07/29/87	87-021	0%	Control Room Ventilation Intake Noble Gas Monitor	Control Room Essential Filtration Actuation	ESF Actuation	Electrical storm apparently had reset the noble gas monitor to its default/alarm trip setpoint.
155	09/21/83	83-013	Not Stated	Static Inverter Fuse	Containment Vacuum Relief	Technical Specification Report	Additional damage to telephone and security equipment and domestic water controls.
220	08/30/80	80-020	100%	Meteorological Instruments	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower power transformer.
259	01/12/80	80-002	Not Stated	Meteorological Instruments	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
259	05/27/81	81-026	Not Stated	Wind Speed Fuse.	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.
259	01/03/82	82-001	Not Stated	Meteorological Instruments' Transistors and Fuses.	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.
259	01/09/82	82-015	Not Stated	Meteorological Instruments' Fuses.	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.
259	06/30/82	82-043	Not Stated	Meteorological Instruments' Fuses.	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.
259	08/10/82	82-058	Not Stated	Meteorological Instruments' Fuses.	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower.
271	09/08/80	80-028	89%	Environmental Sampling Station Fuse.	Environmental Sampling Station System	Technical Specification Report	Lightning caused blown fuse. Corrective action was to install lightning surge suppressors in the nine stations.
271	07/23/84	84-014	0%	Environmental Sampling Station Fuse.	Environmental Sampling Station System	Technical Specification Report	Lightning caused blown fuse.
281	04/13/82	82-022	Not Stated	One Nuclear Power Range Instrument	Reactor Protection System	Technical Specification Report	Lightning arrester failure caused lock-out of an auto-tie transformer which caused de-energizing of power supply to nuclear power range instrument.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
293	05/12/81	81-018	Not Stated	Stack Gas Radiation Monitor	Radiation Monitoring System	Technical Specification Report	Lightning struck in area of main stack damaging pre-amplifier and discriminator.
298	06/17/90	90-007	100%	Service Water Pump Room Halon Fire Suppression Control Board.	Fire Suppression System	Technical Specification Report	Lightning believed cause of spurious operation of Halon system. Subsequent testing revealed failed circuit board.
302	06/17/81	81-034	Not Stated	Meteorological Instruments	Environmental Monitoring	Technical Specification Report	Lightning rendered Meteorological instruments inoperable.
302	07/15/82	82-048	Not Stated	Meteorological Instruments	Environmental Monitoring	Technical Specification Report	Lightning damaged wind and temperature instruments.
302	08/05/83	83-032	Not Stated	Meteorological Instruments	Environmental Monitoring	Technical Specification Report	Lightning rendered Meteorological instruments inoperable.
320	06/01/82	82-018	Not Stated	Air Intake Tunnel Halon System Ultraviolet Light Detector	Fire Protection System	Technical Specification Report	Lightning flash set off ultraviolet light Halon system detector.
320	06/29/82	82-023	Not Stated	Air Intake Tunnel Halon System Ultraviolet Light Detector	Fire Protection System	Technical Specification Report	Lightning flash set off ultraviolet light Halon system detector.
320	06/21/83	83-025	Not Stated	Air Intake Tunnel Halon System Ultraviolet Light Detector	Fire Protection System	Technical Specification Report	Lightning flash set off ultraviolet light Halon system detector. Permanent corrective action subsequently taken.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
320	06/01/82	82-019	Not Stated	Meteorological Instruments 12 Volt Power Supply	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower and failed amplifier components and fuse of power supply.
327	08/01/80	80-138	0%	Cooling Tower Flow Meter	Environmental Monitoring	Technical Specification Report	Lightning strike believed cause of flow monitor sensors.
346	09/01/80	80-068	0%	Meteorological Instrument	Environmental Monitoring	Technical Specification Report	Lightning struck meteorological tower and damaged wind sensor and computer.
348	08/12/93	93-002	100%	4 of 5 D/G Fuel Oil Storage Tank Level Indicators	Diesel Generator Fuel Oil Supply	Technical Specification Report	Lightning strike failed 4 level indicators.
368	11/22/82	82-040	Mode 2	Control Element Assembly Calculator (CEAC)	Core Protection Calculators	Technical Specification Report	Postulated that lightning storm in progress blocked power to CPC channels.
368	05/27/83	83-024	Mode 3	Pressurizer Proportional Heater Cabinet Fuses	Reactor Coolant System	Technical Specification Report	Believe power surge caused by lightning strike caused fuses to blow.
369	06/01/82	82-046	Not Stated	Conventional Waste System Flow Meter Power Supply	Conventional Waste System	Technical Specification Report	Severe electrical storm caused interference with power supply.
369	11/04/82	82-076	Not Stated	Fire Pump Power Supply Lost, 44 kV Insulator	44 kV Independent Power Supply to Fire Pump	Technical Specification Report	Lightning failed insulator on fire pump independent power source.
387	08/16/93	93-010	0%	Simplex Fire Protection System Transponder Card	Fire Suppression System	Technical Specification Report	Severe lightning storm failed transponder card causing numerous alarms.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
387	08/02/94	94-012	100%	Simplex Fire Protection System Disabled	Fire Suppression System	Technical Specification Report	Lightning strike caused electrical impulse disabling Simplex system.
387	08/18/94	94-014	100%	Simplex Fire Protection System Panel A	Fire Suppression System	Technical Specification Report	Lightning strike caused panel A of Simplex system to be disabled.
389	09/25/83	83-059	94%	Control Room Monitoring Instruments	I & C	Technical Specification Report	Lightning strike rendered control room monitoring instruments inoperable. Portable instruments available for local monitoring.
389	09/24/83	83-063	94%	Containment Gaseous Monitor	RCS Leakage System	Technical Specification Report	Lightning strike caused voltage spike which failed solid state circuitry in gaseous monitor.
395	07/29/87	87-018	100%	Integrated Fire & Security System	Integrated Fire & Security System	Technical Specification Report	Severe electrical storms failed the integrated fire & security system.
395	08/30/88	88-010	100%	Integrated Fire System Computer Signal Processing Units	Integrated Fire System	Technical Specification Report	Lightning actually struck meteorological tower but it is believed to have caused a logic shift in the signal processing units.
413	07/27/89	89-021	100%	Refueling Water Storage Tank Level Instruments, Level Transmitter	ECCS	Technical Specification Report	Lightning struck on or near RWST causing two level instruments to become inoperable and damaging a level transmitter.

Table A.7 (Cont'd)

Docket	Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
416	06/16/82	82-003	Not Stated	Forced Balance Accelerometer (FBA) Amplifiers	Seismic Monitoring	Technical Specification Report	Lightning caused amplifier failures in free field FBA.

Table A.7 (Cont'd)

Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
08/18/88	NPRDS	100%	Steam Generator Flow Indication Power Supply Card	Main Steam, RPS Steam/Feedwater Mismatch	Other	Believe electrical surge from lightning strike caused steam flow indicator power supply card to go out of calibration.
07/14/94	NPRDS	100%	Service Water Pump Motor	Service Water System	N/A, redundant pump supply to Reactor Building closed loop cooling water system available.	Lightning surge grounded the motor's stator winding.
10/17/91	NPRDS	100%	Condensate Pump Motor Surge Capacitor	Condensate	N/A	Lightning strike believed cause of capacitor explosion. Plant shutdown 2 days earlier than planned.
11/26/88	NPRDS	0%	RPS "B" Alternate Supply Breakers Tripped	RPS	Other	Lightning strikes apparently caused RPS alternate "B" supply breakers to trip. Unit was in refueling at time.
07/20/94	NPRDS	100%	Battery Charger A Fuse.	A Train ECCS 24 Volt DC Power System	N/A. Battery A continued to Power A ECCS Analog Trip Transmitters.	Probably same thunderstorm discussed in above LER.
11/04/88	NPRDS	90%	Div. 2 and Div. 4 125 Volt DC Battery Chargers' Thyristors, Fuses, and Diodes	125 Volt DC System	Other	Believe lightning strike caused battery charger failures via a voltage transient through the common 480 Volt station that feeds the chargers.

Table A.7 (Cont'd)

Date	LER No.	Power Level	Component	System	ESF Actuation	Remarks
01/10/89	NPRDS	100%	Radial Well Pump-Motor Circuit Breaker	Essential Service Water	Other	During severe thunderstorm the radial well pump-motor circuit breaker tripped.

APPENDIX A - REFERENCES

In addition to evaluating the LERs and NPRDS records a reference check on lightning was performed to ensure that no event was missed. Not all of the references below had as their sole purpose or as a major purpose the identification of lightning initiating events for a PRA.

A.1 Wyckoff, H. "Losses of Off-Site Power at U. S. Nuclear Power Plants Through 1991", NSAC-182, 1992 (Also: NSAC-203, -194, -147, -118, -111, -103, -85, -80).

A.2 Mazumdar, S. "Engineering Evaluation Report: Evaluation of Loss-of-Offsite Power Due to Plant-Centered Events", AEOD/E93-02, March 1993

A.3 Battle, R.E. "Collection and Evaluation of Complete and Partial Losses of Offsite Power at Nuclear Power Plants", NUREG/CR-3992, February 1985

A.4 Kimura, C.Y. and Prassinos, P.G. "Evaluation of External Hazards to Nuclear Power Plants in the United States", NUREG/CR-5042, Suppl. 2, February 1989

A.5 Gehl, A.C. and Hagen, E.W. "Aging Assessment of Reactor Instrumentation and Protection System Components", NUREG/CR-5700, July 1992

A.6 Mazumdar, S. "Engineering Evaluation Report: Operational Experience on Bus Transfer", AEOD/E90-05, June 1990

A.7 Hoy, H.C. "Potentially Damaging Failure Modes of High and Medium Voltage Electrical Equipment", Nuclear Safety, Vol. 25, No. 2, March-April 1984

A.8 Ryder, C. "Report on the Effects of Lightning on Nuclear Power Station Systems", USNRC ACRS, December 9, 1982

A.9 NRC Information Notice 93-95: Storm-Related Loss of Offsite Power Events Due to Salt Buildup on Switchyard Insulators, December 13, 1993

A.10 IE Information Notice No. 85-86: Lightning Strikes at Nuclear Power Generating Stations, November 5, 1985

APPENDIX B

SURGE SUPPRESSOR

TABULATED DATA BASES

B.1 Surge Suppressor or Overvoltage Device Failure

B.2 Plant Overvoltages - Proposed Corrective Actions

Table B.1 Surge Suppressor or Overvoltage Device Failure

Docket	LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
293	93-022	09/10/93	100%	345 Kv air circuit breaker (ACB) surge suppression circuit.	Surge Suppressor	Lightning struck one of the 345 Kv switchyard air circuit breakers which resulted in a loss of preferred offsite power and reactor scram. (Surge suppressor circuit was replaced but no information on whether old one had failed). (Same event in Table A.4).
483	85-034	07/18/85	100%	Overvoltage arrestor failed due to inadequate cooling of a rod drive power cabinet.	Overvoltage Arrestor	While at 100% power, a reactor trip occurred as a result of a power range high negative flux rate signal caused by control rods dropping from loss of both M-G sets caused by a rod drive power cabinet overvoltage arrestor failing from excessive heat.
370	92-009	08/05/92	100%	Failed blocking diode in solenoid valve control circuitry caused a blown fuse and subsequent loss of power.	Blocking Diode	While at 100% power a reactor trip occurred due to a steam generator low-low water level which was caused when the main feedwater regulating valve moved to its fail-safe (closed) position upon loss of power caused by a blown fuse in the control circuitry of the solenoid.
244	90-018	12/20/90	22%	Rod Control System: Circuit supplying power to the stationary, movable and lift coils of control rods.	Power Bridge Thyristor (suppression filter capacitors)	Thyristor degradation allowed one rod to drop in the core which caused a turbine runback and eventual turbine trip and reactor trip.

Table B.1 (Cont'd)

Docket	LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
344	81-003	01/30/81	0%	Improper actuation of nuclear source range crowbar circuit.	Crowbar Circuit	During reactor shutdown, the minimum required number of source range channels was not met when both channels of nuclear source range indications failed to automatically energize because of improper actuation of the crowbar circuit. Reactor was manually tripped.
397	84-030	04/12/84	1%	A grounded varistor on an RCIC motor operated valve contributed to inducing voltage spikes.	Varistor	A grounded varistor on an RCIC motor operated valve contributed to allowing voltage spikes to be induced in the control room outside air radiation monitoring system when the motor operated valve was stroked.
263	87-006	02/16/87	100%	Wide Range Gas Monitor (WRGM): The WRGM had failed metal oxide varistor, fuse and processor unit.	Metal Oxide Varistor	The wide range gas monitor failed following a more general upset of the uninterruptible power supply (UPS) that caused a reactor scram.
272	90-031	09/17/90	87%	Two failed electrolytic capacitors in power supply filtering circuit.	Filter	The control room general area radiation monitoring system spiked high causing the automatic switching of control room ventilation from normal to accident. The failed capacitors allowed EM/RFI to pass thru unfiltered.

Table B.1 (Cont'd)

Docket	LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
305	92-002	02/03/92	100%	Liquid radiation monitor power supply's low alarm relay surge suppressor.	Surge Suppressor	Testing of radiation monitor caused isolation of steam generator blowdown valves and sample valve from radiation monitor's low alarm relay chatter.
333	91-022	10/15/91	100%	High radiation monitor filter input assembly.	Filter Input Assembly	A spurious primary containment high radiation monitor A isolation signal via the off-gas vent line isolation delay timer was initiated. The input filter assembly was identified as the initiation pathway.
458	86-049	08/05/86	100%	Failed under-sized transient voltage suppressor in radiation monitor circuit.	Transient Voltage Suppressor	Fuel building filtration system was initiated by a spurious signal generated on radiation monitor. The root cause was a failed under-sized transient voltage suppressor. A modification will upgrade the size of six transient voltage suppressors in the circuitry.
286	88-008	08/17/88	100%	Diesel Generator field circuitry.	Surge Suppressor	Dirty contacts on Unit parallel relay in diesel generator paralleling circuit caused loss of droop control. Surge suppressor failed from load fluctuations.

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	10/12/89	Not Stated	A control rod gripper coil.	Suppression Diode	A control rod would not withdraw because no current was getting to the gripper coil. The diode which prevents an inductive kick from getting into the rectifier was open.
NPRDS	02/08/89	Not Stated	Control card and suppressor in UPS.	Suppressor Card	Transfer from UPS to alternate power supply would not have occurred due to suppressor and control card failures.
NPRDS	05/30/90	0%	Transformer failure in static switch section of uninterruptible power supply caused erratic inverter output.	Suppressor Assembly	Suppressor assembly may have failed due to failure of transformer in static switch section of UPS.
NPRDS	09/03/85	Not Stated	Engineered safeguards bus relay failed surveillance test because of shorted metal oxide varistor.	Metal Oxide Varistor	During surveillance test an engineered safeguards bus relay failed its test because of a shorted metal oxide varistor in its circuit.
NPRDS	03/03/86	0%	Second level undervoltage protective relay and surge protector.	Metal Oxide Varistor	Test equipment spike apparently failed both the surge protector and the relay it was protecting.
NPRDS	07/03/88	100%	Reactor vessel narrow range level indicator relay circuitry.	Suppression Diode	The relay circuitry failed for the reactor vessel narrow range level indicator when the suppression diode shorted across relay due to age.

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	04/20/88	Not Stated	Relay integral transient suppression device mechanically ruptured.	Metal Oxide Varistor	RHR shutdown cooling isolation valve relay failed causing automatic closure. Failure of metal oxide varistor is likely thermal runaway.
NPRDS	04/25/92	100%	Preheater bypass valve in feedwater system failed shut.	Varistor	A shorted varistor caused the preheater bypass solenoid valve to fail shut and a fuse to blow. Cause is unknown but likely age-related.
NPRDS	03/20/94	Not Stated	Alternate supply voltage line regulator control logic board	Spike Suppression Varistor	The output of the alternate supply voltage line regulator for bus inverters were reading higher due to spike suppression varistor and control logic board failures. Cause is unknown but likely wear out.
NPRDS	05/14/90	Not Stated	Instrument AC power system regulating transformer/ line regulator board	Varistor	Regulating transformer lost its function due to varistor and a capacitor in the line regulating board being burned out.
NPRDS	02/04/89	Not Stated	Effluent gas monitor controller module.	Suppression Capacitor, Diode Varistor	Effluent gas monitor controller module lost its functions due to bad suppression capacitor and diode varistor. Cause is unknown.
NPRDS	11/21/83	0%	Inverter surge voltage suppressor, 2 silicon controlled rectifiers, and fuse blown.	Surge Voltage Suppressor	Inverter had a hard ground indication from a number of internal component failures. (Failures attributed to age).

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	09/20/91	Not Stated	Inverter output circuit breaker would not close.	Ceramic Arc Suppressor	Inverter output circuit breaker would not close because a ceramic arc suppressor had broken due to age/cyclic fatigue.
NPRDS	01/14/89	Not Stated	Inverter leg of uninterruptible power supply had a blown fuse from faulty transient suppressor network.	Transient Suppressor Network	Inverter output of uninterruptible power supply failed due to shorted capacitors and a leaky capacitor in the transient suppressor network.
NPRDS	04/24/89	100%	Rectifier bus fuse blown and surge suppressor damaged.	Metal Oxide Varistor	Rectifiers bus "A" and "B" tripped when placed in equalize charge. Cause of failures in rectifier bus "A" are unknown.
NPRDS	01/11/88	100%	Inverter rectifier, surge suppressor, regulator control and static switch cards.	Surge Suppressor	During normal operation the 120 VAC instrumentation power supply became inoperable due to a number of component grounds. Cause is unknown.
NPRDS	01/02/91	Not Stated	Battery charger had a burnt surge suppressor, burnt resistor, blown fuse and bad silicon controlled rectifier.	Surge Suppressor	Battery charger started cycling due to failed components. Failure cause unknown but many subcomponents replaced.
NPRDS	07/24/93	Not Stated	Battery charger had two defective surge suppressors.	Surge Suppressor	Battery charger was found to be smoking due to two charred surge suppressors. Failure cause is age/cyclic fatigue.

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	08/23/88	Not Stated	Battery charger showed low voltage output due to failed surge suppressor.	Surge Suppressor	Battery charger had low voltage output due to failed surge suppressor and blown fuses. Failure attributed to age/wear.
NPRDS	08/23/88	Not Stated	Battery charger producing low output voltage due to shorted surge suppressor.	Surge Suppressor	Battery charger had a failed surge suppressor and blown fuses causing low output voltage. Failure attributed to age/wear.
NPRDS	06/23/87	0%	Battery charger had a failed output due a failed voltage surge suppressor.	Surge Suppressor	Battery charger had failed output due to failed surge suppressor. Failure attributed to age/wear.
NPRDS	09/19/92	100%	Battery charger's phase surge suppressor off silicon controlled rectifier.	Surge Suppressor	Rectifier unit's surge suppressor burst into flames due to a phase imbalance. Failure attributed to 1 of 3 phases of AC power input breaker feeding the battery charger failing.
NPRDS	03/22/84	Mode 6	Battery charger surge voltage suppressor.	Surge Suppressor	The battery charger in the "1A" DC distribution system failed due to a burned out surge suppressor. Cause attributed to age.
NPRDS	12/06/89	100%	125 VDC battery charger.	Surge Suppressor	Voltage fluctuations occurred on the 125 VDC battery charger because of charred capacitors in the charger cabinet. Surge suppressor actually burned out and caused capacitor damage.

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	10/20/88	0%	Diesel generator under frequency protective relay and fuse.	Metal Oxide Varistor	During routine surveillance test a defective under frequency relay, defective metal oxide varistor, and blown fuse were found for diesel generator no. 2.
NPRDS	08/04/87	Not Stated	Diesel generator field excitation circuit/saturable transformer, surge suppressors, voltage regulator card.	Selenium Surge Suppressors	During surveillance testing the "A" diesel generator failed to attain rated voltage due to failure of the saturable transformer in the excitation/field flash circuit.
NPRDS	02/18/92	100%	Diesel generator excitation system/surge suppression boost assembly.	Selenium Rectifier in Surge Suppressor	Upon completion of monthly surveillance test, a diesel generator exhibited voltage and speed oscillations due to failure of one of the selenium rectifiers in the surge suppressor portion of the excitation system's series boost assembly.
NPRDS	10/19/93	0%	Diesel generator engine controller fiber optic board/transistor	Surge Suppressors	Diesel generator started inadvertently due to a failure of a transistor in the engine controller fiber optic board. The transistor failed because the surge suppressors had degraded in the control circuitry. Age-related degradation.

Table B.1 (Cont'd)

LER No.	Date	Power Level	Component/System Protected	Device Type	Remarks
NPRDS	11/12/93	100%	Diesel generator control power breaker/coil	Metal Oxide Varistor	Diesel generator control power breaker tripped due to a shorted coil (which provides alarm only) from a metal oxide varistor arcing and opening. Failure of varistor is age.

Table B.2 Plant Overvoltages - Proposed Corrective Actions

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
331	92-013	08/17/92	100%	An automatic scram was initiated due to a perceived high average power range (APRM) neutron flux level but was actually caused by a noise signal which affected the recirculation flow signals and reduced the flow-biased scram setpoint below the operating level.	The use of light-emitting diodes (LEDs) has been approved for use in the control rod indication because of their improved reliability over the incandescent lamps that failed during this event.
424	88-025	07/31/88	16%	Lightning struck the containment building and a reactor trip occurred due to the electrical surge that shutdown the output of the control rod drive mechanism power supplies, allowing the rods to drop into the core.	Installation of surge suppressors in the rod control power circuits has been recommended.
206	89-017	05/03/89	0%	Intermediate range channels receiving high startup rate. Predominate sources come from 1) pulse-to-analog DC stepper motor and, 2) the rod position deviation alarms. Other sources of noise include 1) the control rod drive mechanism control circuit cam actuated switches and contactor coils, and 2) the rod bottom signal relays.	Circuit modifications consisting of noise suppression devices (i.e., resistor-capacitor filters and diodes) have been installed.
237	91-037	11/13/91	1%	An automatic reactor scram occurred due to spurious hi-hi neutron flux signal on the intermediate range monitors. An extensive investigation into the spiking determined the cause to be electromagnetic interference (EMI) produced by the DC valve motor of a HPCI steam isolation valve opening at that time.	Installation of varistors on HPCI 250 VDC valve motor circuitry to reduce the amount of EMI produced by valve operation. (Other corrective actions are identified in this LER).

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
220	94-004	04/11/94	1%	During startup a spurious intermediate range monitor (IRM) "high-high" neutron flux trip occurred from electrical noise generated from actuation of relays external to the neutron monitoring system.	Install noise suppression circuits to correct probable causes of IRM spiking.
245	86-018	05/24/86	0%	A noise spike on intermediate range monitor (IRM) 12 and 16 caused by a source range monitor (SRM) drive relays chattering during its withdrawal resulted in an RPS actuation.	The SRM/IRM drive relays have been replaced by relays with arc suppression.
285	84-013	07/22/84	83%	Noise spikes received by temperature loops feeding TMLP calculator inputs caused tripping of 2 out of 4 channels of TMLP trip channels (and subsequent reactor trip). Noise was generated by pressurizer quench tank valve.	Noise suppressors were installed across the solenoid valve coil electrical leads and electrical leads of an associated control relay.
324	91-002	04/02/91	0%	An unexpected trip was caused by an IRM channel spiking upscale. A signal noise created by RPS trip system "A" scram relays de-energizing was induced into the IRM detector circuitry.	Metal oxide varistors have been installed across the coils of the associated scram relays on a temporary basis until permanent installation can be effected; have proven to be effective in suppressing high voltage spiking.
325	89-002	02/07/89	0%	With Unit in a refuel/maintenance outage, full reactor protection trips were received due to noise in the IRM circuitry. A previous modification had changed the routing of cables to minimize induced voltages.	Another investigation has resulted in the installation of 8 additional electrical noise suppression circuits on Unit 1. Unit 2 is also being evaluated for similar fix.

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
213	88-008	03/19/88	0%	Automatic trip during startup physics testing caused by a spurious, high startup rate trip signal from electrical noise in nearby annunciator cabinet.	A suppression diode is to be placed across the annunciator relay coil.
499	94-003	04/29/94	0%	Diesel generators 21, 22, and 13 have inadvertently started in test mode from the fiber optic boards' susceptibility to noise in conjunction with transient DC spikes.	A modification was installed in the DC distribution panel to attenuate the level of DC noise and spikes. An additional modification was installed in specific diesel control circuit relays to dampen inductive responses to DC power disturbances.
255	90-009	05/16/90	0%	With the plant in hot standby, the atmospheric dump valves unexpectedly opened due to electrical noise that was induced in the Tavg input signal to the atmospheric steam dump and turbine bypass control circuit by adjacent electric power cables.	A temporary modification was installed to suppress the noise on the Tavg input signal.
271	94-009	07/20/94	100%	Lightning strike to plant site resulted in the failure of various pieces of plant equipment including an apparent failure internal to the Vital AC transfer switch: (1) transfer of 120/240 V Vital AC bus from normal to alternate source; (2) primary containment isolation system partial isolations; (3) initiation of SBGT system; (4) shutdown of electronic pressure regulator (EPR); and (5) lockups of feedwater regulation valves and recirculation pump M-G set scoop tubes.	The installation of surge/lightning suppression devices on the affected equipment is currently being evaluated.
272	80-031	06/08/80	100%	Lightning hit containment and caused transient on 7 main steam pressure transmitters with 2 failing. A safety injection occurred for four minutes.	Suitable surge protection is being investigated and the results reported in a follow-up report.

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
311	82-147	12/05/82	Not Stated	Spurious actuation of no. 2A safeguards equipment control (SEC) cabinet resulted in de-energizing of no. 2A vital bus.	Noise suppression circuitry is scheduled for installation in SEC system during next refueling outage.
311	93-008	05/27/93	0%	During testing an RCCA withdrew instead of inserting because integrated circuit chips on two slave cycler decoder cards had failed due to the relay driver circuit card connector pin no. 4 not making electrical contact with the surge suppression diode.	An additional corrective action was the installation of suppression diodes on the rod step counters of the RCS circuitry, of each Unit, to mitigate consequences of an open or bad connection on the relay driver circuit card connector pin no. 4.
325	88-011	04/20/88	100%	HPCI pump suction from the suppression pool would not open due to failure of the valve motor in motor operated valve from the suppression pool to the pump suction.	Modifications will be implemented to install surge protection within the shunt coil circuitry of DC motor control circuitry on both Units to prevent failure of motor winding insulation due to high inductive voltage surges across the shunt coil when motor circuit breaker is opened.
271	80-028	09/08/80	89%	Severe electrical storm caused blown fuse in air sample station.	Lightning surge suppressors will be installed in all nine environmental sample stations.
325	89-005	02/16/89	0%	With Unit in a refuel/maintenance outage, the RWCU isolated from the spurious actuation of the RWCU steam leak detection (SLD) isolation module which was due to induced noise from an adjacent module that shares a common power supply.	Time-delay relays will be installed in the SLD circuitry of the RWCU, HPCI, and RCIC systems.

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
275	86-007	07/10/86	79%	Automatic isolation of the containment ventilation system's sample line isolation valves for gaseous radiation monitors. (These kinds of events happened many times).	Time delay circuitry installed.
313	89-009	02/24/89	0%	Between February and September 1989 the control room emergency ventilation system has unexpectedly and automatically started 35 times as a result of initiation signals from radiation monitors or chlorine detectors.	(As part of the corrective actions) Installation of suppression diodes for the operation of the normal control room dampers.
327	84-022	03/30/84	0%	Containment ventilation isolation occurred as a result of a voltage spike on high radiation alarm.	Time delay relays are being added to prevent a containment ventilation isolation from short duration radiation spikes.
327	87-043	07/17/87	0%	Control room isolation occurred during surveillance testing of sample flow switches for process radiation monitor. Chattering of switches caused electromagnetic interference which induced spikes in the radiation monitor that actuated the isolation.	Install arc suppressors in the flow switch circuits to prevent high radiation trips from EMI induced spikes on radiation monitors.
328	86-005	10/16/86	0%	Containment ventilation isolation occurred from spike generated by spurious electromagnetic interference. Heli-arc welding is suspected as possible cause.	Add capacitors to the radiation monitor circuit to act as filters to help prevent EMI from causing a spike. (This type of modification has been performed on other radiation monitors and it has proven to be effective in reducing the magnitude and frequency of spikes).

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
361	84-049	08/24/84	100%	Train "A" containment purge isolation system spuriously actuated due to electrical noise spikes on containment area radiation monitor.	Investigation to include feasibility of adding electrical spike suppression circuits to the containment airborne radiation monitors for Units 2 and 3.
361	88-004	03/10/88	100%	Train "B" control room isolation system actuated when both channels of radiation monitors spiked.	Transient noise suppressors will be installed at appropriate locations in the radiation monitors circuits.
361	88-013	06/06/88	100%	Train "B" fuel handling isolation system (FHIS) spuriously actuated when the particulate/iodine channel of a radiation monitor received an instrument failure signal. Triggering of Train "B" actuation occurs when resetting monitor by switching the normal/bypass switch causes the reset/test lamp to extinguish and lamp power transformer to dissipate stored magnetic energy by discharging high voltage into the FHIS circuitry.	Surge suppression devices have been installed on the radiation monitor and on all Units 2 and 3 engineered safety feature process radiation monitors. It is believed that these services will preclude spurious actuations due to high-voltage surges when the reset/test lamp is extinguished.
361	88-032	12/02/88	100%	Train "A" toxic gas isolation system spuriously actuated due to a failed ammonia analyzer oscillator circuit board which in turn caused a high alarm and actuation through capacitive coupling.	A voltage suppressing circuit will be added, if necessary, to the alarm contacts to further minimize any additional capacitive coupling.
361	91-016	10/10/91	0%	Train "B" control room isolation system actuated because of a momentary (approximately 48 millisecond) instrument failure of the Train "B" particulate/iodine channel.	A temporary modification has been installed which (1) add a filtering circuit to the AC input to the radiation monitor module, and (2) enhances the filtering of the internal DC power supply regulators.

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
362	84-010	04/24/84	100%	Train "A" containment purge isolation system spuriously actuated from containment area radiation monitor noise spikes.	Investigation to include feasibility of adding electrical spike suppression circuits to the containment airborne radiation monitors for Units 2 and 3.
382	92-003	04/27/92	100%	One of four control room outside air intake (CROAI) radiation monitors reached its high alarm setpoint, probably due to an electrical spike, and caused actuation of the control ventilation system to isolate and emergency filtration to start.	New resistor-capacitor (RC) filters have been installed in the control room outside air intake (CROAI) circuitry.
395	83-074	06/03/83	Mode 1	Electrical surge from a lightning storm tripped: (1) the normal power feed breaker for a vital bus on overcurrent, and, (2) the diesel generator output breaker on overcurrent and phase differential.	Evaluation to be made of additional surge suppression circuitry to protect the diesel generator circuitry.
410	93-001	01/05/93	100%	Radio frequency interference in the switchgear room caused a loss of power to the Div. II emergency switchgear resulting in the actuation of several engineered safety features.	Evaluation to be made of using an external time delay circuit to prevent spurious trips of breaker.
454	84-038	12/31/84	0%	A spurious high radiation alarm from a radiation monitor caused the control room ventilation system to switch to the make-up mode of operation.	Noise suppression devices have been installed on the radiation monitor.
456	88-011	04/15/88	0%	Spurious high radiation signals on Train "B" radiation monitor caused control room ventilation to shift to the emergency make-up mode of operation.	Electrocubes had been installed in radiation monitor's circuitry prior to recent occurrences. Further investigation is needed.

Table B.2 (Cont'd)

Docket	LER No.	Date	Power Level	Problem	Proposed Corrective Action
458	86-052	08/22/86	0%	A main control room ventilation system isolation was caused by an induced signal on a radiation monitor resulting from maintenance work being performed on the monitor.	Investigation revealed that electrical noise could be reduced by installing additional noise suppression on the preamplifier power supply lines.
458	88-008	02/27/88	100%	An automatic initiation of Div. II standby gas treatment system and reactor building annulus mixing fan was caused by spurious signals from the reactor building annulus ventilation exhaust radiation monitor.	Two modifications have been initiated to (1) add RC networks to eliminate noise sources, and, (2) adjust the preamplifier discriminator settings to reduce the radiation monitors susceptibility to electrical noise.

Table B.2 (Cont'd)

LER No.	Date	Power Level	Problem	Proposed Corrective Action
NPRDS	05/05/89	0%	Maintenance found rod control bank no. 2 pulse to analog converter receiving sufficient noise from the DC stepper motors to trip both intermediate range channels.	A noise suppression circuit consisting of diodes connected in parallel with the DC coils of the stepper motor, one diode for the up coil and one for the down coil.
NPRDS	12/09/91	100%	Startup rates on nuclear instrumentation channels increased when control room annunciator reset push buttons were depressed.	Suppression diodes were installed across the auxiliary relay coils in the annunciator panel.
NPRDS	01/15/92	100%	A nuclear instrumentation channel spiked when a standby diesel control panel alarm reset push button was depressed.	A suppressor diode was installed across the auxiliary relay coils in the control panel.
NPRDS	04/18/90	Not Stated	The starting air 50% stop overspeed switch relay caused the diesel generator to trip from a false overspeed signal because the overspeed switch relay was experiencing inductive voltage transients that delayed dropout of the 50% relay.	Added a diode to prevent voltage transients across the relay.
NPRDS	11/04/93	Not Stated	Diesel generator containment isolation phase "B" automatic load sequencing restart timer relay would not start loading until safety injection signal was reset. The inductive kick from the de-energizing of the timer's aux relay caused the timer's microprocessor to misoperate.	A suppression diode was installed around the associated auxiliary relay to suppress the inductive kick. All similar circuits within the sequencer were also modified by adding a diode.
NPRDS	06/30/89	Not Stated	During surveillance testing a DC ground alarm occurred while stroking RCIC minimum flow bypass to suppression chamber MOV. Suppression resistor was left out of motor starter circuit.	Suppression resistor added to MOV motor starter circuit.

Table B.2 (Cont'd)

LER No.	Date	Power Level	Problem	Proposed Corrective Action
NPRDS	07/13/89	Not Stated	During surveillance testing a DC ground alarm occurred while stroking RCIC test return MOV. Suppression resistor was left out of motor starter circuit.	Suppression resistor added to MOV motor starter circuit.
NPRDS	05/15/86	Not Stated	Transformer in Security's uninterruptible power supply had frequent power spikes.	Engineering proposed installing a voltage suppressant to regulate the spike.

APPENDIX B - REFERENCES

In addition to evaluating the LERs and NPRDS records a reference check was performed on other component aging studies in which a suppressor was likely to be found such as reference F.5 in Appendix F and the following information notices are of interest:

B.1 NRC Information Notice 94-24: Inadequate Maintenance of Uninterruptible Power Supplies and Inverters, March 24, 1994

B.2 NRC Information Notice No. 94-20: Common-Cause Failures Due to Inadequate Design Control and Dedication, March 17, 1994

B.3 NRC Information Notice 91-81: Switchyard Problems that Contribute to Loss of Offsite Power, December 16, 1991

B.4 NRC Information Notice 91-57: Operational Experience on Bus Transfers, September 19, 1991

B.5 NRC Information Notice No. 90-42: Failure of Electrical Power Equipment Due to Solar Magnetic Disturbances, June 19, 1990

B.6 NRC Information Notice No. 88-57: Potential Loss of Safe Shutdown Equipment Due to Premature Silicon Controlled Rectifier Failure, August 8, 1988

B.7 NRC Information Notice No. 87-24: Operational Experience Involving Losses of Electrical Inverters, June 4, 1987

B.8 IE Information Notice No. 83-83: Use of Portable Radio Transmitters Inside Nuclear Power Plants, December 19, 1983

APPENDIX C: Model Data and Input Files for EMTP Simulation

45 kV Overhead Transmission Line Data

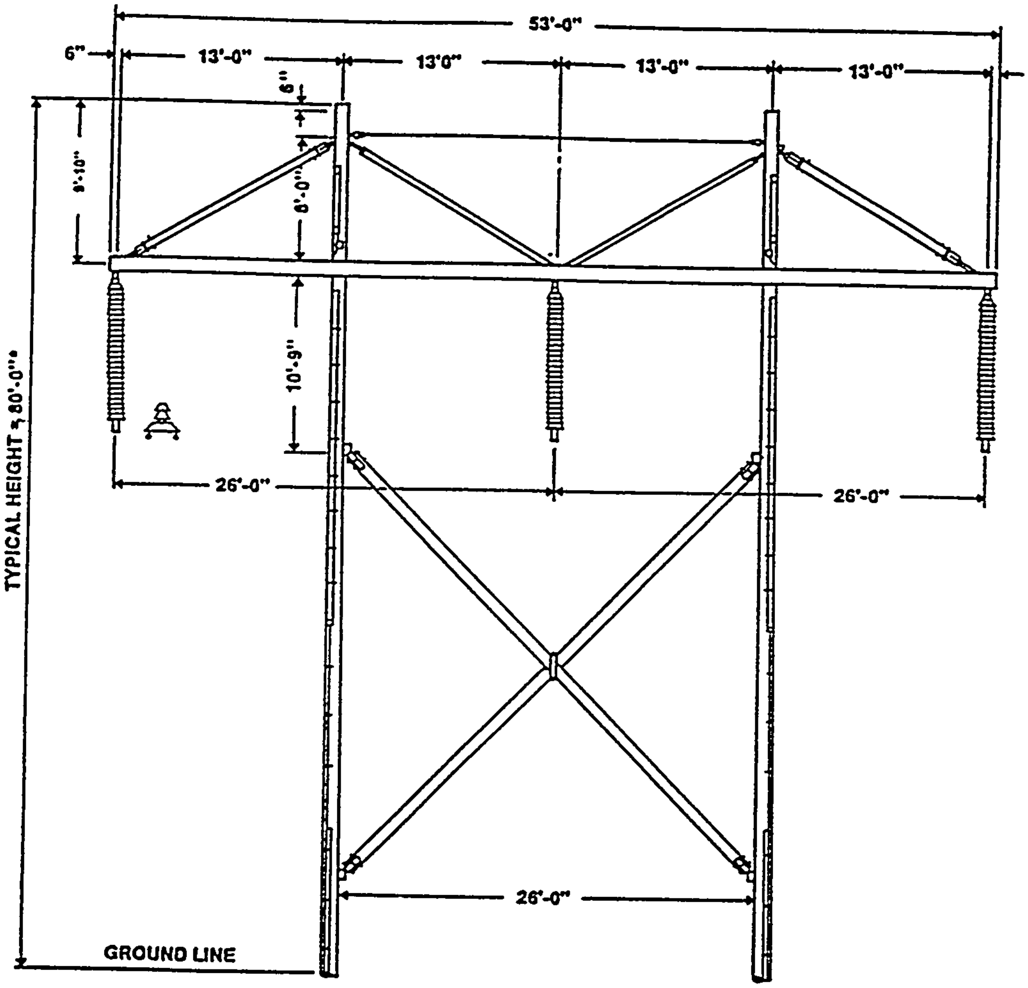

Fig. C-1. Typical 345 Kv transmission tower and conductor layout.

ACSR conductor data:	Twin bundle per phase (18" separation) 1.302" outside diameter (Bunting 45/7) 0.326" core diameter 21 ft sag at midspan 0.0787 ohm/mi dc resistance
Shield wire data:	7/16" outside diameter (EHS steel) 10.7 ft sag at midspan 4.61 ohms/mi dc resistance

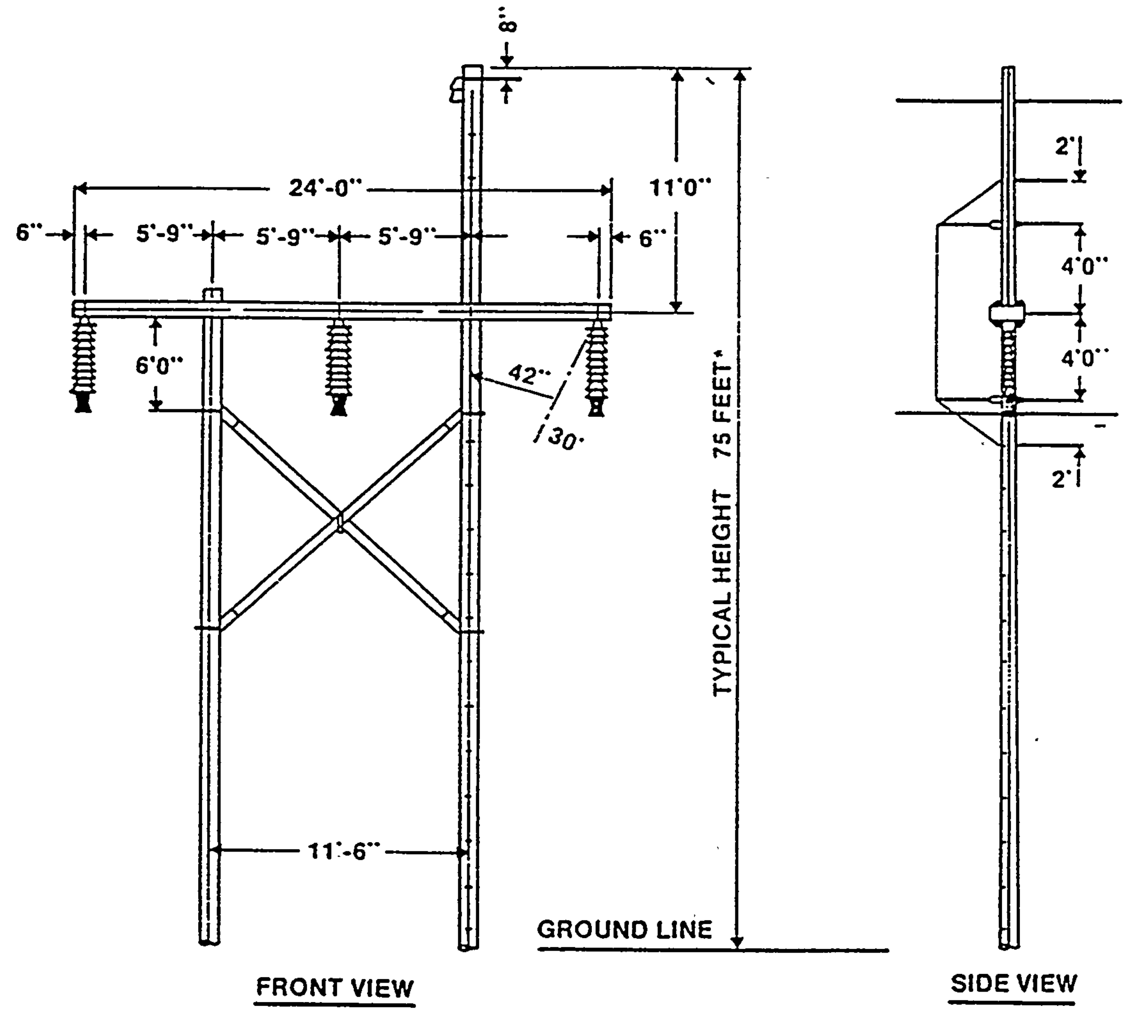

Fig. C-2. Typical 115 kV transmission tower and conductor layout.

ACSR conductor data:	1.108" outside diameter 0.408" core diamater 16 ft sag at midspan 0.1180 ohm/mi dc resistance
Shield wire data:	3/8" outside diameter (HS steel) 8 ft sag at midspan 6.51 ohms\mi dc resistance

Generator Unit Step-up Transformer (T1)

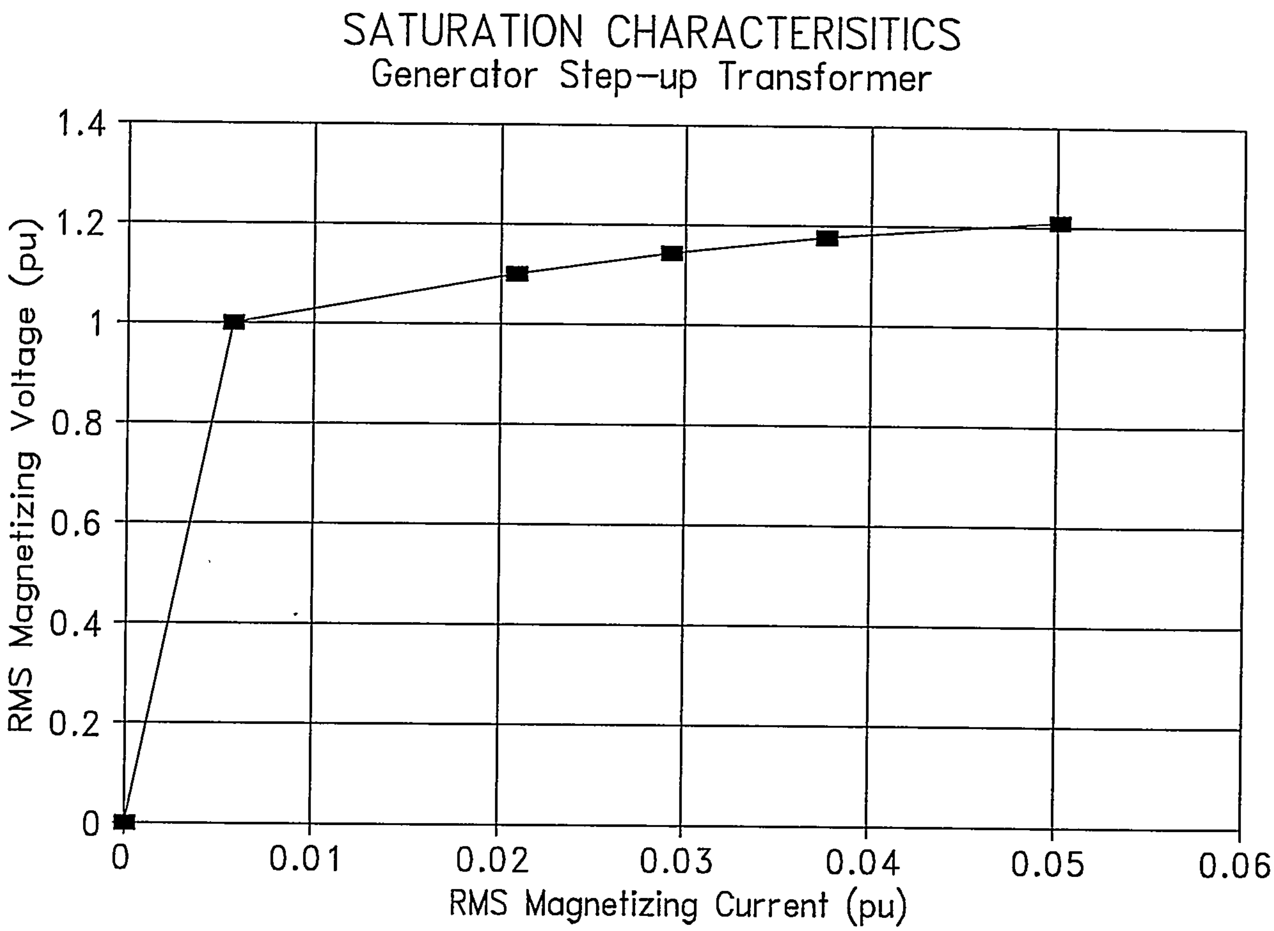

Fig. C-3. Saturation characteristics of generator step-up transformer.

Transformer rating: 408/457 MVA per phase (OA/FA), 345/23.85 kV

Base impedances: 1.394 Ω (low side), 97.24 Ω (high side)

Per phase impedance: 16% total, $9.77(10)^{-4}$ pu resistance per winding

Core loss per phase: 264.9 kW

Model parameters:
$R_1 = 0.00136\ \Omega$, $X_1 = 0.1115\ \Omega$ (LV winding)
$R_2 = 0.095\ \Omega$, $X_2 = 7.7792\ \Omega$ (HV winding)
$R_{mag} = 2148\ \Omega$ (core losses)
$I_{mag} = 137$ A (peak magnetizing current at knee)
$\lambda_{mag} = 89.467$ V-s (peak flux linkage at knee)
Magnetizing branch on LV winding
$C_{hg} = 10$ nF, $C_{lg} = 10$ nF, $C_{hl} = 15$ nF

Normal Station Service Transformer (T2)

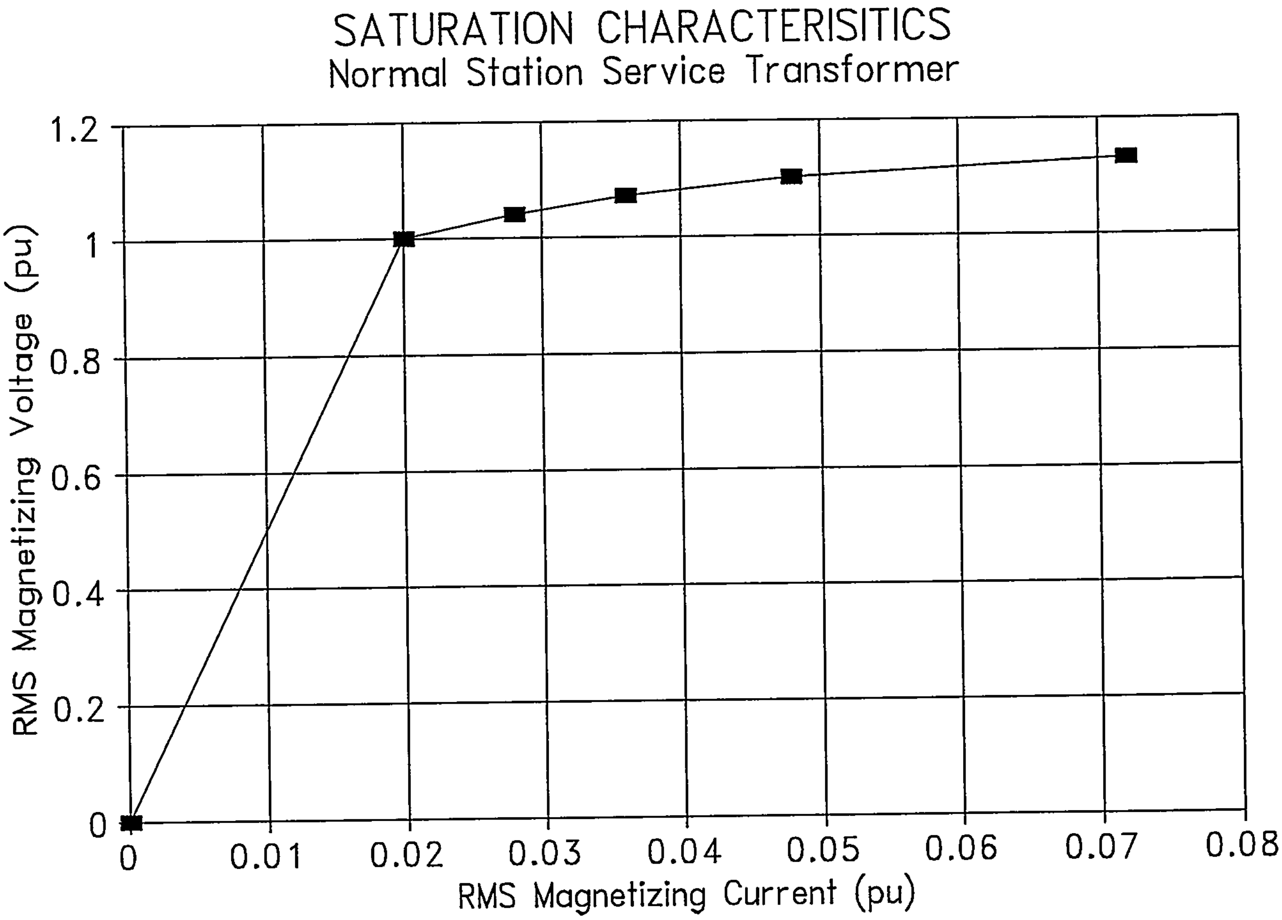

Fig. C-4. Saturation characteristics for normal station service transformer.

Transformer rating: 100 MVA (FOA), 24.9/13.8 kV

Base impedances: 1.9044 Ω (low side), 18.6 Ω (high side)

Per phase impedance: 7.14% total, $1.5(10)^{-3}$ pu resistance per winding

Core loss (three-phase): 126.5 kW

Model parameters:
- $R_1 = 0.0279$ Ω, $X_1 = 0.664$ Ω (HV winding)
- $R_2 = R_3 = 0.00286$ Ω, $X_2 = X_3 = 0.068$ Ω (LV windings)
- $R_{mag} = 14703$ Ω (core losses)
- $I_{mag} = 37.87$ A (peak magnetizing current at knee)
- $\lambda_{mag} = 93.4$ V-s (peak flux linkage at knee)
- Magnetizing branch on LV winding
- $C_{hg} = 10$ nF, $C_{lg} = 10$ nF, $C_{hl} = 15$ nF

<u>Reserve Station Service Transformer (T3)</u>

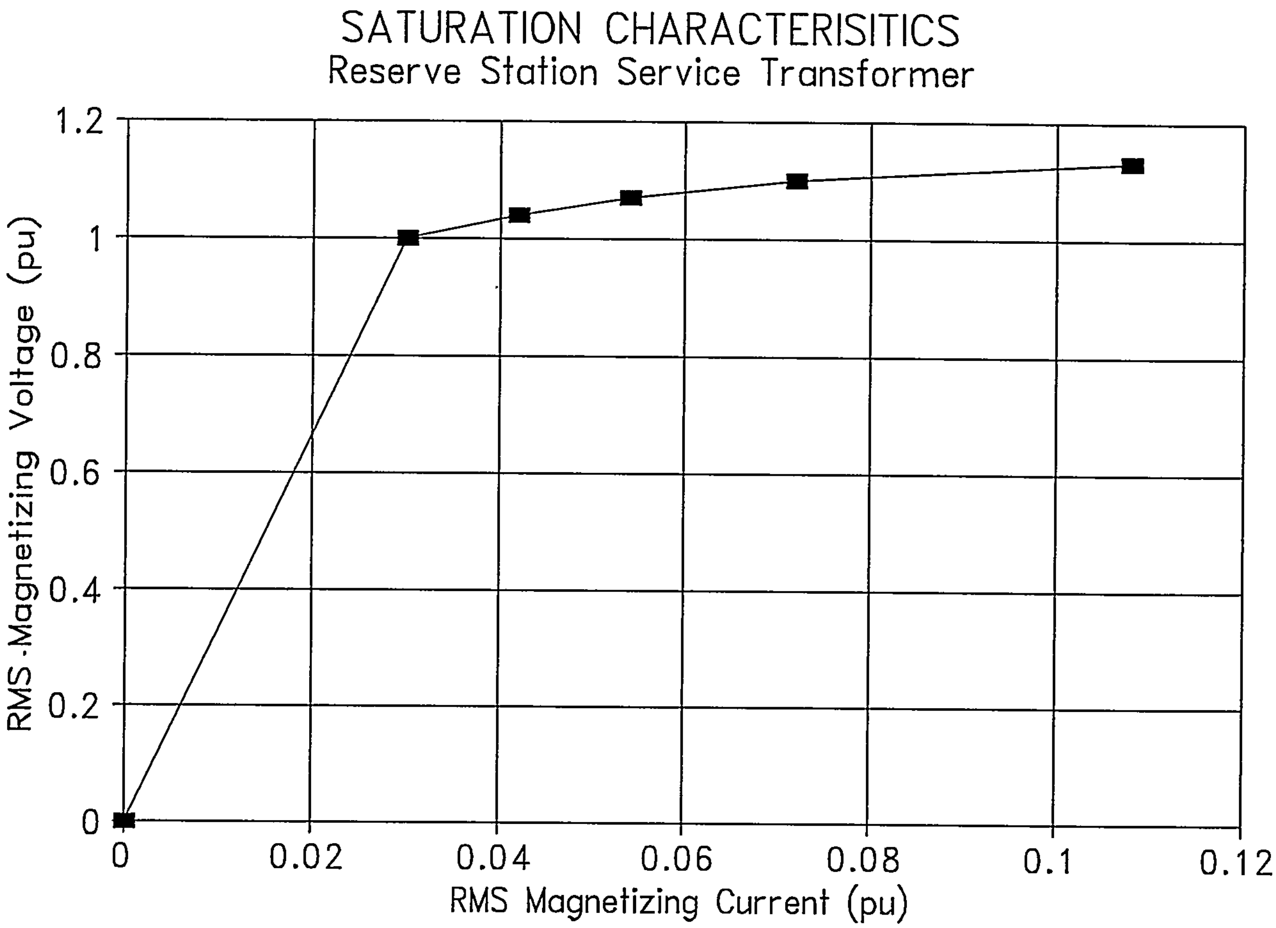

Fig. C-5. Saturation characteristics for reserve station service transformer.

Transformer rating: 42/56/70 MVA (0A/FA/FOA), 115/13.8/4.16 kV

Base impedances: 314.88 Ω (115 kV), 4.534 Ω (13.8 kV), 1.236 Ω (4.16 kV)

Per phase impedance: 6.81% total, $1.85(10)^{-3}$ pu resistance per winding

Core loss (three-phase): 76.23 kW

Model parameters:
R_1 = 0.00229 Ω, X_1 = 0.0421 Ω (4.16 kV winding)
R_2 = 0.5825 Ω, X_2 = 10.72 Ω (115 kV winding)
R_3 = 0.00839 Ω, X_3 = 0.1544 Ω (13.8 kV winding)
R_{mag} = 681 Ω (core losses)
I_{mag} = 142.79 A (peak magnetizing current at knee)
λ_{mag} = 15.605 V-s (peak flux linkage at knee)
Magnetizing branch on 4.16 kV winding
C_{hg} = 8 nF, C_{lg} = 10 nF, C_{hl} = 15 nF

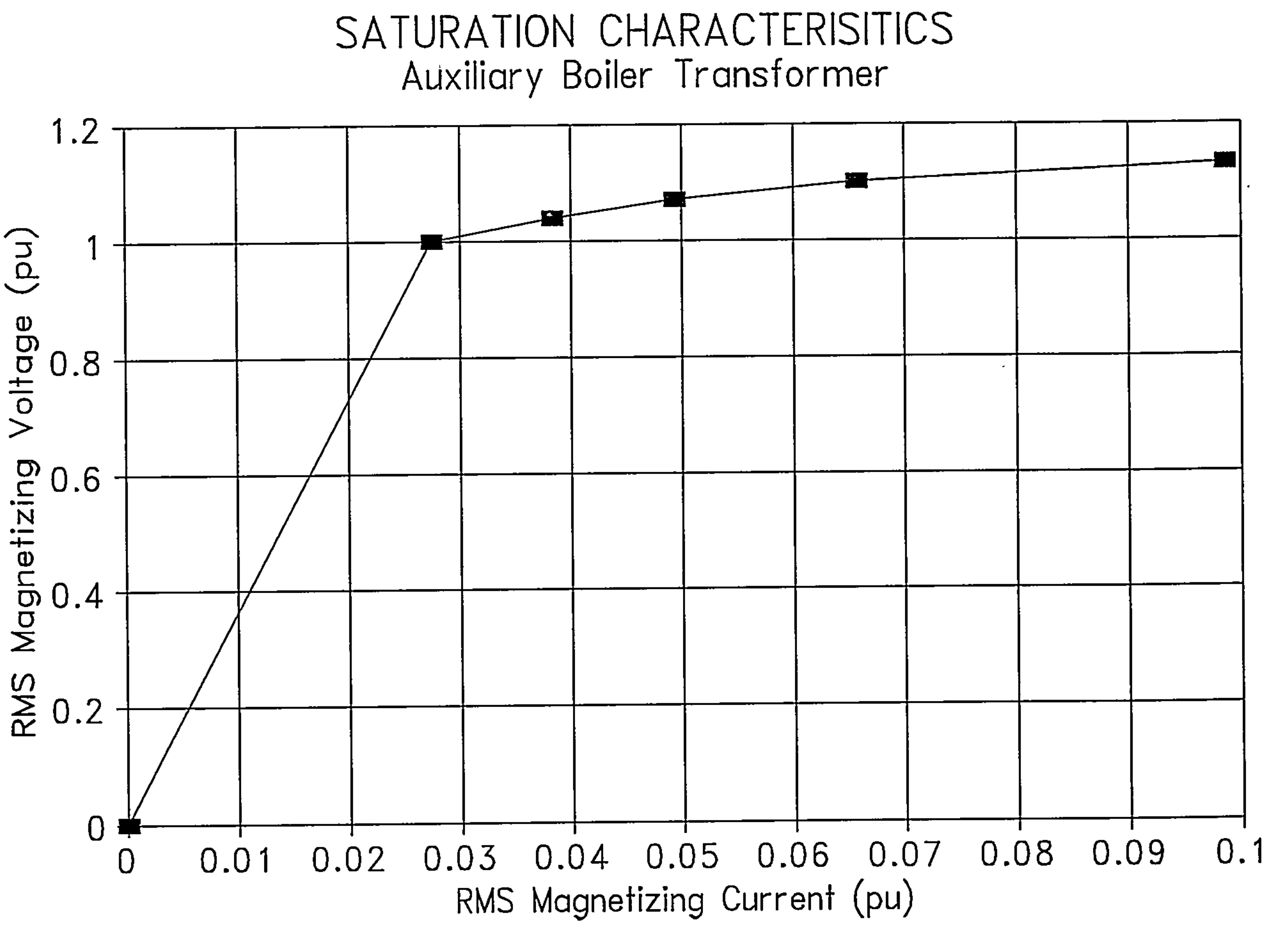

Fig. C-6. Saturation characteristics for auxiliary boiler transformer.

Transformer rating: 16.6/22.08/27.56 MVA (0A/FA/FOA), 115/13.8/4.16 kV

Base impedances: 796.7 Ω (115 kV), 11.47 Ω (13.8 kV), 3.1275 Ω (4.16 kV)

Per phase impedance: 6.9% total, $2.5(10)^{-3}$ pu resistance per winding

Core loss (three-phase): 40.26 kW

Model parameters:
R_1 = 0.00782 Ω, X_1 = 0.1079 Ω (4.16 kV winding)
R_2 = 1.9918 Ω, X_2 = 27.5 Ω (115 kV winding)
R_3 = 0.02868 Ω, X_3 = 0.3957 Ω (13.8 kV winding)
R_{mag} = 1289.5 Ω (core losses)
I_{mag} = 51.54 A (peak magnetizing current at knee)
λ_{mag} = 15.605 V-s (peak flux linkage at knee)
Magnetizing branch on 4.16 kV winding
C_{hg} = 10 nF, C_{lg} = 10 nF, C_{hl} = 15 nF

115 kV Supply Autotransformer (T0)

Transformer rating: 100 MVA, 345/115 kV

Base impedances: 132.25 Ω (115 kV), 529.0 Ω (345 kV)

Per phase impedance: 7.0% total, $1.5(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.7935\ \Omega$, $X_1 = 18.5\ \Omega$ (345 kV winding)
$R_2 = 0.1983\ \Omega$, $X_2 = 4.629\ \Omega$ (115 kV winding)
$C_{hg} = 8$ nF, $C_{lg} = 10$ nF, $C_{hl} = 15$ nF

Nonsafety-Related Transformer (T4)

Transformer rating: 8.5/10.62 MVA (OA/FA), 13.2/4.16 kV

Base impedances: 2.036 Ω (low side), 61.5 Ω (high side)

Per phase impedance: 5.5% total, $2.6(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.1599\ \Omega$, $X_1 = 1.691\ \Omega$ (13.8 kV winding)
$R_2 = 0.00529\ \Omega$, $X_2 = 0.056\ \Omega$ (4.16 kV winding)
$C_{hg} = 5$ nF, $C_{lg} = 10$ nF, $C_{hl} = 10$ nF

Safety-Related Transformer (T5)

Transformer rating: 1500/2025 kVA (OA/FA), 4160/600 V

Base impedances: 0.24 Ω (low side), 34.6 Ω (high side)

Per phase impedance: 4.8% total, $2.8(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.0969\ \Omega$, $X_1 = 0.8304\ \Omega$ (4160 V winding)
$R_2 = 0.00067\ \Omega$, $X_2 = 0.00576\ \Omega$ (600 V winding)
$C_{hg} = 5$ nF, $C_{lg} = 5$ nF, $C_{hl} = 9$ nF

Nonsafety-Related Transformer (T6)

Transformer rating: 1000/1350 kVA (OA/FA), 4160/600 V

Base impedances: 0.36 Ω (low side), 51.92 Ω (high side)

Per phase impedance: 5.75% total, $2.8(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.1454\ \Omega$, $X_1 = 1.493\ \Omega$ (4160 V winding)
$R_2 = 0.00101\ \Omega$, $X_2 = 0.01035\ \Omega$ (600 V winding)
$C_{hg} = 5$ nF, $C_{lg} = 5$ nF, $C_{hl} = 9$ nF

Nonsafety-Related Transformer (T7)

Transformer rating: 15 kVA, 346.4/120/240 V, single-phase

Impedance: 2.3% total, $7.9(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.06326\ \Omega$, $X_1 = 0.0668\ \Omega$ (346.4 V winding)
$R_2 = 0.00759\ \Omega$, $X_2 = 0.008016\ \Omega$ (120 V winding)
$C_{hg} = 2$ nF, $C_{lg} = 2$ nF, $C_{hl} = 4$ nF

Safety-Related Transformer (T8)

Transformer rating: 25 kVA, 346.4/120/240 V, single-phase

Impedance: 2.5% total, $7.5(10)^{-3}$ pu resistance per winding

Model parameters: $R_1 = 0.036\ \Omega$, $X_1 = 0.048\ \Omega$ (346.4 V winding)
$R_2 = 0.00432\ \Omega$, $X_2 = 0.00576\ \Omega$ (120 V winding)
$C_{hg} = 3$ nF, $C_{lg} = 3$ nF, $C_{hl} = 5$ nF

Surge Arresters

Bus Name	Bus Voltage (LL)	Duty Cycle Rating	MCOV
T345	345 kV	258 kV	209 kV
G25	25 kV	18-27* kV	15.3-22* kV
B001	13.8 kV	9-15* kV	7.65-12.7* kV
B003	13.8 kV	9-15* kV	7.65-12.7* kV
B013	4.16 kV	3-6* kV	2.55-5.1* kV
B015	4.16 kV	3-6* kV	2.55-5.1* kV
BUS6	600 V	416 V	337 V
B120N	120 V (LN)	144 V	116 V
Y115	115 kV	90 kV	70 kV
RT13	13.8 kV	9-15* kV	7.65-12.7* kV
BUSD	4.16 kV	3-6* kV	2.55-5.1* kV
B600	600 V	416 V	337 V
B120E	120 V (LN)	144 V	116 V

* higher ratings used for ungrounded transformers

EMTP Model Data for Arresters:

Lightning current pulse, 8/20 μsec: $K = 5.9425(10)^{-3}$ A, $\alpha = 31.1$

Lightning voltage pulse, 1.2/50 μsec: $K = 1.6344(10)^{-3}$ A, $\alpha = 31.1$

Switching surges: K = 12.2 A, $\alpha = 17.2$

V_{ref} = 1.414 x arrester duty cycle rating (above table)

Main Generator

Generator rating: 1348.4 MVA, 0.9 PF lag, 25 kV, 1800 rpm, 60 Hz

Subtransient reactance: 0.29 pu = 0.1344 Ω

Feedwater Pump Motors

Motor rating: 12,000 Hp, 13.8 kV, 4-pole IM, 1787 rpm

Stator resistance: 0.121 Ω

Rotor resistance: 0.121 Ω (referred to stator)

Stator leakage inductance: 0.004402 H

Rotor leakage inductance: 0.004402 H (referred to stator)

Magnetizing inductance: 0.3241 H

Rotor and load inertia: 1349.9 kg-m^2 (N-m-sec^2)

Viscous damping constant: 4.888 N-m-sec

Main Program:

```
BEGIN NEW DATA CASE
C
C       File Name: SURGE820.DAT
C
C       This is a simulation of a typical nuclear power plant electrical
C       distribution system, including the unit generator and offsite 345 kV
C       and 115 kV transmission systems that normally supply the nonsafety-
C       related and the safety-related circuits. Transformers are modeled
C       by high frequency equivalents and surge arresters are represented by
C       exponential models. The simulation is suitable for the study of both
C       lightning surges and switching surges. This particular file is set
C       up to study a 10 kA, 8/20 µsec lightning current pulse.
C
$WIDTH,80
DISK PLOT DATA
ZINC OXIDE                                                             7
C
  2.0E-7 0.0042 60.
   10000       1       0       0       1       0       0       2
C
C     Transformer 2MTX-XMIA,B,C data
C
C                               stdy-state  excitation
C                               |           |
C Request word                  curr  flux  node  Rmag
C |                             |     |     |     |
  TRANSFORMER                   137.0 89.47 TLA   2148.0
C
C     Magnetizing data
C
$INCLUDE, sat2mtx.inc,
C
C     Winding data (resistance, leakage reactance, voltage rating)
C     Magnetizing branch connected to winding 1.
C
C                               R1    X1    VR1
C                               |     |     |
 1G25A  G25B                    .00136.1115 23.85
C
C                               R2    X2    VR2
C                               |     |     |
 2T345A                         .095  7.779 199.2
C
  TRANSFORMER TLA                           TLB
 1G25B  G25C
 2T345B
  TRANSFORMER TLA                           TLC
 1G25C  G25A
 2T345C
```

```
C
C     Transformer 2STX-XNSI data
C
C                             stdy-state  excitation
C                             |           |
C Request word                curr  flux  node  Rmag
C |                           |     |     |     |
  TRANSFORMER                 37.87 93.4  TGA   14703.
C
C     Magnetizing data
C
$INCLUDE, sat2stx.inc,
C
C     Winding data (resistance, leakage reactance, voltage rating)
C     Magnetizing branch connected to winding 1.
C
C                             R1    X1    VR1
C                             |     |     |
 1G25A  G25B                  .0279 .664  24.9
C
C                             R2    X2    VR2
C                             |     |     |
 2T001A NU001                 .00286.068  7.9674
C
C                             R3    X3    VR3
C                             |     |     |
 3T003A NU003                 .00286.068  7.9674
C
  TRANSFORMER TGA                         TGB
 1G25B  G25C
 2T001B NU001
 3T003B NU003
  TRANSFORMER TGA                         TGC
 1G25C  G25A
 2T001C NU001
 3T003C NU003
C
C
C    Auto-Transformer L345 - Y115 data
C
C                             stdy-state  excitation
C                             |           |
C Request word                curr  flux  node  Rmag
C |                           |     |     |     |
  TRANSFORMER                             TYA
          9999
C
C     Winding data (resistance, leakage reactance, voltage rating)
C     Magnetizing branch connected to winding 1.
C
C                             R1    X1    VR1
C                             |     |     |
 1L345A Y115A                 .7935 18.5  132.8
C
```

```
C                        R2    X2    VR2
C                        |     |     |
 2Y115A                  .1983 4.629 66.4
C
  TRANSFORMER TYA                    TYB
 1L345B Y115B
 2Y115B
  TRANSFORMER TYA                    TYC
 1L345C Y115C
 2Y115C
C
C     Transformer 2RTX-XSR1B data
C
C                        stdy-state  excitation
C                        |           |
C Request word           curr  flux  node  Rmag
C |                      |     |     |     |
  TRANSFORMER            142.8 15.61 TBA   681.
C
C     Magnetizing data
C
$INCLUDE, sat2rtx.inc,
C
C     Winding data (resistance, leakage reactance, voltage rating)
C     Magnetizing branch connected to winding 1.
C
C                        R1    X1    VR1
C                        |     |     |
 1RTDA  RTDB             .00229.0421 4.16
C
C                        R2    X2    VR2
C                        |     |     |
 2Y115A                  .5825 10.72 66.4
C
C                        R3    X3    VR3
C                        |     |     |
 3RT13A NU13             .00839.1544 7.9674
C
  TRANSFORMER TBA                    TBB
 1RTDB  RTDC
 2Y115B
 3RT13B NU13
  TRANSFORMER TBA                    TBC
 1RTDC  RTDA
 2Y115C
 3RT13C NU13
C
  NU13                   20.
C
C     Transformer 2ATX-XS3 data
C
C                        stdy-state  excitation
C                        |           |
C Request word           curr  flux  node  Rmag
```

```
C |                          |     |     |     |
  TRANSFORMER                            TS3A
C
C     Magnetizing data termination flag.
C
           9999
C
C     Winding data (resistance, leakage reactance, voltage rating)
C
C                            R1    X1    VR1
C                            |     |     |
 1HI03A HI03B                .1599 1.691 13.2
C
C                            R2    X2    VR2
C                            |     |     |
 2LO03A NUS3                 .00529.056  2.402
C
  TRANSFORMER TS3A                       TS3B
 1HI03B HI03C
 2LO03B NUS3
  TRANSFORMER TS3A                       TS3C
 1HI03C HI03A
 2LO03C NUS3
C
C     Transformer 2EJS-X3A data
C
C                            stdy-state  excitation
C                            |           |
C Request word               curr  flux  node  Rmag
C |                          |     |     |     |
  TRANSFORMER                            TX3A
C
C     Magnetizing data termination flag.
C
           9999
C
C     Winding data (resistance, leakage reactance, voltage rating)
C
C                            R1    X1    VR1
C                            |     |     |
 1BUSDA BUSDB                .0969 .8304 4.16
C
C                            R2    X2    VR2
C                            |     |     |
 2T600A                      .00067.00576.3464
C
  TRANSFORMER TX3A                       TX3B
 1BUSDB BUSDC
 2T600B
  TRANSFORMER TX3A                       TX3C
 1BUSDC BUSDA
 2T600C
C
C     Transformer 2SCN-XD302B data
```

```
C
C                          stdy-state  excitation
C                          |           |
C Request word             curr   flux node   Rmag
C |                        |      |    |      |
 TRANSFORMER                           TX3D
C
C    Magnetizing data termination flag.
C
          9999
C
C    Winding data (resistance, leakage reactance, voltage rating)
C
C                          R1     X1    VR1
C                          |      |     |
 1B600A                    .036   .048  .3464
C
C                          R2     X2    VR2
C                          |      |     |
 2B120E                    .00432.00576.120
C
C    Transformer 2NJS-X3E data
C
C                          stdy-state  excitation
C                          |           |
C Request word             curr   flux node   Rmag
C |                        |      |    |      |
 TRANSFORMER                           TN3A
C
C    Magnetizing data termination flag.
C
          9999
C
C    Winding data (resistance, leakage reactance, voltage rating)
C
C                          R1     X1    VR1
C                          |      |     |
 1T015A T015B              .1454 1.493 4.16
C
C                          R2     X2    VR2
C                          |      |     |
 2BUS6A                    .001   .01035.3464
C
 TRANSFORMER TN3A                      TN3B
 1T015B T015C
 2BUS6B
 TRANSFORMER TN3A                      TN3C
 1T015C T015A
 2BUS6C
C
C    Transformer 2SCA-XD600 data
C
C                          stdy-state  excitation
C                          |           |
```

```
C Request word             curr  flux  node  Rmag
C |                        |     |     |     |
  TRANSFORMER                          TN3D
C
C     Magnetizing data termination flag.
C
          9999
C
C     Winding data (resistance, leakage reactance, voltage rating)
C
C                          R1    X1    VR1
C                          |     |     |
 1BUS6A                    .06326.0668 .3464
C
C                          R2    X2    VR2
C                          |     |     |
 2B120N                    .00759.00802.120
C
C     Generator subtransient reactance.
C
  E25A  G25A                     0.1344
  E25B  G25B  E25A  G25A
  E25C  G25C  E25A  G25A
C
C     Bus B001 load equivalent (60% secondary rating = 30 MW)
C
  T001A                    6.348
  T001B                    6.348
  T001C                    6.348
C
C     Transformer neutral resistors.
C
  NU001                    20.0
  NU003                    20.0
  NUS3                      6.0
C
C    Transmission line to remote 345 kV load.
C
$INCLUDE, line345N.inc,
C
C    Aggregate load equivalent of "normal" 4.16 kV distribution on B003
C    (8 buses, total 6 MVA at 0.85 pf = 50% aggregate transformer rating).
C
  B003A                    26.97 16.72
  B003B       B003A
  B003C       B003A
C
C    Aggregate full load equivalent of "normal" 13.8 kV induction motors on B003
C    except RFPB, RFPC & RCPB (total 10,500 HP at 0.85 pf).
C
  M003A                    17.56 10.89
  M003B       M003A
  M003C       M003A
C
```

```
C       Equivalent induction motor load at 13.8 kV on buses RFPB
C
  RFPBA                       15.8734.757
  RFPBB        RFPBA
  RFPBC        RFPBA
C
C    Aggregate full load equivalent of 4.16 kV induction motors on bus B013
C    (total 4100 HP at 0.85 pf).
C
  B013A                       4.087 2.534
  B013B        B013A
  B013C        B013A
C
C    Aggregate full load equivalent of 4.16 kV motor loads on bus B015
C    (total 500 HP).
C
  B015A                       33.52 20.78
  B015B        B015A
  B015C        B015A
C
C    Aggregate full load equivalent of 4.16 kV "emergency" loads on bus BUSD
C    (total 4250 HP induction motors at 0.85 pf).
C
  BUSDA                       3.943 2.444
  BUSDB        BUSDA
  BUSDC        BUSDA
C
C    Aggregate full load equivalent of 600 V "emergency" loads on bus B600
C    (total 535 kVA at 0.85 pf)
C
  B600A                       .572  .3544
  B600B        B600A
  B600C        B600A
C
C    Aggregate full load equivalent of 600 V "normal" loads on bus BUS6
C    (total 360 HP induction motors + 79 kVA at 0.85 pf)
C
  BUS6A                       1.133 .72
  BUS6B                       1.133 .72
  BUS6C                       1.133 .72
C
C    60% load equivalent of 15 kVA, 120 V (1-ph) "emergency" load on bus B120E
C
  B120E                       .816  .5057
C
C    67% load equivalent of 10 kVA, 120 V (1-ph) "normal" load on bus B120N
C
  B120N                       1.222 .7586
C
C    Shunt switch resistors to prevent UM induction motor problems.
C
  T003A B003A                 1.E8
  T003B B003B                 1.E8
  T003C B003C                 1.E8
```

```
  B003A RFPBA                1.E8
  B003B RFPBB                1.E8
  B003C RFPBC                1.E8
  B003A HI03A                1.E8
  B003B HI03B                1.E8
  B003C HI03C                1.E8
  B003A M003A                1.E8
  B003B M003B                1.E8
  B003C M003C                1.E8
  T345A T345B                1.E8
  T345B T345C                1.E8
  T345C T345A                1.E8
  G25A  G25B                 1.E8
  G25B  G25C                 1.E8
  G25C  G25A                 1.E8
C
C    High frequency capacitors on the x-former terminal
C
$INCLUDE, CAP1.INC,
C
C    High frequency capacitors for cables
C
$INCLUDE, CAP2.INC,
C
C    Arrester data file
C
$INCLUDE, ARR1.INC,
C
BLANK END OF BRANCH DEFINITIONS
C
C    345 kV tie breaker.
C
  T345A L345A -1.0      10.                                             1
  T345B L345B -1.0      10.                                             1
  T345C L345C -1.0      10.                                             1
C
C    13.8 kV bus breakers (bus B003).
C
  T003A B003A -1.0      10.
  T003B B003B -1.0      10.
  T003C B003C -1.0      10.
  B003A RFPBA -1.0      10.
  B003B RFPBB -1.0      10.
  B003C RFPBC -1.0      10.
  B003A HI03A -1.0      10.
  B003B HI03B -1.0      10.
  B003C HI03C -1.0      10.
  B003A M003A -1.0      10.
  B003B M003B -1.0      10.
  B003C M003C -1.0      10.
C
C    4.16 kV bus breakers (bus LO03).
C
  LO03A B013A -1.0      10.
```

```
  LO03B B013B -1.0      10.
  LO03C B013C -1.0      10.
  LO03A B015A -1.0      10.
  LO03B B015B -1.0      10.
  LO03C B015C -1.0      10.
C
C     Emergency 4160 V bus breaker (bus BUSD)
C
  RTDA  BUSDA -1.0      10.
  RTDB  BUSDB -1.0      10.
  RTDC  BUSDC -1.0      10.
C
C     Normal 4160 V bus breaker (bus B015)
C
  B015A T015A -1.0      10.
  B015B T015B -1.0      10.
  B015C T015C -1.0      10.
C
C     Emergency 600 V bus breaker (bus B600)
C
  T600A B600A -1.0      10.
  T600B B600B -1.0      10.
  T600C B600C -1.0      10.
C
BLANK END SWITCH CARDS
C
C     Source data with sine waveforms
C
14E25A    21607.8   60.0      -88.56    0.0                   -1.0
14E25B    21607.8   60.0      151.44    0.0                   -1.0
14E25C    21607.8   60.0       31.44    0.0                   -1.0
14R345A   281691.3  60.       -90.      0.0                   -1.0
14R345B   281691.3  60.        150.     0.0                   -1.0
14R345C   281691.3  60.        30.      0.0                   -1.0
C
C     Lightning current source with 10 kA amplitude, 8/20 usec waveshape.
C
15L345A -110000.    .000008   .00002    5.                    .003754
C
BLANK END OF SOURCE DEFINITIONS
C
C     Node voltages for plotting
C
  T345A T345B T345C G25A  G25B  G25C  T001A T001B T001C B003A B003B B003C B013A
  B013B B013C B015A B015B B015C BUS6A BUS6B BUS6C B120N Y115A Y115B Y115C RT13A
  RT13B RT13C BUSDA BUSDB BUSDC B600A B600B B600C B120E
BLANK CARD ENDING PLOT CARDS
BLANK END OF SIMULATION
BEGIN NEW DATA CASE
BLANK END OF ALL CASES
```

Line Constants Routine:

```
BEGIN NEW DATA CASE
$ERASE
$COMMENT
C
C   File Name: LINE345N.DAT
C
C   LINE CONSTANTS FOR A 345KV TWIN-CONDUCTOR BUNDLE FLAT LAYOUT
C   WITH TWO OVERHEAD GROUND WIRES (Assumed Untransposed).
C
LINE CONSTANTS
BRANCH  L345A R345A L345B R345B L345C R345C
C
C   CONDUCTOR CARDS
C   Col 1-3 (phase number)
C   Col 17,18 (usually 4, but other options for REACT field)
C   4-8    9-16    19-26  27-34   35-42  43-50  51-58  59-66  59-72 73-78
C   SKIN  RESIS    REACT  DIAM    HORIZ  VTOWER  VMI   SEPAR  ALPHA  NAME
C 345678901234567890123456789012345678901234567890123456789012345678
  1.3748 .0787   4        1.302  -26.25   59.5    38.5
  1.3748 .0787   4        1.302  -24.75   59.5    38.5
  2.3748 .0787   4        1.302  - 0.75   59.5    38.5
  2.3748 .0787   4        1.302    0.75   59.5    38.5
  3.3748 .0787   4        1.302   24.75   59.5    38.5
  3.3748 .0787   4        1.302   26.25   59.5    38.5
  0.5    4.61    4        0.386  -13.0    80.0    69.3
  0.5    4.61    4        0.386   13.0    80.0    69.3
BLANK
C
C   FREQUENCY CARDS (MODAL=1 requests untransposed line)
C
C   1-8    9-18                 30-35  37-42   45-52                  69-70
C   RHO    FREQ                 ICPR   IZPR     DIST                  MODAL
  100.     60.0               1      11   11    1 50.00                 1
C 345678901234567890123456789012345678901234567890123456789012345678
C
$PUNCH, line345n.inc
C "Punch" file will be created for later use in line simulation.
C
BLANK
BLANK
BLANK
```

Distributed Line Model Output Data:

```
$VINTAGE, 1
-1L345A R345A             5.64930E-01 6.47549E+02 1.21654E+05-5.00000E+01 1  3
-2L345B R345B             4.14276E-02 3.09266E+02 1.81424E+05-5.00000E+01 1  3
-3L345C R345C             4.08359E-02 2.58201E+02 1.83610E+05-5.00000E+01 1  3
$VINTAGE, 0
  0.59238755 -0.70710678 -0.41274596
  0.00000000  0.00000000  0.00000000
```

0.54603478	0.00000000	0.81196154
0.00000000	0.00000000	0.00000000
0.59238755	0.70710678	-0.41274596
0.00000000	0.00000000	0.00000000

Transformer Saturation Routine (sample for T1):

```
BEGIN NEW DATA CASE
C
C    FILE NAME: sat2mtx.dat
C
C    Computation of the per phase saturation characteristics of a 23.85kV/345kV
C    delta-wye transformer, 408 MVA per-phase, using the SATURATION routine.
C    RMS voltage vs magnetizing current (manufacturer's data) is per-unitized
C    on the delta voltage side, for the input data. The output data is peak
C    magnetizing current vs peak flux linkages in V-sec.
C
C    Vbase = 23.85 kV
C    Pbase = 408 MVA
C    Ibase = 408E6/23850 = 17107 A
C
$ERASE                                    { initialize punch buffer
SATURATION                                { special request word
C
C   freq    Vbase    Pbase    punch    quads
C      |        |        |        |        |
    60.0    23.85    408.0        1        0
C
C    Magnetizing test data
C
C           Irms             Vrms
C              |                |
        .005663              1.0
        .02089               1.1
        .029246            1.144
        .037602            1.177
        .050136             1.21
C
C           Data terminator
C              |
           9999
$PUNCH, sat2mtx.inc               { flush punch buffer into file sat2mtx.inc
BLANK END OF DATA FILE
BEGIN NEW DATA CASE
BLANK END OF ALL CASES
```

Saturation Output Data:

```
  1.37004029E+02  8.94689339E+01
  8.79464078E+02  9.84158273E+01
  1.13310186E+03  1.02352460E+02
  1.48958713E+03  1.05304935E+02
  2.05483294E+03  1.08257410E+02
            9999
```

Transformer Capacitance Include File: CAP1.INC

```
C
C                 High frequency transformer capacitances
C       T1
C
  G25A  G25B                            .01
  G25B  G25C                            .01
  G25C  G25A                            .01
  T345A                                 .01
  T345B                                 .01
  T345C                                 .01
  G25A  T345A                           .015
  G25B  T345B.                          .015
  G25C  T345C                           .015
C
C  T2
C
  G25A  G25B                            .01
  G25B  G25C                            .01
  G25C  G25A                            .01
  T001A                                 .01
  T001B                                 .01
  T001C                                 .01
  T003A                                 .01
  T003B                                 .01
  T003C                                 .01
  G25A  T001A                           .015
  G25B  T001B                           .015
  G25C  T001C                           .015
  G25A  T003A                           .015
  G25B  T003B                           .015
  G25C  T003C                           .015
  T001A T003A                           .015
  T001B T003B                           .015
  T001C T003C                           .015
C
C       T0
C
  L345A                                 .008
  L345B                                 .008
  L345C                                 .008
  Y115A                                 .01
  Y115B                                 .01
  Y115C                                 .01
  L345A Y115A                           .015
  L345B Y115B                           .015
  L345C Y115C                           .015
C
C       T3
C
  Y115A                                 .008
  Y115B                                 .008
  Y115C                                 .008
```

```
   RTDA  RTDB                                   .01
   RTDB  RTDC                                   .01
   RTDC  RTDA                                   .01
   RT13A                                        .01
   RT13B                                        .01
   RT13C                                        .01
   Y115A RTDA                                   .015
   Y115B RTDB                                   .015
   Y115C RTDC                                   .015
   RTDA  RT13A                                  .015
   RTDB  RT13B                                  .015
   RTDC  RT13C                                  .015
   Y115A RT13A                                  .015
   Y115B RT13B                                  .015
   Y115C RT13C                                  .015
C
C       T4
C
   HI03A HI03B                                  .005
   HI03B HI03C                                  .005
   HI03C HI03A                                  .005
   L003A                                        .01
   L003B                                        .01
   L003C                                        .01
   HI03A L003A                                  .01
   HI03B L003B                                  .01
   HI03C L003C                                  .01
C
C       T5
C
   BUSDA BUSDB                                  .005
   BUSDB BUSDC                                  .005
   BUSDC BUSDA                                  .005
   B600A                                        .005
   B600B                                        .005
   B600C                                        .005
   BUSDA B600A                                  .009
   BUSDB B600B                                  .009
   BUSDC B600C                                  .009
C
C       T6
C
   T015A T015B                                  .005
   T015B T015C                                  .005
   T015C T015A                                  .005
   BUS6A                                        .005
   BUS6B                                        .005
   BUS6C                                        .005
   T015A BUS6A                                  .009
   T015B BUS6B                                  .009
   T015C BUS6C                                  .009
C
C       T7
C
```

```
  BUS6A                                     .002
  B120N                                     .002
  BUS6A B120N                               .004
C
C      T8
C
  B600A                                     .003
  B120E                                     .003
  B600A B120E                               .005
```

Cable Capacitance Include File: CAP2.INC

```
C                 Cable capacitances
C        G25
  G25A                                    .01
  G25B                                    .01
  G25C                                    .01
C        B001
  B001A                                   .01
  B001B                                   .01
  B001C                                   .01
C        B003
  B003A                                   .01
  B003B                                   .01
  B003C                                   .01
C        B013
  B013A                                   .01
  B013B                                   .01
  B013C                                   .01
C        B015
  B015A                                   .01
  B015B                                   .01
  B015C                                   .01
C        BUS6
  BUS6A                                   .005
  BUS6B                                   .005
  BUS6C                                   .005
C
  B120N                                   .005
C        Y345
  Y115A                                   .01
  Y115B                                   .01
  Y115C                                   .01
C        BUSD
  BUSDA                                   .01
  BUSDB                                   .01
  BUSDC                                   .01
C        B600
  B600A                                   .005
  B600B                                   .005
  B600C                                   .005
C
  B120E                                   .005
```

Arrester Data Include File: ARR1.INC

```
C
C       Lightning surge arresters
C
C       345 kV arrester
C
92T345A                                5555.                                         1
                    364867.                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
92T345B                                5555.                                         1
                    364867.                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
92T345C                                5555.                                         1
                    364867.                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
C
C       115 kV arrester
C
92Y115A                                5555.                                         1
                   127279.2                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
C 92Y115B                              5555.                                         1
C                  127279.2                  -1.0                        0.0
C                  .0059425                  31.1                        0.5
C                     9999.
C 92Y115C                              5555.                                         1
C                  127279.2                  -1.0                        0.0
C                  .0059425                  31.1                        0.5
C                     9999.
C
C       25 KV arrester
C
92G25A                                 5555.                                         1
                    25455.8                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
92G25B                                 5555.                                         1
                    25455.8                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
92G25C                                 5555.                                         1
                    25455.8                  -1.0                        0.0
                   .0059425                  31.1                        0.5
                      9999.
C
C     13.8 kV arrester
C
C 92B003A                              5555.                                         1
C                    12728.                  -1.0                        0.0
```

```
C                      .0059425            31.1               0.5
C                         9999.
C 92B003B                           5555.                                 1
C                        12728.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C 92B003C                           5555.                                 1
C                        12728.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C
92RT13A                             5555.                                 1
                         12728.            -1.0               0.0
                       .0059425            31.1               0.5
                          9999.
92RT13B                             5555.                                 1
                         12728.            -1.0               0.0
                       .0059425            31.1               0.5
                          9999.
92RT13C                             5555.                                 1
                         12728.            -1.0               0.0
                       .0059425            31.1               0.5
                          9999.
C
C   4.16 kV arrester
C
C 92B013A                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C 92B013B                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C 92B013C                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C
C 92B015A                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C 92B015B                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C 92B015C                           5555.                                 1
C                         4243.            -1.0               0.0
C                      .0059425            31.1               0.5
C                         9999.
C
92BUSDA                             5555.                                 1
                          4243.            -1.0               0.0
```

```
                .0059425                31.1                0.5
                   9999.
92BUSDB                            5555.                           1
                   4243.                 -1.0               0.0
                .0059425                31.1                0.5
                   9999.
92BUSDC                            5555.                           1
                   4243.                 -1.0               0.0
                .0059425                31.1                0.5
                   9999.
C
C       600 V Arrester
C
C 92BUS6A                           5555.                           1
C                  587.9                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C 92BUS6B                           5555.                           1
C                  587.9                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C 92BUS6C                           5555.                           1
C                  587.9                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C
92B600A                            5555.                           1
                   587.9                 -1.0               0.0
                .0059425                31.1                0.5
                   9999.
C 92B600B                           5555.                           1
C                  587.9                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C 92B600C                           5555.                           1
C                  587.9                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C
C       120 V arrester
C
C 92B120N                           5555.                           1
C                  203.7                 -1.0               0.0
C               .0059425                31.1                0.5
C                  9999.
C
92B120E                            5555.                           1
                   203.7                 -1.0               0.0
                .0059425                31.1                0.5
                   9999.
```

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*University of Florida
Gainesville, FL

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J.E. Jackson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

A study has been performed that assesses the effects of aging on the performance and availability of surge protective devices (SPDs), commonly called surge arresters and surge suppressors, used in electrical power and control systems in U. S. commercial nuclear power plants. This study is one of a number of studies performed under the Nuclear Plant Aging Research (NPAR) program. One of the many purposes of that program is to provide a technical basis for the identification and evaluation of degradation caused by age. Although surge protective devices have not been classified as safety-related, they are risk important because they can minimize the initiating event frequencies associated with loss of offsite power (LOOP) and reactor trip. Conversely, their failure due to age, or other causes, might increase the initiating event frequencies. Because of their importance, especially those in (lightning) high flash density regions to the U.S., the proper application and coordination of high voltage and low voltage SPDs are important in ensuring that overvoltage transients will not increase plant risk.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

aging, equipment protection devices, failures, nuclear power plant, surges, electric equipment, lightning, performance power losses, reactor protection systems, reactor safety, resk assessment, scram, switches, voltage regulators

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