The Probability and Consequences of Double Sequencing Nuclear Power Plant Safety Loads, Revision 1

Technical Report

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Final Report, October 2003

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REPORT SUMMARY

Double sequencing refers to an unintended sequence of operations at a nuclear power plant during which safety and accident mitigation loads automatically start, shut down, and restart in rapid succession when called on to operate. This occurs when, for some combination of reasons, safety bus voltages fall below acceptable levels after the plant is shut down and mitigation loads are started. The buses must be isolated and then repowered from diesel generators or some alternate offsite source. Following this, shutdown and mitigation loads can be restarted. This series of actions is called double sequencing. This report provides both generic and plant-specific approaches to evaluating the probability and consequences of double sequencing events.

Background

Double sequencing would be most likely to occur if there were a concurrent loss of coolant accident (LOCA), with its associated plant trip, and a prior stressed transmission grid condition. A plant trip might reduce grid voltage 4 to 5% in some cases. Safety and accident mitigation loads will lower safety bus voltage by perhaps another like amount. These voltage drops are expected and planned for in the plant design. A new factor is the possibility of a stressed transmission grid that is heavily loaded in a way not foreseen prior to industry deregulation. Transmission grid and plant operators have adopted measures and redundant protective features whose purpose is to ensure that safety bus voltages will be adequate in a LOCA/trip situation, whether fed from offsite power or diesel generators.

Nevertheless, questions have been raised: What if a double sequencing condition were to occur? How probable is it? What are the potential consequences?

Objectives

To evaluate the probability and consequences of double sequencing events from a generic and plant specific perspective and to identify methodologies that plant owners can use to examine the probability and consequences of double sequencing at their facilities.

Approach

The project team examined five principal aspects of double sequencing:

1. The probability of double sequencing and how to determine it.

2. The impact of double sequencing on 16 classes of electrical equipment.

3. The potential for water hammer damage due to and following a double sequencing event.

4. The potential time delays in accident mitigation because of double sequencing.

5. The potential impact of double sequencing on core damage frequency.

Results

The report explains why, overall, double sequencing is not a major concern.

1. The simultaneous occurrence of a LOCA and associated plant trip—and a prestressed transmission grid—has a low probability. (The meaning of "prestressed grid" is discussed in the full report).

2. Critical electrical components are not likely to be damaged or made unavailable as a result of double sequencing. There are two key insights. First, large accident mitigation pumps have low rotational inertias and come up to speed quickly without excessive motor heating. Their motors are not unduly challenged by repetitive starts. Second, control circuits for motor control center loads, when derived from a 480-volt source, are not likely to be lost as a result of their fuses blowing due to low voltage. This has occurred when voltage levels are insufficient to change the magnetic state of three-phase starters. The need to protect against the degraded voltage condition was first identified as a result of fuse failures from this cause.

3. Another key insight is that electric-motor-driven pump performance is not adversely impacted (the only consideration being the time-to-effective-pumping, which is summarized below in item 5).

4. Double sequencing is not expected to cause new, or change the nature of, water hammer events.

5. Double sequencing delays the start of effective safety injection by only several seconds. The result is that double sequencing has an insignificant impact on core damage frequency.

The report identifies some equipment, such as motor-driven high-inertia fans, that might be negatively affected by double sequencing and merit specific evaluations at some plants.

EPRI Perspective

Deregulation has increased the possibility that a transmission grid may be stressed from time to time. This conceivably could lead to double sequencing if a LOCA and associated plant trip occurred during such a period. The Nuclear Regulatory Commission's (NRC's) Information Notice 2000-06 discusses double sequencing and the possibility that double sequencing could occur at some plants during certain operational periods involving stressed grid conditions. Plant and transmission grid operators have taken steps, including contractual obligations between the plant and the grid, to make certain that grid conditions are kept adequate for nuclear plant needs. Nevertheless, questions about double sequencing have been raised and merit answers. It is reassuring that double sequencing's impact on a plant during an accident appears to be small. Companion EPRI report 1007966 looks at BWR-specific issues involved in double sequencing.

Keywords

Off-site power	Emergency electrical equipment	Double sequencing
Risk analysis	Safety analysis	

ABSTRACT

This report examines the probability, consequences, and technical subtleties of double sequencing. Double sequencing refers to an unintended series of operations at a nuclear power plant in which safety and accident mitigation loads automatically start, shut down, and restart in rapid succession when called on to operate. This occurs when, for some combination of reasons, safety bus voltage falls below acceptable levels after the required shutdown and mitigation loads are started. The buses must then be isolated and repowered from diesel generators or an alternate offsite source. Following this, shutdown and mitigation loads are automatically restarted. This series of actions is called double sequencing. This report evaluates the generic probability, consequences, and impact of double sequencing from an industry perspective. It also provides a means for plant operators to determine the significance of double sequencing to their facility.

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OVERVIEW

EPRI has completed a review of the subtleties and ramifications of a succession of operating actions, commonly referred to as double sequencing, which can take place at a nuclear power plant. *Double Sequencing* occurs when accident mitigation and safe shutdown systems are automatically started, shut down and restarted in rapid succession when called on to operate. In that this condition previously has not been specifically analyzed, the consequences of double sequencing may not be fully understood. Accident analyses generally have assumed that during a loss of coolant accident there is also a loss of offsite power. The goal of this effort is to help plant operators better understand and plan for managing safe shutdown in the event that double sequencing occurs.

The Institute of Nuclear Power Operations (INPO) has raised the double sequencing issue in their Significant Operating Experience Report (SOER) 99-01, entitled *Loss of Grid*. Additionally, the NRC has documented the issue of double sequencing as Item # 3 in their *Summary of Issues* section of NRC Regulatory Issue Summary 2000-24, entitled, *Concerns About Offsite Power Voltage Inadequacies and Grid Reliability Challenges Due To Industry Deregulation*. NRC personnel attending industry meetings relating to nuclear unit and transmission system interface issues also have alluded to the potential consequences of double sequencing. EPRI's *Grid Stability Project* is part of industry efforts to improve the understanding of nuclear plant operators regarding the current and expected near term reliability of offsite power. The history and statistics of offsite power reliability at U.S. nuclear power plants have been documented in an ongoing series of reports from EPRI. This history is currently updated every two-years.

Deregulation of the electric industry has brought new operating challenges that require the attention of nuclear plant operators, transmission system (grid) operators, and industry overview organizations. Some nuclear plants have, or will have new owners, and in some instances new relationships will need to be established between plant and grid operations. Whatever these relationships may be, the requirements of General Design Criterion 17 will remain and nuclear plants will need to be supported by reliable offsite power. Recent operating experience at several nuclear units has resulted in a heightened awareness of potential grid/nuclear unit interface problems and has led to significantly improved performance by both grid and nuclear plant owners and operators.

In general, nuclear power plant operators have improved the interfaces that are essential to assuring reliable offsite power. In most instances the specifics of these interfaces are contractual. A practical and highly visible relationship between these parties vastly enhances the grid/nuclear plant interface and its reliability. The industry has hosted regional conferences with active representation from parties critical to successful grid/nuclear unit operations. Areas that can be further investigated to better understand and improve offsite power reliability are discussed in this report.

References 1 through 8 in Section 10 address offsite power experience and reliability, and NRC and INPO efforts in this area.

Altran Corporation was retained to make the assessment described in this report as part of an industry initiative by EPRI. The goal is to understand the probability and consequences of double sequencing. Boiling water reactors and pressurized water reactors may exhibit slightly different behaviors under double sequencing conditions. It is also worth noting that there are subtle differences between evaluating boiling water reactors and pressurized water reactors for double sequencing.

1.1 Key Conclusions

Probability of Double Sequencing at Domestic Nuclear Power Plants

No nuclear unit is completely immune to the occurrence of a double sequencing event. It is shown in this report that a delayed loss of offsite power initiated by degraded voltage can cause the shutdown of the affected unit to develop in a manner different than that for the traditionally studied LOOP.

The most probable double sequencing event would be triggered by a nuclear unit trip followed by heavy loading of the unit auxiliary buses. The misfortune of having a grid that is heavily stressed prior to the trip would contribute to the probability of double sequencing occurring. A prestressed grid might occur because of bulk power wheeling that results in some transmission lines being overloaded while others are underloaded. Or it might occur because there is a heavy megavar demand on a nuclear unit that can result in a significant grid voltage drops if that unit is lost, such as would be the case with a loss of coolant accident.

These combinations of conditions as well as others, has elements similar to those that would be encountered following a trip that is caused by a loss of coolant accident (LOCA). A LOCA will trip the nuclear unit and subject its buses to heavy loading; however, the simultaneous stressed grid condition is a randomly occurring event that would not increase the likelihood of a LOCA. However a LOCA does increase the likelihood of a LOOP event.

The use of fast acting automatic voltage controlled tap-changing transformers, or of static vars, on a station bus can reduce the likelihood of double sequencing. Also, at plants and in situations where the grid voltage degrades relatively slowly following a trip, the reduction in normal station loads in the seconds following the trip may offset the effects of the safety load additions. This can serve to prevent the degraded voltage condition that leads to double sequencing and may be a factor not currently considered in nuclear unit voltage studies.

Plant operating events that have occurred over the history of nuclear power have provided a large statistical base of event behavior information; however, there is little or no relevant operating experience relating to double sequencing. This is due to the very good operating history wherein a LOCA (a highly uncommon event) has not occurred concurrent with a stressed grid condition. However there have been instances where an operator has historically determined that if his unit had experienced a LOCA during certain periods, the emergency diesel generators would have started and loaded. This would likely be caused by bus voltage from offsite power remaining below relay setpoints, which prevented their reset following large motor starts. Fortunately much has been done to minimize the probability of a double sequencing event as a result of now understanding these past conditions. Additional efforts are being planned.

Double sequencing can occur at any nuclear unit. A double sequencing event is more likely to occur during a reactor accident than during normal day-to-day operation. Thus, historical performance does not yield the basis for establishing a probabilistic safety analysis value for the combination of an accident together with a double sequencing event.

Since double sequencing can occur, it is appropriate to understand the causes and impact of such an event on safe and orderly shutdown. This knowledge can guide activities that will minimize the likelihood and impact of such an event. The section that follows summarizes the findings of this study.

Potential Consequences of a Double Sequencing Event

This effort reached four important conclusions regarding the potential consequences of double sequencing:

1. **Electrical equipment reliability and availability**

   Safety-related electrical components are not likely to be damaged or made unavailable by double sequencing. The basis for this is discussed in Section 7**.**

2. **The probability and consequences of water hammer**

   Repeated starts and stops of systems needed for accident mitigation and safe shutdown are not likely to cause new or change the nature of already evaluated water hammer events. A nuclear unit that can conservatively withstand piping system loadings associated with conventional LOOP event-related system stops and starts, and that is also GL 96-06 compliant for design basis accident-related water hammer, should similarly be capable of withstanding with appropriate margins, those piping system loadings associated with double sequencing.

3. **The impact of double sequencing on reactor fuel peak clad temperature**

   For the RCS cold leg double-ended guillotine rupture size that results in the highest fuel clad temperature, double sequencing would somewhat increase the best estimate peak temperature. This is because it marginally delays core reflood. However this slight increase would not cause a water/fuel clad oxidation reaction. The very low likelihood of the larger, more limiting breaks, is also an important factor to consider. . The more likely smaller breaks occurring in reactor coolant pump seals and instrument lines, are far more tolerant of delayed reflood.

4. **The impact of double sequencing on a nuclear unit's core damage frequency**

   Double sequencing, if it were to be modeled in unit-specific probabilistic safety assessments, is likely to show negligible impact on core damage frequency since current assessments are already dominated by assumed failures of equipment to start and run. However, models for nuclear units may not include details that accurately reflect the timing of safety equipment's effective operation when double sequencing is involved. It may be possible to use this report and its recommendations to improve the accuracy of these plant specific probabilistic safety analyses.

Some current operator training modules may not deal with mitigating a double sequencing event. Potentially offsetting this is the industry's treatment in the mid-1980s of NRC ISSUE 17 (*Loss Of Offsite Power Subsequent To a LOCA)*. This resulted in emergency procedure changes that improved operator responses to a delayed LOOP condition.

1.2 Key Recommendations

1. Plant engineering staffs can evaluate their unit's expected electrical responses to LOCA induced trips to determine whether safeguards bus voltage will drop to levels that are below relay setpoints and be unable to subsequently reset under potential degraded grid conditions. Section 7 includes a discussion of expected post-trip response of safeguards bus voltage. The ideas and evaluation methods described therein may be useful to establishing a more complete understanding of how a particular unit would respond.

2. Plant engineering staffs can review the equipment listed in Section 7 to determine if it is sufficiently representative of electrical equipment at their facilities that could be exposed to the effects of double sequencing. In particular, motors having high inertia (Wk^2) loads should be identified. The impact that double sequencing might have on these motors' capability to accelerate their loads to speed without thermal or mechanical degradation should be examined along with any unintentional overlapping of motor starts. This study found that in most, if not all instances, exposure to double sequencing would not degrade induction motors or make them unavailable. Table 7-3 in Section 7.2, provides data supporting this conclusion for several large motors at one of the two pilot nuclear units studied in detail. The considerable margins in load inertia accelerating capability noted in the table results in thermal margins in the motors' most limiting components, their squirrel-cage rotors. However, margins may not be as great in large diameter, high inertia fan applications. Thus, systems having high inertia loads may require closer review. The conclusions relating to large induction motors apply to all sizes of induction motors since smaller units have inherently greater built-in margins.

   The conclusion in Section 7 that double sequencing would not degrade induction motors is based on the low inertia loading typically found in nuclear power applications. This conclusion should be valid so long as proper load flow and bus loading and voltage studies have been completed and the resultant degraded voltage setpoints are in place. The scrutiny placed on these studies during the NRC's early-to-mid 1990s electrical distribution system functional inspections should have revealed any fundamental study flaws. Upkeep of the studies is required of plant operators because load growth or reduction affects setpoints.

3. Plants' engineering staffs may find value in evaluating the interruption of cooling water to emergency diesel generators during a double sequencing event. The cooling supply for the diesel generators is usually service water. The large motor operated valves sometimes used in service water system headers may be cycled closed upon a return of ac power. The service water pumps are then started and the motor operated valves opened to reestablish flow. The time required for this evolution should be considered for its potential impact on the heat-up of an already running, even though unloaded diesel generator. This period without active cooling is common to any loss of power event but is usually considered to occur when the diesel generator is started, as contrasted to following a period of operation without load. It is recommended that diesel generators be assumed to be running for at least thirty (30) seconds prior to the LOOP and continue to run through the event while cooling water flow is restarted. Section 8 discusses why the typical remaining plant loads would not be degraded or made unavailable by double sequencing.

4. Operations, engineering and training organizations can benefit from this report by determining if their training modules, and simulator model and its responses, are appropriate for the types of evolutions examined here. We note that the NRC's Issue 17, entitled *Loss Of Offsite Power Subsequent To a LOCA,* is likely to have resulted in improvements in operator training for delayed loss of offsite power events. This was in response to a longstanding industry concern that did not at the time fully factor in double sequencing. This present EPRI effort has not specifically determined the extent of revisions made as a result of Issue 17.

5. Plant engineering staffs may wish to review their unit's status relative to water hammer. If GL 96-06 and conventional LOOP water hammer events are understood and determined to be non-damaging to piping systems, double sequencing should present no new problems.

6. Safety analysis and risk assessment organizations can review this report to understand the delays that double sequencing can cause and to use this input to determine on a best estimate basis whether double sequencing has an impact on core damage frequency. Core damage frequency is the most credible indicator of the significance, if any, of double sequencing. Any decision to conduct additional reviews might best be guided by the conclusions reached relative to core damage frequency. The true risk significance of double sequencing can be determined by quantifying the incremental risk, if any, when double sequencing is included in the probabilistic risk assessment model.

2 INTRODUCTION

2.1 Background

The design of commercial nuclear power plants includes a means for sequencing large electrical loads onto the units' safeguards buses in accordance with prescribed schedules. Sequencing is used to allow the emergency diesel generators to accelerate to speed and then to pick up one load or load set at a time before the next load is started. The inrush currents that accompany the start and acceleration of large induction motors are thus staggered. This avoids cumulatively large current and energy demands. This sequenced loading method enables reasonably sized emergency diesel generators (the onsite ac power sources) to successfully start and accelerate to running speed the required total of loads. In cases not involving an immediate loss of offsite power, some nuclear units block-load their mitigation systems onto offsite power, while at others, motor starts are staggered even when the onsite essential buses remain connected to offsite power. Some of the newer domestic nuclear units are equipped with more than one diesel generator sequencer program, and have a unique sequence for specific combinations of loads that are activated by the accident's demands.

Accident and safe shutdown risk studies, including probabilistic safety assessments, utilize models that reflect what was believed to be the most limiting conditions, i.e., the accident occurs coincident with a loss of offsite power. If offsite power is lost at the onset of a design basis event, the load sequencers strip loads from buses, isolate key buses from other sources of power, start the emergency diesel generators and then start the safeguard loads one at a time. These starts are assumed to be successful with their first attempt. Recent events have suggested that perhaps analyst should consider whether to include the potential for double sequencing in determining the most limiting condition.

It is the purpose of this report to examine, analyze and determine the expected consequences of double sequencing in the most limiting cases. This should allow informed judgments about the impact of double sequencing on the more likely smaller size LOCAs. The results of this work can be used to help licensees estimate the impact, if any, of double sequencing on core damage frequency.

This effort was completed for EPRI as part of its grid stability work. This report applies to both PWRs and BWRs. It should not be considered to be specific for any particular unit without a review of unique plant features and expected system and fuel responses.

2.2 Definition of Double Sequencing

Double sequencing refers to the need to repeat the automatic start of safe shutdown and accident mitigation equipment. Nuclear units differ in terms of their provisions for automatic response to accidents, thus their responses to various scenarios will differ somewhat. In the final analysis however, double sequencing has a similar impact on all units. Since most BWRs have at least one turbine driven injection pump that is independent of ac power, they may have somewhat greater tolerance to double sequencing, especially in the case of the more likely smaller LOCA break sizes.

2.3 Initiators of Double Sequencing

This evaluation examines the situation where immediately following an automatic or manual unit trip, either with or without an accident, the safeguards buses either remain connected, or become connected to the offsite power system as the source of electrical power for plant loads. At many plants the safety loads during normal operation are connected to offsite power via the startup transformer and are not directly affected by a unit trip. At others, safety loads are powered by the unit auxiliary transformer once the nuclear unit is on line. The non-safety buses (and sometimes safety buses), that are normally powered from the unit auxiliary transformer are generally repowered following a unit trip by a high-speed transfer to the startup transformer. At plants that have a main generator output breaker between the generator and the main step-up output transformer and its direct connected unit auxiliary transformer, the generator breaker opens on a unit trip. With this arrangement the unit auxiliary transformer continues to power plant loads from offsite system via a backfeed through the main output transformer.

Plant loads that were running prior to the unit trip (such as service or emergency service water pumps) remain running from offsite power, assuming that source remains or becomes promptly connected (within a few electrical cycles). Loads having safe shutdown or accident mitigation functions are started by their specific control circuit permissives (such as primary system pressure and steam generator level in PWRs, and low reactor water level and high drywell pressure in BWRs) and powered from offsite power. The loads started are a function of the accident conditions sensed by the unit's reactor protection systems. To enable double sequencing to be evaluated as a bounding condition, it is assumed the trip is due to a reactor related upset condition (e.g., LOCA) or some other bounding condition described in Section 7.4 of this report.

The next step in the evaluation is the assumption that, at some point shortly after the unit trip, safeguards bus voltage drops below the setpoints of the undervoltage relays (most likely the level 2 degraded voltage settings) that protect the safety buses. If these relays remain in the trip state for an analysis-specified length of time (trip delay time) the safeguards buses trip free of offsite power, causing the emergency diesel generator output breakers to close and reenergize the safety buses. The accident mitigation loads are then closed onto the safety buses in a preprogrammed order and timing. The sequence of energization, de-energization and then re-energization of these loads is called double sequencing. There may be nuclear units that switch supplies to their second offsite power source before going to the diesel generators for ac power.

Double sequencing is postulated to occur following a unit trip because the voltage relays either drop-out due to a total loss of grid voltage (the UV relays) or are unable to reset following their dropout due to prolonged low voltage caused by large motor starts (the DV relays). Also, the DV relays may activate and be unable to reset some time after the last load application because the grid voltage slowly drifts downward. The unit will disconnect from the grid and become reliant for power on the onsite diesel generators, which, by current designs, will already be operating and ready to accept load. The DV relays protect safety related electrical equipment from the damaging effects of degraded voltage and act to open the auxiliary bus supply breakers. Mitigation loads that have already started are shed and subjected to another start upon power restoration. Loads that remained running following the unit's trip are tripped for the first time. Both of these loads are then restarted in accordance with the sequence program (if there is more than one) for the accident.

A double sequencing event that is initiated by the UV relays alone could be due to a failure of the breaker control system or the grid or plant breakers themselves. This however is unlikely since there is little chance that a breaker or breaker control system failure would be caused by or occur simultaneously with a LOCA, especially in a manner having impact on both safeguards divisions. Double sequencing that is initiated by the DV relays is more likely. It can occur due to any of the following three conditions:

1. A unit trip is generally not caused by a fault in the main turbine generator or main output transformer. For the more likely unit trip initiators, the main generator trip may not take place for a number of seconds following the reactor trip in order to prevent generator overspeed. This subsequently delays the time when grid voltage might become degraded and detected by the DV relays. Plant engineers should consider whether their designs include a delayed unit trip from the grid if there is no concurrent turbine generator-related fault. This is important in determining the likelihood and timing of a double sequencing condition.

2. The post-trip grid voltage may be sufficient for the successful start of the safety loads. However, it is also possible grid voltage may be inadequate to reset the DV relays while starting all required loads, (following the time delay that is provided to carry the plant through the momentary voltage drops caused by the starting of large motors). Load application voltage drops can, and in most cases do, cause DV relays to dropout. However the time delay incorporated in the DV logic circuits blocks the relays' dropout from signaling the onset of a LOOP for a short period while voltage recovers (as large motors approach operating rpm). If the voltage does not recover before the relays time out, the auxiliary buses will be disconnected from the grid to protect plant equipment.

3. The post-trip grid voltage may be sufficiently high to start all required loads and reset the degraded voltage relays after each start. However in some instances the grid voltage may subsequently slowly decline with time. Upon reaching degraded voltage setpoints, the DV relays will trip, time-out and disconnect offsite power. This results in the tripping of just started, as well as already running loads, and causes the essential loads to be sequenced back onto the already operating emergency diesel generators. INPO's SOER 99-01 (Ref 6) describes a scenario of this type that occurred at Africa's Koeberg Nuclear Power Plant.

2.4 Causes of Double Sequencing

Several nuclear plant have identified past instances where grid voltage was unknowingly allowed to drop to a level where, had a LOCA occurred, they might have lost offsite power. Had this happened, shutdown and decay heat removal systems would have been powered by their onsite diesel generators.

The degraded voltage scenarios discussed above and in Section 2.3, have not been included in most analyses. Such scenarios can occur for several reasons.

1. The grid, including generators, was improperly modeled thus yielding incorrect responses to a loss of a nuclear unit together with any one of a number of other contingent grid conditions.

2. The grid, while modeled and analyzed correctly, is being operated outside the guidance of established operating procedures.

3. Power flows on the grid differ significantly from those analyzed, expected and trained for by grid operators, thus yielding unexpected and difficult to correct voltage behavior following a nuclear unit trip. The Callaway plant experienced such a situation.

These initiators are more likely to occur if the grid and nuclear unit organizations are not closely coordinated both contractually and in their operations and communications protocol.

2.5 Potential Consequences of Double Sequencing

Four general areas merit examination relative to the potential consequences of a double sequencing event:

1. Damage or significant degradation of safety related equipment.

   Electrical power and control devices used in nuclear power plants have limitations relating to the manner in which they can be operated. Typical devices need to be evaluated to determine if they are sufficiently robust to handle exposure to double sequencing without significant degradation or failure.

2. Potentially damaging water hammer events

   Generic Letter 96-06, entitled *Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions* (Ref. 9), addresses the potential for water hammer conditions due to high energy release events within the reactor containment, such as a LOCA. The impact of double sequencing on water hammer susceptibility and consequences requires evaluation. This is because of the start/stop/start nature of emergency safety features systems when subjected to double sequencing.

3. Unanalyzed time delays in safe shutdown and accident mitigation systems.

   The delays of interest here would extend from the onset of an automatic or manual plant trip, with or without a reactor accident, until a safeguards process (for example, the removal of decay heat) is initiated. Design basis accident analyses may need to be reviewed to ensure that appropriate time delays have been considered.

4. Impact on the unit's probabilistic risk assessment model and calculated core damage frequency.

   An evaluation of the delays of Item 3 above may be needed to determine if they increase the core damage frequency determined in the probabilistic risk assessment model. This pilot study revealed no detectable change in core damage frequency for the two units considered. This is consistent with the NRC's assessment in their document, NRC IN 2000-06.

3
SCOPE

This report includes descriptions, definitions and an assessment of the subtleties related to double sequencing and the manner in which it may impact safe shutdown. Suggested methods for approaching such issues as “how likely is the event to occur at my plant” and “how do I assess the impact on electrical equipment” are covered. The concept of double sequencing induced delays in accident mitigation is discussed and ideas are presented as to how to assess the ramifications of double sequencing. This report provides a starting point for addressing the likelihood and potential consequences of double sequencing.

4
INPUTS AND ASSUMPTIONS

4.1 Inputs to this Evaluation

- References 1 through 8 of Section 10 relating to the grid and nuclear units
- Reference 9 of Section 10 relating to water hammer.
- Typical logic diagrams for UV and DV protection systems
- Typical schematic diagrams depicting equipment control features
- Typical one-line electrical diagrams
- Typical Final Safety Analysis Report descriptive excerpts relating to electric power and sequencer operation

4.2 Assumptions in this Evaluation

- The definition of "double sequencing" is given in Section 2.2.
- No high inertia motor driven loads that exceed NEMA limits are considered. This assumption is believed to be conservative and reasonable based on the motors that were identified in the pilot effort.
- It is assumed that the setpoints of the degraded voltage relays and the voltage and loading studies that serve as the basis for these are correct. The protection against degraded voltage is intended to ensure that no essential loads are exposed to unacceptably low voltage and allowed to operate for prolonged periods with operating currents in excess of what could be withstood indefinitely. Also, some loads that require a change in state must be protected against the potential that they will be unable to operate (change states) without sufficient voltage. This is a basic industry requirement.
- It is assumed that the degraded voltage relays setpoints, and the voltage and loading studies that serve as the basis for these, provide protection against a sustained marginal condition that could prevent the magnetic circuit of 3 phase motor control starters from operating within manufacturers specified times.
- BTP PSB-1 or GL 79-36 compliance is maintained at the units for which they are individually applicable, depending on their regulatory commitment.

5
DEFINITIONS

Electric Grid

The "grid" is the interconnected transmission system to which the nuclear generating unit output is supplied and from which offsite power is provided for plant loads when needed. Since most of the United States has a tightly interconnected grid, grid performance local to the nuclear unit can be significantly impacted by events that occur hundreds of miles away. Ultimately, unacceptable grid performance cannot be entirely prevented and must be protected against within the nuclear unit so that common mode failure or degradation of safety equipment does not occur.

GDC 17

General Design Criterion 17 is the basic NRC guidance for nuclear generating station power supplies, including offsite power. Regarding offsite supplies, the GDC states that *Electric power from the transmission network to the onsite electric distribution system shall be supplied by two physically independent circuits (not necessarily on separate rights of way) designed and located so as to minimize to the extent practical the likelihood of their simultaneous failure under operating and postulated accident and environmental conditions.*

Onsite Electric Power System

Per GDC 17, the onsite power system includes "*the batteries, and the onsite distribution system*" and *"the onsite alternating current power supplies"* (the emergency diesel generators and uninterruptible ac power supplies).

Offsite Electric Power Supplies

Offsite power supplies consist of the sources of ac auxiliary power that are derived from the grid and are generally not dependent on the operating status of the nuclear unit. GDC 17 defines these as *Electric power from the transmission network to the onsite electric distribution system* that *shall be supplied by two physically independent circuits….*

Double Sequencing

Double sequencing, describes a situation involving the necessity to repeat for a shutdown-requiring event, the automatic start of safe shutdown and accident mitigation equipment.

Unit Auxiliary Bus Voltage Relays

These consist of two levels of voltage relays. One is set at a level that is indicative of an impending total loss of voltage (UV). The other, is set to protect against a prolonged (greater than several seconds) voltage level (DV) that is less than that required to ensure safe, reliable and sustained operation of essential electrical equipment. These are commonly referred to as the first (UV) and second (DV) level voltage relays.

First Level Undervoltage Relays

These voltage relays are installed on station safety buses for the purpose of detecting and promptly disconnecting buses from the grid, upon a complete loss of offsite power. These relays are commonly referred to as undervoltage (UV) relays). The UV relays are generally set at a level of between 50% and 70% and are intended to trip when a total loss of power is pending.

Second Level Undervoltage Relays

These voltage relays are installed on station safety buses for the purpose of detecting and disconnecting buses from the grid upon a sustained degraded voltage (DV) condition. These relays are nominally set at about 90% of rated voltage with exact setpoints specified by the output of nuclear unit-specific loading, load flow and voltage studies.

Moment of Inertia

Moment of inertia is the name given to rotational inertia. It is the rotational analog of mass. It appears in the relationships for the dynamics of rotational motion and is normally expressed in, pound-foot^2 (Wk^2). Its importance to double sequencing lies in the way that inertia slows the acceleration of loads and their induction motors to rated speed. An induction motor accelerating a load having a higher Wk^2 experiences a longer acceleration time, a longer period of inrush current, and greater heating of its squirrel cage rotor.

Inrush Current

Induction motor inrush currents of varying but significant levels exist from the time power is applied (rpm = 0) until the motor has accelerated to a large fraction of its full running speed. Properly set time-overcurrent protective relays will trip the motor power supply if inrush current has not subsided within a reasonable, expected interval. It is typical for these relays to be set to accommodate approximate 20 to 30 seconds of inrush current.

Small 3-phase induction motors generally have 3-phase magnetic starter contactors (NEMA sizes 1 though 4 with 120 volt ac control coils). The coils of these contactors draw inrush currents for a small fraction of a second while the magnetic circuit is being made-up. With insufficient voltage to make-up the magnetic circuit, inrush current is maintained until such time as power is removed from the contactor. This happens when the control circuit fuse blows. The failure (by blowing) of a fuse in Millstone Nuclear Power Station Unit 2's charging pump control circuit due to degraded voltage, and the resulting failure of the 3-phase ac contactor to pick-up when the voltage returned to normal, led to identification of the degraded voltage phenomena in 1976. The addition of a second level of higher set degraded voltage relays, with a time delay to enable large motor starts and the associated momentary large voltage drops, served to render an event similar to that occurring at Millstone implausible.

Block Loading

A term used to describe the practice of applying all loads within a block of loads at the same time. In the case of nuclear power plants, the block may represent the total loads required to mitigate an upset event or a subset of these.

6 REVIEW METHODOLOGY

This project benefited from the use of individuals with industry experience in the design, construction, operation and management of commercial nuclear units. This experience included knowledge of nuclear power station systems and, more specifically, the design, operation and historical behavior of electrical power and piping systems. The project's access to Millstone Nuclear Power Station personnel provided further input. However, no detailed calculations or precise evaluations were completed during the review. The approach was "best estimate" in nature. A more accurate approach involving modeling and highly detailed analysis was judged not to be appropriate for the current scope of investigation.

The review comprises a consideration of the probability and potential consequences of double sequencing and includes a suggested method for assessing:

- The likelihood of a double sequencing event at a nuclear unit,
- The potential for damage to or significant degradation of safety related electrical equipment due to multiple starts, stops and in some cases, inability to change state.
- An assessment of potentially damaging water hammer due to the multiple starts and stops of systems when subjected to double sequencing,
- Consideration of time delays in safe shutdown and emergency safeguard feature system capabilities caused by double sequencing and the impact on fuel cladding (and the potential for water/fuel cladding reactions),
- The impact of double sequencing on unit-specific core damage frequency values.

7 DETAILED REVIEW

7.1 Determining a Best Estimate Probability for Double Sequencing

The historical performance of nuclear units is of little use in providing insight into the probability of double sequencing. The reasons are:

- A lack of awareness until recent years of the double sequencing potential that existed. This made it difficult to know when unacceptable performance might have occurred,
- The very small number of LOCA events that occurred and required the highest levels of bus loading, and
- The past ability of utilities that own nuclear plants to more directly control the connected grid.

Because a LOCA (a very rare event) has not occurred concurrent with a degraded grid condition, there has been no relevant experience with double sequencing. Going forward, the wide dissemination of information via such documents as LERs, SOER 99-01, and the Callaway event (Reference 7) has served to increase awareness and improve performance of the offsite grid and the interface of the units with the grid.

For this reason, an intuitive approach was taken to establish a basis for determining best estimate values for the probability of double sequencing. The following are considerations that bear on the estimation of this value:

1. The analyst needs a good understanding of the degraded voltage margins that are inherent in the second level undervoltage (DV) relay settings. Frequent instances that require entry into technical specification action statements because offsite power would not be available, if a LOCA were to occur, would indicate an increased double sequence probability.

2. The use of automatic voltage driven tap changing transformers, or static vars on station buses for power factor correction, serves to support bus voltage somewhat independent of offsite power voltage levels, i.e., the probability of a double sequencing event is likely to be lower at these stations.

3. An understanding of the percent of the time that a grid serving a nuclear unit is under stress is a useful input to estimating the probability of occurrence. “Under stress” means that loss of the nuclear unit’s output to the grid might cause degraded grid voltage.

4. An understanding of grid behavior in the initial period (perhaps one hour) following a nuclear unit’s trip is useful. It is a good sign if it is common for the grid to take a step drop

to a reduced but acceptable voltage and then remain at that level until corrective actions are taken. Following a plant trip, the grid will probably experience degraded voltage early on or not at all. However there have been cases where grid voltage has decayed over time following a unit trip. The reasons for such behavior need to be understood and corrected.

5. A plant operator needs to understand the protocol by which a reactor trip due to a design basis accident ultimately disconnects the main generator from the grid. Many units have designs where tripping the generator is delayed if there is no generator or turbine fault. This is to expend steam energy in the main steam piping and to reduce the extent of turbine generator overspeed. If tripping the generator is delayed, it is useful to know for how long. This can be determined from past trips if the needed parameters have been monitored and retained. This is important because the full impact of a unit trip does not occur until the generator isolates from the grid. At some plants, a high-speed transfer of the station auxiliary buses to the startup transformer does not occur until the generator trips. While these transfers have proven reliable, their failure could be the cause of double sequencing if the design incorporates a delay in generator tripping. Failures within both safeguards divisions' transfer schemes are extremelyly unlikely..

6. If a generator trip delay is a design feature, the delay time is important. If it is only a few seconds, delay in the operation of accident mitigation systems due to double sequencing is unlikely. Depending on the accident analysis assumption for time to restore ac power when lost during a LOCA, it is possible that the generator trip delays would not cause double sequencing.

7. A nuclear unit should have proper load, load flow and voltage studies, and degraded voltage setpoints. This is a starting point without which a plant operator would not be able to estimate the probability or consequences of a double sequencing event. Many nuclear units assume in their voltage studies that all accident loads are added and no normal operating loads are shed. While this is a correct assumption in the early seconds of an event, shortly thereafter, many large balance-of-plant loads either automatically trip or are tripped by the operators. Thus, a conclusion that, "had we experienced a LOCA during a certain stressed grid period, we would have disconnected from offsite power" may be incorrect. Quite likely, in cases where grid voltage slowly degrades following a unit trip, analysis would show that the reduction in normal station loading due to the unit being off line would more than offset the impact of a slowly decaying grid and added safety related loads. Grid voltage and bus loading influence bus voltage. Load reductions result in improved bus voltage while the converse is true of load increases, such as the activation of safety loads without offsetting load reductions.

8. It is useful to understand the grid operators' plans and expectations for system performance following the trip of a nuclear unit. GL-79-36 suggests that a nuclear unit trip should not require it to isolate from offsite power in order to support safe shutdown, either with or without a design basis event. Further, the grid should be able to accept the next most limiting grid contingency while still powering the unit auxiliary buses, i.e., the DV low voltage relays should not drop out, be unable to reset and ultimately timeout and create a LOOP condition. Adherence to these guidelines minimizes the likelihood of double sequencing.

9. Plant engineers may find it useful to evaluate fast and slow speed transfer voltage setpoints to ensure that they are not set arbitrarily high. If permissive features are present in the transfer designs, they should be derived from voltage studies that assume a plant trip condition, using the minimum voltage prior to transferring maximum load. It can be assumed that if voltage does not dip below the selected level, an allowed transfer will be successful. The nuclear unit can then be expected to remain connected to offsite power, considering that plant bus loading decreases with time as discussed above. It is important to know the degree to which normal plant load reductions over time can offset the impact of declining grid voltage during the post-trip period.

10. Plant operators can use the above considerations to determine changes, if any, to the LOOP frequencies that are in their probabilistic safety analyses. The current unit-specific LOOP initiating event frequency values are unlikely to include degraded voltage-induced losses. This is because there is no valid statistical basis for determining this value. In a trip or LOCA event without full safeguards system operation, bus voltage may be acceptable, even though it might not be a sufficient to handle a worst case LOCA.

The above guidelines should assist in determining a best estimate LOOP frequency that includes degraded voltage-situations.

that the use of tap changing auxiliary transformers and installed static vars can help avoid degraded voltage following a LOCA. While a LOOP is not likely to cause a LOCA, a LOCA may under some circumstances result in a LOOP. This is because the loading caused by the safety equipment puts the unit at a greater than normal likelihood of experiencing a degraded voltage-induced trip. This situation may result in double sequencing since degraded voltage requires time to be detected. Taking credit for balance of plant loads that decrease in the post-LOCA period is likely to reduce the probability of a double sequencing event and would provide a better estimate of what would actually happen.

7.2 Impact of Double Sequencing on Safety Related Electrical Equipment

This effort reviewed the impact of double sequencing on a wide range of equipment commonly found in nuclear power plants. The scope of equipment that was evaluated is near complete for most nuclear units. Plants that decide to use this approach can start with this effort and determine the applicability to their unit(s). Additions and deletions to the list can be made as appropriate.

This approach assumes that a LOCA occurs at a time when the grid is stressed and that a double sequencing event results as follows:

- The possible occurrence of a LOCA is signaled by the activation of the reactor protection system. This results in a reactor trip and a trip signal to the turbine generator. Additionally, start signals are sent to the emergency diesel generators which start (whether needed or not).
- The main steam valves close. It is likely that no mechanical or electrical turbine generator faults are present. Most generators will thus remain connected to the grid until steam energy in piping between the last set of main steam valves and the turbine is expended. The delay in tripping the turbine is nominally about 30 seconds, however the reverse power relays usually

operate considerably sooner and trip the generator. As noted in Section 7.1, knowledge of the design and the extent of trip delay is useful to understanding the potential for double sequencing and the way it evolves.

- Emergency safeguards feature equipment starts from standby per the interlocks and timers associated with their specific control systems. At some units this equipment is block-started onto the offsite power source. Most mitigation equipment has started by the time the generator trips free of the grid.
- In most designs that include a high speed bus transfer, once the generator trips, the opening of the unit auxiliary transformer low side supply breakers commands the startup transformer low side supply breakers to close. This high speed transfer, when successful, is so fast as to have no impact on already started and running equipment. In most designs, this high-speed transfer would be blocked if low side voltage on the startup transformer was low, or if the transfer did not occur within several electrical cycles. High-speed transfer schemes have historically functioned very reliably. Most failures to transfer have been due to severe weather making the offsite supply unavailable. Some units have installed full load generator breakers, in which case no high-speed transfer is needed. The generator output breaker opens leaving the unit auxiliary transformer connected in a backfeed mode to offsite power with no interruption.
- With continuing adequate grid voltage, the post-trip shutdown and cooldown of the unit would be completed on offsite power.
- With adequate grid voltage to satisfy the transfer permissive but not sufficient for the full complement of station loads (including accident mitigation loads), a degraded voltage condition would ultimately be sensed, timed out and the unit buses automatically put into a loss of power mode. Depending on the particular design, a transfer to the second source of offsite power might be attempted. Ultimately, large motors would trip, and safety buses would be automatically isolated from non-safety buses. This would signal diesel generator breakers to close onto their buses, constituting the start of a double sequencing event.

The following assumptions are important to identifying equipment that requires assessment relative to double sequencing: (While reference is made to 4kV buses, some stations have a different utilization voltage for their highest voltage safeguards buses.)

- Safe shutdown, with or without a concurrent LOCA, can be achieved solely with Class-1E equipment powered from Class-1E buses.
- Understanding the double sequencing issue and its impact on a unit-specific basis is useful for evaluating the potential for damaging or undesirably tripping (or not starting) ac powered safety equipment.
- The term *direct-connected equipment* is used to differentiate between ac equipment that is directly powered from the safety buses or safety bus powered sources, and ac equipment that is buffered from the safety buses by such means as batteries or uninterruptible power supplies.
- Voltage relays of the *loss of voltage* (UV) and *degraded voltage* (DV) type, sense voltage on the safety buses. It is these relays that monitor for conditions that are unacceptable and that,

when actuated, may result in double sequencing. These relays are designed to differentiate between acceptable and degraded or lost sources of power.

- When ac-powered equipment is buffered from the safety buses by such equipment as batteries or uninterruptible power supplies, it is immune to the effects of double sequencing. Correct function is assumed so long as the duration of safety system deenergization is small compared to the capabilities of the batteries.
- Battery chargers and invertors are the means for buffering. For the purposes of this assessment, it is assumed that double, triple or even quadruple sequencing (if possible), would not disrupt what is essentially continuous charging of the batteries. With no charging, station batteries nominally have at least a 1-hour useful discharge life. This duration is significantly in excess of input power interruption durations that are caused by double or multiple sequencing.
- The scope of equipment being considered relative to double sequencing is limited to that connected in a direct, or indirect but non-buffered manner, to safety buses.
- Motors of all voltage ratings that could be subjected to double sequencing are induction type that have squirrel-cage rotors and are generally started *across the line*; i.e., without the benefit of reduced voltage or other “soft start” circuitry.

Table 7-1 lists twenty types of equipment (consisting of sixteen equipment classes) whose potential for unreliability or degradation due to double sequencing was considered. In some instances, non-impacted components and circuits are discussed to explain why further review is not necessary.

Table 7-1
Evaluated Equipment and Assessed Status

Equipment	Level of Impact	Basis for Level Assignment	Additional Information
1. 4kV motor and control switchgear buses and breakers	None	Non-severe duty for switchgear	Section 7.2 Note 1 below
2. 4kV protective relaying	None	This must be addressed at supply and load levels	Section 7.2 Note 2 below
3. 4kV 125Vdc control power	None	Non-issue since control power is from a 125Vdc source	Section 7.2 Note 3 Below
4. 4kV pump induction motors	None	NEMA MG 1-20	Section 7.2 Note 4 below
5. 4kV fan induction motors	Negligible	NEMA MG 1-20	Section 7.2 Note 4 below
6. 4kV pressurizer heaters	None	Resistive loads with no inrush current	Section 7.2 Note 5 below
7. 4kV/480V load control center transformers	None	Non-severe duty especially with some loads shed and resequenced onto load control centers	Section 7.2 Note 6 below
8. 480V load control center switchgear and breakers	None	Non-severe duty for switchgear	Section 7.2 Note 7 below
9. 480V load control center protective relaying	None	This must be addressed at supply and load levels	Section 7.2 Note 8 below
10. 125Vdc control power for 480V load control centers	None	Non-issue since control power is from a 125Vdc source	Section 7.2 Note 9 below
11. 480V load control center powered pump motors	None	NEMA MG 1-10, 1-12 & 1-20	Section 7.2 Note 9 below

Equipment	Level of Impact	Basis for Level Assignment	Additional Information
12. 480V load control center powered fan motors	Negligible		Section 7.2 Note 4 below
13. 480V motor control centers molded case circuit breakers	None	Non-severe duty for switchgear	Section 7.2
14. 480V motor control center protective relaying	Minor	This must be addressed at supply and load levels	Section 7.2 Notes 10 & 11 below
15. 120Vac control power for 480V motor control centers	Minor		Section 7.2 Note 12 below
16. 480V motor control center powered motors	Negligible	NEMA MG 1-10 & 1-12	Section 7.2 Note 12 below
17. 480V motor operated valve reversing and non-reversing contactors	Minor		Section 7.2 Note 13 below
18. Short duty cycle (15 minute) motors	Minor		Section 7.2 Note 14 below
19. Pilot solenoid valves	None		Section 7.2 Note 15 below
20. Direct acting solenoid valves	None		Section 7.2 Note 16 below

1. Double sequencing-caused reloading of the metal-clad switchgear buses is not severe duty for the switchgear since the loads being reapplied are small compared to those that support normal operation. This same type of switchgear is broadly applied in utility distribution and industrial applications, and is commonly subjected to multiple transmission and distribution system breaker reclosure operations.

2. Properly applied and set protective time-overcurrent relaying (NEMA nomenclature 51) is started into motion during motor starts. Repeated starts within a short period will likely move the protective relay's induction disk toward the trip contact. The second level undervoltage relays seek to protect the induction motor's rotor from thermal damage and to avoid nuisance trips. The low inertia nature of the safety pumps, etc. compared to their drive motor capabilities gives rise to rapid starts and significantly less rotor heating than is allowed by the NEMA standard discussed in No. 4 below. The induction disks do not move substantially toward the trip settings with each motor start. During periods when the buses are deenergized, the relay disks move back toward the "at rest" position. Only if the deenergized periods are extremely short (less than two seconds or so) would relay resetting not occur. Some stations give their over-current relays for safety related motors longer time settings so the potential for spurious trips is avoided.

3. Control power for the metal-clad 4kV switchgear at most if not all units is supplied by a 125Vdc battery system and is therefore not subject to the affects of double sequencing.

4. The discussion that follows, up to Item 5, applies to 4kV large motor driven pumps. However, it also is applicable to motors of other sizes and voltage ratings, since the 4kV large motor case is bounding and thus applicable to Items 5, 11, 12 and 16 in the listing of evaluated components.

Part 20 to NEMA MG 1, entitled, *Large Apparatus – Induction Motors* (Ref. 27) is the basic governing standard applicable to all safety related 4kV motors. MG 1-20.43, entitled *Number of Starts*, states the following:

A. *Squirrel-cage induction motors shall be capable of making the following starts, providing the Wk^2 of the load, the load torque during acceleration, the applied voltage, and the method of starting are those for which the motor was designed:*

   1. *Two starts in succession, coasting to rest between starts, with the motor initially at ambient temperature, or*

   2. *One start with the motor initially at a temperature not exceeding its rated load operating temperature.*

B. *If additional starts are required, it is recommended that none be made until all conditions affecting operation have been thoroughly investigated and the apparatus examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum since the life of the motor is affected by the number of starts.*

C. *When requested by the purchaser, a separate starting information plate will be supplied on the motor.*

Properly specified and designed motors for nuclear units satisfy the above-specified conditions relative to load inertia and accelerating torque demand, applied voltage and the method of starting.

As stated above, a motor at rest can be routinely subjected to two consecutive starts from ambient temperature with the motor coasting to rest from the first stop. While a coastdown to rest will likely occur in all instances of double sequencing, the motor is subjected to less rigorous duty if it does not stop, so long as the reapplication of ac power does not occur in less than one second. This is sufficient to allow motor residual voltage to drop to 30% or less of rated. This protects the motor stator windings' end turns from excessive overvoltage derived, torque-related shock. No reapplication of power would occur due to double sequencing in less than one second. Thus, for motors at rest following a unit trip, with or without a design basis accident, two starts can be accommodated per the standard, whether or not a full coastdown to a stop position occurs between starts.

A motor that is already running when the unit trips and is then subjected to two start attempts falls outside the standard's normal allowance. This would entail two consecutive starts from a prior running mode and motor temperature, as opposed to ambient temperature. The reality is, however, that from the standpoint of capability, these motors could accept an additional start for either initial condition. This is because there are large margins in most if not all nuclear unit motor applications. The following explains why this is so.

The design of a squirrel-cage induction motor is such as to subject the motor rotor to significant heating and heat related stresses upon starting and acceleration to rated speed. This is because of the relatively high frequency voltage induced in the rotor. The rotor is, for all practical purposes, a set of heavy-duty, short, solid copper bars (called windings) that are short circuited at each end. At motor start, the rotor slip frequency is 60 Hz; at running rpm, slip frequency is on the order of 2 to 3 Hz. As a result, from standstill to near full speed, significant inrush currents flow in both the stator and rotor windings, resulting in significant heating of the rotor short circuiting end rings and the rotor bar connections. The rotor is by far the more limiting of the rotor/stator pair in terms of tolerance to starts; thus the stator is not discussed further. Excessive and repeated motor heating has the impact of reducing motor life, i.e., accelerated aging occurs.

The NEMA standard states that, *It should be recognized that the number of starts should be kept to a minimum since the number of starts affects the life of the motor*. Motors are nominally designed for a life of from 20 to 40 years and, in many applications have, with reasonable preventive maintenance, lasted significantly longer than the design life. NEMA standards are geared toward average applications, i.e., motors are assumed to start relatively frequently, certainly several times a day. In nuclear applications this is not the case. As an example, accident mitigation equipment like HPSI and LPSI pump motors are started monthly during surveillance test runs. A normally running service water pump may run many months before it is relieved by an alternate pump or it may run an entire nuclear fuel cycle. Thus, unless specifically identified, standard life ratings for motors in nuclear generating station applications are highly conservative. The total number of starts in a unit's forty-year life is significantly below the average that NEMA assumes. This gives rise to margins that can be used in the unlikely event of a double or even triple sequence event. At worst, insignificant motor life reduction as opposed to catastrophic and instant failure may result. One might conservatively estimate that one exposure to a double sequencing event might accelerate the aging of a motor from the equivalent of a day to a week of normal operation.

Table 7-2 is NEMA Standard MG 1-20.42, entitled *Load Wk^2 for Polyphase Squirrel-cage Induction Motors*. The vertical axis is motor horsepower and the horizontal axis, motor speed. The intersection of the two axes specifies the maximum load inertia (Wk^2) than can be applied for a standard design of motor at a given hp and rpm.

Table 7-2
Load Wk^2 for Polyphase Squirrel-cage Induction Motors

The following table lists load Wk^2 which polyphase, squirrel-cage motors having performance characteristics in accordance with Part 20 can accelerate without injurious temperature rise under the following conditions:

1. Applied voltage and frequency within the limits set in MG 1-20.45.
2. During the accelerating period, the connected load torque shall be equal to, or less than, a torque which varies as the square of the speed and is equal to 100 percent of full-load torque at rated speed.
3. Two starts in succession (coasting to rest between starts) with the motor initially at ambient temperature or one start with the motor initially at a temperature not exceeding its rated load operating temperature.

	Speed, Rpm										
	3600	1800	1200	900	720	600	514	450	400	360	327	300
Hp	Load Wk^2 (Exclusive of Motor Wk^2), Lb-ft^2											
100	...	...	...	...	...	...	...	12670	16830	21700	27310	33690
125	...	...	...	...	...	...	...	15610	20750	26760	33680	41550
150	...	...	...	...	...	...	13410	18520	24610	31750	39960	49300
200	...	...	...	...	...	12060	17530	24220	32200	41540	52300	64500
250	...	...	...	...	9530	14830	21560	29800	39640	51200	64400	79500
300	...	...	...	6540	11270	17550	25530	35300	46960	60600	76400	94300
350	...	...	...	7530	12980	20230	29430	40710	54200	69900	88100	108800
400	...	...	4199	8500	14670	22870	33280	46050	61300	79200	99800	123200
450	...	...	4666	9460	16320	25470	37090	51300	68300	88300	111300	137400
500	...	...	5130	10400	17970	28050	40850	55600	75300	97300	122600	151500
600	443	2202	6030	12250	21190	33110	48260	66800	89100	115100	145100	179300
700	503	2514	6900	14060	24340	38080	55500	76900	102600	132600	167200	206700
800	560	2815	7760	15830	27440	42950	62700	86900	115900	149800	189000	233700
900	615	3108	8590	17560	30480	47740	69700	96700	129000	166900	210600	260300
1000	668	3393	9410	19260	33470	52500	76600	106400	141900	183700	231800	286700
1250	790	4073	11380	23390	40740	64000	93600	130000	173600	224800	283900	351300
1500	902	4712	13260	27350	47750	75100	110000	153000	204500	265000	334800	414400
1750	1004	5310	15060	31170	54500	85900	126000	175400	234600	304200	384600	476200
2000	1096	5880	16780	34860	61100	96500	141600	197300	264100	342600	433300	537000
2250	1180	6420	18440	38430	67600	106800	156900	218700	293000	380300	481200	596000
2500	1256	6930	20030	41900	73800	116800	171800	239700	321300	417300	528000	655000
3000	1387	7860	23040	48520	85800	136200	200700	280500	376500	489400	620000	769000
3500	1491	8700	25850	54800	97300	154800	228600	319900	429800	559000	709000	881000
4000	1570	9460	28460	60700	108200	172600	255400	358000	481600	627000	796000	989000
4500	1627	10120	30890	66300	118700	189800	281400	395000	532000	693000	881000	1095000
5000	1662	10720	33160	71700	128700	206400	306500	430800	581000	758000	963000	1198000
5500	1677	11240	35280	76700	138300	222300	330800	465600	628000	821000	1044000	1299000
6000	...	11690	37250	81500	147500	237800	354400	499500	675000	882000	1123000	1398000
7000	...	12400	40770	90500	164900	267100	399500	565000	764000	1001000	1275000	1590000
8000	...	12870	43790	98500	181000	294500	442100	626000	850000	1114000	1422000	1775000
9000	...	13120	46330	105700	195800	320200	482300	685000	931000	1223000	1563000	1953000
10000	...	13170	48430	112200	209400	344200	520000	741000	1009000	1327000	1699000	2125000
11000	...	...	50100	117900	220000	366700	556200	794000	1084000	1428000	1830000	2291000
12000	...	...	51400	123000	233500	387700	590200	844800	1155000	1524000	1956000	2452000
13000	...	...	52300	127500	244000	407400	622400	893100	1224000	1617000	2078000	2608000
14000	...	...	52900	131300	253600	425800	652800	934200	1289000	1707000	2195000	2758000
15000	...	...	53100	134500	262400	442900	681500	983100	1352000	1793000	2309000	2904000

The values of Wk^2 of connected load given in the foregoing table were calculated from the following formula:

$$\text{Load } Wk^2 = A\left[\frac{Hp^{.95}}{\left(\frac{Rpm}{1000}\right)^{2.4}}\right] - 0.0685\left[\frac{Hp^{1.5}}{\left(\frac{Rpm}{1000}\right)^{1.8}}\right]^{*}$$

Where A—24 for 300 to 1800 rpm, inclusive, motors
A—27 for 3600 rpm motors

* This formula may not be applicable to ratings not included in the above table. Consult the manufacturer for the ratings which are not shown.

Authorized Engineering Information 11-12-1953, revised 6-1-1959; 7-13-1967; 5-17-1971; 11-8-1973.

The motor manufacturer, when designing a line of motors, cannot know the kinds of load the customers will be applying over the line's market life. He designs and designates the motor's capability in terms of the *number of starts* in rapid succession, using a load inertia value that is representative of what the motor could need to accelerate (See NEMA motor capability table). This accommodates a range of load types. The table lists inertia values that are representative of large diameter, high inertia loads like those of large diameter fans and flywheels. These inertia values envelope the inertia presented by small diameter water pumps such as those found in nuclear generating plants. A lower inertia load results in considerably less rotor heating when accelerating to speed since accelerating time is shorter. A practical example is the reactor coolant pump motor start with its long acceleration time to rated speed. This is due to the large flywheel installed on the motor's rotor to provide reactor coolant coastdown flow upon loss of power to the pump. Compare this to a LPSI, HPSI, service water or other more typical type of pump loads and note their much faster acceleration to rated speed. The net effect is that the acceleration of low inertia pump loads to operating speed is not rigorous duty for the squirrel-cage induction motors that are used in nuclear power stations. Thus, their rotors experience less stress due to heating upon starting than NEMA standard provision A provides for.

Table 7-3 presents data relating to nuclear generating station large motor loads taken from specific specification sheets for one of Millstone's units. Sizeable safety margins are evident between the inertia the motors could accelerate to rated speed and the inertia of the actual plant loads. These motor/load combinations are representative of most nuclear units, however plant operators will likely find it worthwhile to confirm the appropriateness of this data to their particular units. This table indicates the differences in starting-related stresses in motors starting high-inertia loads and low-inertia loads.

Table 7-3
Comparison of Selected Large Nuclear Unit Induction Motor Load Wk^2 to NEMA Standard MG 1-20.42 Limits from one of the pilot PWR plant studied.

(-) designates non-safety related and (*) designates safety related motor/load combinations)

Pump Designation	Horsepower	RPM	Load Wk^2 ($lb\text{-}ft^2$)	NEMA Wk^2 ($lb\text{-}ft^2$)	Safety Factor
CDS (-)	250	1,800	13.5	900	66.6
AFW (*)	600	3,600	10.4	443	42.6
CCP (*)	800	1,800	295	2,815	9.5
SWP (*)	600	900	375	12,250	32.6
CWS (-)	1,500	277	9,670	45,000	4.6
FWS (-)	12,000	1,800	4,620	15,000	3.2
QSS (*)	500	1,800	44.9	2,000	44.5
SWT (-)	400	12,000	105	4,199	40.0
CSS (-)	450	1,800	46	2,000	43.5

Key to Table 7-3

CDS	Containment Depressurization System
AFW	Auxiliary Feedwater System
CCP	Component Cooling System
SWP	Service Water Pump
CWS	Circulating Water System
FWS	Feedwater System
QSS	Quench Spray System
SWT	Spare Electric Driven Main Feedwater System
CSS	Condensate Storage System

Table 7-4 shows typical PWR reactor coolant pump motors with their very high inertia flywheel loads. These motors are non-safety related, and are not safe shutdown loads. They are not subjected to double sequencing.

Table 7-4
Comparison of Typical Reactor Coolant Pump Motor Load Wk^2 to NEMA Standard MG 1-20.42 Limits

Pump Designation	Horsepower	RPM	Load Wk^2	NEMA Wk^2	Safety Factor
Pilot 1	6,500	900	110,000 *	85,000	less than 1
Pilot 2	7,000	900	122,000 *	90,500	less than 1

Note: * Approximate values

(Note that these non safety-related motors and loads are exceptions to NEMA standard loading allowances and are the reason plant operators should attempt to minimize the number of starts. Motor starting times are on the order of 20 seconds for these pumps)

NEMA MG 1-20.43 states that: C. *When requested by the purchaser, a separate starting information plate will be supplied on the motor.* The intent of this clause is to allow the manufacturer to rate the capability of the motor to carry a specific load. In this way the manufacturer can rate the motor for a greater number of motor starts within a given period than the NEMA standard allows if the total inertia of the motor/load combination is appropriately low.

Based on the above discussion, insignificant motor life degradation would result if double sequencing were to occur. Even additional starts beyond those caused by double sequencing could be tolerated.

The above discussion also is applicable to 480V load control center and motor control center fed motors with the exception of those powering motor operated valves. These are discussed in note 14 below. There are NEMA standard sections that are specifically applicable to the load control center and motor control center motors; however, the conclusions are essentially the same. For reference, the following are additional NEMA Sections that are applicable to the smaller horsepower range of motors powered from load control centers and motor control centers (from fractional to 250 hp).

- NEMA Part 12, entitled *Tests and Performance, AC Fractional and Integral Horsepower Motors*
- NEMA Part 12.50, entitled *Number of Starts*

NEMA Parts 12 and 20 overlap in horsepower ratings, however since they impose the same requirements the overlap is of no concern. As would be expected, the design and construction conservatism of smaller motors is greater; i.e., there is less need to refine the design to the extent needed for very large motors.

5. Pressurizer heaters are resistive loads that are not negatively impacted by double sequencing or frequent on/off cycles.

6. Transformers are designed for transmission and distribution system applications and are able to stand multiple reclosure operations under full load. Nuclear unit load control center transformers power large motors (generally 70 hp and above). The transformer insulation is designed to withstand voltage stresses far exceeding those caused by double sequencing. Additionally, the windings are braced for full short circuit duty that conservatively envelops that imposed by double sequencing.

7. Double sequencing caused reloading of 480V metal-clad switchgear buses is not severe duty since the loads being reapplied as a block are small compared to the loading that exists during normal operation. This type of switchgear is broadly applied in utility distribution and industrial applications and is commonly subjected to multiple transmission and distribution system breaker reclosures.

8. Time-overcurrent is the only type of protective relaying even marginally challenged by double sequencing. Double sequencing will not cause improper operation if the relays are set in accordance with standard industry practice.

9. Control power for the metal-clad 480V load control center switchgear is usually derived from the 125Vdc system and is therefore not subject to the affects of multiple sequencing.

10. Nuclear unit motor control centers are usually block tripped and reloaded. This is normal, non-severe duty and is comparable to that in distribution substations. This same type of switchgear is broadly applied in utility distribution and industrial applications, and is commonly subjected to transmission and distribution system breaker reclosures.

11. As previously discussed, the only protective relaying in motor control centers that is even marginally challenged by double sequencing are the time overcurrent devices. These devices are commonly referred to as “thermal overload protectors”. Double sequencing will not cause improper operation if these relays are set per standard industry practice.

12. Motor control centers generally derive their control power from a relatively small 480/120V control transformer with its primary side connected to two of the three phases of the 480V main power buses within the cubicle. The control circuit devices (relays, lamps, etc) and the 120Vac circuit’s fuses will not be unacceptably stressed by double sequencing. Control relays operate within a few electrical cycles. Timing relays draw only nominal current.

    The potential for the equipment to draw excessive current during operation above or below its voltage rating must be addressed when selecting degraded voltage setpoints. Unwanted isolation could leave the equipment unavailable when the voltage returns to normal and could be a common mode concern. The combination of reliable voltage studies and proper degraded voltage and protective overcurrent relay setpoints, in accordance with standard industry practice, should preclude motors from improperly tripping due to sustained periods of lower voltage. One of the events presented in SOER 99-01 is a condition where motors tripped due to sustained periods of overcurrent due to prolonged operation at degraded voltage. Occurrences such as this are avoidable.

13. This effort included a review of the impact of double sequencing on motor starters. Motor control center cubicles (480V) equipped with NEMA sizes 1 through 4 starters, of both the reversing and non-reversing type, generally power their starter’s coils from the type of

cubicle mounted control transformer discussed in note 12 above. Unlike other devices in these control circuits, the starter coils draw considerable current (when energized) while they change state. The duration of high current is normally exceedingly short, but, should the contactor fail to physically close, high current levels continue. This is due to the heavy-duty nature of the 3-phase contactor and the fact that inrush current flows until the starter's magnetic circuit is completed. This is the problem that first exposed the degraded voltage phenomena at Millstone 2 in 1976. In this instance the inability of a charging pump non-reversing starter to pick up on command ultimately blew the properly sized control circuit fuses after a sustained period of inrush current.

If the voltage and load flow studies and degraded voltage relay setpoints are appropriate, these contactors will change state in a small fraction of a second. Multiple changes in state can be tolerated as well, without challenge to the control circuit fuses. In fuse blowing experiments conducted at Millstone 2 in 1976, at a voltage barely beneath that required for the starters to change state, properly sized fuses remained intact with inrush current flowing for from 40 to 60 seconds. This is an indication that double or multiple sequencing does not adversely affect the 480V motor control center-housed NEMA motor starters.

14. Short duty cycle motors have a nominal running time limitation of fifteen (15) minutes. They must then cooldown before subsequent runs are made. These are the types of motors used in motor operated valve applications. The need to provide high torque in a small environmentally sealed package results in a motor that cannot be run continuously. When the motor is operating, winding temperature rises until the power is removed. The temperature would increase to a destructive level if the motor were operated significantly beyond its 15-minute rating. In even the most severe applications, several strokes from one position (perhaps open) to the other (perhaps closed) can be completed without violating the 15-minute criteria. Thus, double sequencing presents no problem to short duty cycle rated motors.

15. Pilot solenoid valves are used to operate air-operated valves. These valves are commonly found in containment isolation systems. Critical solenoids are powered either from vital ac or 125Vdc sources and are not impacted by double sequencing. Applications powered by 120Vac sources that are double sequencing-vulnerable generally have a "fail safe" design if they are needed for safe shutdown or accident mitigation. Such pilot solenoid valves move to their safe state when they are deenergized. In most cases, this vents air from the main air operated valve they are controlling. (In most instances, systems that require air to operate valves against their internal springs are non-safety related). Safety related applications where multiple operations are required usually have local air accumulators with sufficient volume to complete the required number of open/close cycles. In these cases, vital ac or 125Vdc is used as the control power source since operation requires energization and deenergization of the pilot solenoid valve. In any event, pilot solenoid valves do not draw heavy currents and are not degraded by frequent changes in state when appropriate voltage is provided, i.e., the proper degraded voltage setpoints ensure adequate voltage.

16. Direct acting solenoid valves are normally installed in "keep ready" systems such as to maintain proper nitrogen pressure in safety injection accumulator tanks. Such systems are not required to remain operable following a design basis event. These tanks are precharged and need only to discharge their borated water once.

Another application for direct acting solenoid valves is the post-TMI required high point reactor cooling system vents. These valves are locked in a deenergized state and would only be activated if the emergency response organization approved their use to vent hydrogen from high points in the vessel and pressurizer (PWRs). This would occur a considerable period following onset of an accident. In any event, sources that are not susceptible to double sequencing generally power these valves. All evidence indicates that solenoid operated valves are not vulnerable to double sequencing.

In summary, the preceding sections provide confidence that electrical equipment will not fail, be damaged or made unavailable by double sequencing.

7.3 Potential for Water Hammer Damage Due to Multiple System Stops and Starts from Double Sequencing

Generic Letter (GL) 96-06 (Ref. 9), entitled *Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions*, was published by the NRC on September 30, 1996. This GL required licensees to investigate and provide input relating to three issues involving system performance in a post-accident elevated temperature environment. A brief description of these issues follows:

Issue 1 -- When accompanied by a LOOP, a LOCA could potentially cause momentarily stagnant cooling water in the containment air recirculation system of PWRs to heat to the point where two-phase flow might occur when flow is reestablished. Licensees were to determine if their analyses predicted the possibility of two-phase flow. If yes, a review was required to determine if the systems would remain operable when subjected to the associated potential water hammer.

Issue 2 -- If two phase flow was possible, a review was required to determine if there would be sufficient cooling water flow to remove containment heat from a postulated design basis event.

Issue 3 – Following a LOCA or main steam line break, stagnant sections of cooling system piping might pressurize. Would cooling system valves open under the possible higher pressure differentials across the valves?

Double sequencing has a bearing on Issue 1 above since the cooling water flow loss duration could be different than that analyzed for the normally postulated LOOP with a concurrent LOCA scenario. While the GL specifically indicates that the containment air circulation system cooling water "could flash to steam in the cooler unit coils during a design-basis LOCA with a concurrent LOOP or with a delayed sequencing of equipment," it is not clear to what extent licensees considered other than the normally postulated concurrent LOCA and LOOP situation.

Issue 2 is not a factor to double sequencing if Item 1 is appropriately dealt with.

Issue 3 is judged to have no relationship to double sequencing.

GL 96-06 was limited in scope to piping systems that are inside containment and thus exposed to the design basis accident environment. There has been industry experience with water hammer occurring in systems required for safe shutdown that are outside of containment. Double sequencing raises a question as to whether multiple occurrences of LOOP-induced water hammer might cause inoperability in these systems.

The following section offers an approach for determining if double sequencing could cause different or more severe water hammer conditions, potentially resulting in system inoperability beyond that considered in response to GL 96-06.

1. In responding to GL 96-06 (Ref. 9), it can be assumed that at a minimum, licensees evaluated their in-containment systems using the ac power unavailability duration for the "as-designed" plant with concurrent LOCA and LOOP events. Determining the loss of forced cooling water flow duration for this case is relatively straightforward. A means is needed to determine if double (or even triple) sequencing would meaningfully increase the loss of forced cooling water flow duration due to the degraded voltage-induced first and even second loss of ac power. Some plants make successive automatic attempts to transfer to an energized offsite power supply and could experience three starts of some systems.

Section 7.1 above proposes that licensees develop a thorough understanding of their unit's response to a LOOP, to a delayed LOOP, and the potential for a second LOOP that could cause some loads to start three times. The second LOOP is related to plants that attempt transfers to successive offsite power sources before utilizing the emergency diesel generators. It is likely that most units, when studied for a double or third sequencing event, will conclude that the duration of lost forced cooling water flow actually is reduced for the first, and if applicable, second loss of ac power when compared to the concurrent LOCA and LOOP case. Consider the following:

- The traditionally studied most limiting accident assumes the LOCA occurs concurrent with the LOOP event. Forced cooling water flow is disabled for at least as long as the diesel generator start times (commonly on the order of 10 to 15 seconds). Most likely the inside containment systems (like the containment air recirculation system) are not started immediately upon diesel generator energization of the buses, but rather, start as one of the delayed sequence steps. As a result, cooling water flow loss times during which the water can rise significantly in temperature can be considerable (perhaps between 15 and 30 seconds). This is the case that would have been studied in response to GL 96-06 (Ref. 9) if a licensee took the least comprehensive view of the issue. (BWRs do not have the containment or recirculation fans alluded to in GL 96-06).
- It is informative to consider a LOCA with a delayed LOOP. In the early moments post-LOCA, the absence of cooling water flow would be of shorter duration than for the concurrent LOCA/LOOP case, since there is no need to wait for the diesel generators to start. Most nuclear units have designs that automatically start the diesel generators upon an accident signal even without a LOOP so that they are ready if needed. Any pumping prior to the LOOP would prevent stagnancy in piping systems such as for containment air recirculation, until a LOOP occurs. The resulting loss of cooling water flow would be shorter for this case since the already running and up-to-speed diesel generators would reenergize the station buses. It is reasonable to assume that during the period while degraded voltage relays are timing out (on the order of 7 to 10 seconds), pump operation and cooling water flow is normal. Induction motors will run on significantly reduced voltage for short periods (a slight reduction in speed increases their slip frequency and as a result their torque capability but no appreciable flow reduction would be noted). The preceding discussion is

not applicable where the diesel generators would not be started upon occurrence of a LOCA in anticipation of a LOOP.

- Most safety bus designs are such as to experience only very short deenergization after occurrence of a LOOP if the diesel generators are already running. Generally the permissives required to allow the diesel generator breakers to close are the bus being isolated and residual voltage being at a level of less than about 30% of rated. Residual voltage due to induction motors spinning down and behaving momentarily as induction generators is above 30% of rated for at most one second. The other permissives, such as those relating to bus tie and supply breaker status (to ensure bus isolation) occur in a small fraction of a second. Thus, when compared to a concurrent LOCA/LOOP event, the 10 to 15 second reenergization time is reduced to about 1 second when the diesels are already running. The normal sequence time for the required cooling water pumps is added to that delay. From a water hammer standpoint, the already operating diesel scenario is a preferred situation compared to the concurrent LOCA/LOOP case.
- A slow-speed transfer is usually used to connect the safety buses to the second backup offsite source for units that utilize two backup offsite power sources (first one, then the other) before connecting to the diesel generators. While there are differences in slow-speed transfer designs, at most, a 3 second delay would be expected between failure of the high-speed transfer to the first backup source of offsite power and the reenergization of the buses via the slow-speed transfer to the second backup source. This too is far less than diesel generator starting time and results in a shorter loss of cooling flow even if it is unsuccessful and there is a need to automatically connect the diesel generators' output to the safety buses.

Based on the above, water hammer is less severe for double or even triple sequencing than is determined using GL 96-06 for the most conservative assumption of concurrent LOCA/LOOP. Issue 2, that of ensuring effective containment heat removal, is also reduced in severity for the anticipatory diesel generator start case is enveloped by the concurrent LOCA/LOOP case.

Plant operators may wish to use the above evaluation process to determine how their bus transfer designs perform and to determine if the generalized logic and conclusions presented above are applicable to their units.

As noted above, there are systems outside of the scope of GL 96-06 that can experience water hammer due to system starts and stops. The following are ways to address these:

- If a plant system has no history of water hammer during normal operation, testing or actual LOOP events, it is highly unlikely that a delayed LOOP without a LOCA will result in water hammer.
- If the preceding is true for a particular nuclear unit, and the system is not predicted to void or generate water hammer during accident scenarios, it can be assumed that double sequencing will not cause water hammer following a LOCA.
- Systems that have low flows and high operating pressures, like the feedwater system in BWRs and charging system in PWRs, and that have not experienced water hammer, are unlikely to be affected by double sequencing.

- Closed loop systems that do not void or develop steam pockets during LOOP or postulated accident conditions are not susceptible to double sequencing induced water hammer.
- Systems where there has been a concern that a LOOP might cause water hammer are the ones most likely to need consideration relative to double sequencing.

The above guidelines, when applied to nuclear power station piping and electrical system designs and functions, are likely to yield results similar to those of this effort's pilot plant studies. Thus, there should be no new or more severe water hammer events caused by double sequencing.

7.4 Approximate Delay in Effective Accident Mitigation Because of Double Sequencing

Example Event Description

This example event is discussed for a PWR since PWRs have no turbine driven primary system injection pumps that would be unaffected by a LOOP. Most BWRs have ac-independent injection pumps for some functions and, to some extent, BWRs are less affected by double sequencing.

The event is preceded by normal 100% steady state power operation. At time, t= 0, a bounding LOCA occurs and is immediately sensed by the reactor protection system. It trips the reactor and the main turbine, and starts the emergency diesel generators. The assumed accident is for up to a full sized double ended cold leg guillotine break in the reactor coolant system. Accident mitigation and safe shutdown loads that are required but not already running are automatically started within the first several seconds.

The now running accident mitigation pumps and the safety injection accumulators (PWRs), while delivering water to the reactor vessel, are generally ineffective in the early seconds due to the occurrence of blowdown and bypass flow. At a time on the order of 20 to 40 seconds, the reactor vessel lower plenum begins to refill and by perhaps 30 to 50 seconds, water level is restored to the lower core support plate elevation. This begins the reflood phase, during which fuel peak clad temperature is reached at something in the 150 to 300 second range (assuming double sequencing does not occur). Based on these estimated times, a LOOP delay in the range of 20 to 50 seconds would seem to be most limiting in terms of fuel peak clad temperature.

The example now assumes that just prior to the beginning of reflood, with the main generator now disconnected from the grid, an attempt is made to transfer station loads to offsite power. The transfer to offsite power is assumed to be unsuccessful, causing an attempt to either power essential buses from the emergency diesel generators or to transfer to the second backup source of offsite power (if that transfer is part of the design). In this later case, the attempted transfer to the second source is assumed to also fail. Since the emergency diesel generators are already at rated speed, their output breakers automatically close when all permissives are satisfied. These permissives ensure that the respective safety buses are isolated and residual voltage due to motor coastdown has decayed. The diesel generator breakers close and the load sequencer begins to connect the large loads in the scheduled order. It is estimated that bus dead time would be on the order of one second for nuclear units that do not automatically transfer to a second backup source of offsite power but instead turn directly to the diesel generators. It would be on the order of 4 seconds for units that first unsuccessfully attempt a transfer to the second offsite source.

Estimated Time Delay

The following is a method for understanding the impact of time delay caused by double sequencing on the effective operation of accident mitigation systems:

- In the early stages of accident mitigation, the injection of borated water into the vessel and replenishment of cooling water level are vital to assuring that fuel temperatures do not reach unacceptable levels. The focus is on the impact of double sequencing on the delay in pumping water into the reactor vessel immediately following the LOCA.
- There is a need to estimate a bounding time delay that will occur before injection flow is restored. This scenario is judged to be the most limiting since the delayed LOOP is assumed to occur at the most critical time for the most limiting double ended cold leg guillotine break, i.e., during the refill or reflood stages when there is little or no cooling water in the vessel.
- The term "assumed average delay time" is used to describe the average delay in reactor cooling system water replenishment. It is the sum of the bus dead time (from 1 to 4 seconds) and the average of the starting sequence times for the various injection pumps. Consider the following hypothetical example:
  - Bus dead time is 1 second
  - High pressure safety injection pumps start at 4 seconds (per the sequencer)
  - Charging pumps start at 10 seconds
  - Low pressure safety injection pumps start at 16 seconds

A straightforward calculation of the assumed average delay time would be:

1 + (30/3) = 11 seconds

However, since the most critical pump for the large pipe break is the low pressure safety injection pump (with its low head/high capacity capability) and since it is the last pump started, one might choose to count it twice in the calculation. The summed times would then be divided by four. This would give the following result:

1 + (46/4) = 12.5 seconds

Once the assumed average delay time estimate is derived, it can be factored in at the worst time during the worst-case design basis accident. If it can be determined by best estimate techniques that, even though the peak clad temperature increases because of the delay, it does not increase to a point where a fuel clad/water reaction would occur, it may be reasonable to conclude that even with double sequencing, the accident can be mitigated. If this can not be said with reasonable assurance, it may be necessary to make additional calculations that are specific to the double sequencing/LOCA scenario of interest.

Impact of Time Delay

- A best estimate evaluation of the delay in effective pumping that is caused by double sequencing will most likely conclude that, while fuel peak clad temperatures would be higher than without the delay, the impact would be insufficient to cause a fuel cladding/water reaction. Nor would it cause release limits to be exceeded.
- Use of a best estimate approach is appropriate since the probability of a double ended cold leg guillotine LOCA is, by itself, on the order of 1×10^{-6} to 1×10^{-7} per reactor year. When combined with a LOOP event, the occurrence would be on the order of 1×10^{-8} to 1×10^{-9} per reactor year. The LOOP occurring as a result of a delayed degraded voltage condition (the cause of the double sequencing event) is a factor that serves to make this occurrence exceedingly remote. (The conditional probability of 0.01 LOOPs per LOCA was used in this approximate calculation.)
- The assumed double-ended guillotine LOCA ensures that the assumed average delay time clearly bounds the smaller, more probable LOCAs.
- The smaller break size more probable LOCAs are significantly bounded by the double ended cold leg guillotine failure and are far more tolerant of injection delays or momentary flow stoppages. Thus, these were not examined beyond making the judgement they would be bounded.
- A LOOP occuring somewhere in the range of 20 to 50 seconds represents a worst case due to the little or no amount of reflood that has been completed when pump flow is lost; thus a minimum of heat removal occurs during the dead time.
- An assumption that the LOOP due to delayed degraded voltage occurs at later than 50 seconds is less severe. This is because there would be additional water in the reactor vessel and this would make the average delay time less severe since some heat removal will occur through boiling. However, it is likely that a LOOP due to degraded voltage and the ensuing double sequencing would occur later than is assumed in this hypothetical example.
- The chosen timing (of 20 to 50 seconds) most likely precludes operator intervention to reset accident signals. To cover the case where operators override automatic actuations, it is assumed they are also adequately prepared to manually compensate for prior manual actions. They would likely have this capability due to reviews brought about by the early 1980s NRC ISSUE 17, entitled *Loss of Power Subsequent to a LOCA* (Ref. 3).

In summary, the use of a best estimate approach for judging the impact of double sequencing induced interruptions in injection flow can be expected to yield reliable results.

7.5 Potential Impact of Double Sequencing on Core Damage Frequency

Plant probabilistic risk assessment and safety analysis organizations will want some indication of whether their unit's core damage frequency is measurably changed by the potential for a double sequencing event. It is likely that any change will be minimal based on the following:

- Best estimate techniques probably will show that a worst case double ended cold leg guillotine LOCA with a double sequencing evolution is mitigable without exceeding regulatory release limits. (A double ended cold leg guillotine LOCA has the least tolerance to delays in the start or momentary stoppage of injection flow. Calculations for the duration of flow interruption should place the timing of that interruption at the worst possible time; i.e., at or near the start of the reactor reflood phase. The use of a best estimate approach to evaluating core damage frequency changes is appropriate since the annual probability of the double ended guillotine LOCA is, by itself, on the order of 1×10^{-6} to 1×10^{-7} per reactor year of operation. When combined with a LOOP event, the occurrence would be on the order of 1×10^{-8} to 1×10^{-9} per reactor year. The assumption that the LOOP occurs as a result of a delayed degraded voltage condition (the cause of the double sequencing event) is a factor that serves to make this occurrence remote.)

- The LOCAs that have a higher probability of occurrence (smaller break sizes) are considerably more tolerant of delays in starting or momentary losses of injection flow. While these LOCAs have probabilities that would have marked impact on core damage frequency if not properly mitigated, a 10 to 20 second interruption in flow at essentially any time post-LOCA is likely to be tolerable with only insignificant changes in the impact on reactor fuel peak clad temperature. The results are bounded by the double ended guillotine LOCA whose consequences have already been estimated to be acceptable.

NUREG/CR-5750 provides the following values for the frequencies of specific initiating events that have relevance to this study:

NNP Type	Small LOCA	Medium LOCA	Large LOCA	LOOP
BWR	5.0E-4/year	4.0E-5/year	3.0E-5/year	4.6E-2/year
PWR	5.0E-4/year	4.0E-5/year	5.0E-6/year	4.6E-2/year

Based on the above, it can be concluded that the impact of double sequencing on core damage frequency is insignificant. A formal probabilistic safety analysis model or a modified reactor accident analysis reflecting this condition could be designed to provide additional evidence if that was deemed necessary.

8
SUMMARY AND CONCLUSIONS

The following summarizes this efforts' finding on double sequencing:

8.1 Likelihood of a Double Sequencing Event

The nuclear power industry has a comprehensive statistical base of event response information however there is little or no relevant experience relative to double sequencing. This is due to the very good experience wherein a LOCA (already a rare event) has not occurred concurrent with a degraded grid condition. There have been instances however where a plant operator has determined that were his nuclear unit to have experienced a LOCA during specifically investigated periods, the onsite diesel generator power supplies would have been called upon. This is because degraded voltage would have caused low voltage relays to trip.

It may be that a factor should be added to nuclear plant LOOP statistics to account for degraded voltage conditions that have occurred for a short period following the trip of nuclear units or that a separate statistic should be compiled for degraded voltage following unit trips. No nuclear unit can be said to be completely immune from double sequencing. A delayed LOOP event initiated by degraded voltage will cause the affected unit to shutdown in a manner different than that for the traditionally studied LOOP.

The most probable double sequencing event will be triggered by a nuclear unit trip from a stressed electrical grid with heavy auxiliary bus loading following the trip. This combination of conditions includes elements similar to those encountered following a trip induced by a LOCA. A LOCA also will trip the nuclear unit and subject its buses to heavy loading. The simultaneously stressed grid condition is a randomly occurring event that does not increase the likelihood of a LOCA.

The use of fast acting automatic voltage controlled tap-changing transformers or the installation of static vars on a station bus can reduce the chance of double sequencing. Also, at plants and in situations where the grid voltage degrades relatively slowly following a trip, the reduction in normal station loads may offset the effects of the safety loads and act to avoid double sequencing.

Much has been done to minimize the probability of double sequencing. Further, it behooves plant owners and operators to take advantage of the information and guidance that is now available. In general, nuclear power plant operators have improved their interface with grid operators to achieve a high degree of offsite power reliability. In most instances, the specifics of these interfaces are contractual. The industry has hosted regional conferences with representatives from the parties critical to successful grid/nuclear unit operations. The need for, and value of, a strong and continuing interface of key grid and nuclear unit personnel cannot be overstressed. The areas that remain to be investigated to better understand the likelihood of double sequencing are covered in Section 7.1 in the form of a proposed methodology.

Double sequencing cannot be deemed incredible at any nuclear unit. The event is more likely to be brought about by a reactor accident than to occur during normal day-to-day operation. Thus, historical performance cannot be used to develop a probabilistic safety analysis input value for calculating the probability of an accident together with a double sequencing event.

Since double sequencing can occur, it is important to understand the impact of such an event on safe and orderly shutdown. This understanding will enable follow-on activities that can help minimize the impact of such an event.

8.2 Potential Consequences of a Double Sequencing Event

The following are four findings relative to the consequences of a double sequence event:

1. Critical electrical components are not likely to be damaged or made unavailable by the affects of double sequencing. The basis for this conclusion is covered in Section 7.2.

2. Repeated starts and stops of systems needed for accident mitigation and safe shutdown are not likely to cause or change the nature of water hammer events and associated consequences that are not already identified and analyzed**.** We note that a nuclear unit that:

   – Has been determined to be able to conservatively withstand piping system loadings associated with conventional LOOP event-related system stops and starts, and,

   – Is GL 96-06 compliant for design basis accident-related water hammer events,

   is likely to be similarly capable of withstanding, with appropriate margins, double sequencing induced piping system loadings. Section 7.3 includes a method that licensees can use to evaluate their plant's water hammer status.

3. A review of hypothetical double sequencing induced delays on the mitigation of a hypothetical worst case analyzed accident for a PWR (i.e., the double-ended cold leg guillotine rupture) was completed. The review indicates that for the rupture size that yields the highest peak fuel clad temperature, the clad temperature will be somewhat higher if double sequencing occurs. This is because double sequencing slightly delays the refill and reflood of the reactor vessel plenum and core. A best estimate of the consequences indicates that the clad temperatures would not reach levels that would cause a water/fuel clad reaction. While the double-ended guillotine rupture was specifically addressed, there is a range of large breaks somewhat smaller than this rupture which could have similar results. They would need to be analyzed to provide assurance that their probability of occurrence is sufficiently low to arrive at this same conclusion.

   It is expected that a review of a typical BWR would yield similar or better results because in most instances, these units have one or two steam turbine driven injection pumps that are not dependent on ac power. The assumed average delay time that is set forth in Section 8.4

would be reduced because the turbine powered pumps are not delayed. The assumed average delay time would likely be of a shorter duration. However, these turbine driven pumps are of relatively low pumping capacity and may not significantly contribute to decay heat removal during LOOP dead bus periods. It seems probable that any amount of water introduced into the vessel will flash to steam and have some impact that increases fuel cooling and reduces the peak temperature.

While double sequencing would slightly increase the time to establish accident mitigation, consideration of offsetting factors such as very low likelihood of the very large breaks, and the greater tolerance to flow delay in the case of the far more likely smaller breaks, lead to Conclusion No. 4, below. It is estimated that any delay in mitigation caused by double sequencing would not cause release limits to be exceeded.

4. Double sequencing, if it were to be modeled in unit-specific probabilistic safety assessments, is unlikely to measurably impact core damage frequency values. However, the current models for nuclear units may not include details that accurately reflect the timing of accident mitigation equipment availability, following the onset of a reactor accident, when double sequencing is involved. It may be possible to improve the accuracy of the current models with respect to loss of offsite power, both with and without an accident, by taking advantage of some of the insights in this report.

9 RECOMMENDATIONS

1. Plant engineering, particularly motor specialists, may find it useful to review any essential systems having motors with high inertia loads. Section 7.2 of this report, covering the impact of multiple starts on motors, finds that, in general, the motors that are credited in accident and safe shutdown analyses can handle double sequencing. This is because the safety pumps at nuclear power plants have low inertia rotors. However, systems such as safety related containment air recirculation fans in PWRs and reactor building fans (standby gas etc.) in BWRs should be examined since fans generally have higher inertias and will have longer accelerating times.

   Section 7.2 points out that there are significant margins between the starting capability of the motors and the loads they must accelerate. The loads, in almost all cases, are low inertia small diameter pumps that are rapidly brought to rated speed. Table 7-3 provides specific data supporting this conclusion for several large motors from one of the pilot plants that was evaluated. Of greatest importance, there is adequate thermal margin in the motor's squirrel cage rotor, which is its most limiting element. Margins may not be as great in high inertia loads such as large diameter fans. These may need a more detailed review.

2. Plant engineers may find it useful to evaluate the interruption due to double sequencing in the flow of service water for cooling the diesel generators. The large motor operated valves generally used in service water systems are usually closed upon the return of ac power following its loss. The service water pumps are then started after which the motor operated valves are reopened. The time required for this evolution should be considered for its impact on the heat-up of an already running, even though unloaded diesel generator. This evolution is common to any loss of power event but normally is considered to occur at the onset of the diesel generator's operation before the engine has heated following a period of operation. In the case of double sequencing, it is proposed that the diesel generators be assumed to be running for thirty seconds prior to the loss of power and continue to run through the event while cooling water flow is being reestablished.

3. Operator training departments can use this report to determine if their training scenarios and simulator models and responses are appropriate. This could potentially lead to improvements to training modules and improved simulator fidelity. (NRC's Issue 17, entitled *Loss Of Offsite Power Subsequent To a LOCA* is likely to have improved operator response training for delayed loss of offsite power events).

4. Nuclear units with remaining GL 96-06 issues should bring these to closure. The potential for double sequencing is incentive to complete this work.

5. Probabilistic risk assessment organizations can review this report and any input from their safety analysis personnel to determine if there is a need to update probabilistic safety analysis models to include double sequencing. This could help them determine if double sequencing detectably impacts core damage frequency. Discussions with the supervisor of the probabilistic risk assessment group for the two pilot plants suggested that the core damage frequency values would not be significantly, or perhaps even detectably, altered. Additionally, accident analysis with modified assumptions to include the potential for double sequencing could be run to determine worst case peak clad temperatures.

   There are at least two approaches to modeling the risk impact of double sequencing in plant-specific PRA models. They are:

   – Increase the failure probability of the diesel generators both as relates to their failure to start on demand and failure to run given they have started.

   – Increase the grid-related LOOP initiating event frequency. Most probabilistic risk assessments model the three components of the LOOP initiating event frequency. The three components are: plant-centered LOOP, weather-related LOOP and grid-related LOOP.

   This approach can be easily implemented in the nuclear plant risk monitor such as the equipment-out-of-service (EOOS) computer program. This risk monitor models the environmental impacts using these event frequencies. The PRA analyst can easily adjust the input event frequencies. After the change is made, the EOOS program can quantify the core damage frequency and calculate the associated incremental risk.

6. Safety analysis organizations can use this analysis to consider the delays that multiple sequencing can introduce to accident mitigation systems (mostly pumps). The results of their reviews can be provided to the probabilistic risk assessment organizations for use in determining what impact double sequencing has on core damage frequency. From discussions with the risk assessment supervisor at the pilot plants, we concluded that double sequencing would not significantly change analysis results for accidents having the break sizes that are most likely to occur.

10
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2. Branch Technical Position (BTP) Power Systems Branch (PSB) –1, Revision 0, dated July 1981 entitled *Adequacy Of Station Electric Distribution Systems Voltages*
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5. NRC INFORMATION NOTICE 98-07, dated February 27, 1998 entitled *Offsite Power Reliability Challenges From Industry Deregulation*
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