IAEA TECDOC SERIES

IAEA-TECDOC-1770

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Design Provisions for Withstanding Station Blackout at Nuclear Power Plants

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DESIGN PROVISIONS FOR WITHSTANDING STATION BLACKOUT AT NUCLEAR POWER PLANTS

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FOREWORD

International operating experience has shown that the loss of off-site power supply concurrent with a turbine trip and unavailability of the standby alternating current power system is a credible event. Lessons learned from the past and recent station blackout events, as well as the analysis of the safety margins performed as part of the 'stress tests' conducted on European nuclear power plants in response to the Fukushima Daiichi accident, have identified the station blackout event as a limiting case for most nuclear power plants.

The magnitude 9.0 earthquake and consequential tsunami which occurred in Fukushima, Japan, in March 2011, led to a common cause failure of on-site alternating current electrical power supply systems at the Fukushima Daiichi nuclear power plant as well as the off-site power grid. In addition, the resultant flooding caused the loss of direct current power supply, which further exacerbated an already critical situation at the plant. The loss of electrical power resulted in the meltdown of the core in three reactors on the site and severely restricted heat removal from the spent fuel pools for an extended period of time. The plant was left without essential instrumentation and controls, and this made accident management very challenging for the plant operators. The operators attempted to bring and maintain the reactors in a safe state without information on the vital plant parameters until the power supply was eventually restored after several days.

Although the Fukushima Daiichi accident progressed well beyond the expected consequences of a station blackout, which is the complete loss of all alternating current power supplies, many of the lessons learned from the accident are valid. A failure of the plant power supply system such as the one that occurred at Fukushima Daiichi represents a design extension condition that requires management with predesigned contingency planning and operator training. The extended loss of all power at a plant may lead to fuel damage. It is current practice that the design of the electrical power systems for both operating plants and new builds considers events such as station blackout. The intent of a controlled station blackout event is to manage consequences prior to degrading to design basis accidents.

This publication provides information for new plant designs as well as modifications to existing operating nuclear power plants to cope with extended station blackout (or similar). It describes a common international technical basis to be considered when establishing all the criteria for a station blackout event, and outlines critical issues which reflect the lessons learned applicable to electrical systems from the Fukushima Daiichi accident. The publication also describes current plant practices and design provisions for withstanding a station blackout event already implemented at some nuclear power plants, as well as proposals for improvement of existing plant design and qualification requirements to increase the robustness of the plant electrical design for contending with a station blackout event.

The information provided in this publication may also benefit designers, operators and regulators of other nuclear facilities. The IAEA wishes to thank the committee of international experts and advisors from Member States participants and the Member States for their valuable contributions. The IAEA officer responsible for this publication was A. Duchac of the Division of Nuclear Installation Safety.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

A station blackout (SBO) is defined in IAEA Safety Guide SSG 34 [1] Design of Electrical Power Systems for Nuclear Power Plants as a plant condition with complete loss of all alternating current (AC) power from offsite sources, from the main generator and from standby AC power sources important to safety to the essential and nonessential switchgear buses. Direct Current (DC) power supplies and uninterruptible AC power supplies may be available as long as batteries can supply the loads. Alternate AC power supplies, provided to cope with such an event, are available.

A Loss of Offsite Power (LOOP) is considered to be within the design basis for all plants and is managed through a range of redundant and diverse means. SBO has been considered for most nuclear power plant (NPP) designs as a design extension condition (DEC). Prior to the Fukushima Daiichi Accident, the international trend was evolving to consider the station blackout (SBO) as a design basis event. The Fukushima Daiichi accident, which started as a SBO event but had consequences that went well beyond the coping capability of the units, made it a major consideration for commercial nuclear plants to develop a strategy for SBO as a part of DEC.

The coping time for an SBO event for a specific NPP design determines the safety margin in the plant design when responding to the SBO event. The SBO coping time provides a measure by which effective countermeasures must be implemented in order to prevent fuel damage. For some NPP designs, the SBO coping time is very short, which complicates implementation of effective measures to either restore the electrical power supply or activate an effective heat removal strategy. Moreover, SBO events can compromise the performance capabilities of some systems and components; e.g. integrity of reactor coolant pump seals, loss of equipment due to overheating or loss of ventilation, etc.

Requirements for coping with SBO events as well as design and organizational provisions currently implemented at NPPs vary in different Member States. Some countries rely on additional portable diesel generators available onsite while others have incorporated specific SBO provisions into the design as a second level of protection (e.g. alternate AC power supplies such as fixed diesels, or diesel driven pumps, bunkered systems qualified to external events conditions, etc.). Requirements for sizing of additional power sources to be used for an SBO event and their qualification requirements are not documented in international standards and Member States have developed their own guidelines and practices.

1.2. OBJECTIVE

The Safety Guide entitled Design of Electrical Power Systems for Nuclear Power Plants (SSG34), Ref. [1] provides recommendations regarding the design of electric power systems to comply with the Safety Requirements in the IAEA Safety Standards Series No. SSR-2/1 [2]. The Safety Guide Ref. [1] makes recommendations and provides guidance on the measures that are necessary for both new and operating NPPs to meet the requirements in Ref. [2] relating to the functions of electrical power systems.

Section 8 of Ref. [1], entitled Alternate AC Power Supplies, provides basic recommendations regarding the design of electrical power systems for DEC, as applicable to SBO event.

The objective of this TECDOC is to further develop recommendations regarding the design of electrical power systems for DEC and to provide technical guidance for the design provisions to cope with an SBO event at NPPs. This involves a discussion of current plant practices and design provisions implemented at some NPPs, as well as proposals for the improvement of current plant designs and qualification requirements to better manage an SBO event.

In 1985, the IAEA published a TECDOC Safety Aspects of Station Blackout at Nuclear Power Plants (IAEA-TECDOC-332) [3]. This original version of the TECDOC focused mainly on the safety aspects of an SBO event. Although most of the information in Ref. [3] is still valid, this publication is being issued to account for lessons learnt from SBO events experienced since 1985, as well as from the Fukushima Daiichi accident.

1.3. SCOPE

The publication intends to cover, in a comprehensive way, relevant aspects of the SBO design and organizational provisions in order to ensure that plants can cope with an SBO event for an extended duration. The critical areas are related to:

- The flexibility and capability of AC electric power supply systems to facilitate restoration of power in DEC;
- Adequate staffing, procedures and training to restore offsite and onsite standby AC power in a timely manner;
- The selection of equipment and its functional and environmental qualification;
- Lessons learnt from the Fukushima Daiichi accident, and key implementation and operational experience.

This publication provides guidance for all personnel involved in the design, manufacture, licensing, operation, and maintenance of NPP electrical power supply systems. This publication provides specific details for utility engineers, operators, researchers, managers, and personnel responsible for all aspects of plant design and operation to better understand protective measures for coping with extended SBO events. The TECDOC will also aid regulators who stipulate requirements for the plant systems important to safety.

SBO events result in the loss of capability to remove decay heat by normal cooling systems. Hence to recover from, or cope with, an SBO event, the AC power supply must be restored from normal operation sources, standby sources or alternate AC power sources as soon as possible to prevent fuel damage.

Many plant designs are equipped with non-electric circulation or water injection systems, e.g. turbine driven or diesel driven feedwater pumps, which are independent of AC power supplies. However these pumps may need a DC power supply to control speed and flow valves, or local manual operations may be required. SBO events also result in the loss of heating, ventilation and air conditioning (HVAC) systems and cooling water systems, which in some cases, may result in loss of functionality due to overheating of the operating equipment.

The inability to recover from an SBO event within the coping time may result in fuel damage. Plants equipped with passive features for residual heat removal can cope for an extended duration but it is important to recognize that efforts to restore AC power must continue to minimize potential fuel damage and maintain continuity of the DC power supply. The complete discharge of station batteries results in the loss of all remote controls and critical instrumentation, as experienced at Fukushima Daiichi plants. The coordination of the equipment dedicated for coping with SBO may be used with Severe Accident Management Guidelines (SAMGs). However, severe accident management is not within the scope of this publication.

1.4. STRUCTURE

This TECDOC contains seven main sections referred to as the main body, followed by additional material such as references, glossary items, and annexes.

Section 1 introduces the topic by addressing the motivation for the preparation of this publication, as well as the objective and scope of the publication including the intended audience.

Section 2 discusses the coping capabilities of the plant and the plant features such as robustness and defense in depth applied in the design of the plant electrical systems to cope with SBO conditions.

Section 3 discusses current requirements for SBO design contained in the IAEA and International/national standards, sizing and qualification of dedicated equipment and the criteria for backup AC power (i.e. Emergency Diesel Generators, and/or Alternate AC power sources).

Section 4 summarizes the SBO recovery strategies, design philosophy, as well as existing guidance.

Section 5 describes design provisions which resulted in modification of existing plants in order to increase robustness of the plant electrical systems for implementing effective SBO event recovery strategies, as well as electrical diagrams, characteristics, implementation and the use of alternate AC power sources, maintenance and testing requirements, and training issues. Additionally, this section provides examples of modifications implemented at existing plants to address potential SBO events.

Section 6 provides examples of operating experiences from past SBO events.

Section 7 contains conclusions and key recommendations, based on information in the body of the report, to improve robustness of electrical power systems particularly for SBO event.

References shown in this publication provide links to important documents, codes, standards, and other published guidance documents that are relevant to the design of electrical power systems in NPPs.

The Glossary provides definitions of terminology used within the nuclear industry with respect to, electrical power supply and is based mainly on the IAEA Nuclear Safety Glossary and publications of other international organizations.

Annexes contain the experiences of different countries with respect to the design, development, implementation, and application of SBO provisions at NPPs.

2. ROBUSTNESS OF ELECTRICAL SYSTEMS

2.1. INTRODUCTION

Nuclear power plant electrical systems are designed with several levels of defense in depth which maintain plant safety during operational states and accident conditions. However, there may be design weaknesses and/or human errors, operational occurrences or conditions from external event(s) which may compromise multiple levels of safety systems leading to SBO conditions at the plant.

Results from analysis of past reported SBO events have generally shown that there is no single precursor event. In general, there was a sequence of events that contributed to the total loss of all AC power supply. An initiating event due to environmental conditions (e.g. induced by severe weather), in combination with equipment malfunctions, or human errors (including maintenance errors) have resulted in SBO events. The major cause of the Fukushima Daiichi accident was a combination of a seismic event which caused LOOP conditions together with common cause failure of the plant electrical supply systems due to flooding.

A plant may experience SBO conditions following the combination of a LOOP event and failure to transfer to house load operation (if the plant has such a feature), and a failure of standby AC power supply systems. If the AC power supply is restored in a short period of time, i.e. less than the SBO coping time for the plant, the normal cooling systems can be restored and the safety function of heat removal re-established. In such a case, there are minimal or no adverse consequences to the safety of the plant. To minimize the consequences of an SBO event, it is important to incorporate procedural guidance for coping with SBO and design provisions such as alternate AC power supply sources, with

sufficient power to supply critical equipment needed to remove residual heat from the fuel in the reactor or spent fuel pools (SFPs).

Although the probability of an SBO due to electrical malfunctions is low, it is important that the overall NPP design considers possible common mode failures in the electrical systems. Such SBO events are likely to be initiated by external hazards such as seismic, severe weather or flooding. Since NPPs are built near large bodies of water essential for plant cooling systems, the plant design and siting considers protection against vulnerabilities from postulated flooding.

2.2. DEFENSE IN DEPTH CONCEPT FOR ELECTRICAL POWER SYSTEMS

The electrical power supply systems are support systems necessary for all levels of defense in depth. It is essential that the plant has a reliable power supply system to control anticipated deviations from normal operation as well as to power, control and monitor the plant during postulated events, including design extension conditions.

An electrical event or disturbance, which can challenge operation of electrical power supply systems, has to be managed in a controlled manner to assure that the safety functions of the power plant can be fulfilled. The onsite safety systems (for example component cooling water, heating and ventilation systems, charging pumps, etc.) that support normal plant operation are designed to withstand expected voltage and frequency transients. Operating experience has shown that loss of transmission system elements or failures in the onsite power systems can jeopardize the safety of the plant, as described in Ref. [4], Section 6 on operating experience.

Many overlapping system design features are required to obtain reliable and robust electrical power systems that provide the different levels of defense in depth. These system characteristics apply to grid systems and all onsite power systems. Even though more stringent criteria are applied to safety grade power supply systems, the entire onsite and offsite power systems contribute to the reliability and robustness of safety power supply systems.

The levels of defense in depth and associated requirements are described in Ref. [2]. Application of the concept of defense in depth in the design of a nuclear power plant provides several levels of protective measures (inherent features, equipment and procedures) to maintain integrity of plant systems and prevent release of radioactive materials into the surrounding environment. This concept provides methods to mitigate the consequences of an event in case several levels fail. Independence between the different levels of defense is an essential element of this concept. This is achieved by incorporating measures to avoid the failure of one level of defense cascading into failures of other levels. There are five general levels of defense related to the plant electrical systems:

2.2.1. First level of defense in depth

The design basis for the onsite electrical power supply systems provides the fundamental elements for reliability and robustness. The design basis ensures that the onsite electrical power systems are capable of operating through:

- The specified operating range of voltage and frequency;
- All credible internal and external events (switching surges, lightning strikes, etc.) that cause transients in power systems;
- Dynamic variations (large motor starts, etc.) or steady state noise[1] (sub-harmonics, etc.) that can degrade the performance capabilities of the power supply to the plant.

[1] Random fluctuation in an electrical signal.

The offsite power system is composed of the transmission system (grid) and switchyard connecting the plant with the grid. The grid is part of the preferred power supply for the NPP and the safety power systems (see Fig. 1). During normal operation, the power supply to the plant auxiliaries is typically provided from the turbine generator.

An integrated transmission system with large generation facilities and high voltage interconnections forms a strong grid and provides stable offsite power. The stability is a measure of the grid to withstand load and generation variations and anticipated operational occurrences (AOO) such as loss of network elements without exceeding the specified voltage and frequency limits. The integration of NPPs and the inter dependency of the NPP and the grid is discussed in Ref. [5].

The onsite power distribution systems for safety and non safety loads are linked together and consequently an electrical event on a non safety bus has the potential to affect the safety power systems. It is therefore important to incorporate design measures to provide assurance that events originating in the offsite power system or in the non safety part of the plant will not adversely impact the safety systems.

A reliable onsite power supply system implies an installation which has a low probability of failure of critical and non-critical loads. A substantial part of this requirement is covered by national electrical codes, but qualification (environmental and electrical) of equipment as well as unique NPP equipment specifications which comply with the plant design basis also contribute.

A robust design coupled with good operation and maintenance practices will reduce the risk of failures. A proper understanding of plant behaviour during different modes of operation (start up, bus and load transfers, and shutdown and power system outages) will minimize the risk for degradation of plant equipment due to voltage and current variations.

The robustness and reliability of the onsite power systems is analyzed for all plant configurations, including those where part of the electrical power supply system may be taken out of service during refueling outages or preventative maintenance on electrical supply system components/equipment.

The potential for common cause failures may exist as redundant divisions of the safety power system are connected to a common preferred power supply during most modes of plant operation. Design measures such as diversity in power systems (normally a built-in feature by design) are essential. Events such as open phase conditions (OPC) in the offsite power system (Byron, United States of America, 2012), switching transients (Forsmark-1, Sweden, 2006), and successive loss of offsite supply events over short interval (Hunterston B, United Kingdom, 1998), can result in a common mode failure of redundant safety systems.

Maintenance programmes and procedures are of high standards for systems important to safety and for all systems and components that can result in a plant trip or perturbations in the onsite electrical power systems. Surveillance testing and/or performance testing is the preferred way of establishing performance capabilities and any degradation of plant equipment.

Plant modifications can impact the operating characteristics of electrical power systems. Load changes or reconfiguration of interconnections can impact power flow and voltage profile of the electrical system. Changes in control systems, protective device settings, automatic actuation setpoints or logic can impact plant load behaviour. Changes in control systems can also alter the duration or mode of operation of low voltage systems and potentially impact power supplies and DC system capabilities. Hence all plant modifications need to be thoroughly analyzed for impact on plant electrical systems and related equipment.

Power supplies for lighting and communication equipment are important for coping with abnormal operational disturbances and events, although they are not generally classified as important to safety; it

is advised that power supplies for lighting and communication equipment are included in the review of SBO coping capability.

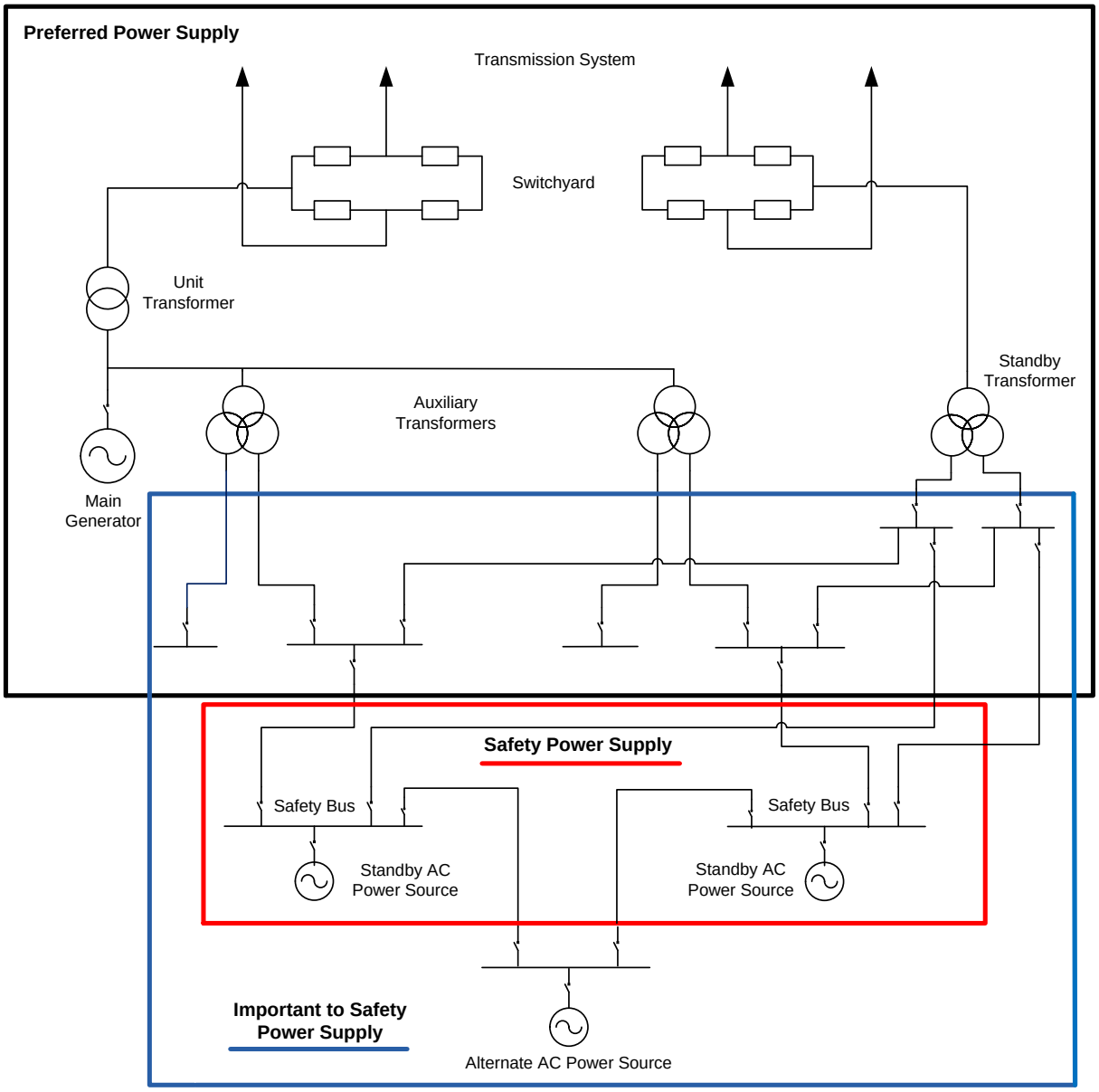

FIG. 1. Relationship of electrical power supplies important to safety, safety power supplies, and the preferred power supply for a nuclear power plant (an example).

2.2.2. Second level of defense in depth

Reference [1] recommends that in order to minimize the effects of propagation of faults in the electrical power systems, coordination of protection and fault clearing systems should be provided to selectively disconnect only the faulted equipment. Backup features should also be provided in the event that a primary protection feature or a fault clearing device fails.

Protection systems are designed to disconnect the non safety buses from the safety buses to avoid propagation of faults and degrade the capabilities of equipment essential for safe shutdown. Disturbances that originate in offsite power systems and can propagate into redundant safe shutdown equipment require specific protective measures. Examples of such faults include OPC and switching overvoltage transients that can impact the plant AC systems and may affect the DC power system rectifiers and inverters, resulting in degraded voltage conditions throughout the plant.

Battery chargers, inverters and motor generator sets generally provide limited short circuit current and have current limiting features for protecting internal components. Selective tripping of loads and coordination of protective devices generally considers the unique features associated with the limited fault current.

Protective schemes are designed to function in a coordinated manner during all modes of plant operation. However, it may be desirable to bypass some non-critical protective features to allow safe shutdown equipment to perform its intended functions during accident conditions.

Offsite power is normally supplied by at least two physically independent offsite circuits designed and located to minimize, to the extent practical, the likelihood of their simultaneous failure.

There are several different schemes used to supply plant auxiliary systems from offsite and onsite power sources:

- For plants with capability to supply house loads from the main generator, perturbations in the grid system which result in isolating the plant from the grid with no reactor trip, will result in maintaining the main generator as the preferred power source. In the event of reactor trip, an automatic transfer to an alternate offsite source is initiated.
- For plants that do not have capability to supply house loads without grid connection, a generator output breaker opens allowing a seamless transfer to offsite power source supplying power through the main step up transformer and unit auxiliary transformers. This type of design also incorporates automatic transfer to a second offsite source in the event of unavailability of the primary source.
- For plants that do not have a generator output breaker, a perturbation in the grid or plant auxiliary systems that necessitates a trip of the reactor, turbine or main generator will result in automatic transfer of the power source from the main generator to an offsite source. The automatic transfer may be simultaneous to two independent sources supplying power to different onsite safety and non safety divisions or it may be a staggered operation from one source to another depending on the availability and capability of the first source.
- There are variations on the above described basic designs. Some plants connect the safety systems in standby mode directly to the offsite source with non safety systems powered by the main generator during normal plant operation. For these plants, the non safety systems may have automatic transfer capability similar to one of the designs discussed above.
- For all cases, in the event of loss of one offsite power circuit, the transfer to the other alternate offsite circuit(s) is normally automatic but provisions are made to initiate manual transfers also. The automatic transfer is critical to ensure that safety systems required to mitigate the consequences of an event are available immediately to maintain core cooling functions. The manual transfer facilitates maintenance activities and also provides additional options to transfer in the event of issues with auto transfer systems.

Some NPPs are designed to operate in an island mode such that the plant supplies power to its own auxiliary systems. This capability is available when the entire external load connected to the power plant is disconnected and there is no reactor or turbine trip. During this ‘house-load’ operating mode, the reactor operates at a reduced power level (typically 5% to 10% of full power) that is sufficient to generate enough electrical power to supply auxiliaries. This type of design affords an uninterrupted power supply for the house loads. This mode of operation imposes complex challenges to reactor systems due to reactivity feedback and control of the large step change required in reactor power. In addition, the load rejection also results in a perturbation in the plant electrical system, which has to be designed to withstand the transient voltage and frequency variations. This design adds diversity to power supplies for the plant and provides an additional layer of defense.

Nuclear power plants designed for runback to house load operation have a main generator output breaker in order to facilitate full flexibility in supplying auxiliary power from either the normal offsite

circuit or the turbine generator or both. Other key design features requiring consideration for this capability include sizing criteria of the main steam turbine condenser, steam bypass (and/or atmospheric dump) valves, and the turbine and reactor controls to accomplish the runback to house loads. Additionally, the electrical control system is capable of responding to a mode transfer from 100% power generation to the lower levels needed to support house load operation. Also, the design of the relay protection system tripping logic and synchronizing systems are more complex.

2.2.3. Third level of defense in depth

The normal power source for the safety systems of a nuclear power plant is the preferred power supply (i.e. the grid or the main generator). In case of LOOP, the onsite standby AC power source is used.

Non safety loads are generally disconnected when the preferred power supply is not available to avoid overloading the onsite power sources and preclude faults in the non safety systems degrading the onsite power sources. Some essential loads (e.g. instrument air, reactor coolant system charging pump, generator seal oil pumps, etc.) may be powered from the safety grade power supply system and where this is done, these loads are generally not automatically started after a LOOP as they could affect the availability of the safety loads. The non safety loads may be manually started to facilitate safe shutdown after it has been determined that there is adequate spare capacity and capability for starting and operation. In some specific reactor designs, select non safety loads may be automatically sequenced with careful consideration to the consequences of failure modes.

The prime purpose of plant safety systems is to maintain the multiple barriers that are designed to contain fission products within plant systems. The onsite AC and DC safety power systems that supply different loads at different voltage levels are critical for maintaining the ability of the NPP to withstand a range of initiating external or internal events considered in the design basis that could challenge the barriers that prevent the release of radioactive material from the plant.

Events on the electrical power systems which originate from preferred power supplies can cause common cause failures on all divisions. Adequate countermeasures are therefore essential during design, construction, and operation of the plant. In the event of loss of the preferred power supplies, the plant relies on the standby AC power sources, one per safety division, to mitigate the consequences of any design basis event. The redundant divisions have separation, isolation and independence from each other and external events to reduce the risk for common cause failures.

The DC systems supply power to vital control and instrumentation systems, as well as operation of critical equipment during loss of AC power systems. The DC power system is designed such that no single failure of a battery, or a battery charger, or support systems will result in a condition that will prevent the safe shutdown of the plant. In addition, selective protective schemes ensure that disturbances on the preferred power supply, originating either offsite or from the main generator will not degrade the performance capabilities of the DC power systems. The uninterruptible AC power systems may also be vulnerable to such disturbances (see Ref. [4] for details).

2.2.4. Fourth level of defense in depth

The reliance on electrical power systems for safety functions at an NPP requires consideration of the consequences resulting from the loss of offsite and standby AC power sources. Consideration for an SBO involves determining the duration for which a plant can withstand the loss of all AC power. This duration is referred to as the coping time.

An alternate AC power supply or at least one offsite or standby source is connected to the safety buses within the coping time to maintain plant safety. The NPP battery system has to be designed to power vital control and instrumentation systems with DC power until an AC source can be restored to cope with SBO conditions.

2.2.5. Fifth level of defense in depth

The purpose of the fifth level of defense is to mitigate the radiological consequences of releases that could result from accident conditions. This requires the provision of an adequately equipped emergency control centre with its own autonomous power system, emergency plans and emergency procedures for onsite and offsite emergency response.

2.3. LOSS OF OFFSITE POWER

2.3.1. LOOP coping capability

The availability and reliability of the offsite power supply is mutually dependent on grid characteristics and capabilities. Large grid systems that are integrated typically provide better quality and reliability of offsite power sources. Isolated grid systems, or systems with limited reserve capabilities, are often subject to frequent and longer perturbations and, therefore, are of lower reliability when used as the offsite source for a NPP. Grid reliability studies for countries with NPPs show that LOOP events occur at least once per plant operating life, and therefore are accounted for in the plant design as an anticipated operational occurrence (AOO).

It is recognized that the availability of AC power to NPPs is essential for safe operations and successful accident mitigation. A LOOP event is considered an important contributor to the total core damage frequency (CDF) at NPPs. The LOOP event is within the design basis of all plants and is managed through a range of redundant and diverse means.

Typically, the preferred power supply to the power plant is ensured via several independent power sources. If these fail, there are redundant safety grade standby AC power sources, typically diesel generators. Other alternate power sources such as additional diesel generators, gas turbines or dedicated hydropower plants can power the plant safety buses. To ensure reliable operation of the onsite power sources for an extended LOOP duration, the onsite fuel oil, lubrication oil, gas and other consumables for each diesel generator or alternate sources are sufficient to operate the standby AC power source for about 7 days. Lower capacities may be acceptable if it can be demonstrated that the time required to replenish the fuel from external sources is adequate to support continuous operation.

When the preferred power supply is lost, the plant safety buses are powered by standby AC power sources. The type and configuration of standby AC power sources depends upon the plant design; typically high capacity diesel generators or gas turbines are used as the primary power generating source. The capacity of standby AC power sources depends upon the most limiting design basis accident (DBA) in combination with a LOOP event; typically the DBA is a large break loss of coolant accident (LOCA), or a steam line break which requires actuation of safety systems to ensure (a) safety injection to shut down the reactor, (b) maintain it in safe shutdown state, and (c) heat removal for cooling of the core and SFP. Typically, each standby AC power source has a continuous rating equal to the sum of the conservatively estimated connected loads.

2.3.2. Restoration of offsite power

The offsite power sources have higher capacity and capability to power all station loads including circulating pumps on non safety buses that support heat removal using the normal cooling configuration (e.g. large loads to ensure forced circulation through the reactor core, large feedwater pumps, turbine condenser cooling pumps, etc.). The onsite source has limited capacity and cannot power such loads. It is therefore important to restore offsite power to the NPP buses in a timely manner.

Restoration of offsite power typically requires coordination between the plant and grid operator. Restoration procedures provide guidance on paths for restoring specific offsite line(s).

2.4. STATION BLACKOUT

An SBO event was considered a beyond design basis event for many plant designs. Lessons learned from the Fukushima Daiichi accident however have led to a paradigm shift and the SBO event is now considered part of the plant Design Extension Condition (DEC). SBO events have typically been underreported, but the operating experience section of this publication, which details those events reported through the IAEA IRS[2] system, shows that they are occurring at frequencies above that traditionally considered for beyond design basis events. Consequently, the latest revision of SSR 2/1, Ref. [2] requires an alternate AC power source which, in cases of unavailability of standby AC power sources, can provide power during a DEC.

2.4.1. Heat removal in an SBO event

There are several safety aspects associated with SBO events which may lead to the deterioration of key safety functions. The loss of grid is generally an initiating event and coincidental failure of onsite AC power supplies results in an SBO. The loss of grid leads to a trip of the reactor and turbine/generator. Heat from RCS is removed via steam generator (SG) relief and/or safety valves in PWRs, or via safety/relief valves to the suppression pool in BWRs. It is worth noting that in PWRs, a rapid pressure increase in the SGs following the turbine trip along with a simultaneous trip of all reactor coolant pumps (RCPs) may result in a brief lifting of the pressurizer relief or safety valves. (RCS pressure control system - pressurizer spray is not available due to loss of all RCP and charging pumps).

For PWRs, heat removal from the RCS is ensured via SG relief valves, with the auxiliary or essential feedwater system providing water from the condensate storage tank (CST) or essential feedwater tank (EFT), typically using steam turbine driven pumps. For BWRs, heat removal from the reactor is typically ensured via safety/relief valves to the suppression pool, with feedwater typically pumped to the reactor vessel via turbine driven pumps from a CST or the suppression pool.

Absence of normal cooling requires that the decay heat is removed via dumping of the steam to atmosphere (PWR) or to the suppression pool (BWR). Long term cooling in a feed and bleed mode in PWRs requires sufficient storage of water in the EFT or CST; BWR plants are equipped with safety relief valves (SRV) to protect the reactor from over-pressurization. Plant operational transients, such as turbine trips, will actuate the SRVs. Once an SRV opens, steam released from the reactor is discharged through SRV lines to the suppression pool in the primary containment. The discharged steam is then condensed by the subcooled water in the suppression pool. Extended steam blowdown into the pool, however, will heat the pool to a level where the condensation process may become unstable and may cause cavitation of feed pumps.

Generation of reactor decay heat typically drops to approximately 1% within 2 hours following a reactor trip (considering operation at full power before SBO conditions) and continues to decrease down to 0.5% within 24 hours.

While a high pressure peak in the RCS and SG is typical at the beginning of SBO conditions, a drop of reactor decay heat and feeding the SG (or reactor vessel at BWR) with cold water either from the EFT, CST or suppression pool causes a depressurization. In particular for PWRs, cool down of the RCS causes volume shrinkage and pressure decrease. If sufficient sub-cooling margin is not maintained, the formation of a steam bubble in the reactor pressure vessel may cause the loss of natural circulation. Re-criticality may also be an issue if the injection of boron is not possible.

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[2] The IAEA/NEA International Reporting Systems for Operating Experience.

For CANDU PHWRs reactors, an SBO condition is followed by a shutdown of the reactor by the shutdown systems. Since the RCS pumps are not available due to loss of power, the fuel heats up and the decay heat is transferred to the heavy water coolant. A temperature gradient develops between the coolant in the core and the SG region, which promotes natural circulation between the two regions allowing heat to be transferred from the RCS to the secondary side of the SGs.

However, if make-up feedwater is not supplied to the SGs, boil-off of the secondary side inventory and a deterioration of natural circulation will eventually occur causing the RCS pressure in the fuel channels to increase. The RCS pressure will continue to increase until the set point of the liquid relief valves (LRV) is reached causing them to open and close to reduce the RCS pressure. As the RCS coolant is discharged through the LRVs, the fuel bundles in the pressure tubes will eventually begin to uncover to the point of dryout in the fuel channels.

The SBO condition are also be considered for SFPs. Similar to power reactors, the SBO scenario is also the limiting case for the SFP, especially when the entire core is off loaded during the refueling outages. The SFP heat-up is typically slower than the core heat-up in power reactors due to the low residual decay heat of the fuel assemblies and the large amount of water in the SFP. Nevertheless, restoration of SFP cooling either from AC power sources or an alternate AC power source is necessary within a reasonable time to prevent boiling.

As can be seen from the above descriptions of reactor designs, an extended loss of AC and DC electric power can severely impair the ability to maintain key safety functions such as core sub-criticality, heat removal, and volume and pressure control in the RCS.

2.4.2. SBO duration

The plant capability to cope with an SBO event depends upon a ‘coping time’ which varies for different plant designs. A common definition of ‘SBO coping time’ is the ‘time available from loss of all permanently installed AC power sources until onset of core damage’. In some countries, loss of natural circulation in the RCS may conservatively be used as the coping-time criterion. When the plant is in SBO coping mode, the RCS is gradually depleted due to boil-off and leakage, and reserves of support features such as make up water, DC power supplies and compressed air are diminished. Core uncovery and fuel damage may occur if AC power to at least one safety bus is not restored in a timely manner.

For plants operating at full power prior to an SBO event, the reactor core heat-up typically ranges from 1-4 hours for a large PWR, approximately 10 hours for a small PWR and advanced gas cooled reactor (AGR), and 2-9 hours for PHWR, if no countermeasures are taken. For some BWR designs which are fully electric (i.e. without turbine driven feedwater pumps), the SBO leads to core heat-up within 30-40 minutes, if no countermeasures are taken. If an SBO event occurs during a refueling outage within a few days after shutdown, PWR and BWR plants could be susceptible to relatively fast core heat-up. In this case, the core heat-up is typically in the range of 1-3 hours, if no countermeasures are taken.

For PWRs, an SBO event during mid-loop operation is a significant safety concern and represents the most challenging operating state. The mid-loop operation is required to allow entry into the steam generators for maintenance and for RCS gas removal. The average scheduled time after shutdown before entering mid-loop is about 80 hours. Due to the relatively high residual heat generated in the core and reduced reactor inventory, the PWR plants have very short SBO coping time (on average 45 minutes or less).

Analysis of SFPs that store the fuel with the low decay heat demonstrates operation margins for SBO cases in the range of several days if no countermeasures are taken and therefore are not on an immediate critical concern following a SBO event.

2.4.3. SBO recovery

An important factor to consider is the effectiveness of measures that can be implemented within the coping time to prevent fuel damage. The restoration of AC power depends upon the initiating event and failure modes of the onsite power systems. It is critical to restore power to at least one safety bus within the coping time. Generally speaking, plants that have longer coping times are more likely to have the AC power restored prior to degrading radiation barriers. In order to extend the coping time, some plants have provisions to feed buses from an alternate AC power source.

The alternate AC power source may be automatically started but is manually aligned to the respective AC bus. If the initiating event leading to loss of AC power is an external event affecting the plant site (e.g. seismic, flooding) then the restoration of alternate AC power supply may also become complicated if interconnecting systems are impacted.

The alternate AC power supply may be provided by a number of redundant and diverse onsite systems such as safety or non safety grade diesel generators, gas turbine generators, or nearby power plants. In addition, some plants have a second level of defense provided by either stationary or portable power systems that are protected and qualified to withstand the impact of extreme external events.

3. SBO EVENT MANAGEMENT

This section describes the design philosophy and station blackout recovery strategies as well as coping guidance for existing plant designs.

3.1. SBO COPING STRATEGIES

SBO event management depends upon several aspects, including:

- Status of the plant prior to SBO event (power operation, shutdown, mid-loop, etc.);
- Ability to restore AC power within the coping time;
- Unavailability of critical equipment required for coping with SBO due to maintenance or repair;
- Nature of the initiating event such as severe weather, earthquake, flooding, etc.

The following discussion is related to consequences and preventive measures to avoid fuel damage during SBO scenarios.

For the purpose of this TECDOC, the three SBO cases are considered:

1. SBO event from which recovery can be made within the coping time (i.e. preferred power source or standby AC power source is recovered).
2. Extended SBO event where alternate AC power source is connected within the coping time but is required to continue operating for extended duration (e.g. more than 12 hours).
3. SBO event that may lead to a breach of radiation barriers and potential fuel damage.

3.1.1. SBO recovery within the defined coping time

This case is characterized by a period during which the preferred power supply or standby AC power source can be recovered. An alternate AC power source, if available, can be started and connected to a plant safety bus to extend the time for the recovery of the preferred or a standby AC power source. Alternate AC power sources enhance the coping capability of the plant.

The coping strategies vary depending on:

- The initiating event that resulted in the SBO conditions;
- The plant capability to respond to the SBO condition;

- The robustness of the plant design; and
- The resources available on site or offsite.

For those plants equipped with turbine driven pumps for supplying feedwater to the SGs (PWRs) or reactor vessel (BWRs), the heat removal capability is maintained during the SBO event. In these designs, the DC power systems and Uninterruptible Power Supply (UPS) buses provide power to support control and monitoring functions.

For plants without turbine or diesel driven pumps, which depend fully on AC power supply, an expedient restoration of either the preferred or standby AC power source is critical.

For short duration SBO events, the following assumptions are considered for the coping duration:

- Reactor coolant inventory (RCS) is sufficiently maintained;
- SG inventory is sufficiently maintained;
- Re-criticality does not occur;
- Integrity of reactor coolant pump seals is maintained;
- Battery capacity is sufficient to power necessary DC/AC loads;
- Alternate AC power source mission time is sufficient, i.e. longer than the coping time;
- EFT (emergency feedwater tank) or CST (condensate storage tank) has enough capacity;
- Emergency Water Storage Tank and/or deaerator has enough capacity (PHWRs);
- Spent fuel pool (SFP) heat up is a slow process;
- Habitability of the main control room is maintained;
- Room temperatures are acceptable for electrical equipment.

If RCPs are not equipped with pressure-tight seals or seals designed for operation in high temperature, quick automatic start of seal injection is necessary just after the SBO condition occurs in order to avoid seal damage and excessive loss of coolant from the primary system.

The following strategies are proposed for coping with a short duration SBO event (performed in parallel):

- Restoration of standby AC power source or offsite AC power supply;
- Start and connect the alternate AC power source to a safety bus;
- Establish SG make up from EFT, CST, EWST or deaereator;
- Establish reactor vessel make up (e.g. from the suppression pool);
- Extend DC power capability by shedding non-essential loads.

The mission time for stored water supply for the turbine driven feedwater pumps which provide the SGs with water from the EFT or CST is typically several hours and generally there is no immediate concern with respect to available water inventory.

Generally, the alternate AC power source capacity is limited and cannot supply large loads (e.g. cooling systems for turbine condenser, or residual heat removal from suppression pool of BWR). In view of this limited capacity, it is considered a temporary measure until the AC power supply is recovered from either offsite or standby AC power sources.

The alternate AC power source is typically capable of supplying its loads for several days and therefore there is generally no concern with respect to its availability during a short duration SBO event.

Sizing of alternate power supply sources that increase coping duration depends on the plant design; for example:

- Plants with turbine or diesel driven capabilities (i.e. feedwater provided by turbine driven pumps into the SGs or reactor pressure vessel (BWR case) do not require the alternate power source sizing criteria to include the motor driven feedwater pumps;
- In fully electric plants, an alternate electrical power supply is sized to include power necessary to operate feedwater pumps;
- SG or RCS makeup capability, unless this can be provided by other portable means;
- Availability of critical instrumentation and monitoring of loads.

Note: During a short duration SBO event, the suppression pool is not expected to heat up sufficiently to challenge net positive suction head for injection pumps.

The DC system is required to provide sufficient power to Instrumentation and Control (I&C) systems, plant process monitoring, and ensures minimum control power to operate valves, circuit breakers, etc. The batteries associated with DC power systems can typically last several hours and the expectation is that an AC power supply can be restored to recharge the batteries before they are completely discharged. Load shedding may be required to extend the battery run time.

3.1.2. Extended SBO

In a situation where it may not be possible to recover the offsite or standby AC power sources within the expected coping duration for a short-term SBO event, the plant enters the extended SBO condition which can last from several hours to several days.

The extended SBO event is characterized by, but not limited to, the following challenges:

- Fuel integrity;
- Integrity of RCP seals;
- Station battery capacity (considering low temperature if extremely cold outside the plant and high temperature if extremely hot outside the plant or there are heat generating sources in the vicinity of the batteries);
- RCS inventory and subcooling conditions;
- Subcriticality of the reactor core;
- Autonomy of EFT, or CST inventory;
- Suppression pool heat-up;
- Operating capability of the alternate AC power source (e.g. management of fuel and lube oil reserves);
- SFP heat-up;
- Temperature rise in rooms and equipment, which may affect equipment operability;
- Availability of compressed air to operate air operated valves and steam relief valves;
- Lighting of internal plant rooms and corridors;
- Lighting of the site (may be needed to deploy corrective measures);
- Habitability of the control room, or areas where manual actions are necessary;
- Communication and security systems of the plant;
- Availability of staff;
- Debris removal (may need to clear roads and areas to gain access or replenish supplies/resources).

In view of the above challenges, the following systems need additional consideration during an extended SBO event:

- The alternate AC power source becomes essential. Sizing and autonomy of alternate power source (fuel and consumables) factors loads that are needed to cope with extended SBO conditions.

- RCP integrity may be challenged if injection pumps which provide cooling water to the RCP seals are not available and the seals degrade resulting in excessive RCS leakage. It is desirable to start an injection pump to cool the RCP seals from an alternate AC power source or provide cooling from a portable diesel/turbine driven pump.
- The water inventory of EFT or CST is limited and typically lasts for several hours. These tanks need replenishing from an external source. Consequently, mobile equipment may be necessary.
- As the residual heat removal system is generally not operating, the suppression pool heats-up to saturation point as steam is discharged into it. As a consequence, the injection pumps, which take suction from the suppression pool may cavitate, resulting in the loss of heat removal capability.
- For PWRs or PHWRs, the decay heat produced in an SBO event is removed from the core through natural circulation. A combination of RCS inventory shrinkage due to temperature decrease and normal leakage from the RCS will cause a drop in the RCS pressure. The rate of pressure decrease depends on the particular reactor design but is typically about 1MPa per hour. Maintaining the RCS inventory and sufficient subcooling margin is therefore important to avoid formation of a bubble in the reactor pressure vessel which could potentially degrade heat removal capability.
- If RCP seals start to degrade due to lack of cooling, the RCS losses will increase similar to a small break LOCA. If RCS seal failure occurs, then maintaining the RCS inventory and sub-cooling margin may be a challenge.

During an extended SBO, SFP cooling will be required to maintain water temperature and inventory. It is advised that the alternate AC power source has sufficient capacity to power loads in the SFP cooling system. Contingency cooling strategies via mobile pumps or gravitational sources may be used if available.

The following strategies are recommended for coping with an extended SBO event (performed in parallel):

- Maintain the alternate AC power source connected to the safety bus in operation by replenishing fuel tank and lubrication oil (if needed);
- Ensure RCP injection;
- Ensure SG (PWR) or reactor vessel (BWR) make up;
- Replenish the EFT or CST to maintain its inventory;
- Ensure SG make up using portable pumps;
- Maintain the fuel cooling of the fuel in the refueling machine (PHWR);
- Ensure RCS make up from the High Pressure Emergency Core Coolant Injection System to account for RCS shrinkage (PHWRs);
- Initiate suppression pool heat removal before saturation occurs;
- Ensure subcriticality of the core;
- Maintain RCS inventory and sub-cooling conditions;
- Ensure continuity of DC power supply, which provides sufficient capacity to power I&C systems, plant process monitoring, and ensures minimum control power to operate valves, circuit breakers, etc.;
- Maintain high priority for efforts to recover the offsite power;
- Maintain high priority to recover at least one division of standby AC power sources. Ensure the ability to resupply support systems such as DC power and compressed air which may be depleted due to attempted starts.
- The continuity of DC power supply is essential to maintain monitoring of critical plant parameters control or modulate residual heat removal systems and ensure alignment of electrical circuit breakers, operation of valves, etc. It is advised that the alternate AC power source has sufficient capacity to keep at least the batteries charged, or a mobile battery charger may be necessary.

- Ensure that hydrogen limits in battery rooms remain below combustibility limits (i.e., less than 4% concentration).
- Ensure room temperatures remain within equipment design limits.

3.1.3. SBO progression to severe accident

An SBO event could lead to a severe accident if there are complications in the restoration of electrical power to plant buses within the coping time, for example:

- The offsite or standby AC power sources could not be restored;
- The alternate AC power source (if installed) could not be started and/or connected to the safety bus;
- The alternate AC power source was able to connect, but fails to operate for the required period (e.g. insufficient diesel fuel, damage due to extreme external events, etc.);
- If the offsite, standby and alternate AC power systems are unavailable, and non-electrical means were unavailable or inadequate;
- If the plant switchboards are unavailable due to common mode type damage (e.g. flooding, fire);
- The SFPs also require heat removal capability and extended loss of cooling capability can result in fuel damage.

Note: If all attempts to provide power supply to the safety buses fail, it may be practical to energize certain predefined loads using temporary provisional cable connection from available resources. Mobile battery chargers are essential to keep at least one station battery charged and to maintain the minimum set of critical I&C equipment. Manual capabilities to monitor critical parameters (locally) may be an available option

3.2. SBO RELATED CONSIDERATIONS

3.2.1. DC power supply

Batteries play an important role during SBO conditions since they are required to power a minimum set of critical equipment important to safety, as well as critical instrumentation for monitoring of plant parameters, and emergency lighting. Battery discharge time depends on DC loads and ambient temperature. Battery run time can be extended by shedding non critical loads, removing a battery train/division from service then restoring it after the primary train nears depletion, recharging station batteries via small diesel generators, or using backup temporary batteries that can be connected to the DC bus via temporary cable connections.

3.2.2. Instrumentation and control

Instrumentation and control systems play an important role in SBO event management. Operational personnel rely on instrumentation to assess the plant conditions during an SBO event and take actions based on Emergency Operation Procedures (EOPs). These I&C systems are critical to the SBO event management and are normally powered by UPS and/or DC power systems. The critical parameters selected must be able to confirm the success of the strategies at maintaining the key safety functions as well as indicate core status and spent fuel pool conditions in order to facilitate emergency response decisions. In case of total loss of DC power during an SBO event, operators may consider monitoring key RCS parameters (i.e., using portable self-powered measurement equipment). These parameters could be measured at the electrical penetrations or some other access point.

3.2.3. Availability of emergency support facilities during SBO

The emergency management support centre may be located onsite or in an offsite emergency response facility. During SBO conditions, the power supply for emergency support facilities may also be

unavailable. For onsite locations, the sizing of the alternate AC power source may need to consider the facility loads. When emergency support facilities are offsite, an additional autonomous power source is needed.

3.2.4. Support systems

There are several vital support systems (excluding I&C and electrical power supply) that require specific consideration during SBO event:

- Water sources to replenish EFT or CST;
- Compressed air and/or batteries to provide for restart of stand by AC sources;
- Compressed air to provide for operation of air operated valves;
- Heat ventilation and air conditioning (HVAC) to prevent excessive temperature rise in equipment rooms to ensure equipment operability;
- HVAC to ensure habitability of the control rooms and control points in the plant;
- Emergency lighting in the plant buildings as well as site to ensure safe evacuation, access to auxiliary rooms, buildings, etc.,
- Communication and security systems.

3.2.5. Resources, local infrastructure

Reference [1] recommends that sufficient resources available onsite to ensure independent operation of support systems. Many plants have adequate storage of fuel (diesel or gas) and water at the site that assures operation of support systems (and mobile devices) for several days without resupply. In some designs, the fuel may be available onsite but require additional systems to transfer the fuel to consumers.

Prearrangements are made for resupply of consumables from offsite sources. Prearrangement for water resources are to be made considering the various manmade and natural sources nearest to the plant. The overall coping strategy includes equipment, procedures, spare parts, maintenance, surveillances and drills to demonstrate the coping process.

3.2.6. Accessibility

A physical security means such as access control requires a power supply. When power is lost, the access points must be controlled to allow personnel and equipment access.

4. ESTABLISHING CRITERIA FOR DEDICATED SBO EQUIPMENT

4.1. ESTABLISHING PERFORMANCE CRITERIA

As a result of the Fukushima Daiichi accident, the IAEA Specific Safety Requirements for Design, Ref. [2] has been amended in order to address design requirements for withstanding the loss of offsite power. In particular, the design requires an alternate power source to supply the necessary power in design extension conditions.

The IAEA Safety Guide SSG-34, Ref. [1] section 8, entitled Alternate AC Power Supplies, provides basic recommendations regarding the design of electrical power systems for design extension conditions (DEC), which includes SBO event (i.e., to power equipment dedicated to severe accident consequences mitigation). Ref. [1] recommends that the use of the alternate AC source for the two different functions should be carefully balanced in the framework of the specific design approach to mitigation of severe accidents.

The following design and operational considerations are applicable to alternate AC power sources.

4.1.1. Storage and/or placement

The alternate AC power supply (portable or stationary) can be provided at or near the plant to bring the plant to a controlled state following loss of standby AC power sources and preferred power supply.

Where more than one portable alternate AC power source is provided, they are stored such that external events cannot damage all of the portable AC supply sources at the same time. This can be achieved by storing in diverse locations or in structures designed to protect them from applicable natural external hazards.

One storage location may be acceptable as long as it is an adequate distance away from the site such that the same extreme hazards will not affect both the plant and the storage location. In this case, the storage location would not be required to be built to nuclear safety standards for hazard protection. Consideration should also be given to the transportation from the storage areas to the plant for obstacles restricting normal pathways for movement due to natural external hazards.

The design basis for nuclear plants includes bounding analyses with margin for external events expected at each site. Extreme external events (e.g., seismic events, external flooding, etc.), beyond those accounted for in the design basis are highly unlikely but could present challenges to nuclear power plants and support facilities. Considering the external hazards applicable to the specific site, the equipment dedicated for SBO coping or mitigation strategies, is stored in a location (or locations) that are reasonably protected, such that no one external event can reasonably fail the site facility. The design of storage areas provides an adequate margin against levels of natural hazards more severe than those considered for original plant design and the site hazard evaluation. This has to be a site specific evaluation. As an example, the plant design may be based on maximum flood level postulated over a hundred year period. The storage location is designed to withstand a higher flood level.

Some plants employ stationary alternate AC power sources on site. In these cases the stationary AC power sources are housed in bunkers or the AC power source are ‘hardened’ so that they are adequately protected from external events.

The alternate AC power sources are regularly maintained and tested. It is not necessary to have alternate AC source in a standby mode with automatic connection to plant buses. It has been observed that the plants have adequate provisions for connecting the alternate AC power source within the expected timeframe, including training for plant operating and maintenance personnel (see Annex IV for details).

It is preferable to have diversity in design and manufacture between onsite alternate AC power systems and standby AC power systems to reduce the possibility of common cause failures.

4.1.2. Safety classification

Reference [2] requires that electrical power system functions and design provisions necessary to achieve the basic safety functions, for the different plant states, including all modes of normal operation, are identified. The electrical power system functions are then categorized on the basis of their safety significance by taking into account the following three factors:

- The consequences of failure to perform the function;
- The frequency of occurrence of the postulated initiating event for which the function would be called upon;
- The duration of time following a postulated initiating event during which the function will be required to be performed.

When assigning the safety classification, the timeliness and reliability with which alternative actions are taken and the timeliness and reliability with which any failure in the electrical power system could

be detected and remedied are considered. The standby AC power sources are considered as safety systems and classified accordingly.

The alternate AC power sources (stationary and portable) provide another level of defense in DEC, and are therefore classified, but not necessarily in the same class as the standby AC power sources. The equipment used to connect an alternate AC power source to the plant, including connecting point, has the same safety class as the alternate AC power source. If the connection point to the safety buses is permanently installed and can possibly affect operation of the buses during a design basis event, the connection point has the same safety classification as the safety buses.

4.1.3. Sizing criteria

Reference [1] recommends that the alternate AC power supplies should have sufficient capacity and capability to operate the systems necessary for coping with an SBO for the time required to bring the plant to and maintain it in a controlled state. The sufficient capacity and capability of an alternate AC power source ensures removal of reactor decay heat, ensure primary circuit integrity, maintain the reactor subcritical, and to remove decay heat from spent fuel for a period of time that is sufficient for reliable restoration of onsite standby or offsite power sources.

A conservative approach is to design the alternate AC source with support systems capable of operating for an indefinite period. Intrinsic in the requirement to ensure primary circuit integrity is the requirement to also maintain containment integrity. Note that in order to meet the above requirements, some reactor designs may need to use portable water pumps to maintain steam generator feed and bleed functions.

Reference [1] recommends that if an alternate AC power source serves more than one unit at a site where standby AC power sources are shared between units, the alternate AC power source should have sufficient capacity and capability to operate systems necessary for coping with an SBO for the time required to bring all units that share the safety AC power sources to and maintain in a controlled state. An alternate AC power source is normally disconnected from the onsite power system. It is manually connected to the plant distribution systems after all loads and feeds have been disconnected. The loads are manually connected in a controlled manner such that:

- The alternate AC source can successfully start the largest required load without overloading the source and preclude spurious operation of protective devices;
- The loading sequence does not lead to thermal shock or water hammer in the plant systems.

A design basis event concurrent with SBO is generally not postulated. Therefore, the sizing of the alternate AC power source ensures enough power to operate the residual heat removal system. The requirement to power all accident related loads is not essential.

Support systems such as HVAC, compressed air, battery chargers, lighting, etc. need to be considered in the alternate AC power source sizing criteria. When the alternate AC power source is credited for accident management coping strategies, it is advised that sizing criteria consider post-accident mitigating loads.

The required capacity of the alternate AC power source will depend on the reactor type and the strategy to be used for heat removal. Some designs may require forced circulation while others can rely on natural thermosyphoning.

4.1.4. Application of single failure criterion

The single failure criterion is generally not required for the alternate AC power source. Nevertheless, the redundancy in support systems such as starting devices can be considered to improve reliability.

An alternate AC source has a routine surveillance testing to demonstrate reliable starting and operating capability. In order to load the alternate AC source, it may have to be connected to the plant safety busses. If this configuration is required, then adequate measures are implemented (such as double isolation devices, protection coordination, etc.) in order to avoid any failures in the non safety circuit resulting in degradation of safety systems. It is preferable to connect the alternate AC power source using two breakers in series to preclude potential problems related to connecting and disconnecting different sources during power operation.

The alternate AC sources do not need to be redundant. However, from maintenance and testing perspective, it may be beneficial to have more than one alternate AC source. Depending on the site size (e.g. number of reactor units) there may be several alternate AC power sources. New plant designs typically propose redundant alternate AC sources as an additional defense in depth measure.

4.1.5. Prevention and tolerance of common cause failures

Reference [1] recommends that no single point of vulnerability should exist whereby a weather-related event, natural external hazard, or single active failure could disable standby AC power supply for a reactor unit and simultaneously fail all offsite power supplies and the alternate AC power supplies. In addition, diversity in design, manufacturer and type of units used for standby power and alternate AC sources may preclude common mode failures due to similarity in components, aging mechanism and manufacturing defects.

4.1.6. Independence

The startup and operation of the alternate AC power source is typically autonomous; i.e. be independent from the plant support systems such as pre-heating, lighting, component cooling, instrument air, DC power etc. During normal plant operation auxiliary systems used to maintain the alternate AC source in readiness may be powered from the operating unit.

4.1.7. Additional considerations

The alternate AC power supply is preferably a permanent device with all connections installed and tested. This minimizes the time required to connect the source and also reduces reliability concerns associated with moving the source to the required area. As discussed in section 4.1.1, a permanently installed alternate AC facility is designed to withstand a higher level of external events. In case an alternate power source fails to start or operate, mobile devices capable of powering individual (small) loads may be used as a diverse means of power supply.

When portable power supplies are used, it is important to design connection points which are appropriately marked, protected against internal and natural external hazards. The connection points for onsite or offsite portable equipment are designed and tested to validate adequacy of design. If several connection points are needed, then they are designed with human factors in consideration to accept the dedicated equipment only and preclude erroneous connection of other equipment.

The adequacy of portable and permanent equipment (ratings, voltage, phase order power output, etc.) to power the designated loads must be adequately validated and tested to prevent complications when the equipment is required to support the plant during emergency conditions. The equipment has safety and protective features for startup and continuous operation (e.g., protection for overload, overcurrent, thermal issues, etc.) to isolate the system in the event of equipment malfunctions. Plant personnel must be adequately trained to maintain, start, and connect the equipment.

4.1.8. Mission time

Reference [1] recommends that the alternate AC power systems should be capable of supplying the required loads within the time specified in the plant safety analysis and the plant SBO coping analysis.

The alternate AC power systems are capable of supplying loads within the coping time for loss of all AC power. Restoration of normal offsite and onsite standby AC power systems is a high priority to maintain defense in depth and facilitate restoration of important to safety support system functions (e.g., communication, lighting, and HVAC systems) that significantly enhance the operators' ability to respond to an event and maintain controlled conditions for extended duration.

The alternate AC power source mission time may be limited by the availability of consumables onsite (e.g., fuel and lube oil). Current practice in some Member States requires onsite storage of consumables to support operation of at least 72 hours. A general expectation is to have access to onsite storage facilities with capacity greater than 7 days of continuous operation. Provisions are made to replenish consumables to support indefinite operation of the alternate AC power source.

4.1.9. Functional testing

The alternate AC power system is tested regularly in accordance with a periodic testing programme (e.g. once every three months) to verify system operation and reliability. Similar to standby AC power sources, surveillance may include startup only, startup and idle, connection to a bus, ability to reach and sustain expected voltage and frequency, and operating at load for several hours, etc.

The test includes operator action to startup, align and connect alternate AC power source to the plant. The time required for startup and alignment of the alternate AC power source is demonstrated by test. The permanent alternate AC power system is included in the plant operating limits and conditions (OLC) which further specify criteria for operation, testing and maintenance time.

All alternate AC power supply sources equipment is tested during system commissioning to demonstrate satisfactory performance.

4.1.10. Maintenance and repair

A preventive maintenance strategy is developed and performed regularly to ensure reliability of the alternate AC power source. When the repair or general maintenance is being scheduled, the following are considered from a defense in depth perspective:

- Unavailability of standby AC power systems during the outages;
- Flexibility for redundant AC power sources;
- Contingency planning for potential LOOP due to maintenance activities;
- Specific consideration for low RCS inventory situations (e.g. mid-loop operation).

If a permanent alternate AC power source is declared unavailable (e.g. as a result of maintenance, component malfunctions detected during the walkdown or test), the plant OLC have limitations on the allowed outage time.

4.2. ENVIRONMENTAL CONDITIONS

4.2.1. Qualification

Equipment qualification includes that for functional purposes as well as the effects of internal and external events. Qualification for the environmental effects of internal and external events intends to ensure that these events do not result in equipment degradation or failure resulting in common cause failure.

Reference [1] recommends that the alternate AC power supplies with auxiliaries should be qualified for their intended application. The alternate AC power supply systems are type-tested to demonstrate compliance with the requirements related to functional performance under postulated environmental conditions. Although type testing is the preferred method for demonstrating alternate AC power

supply systems are qualified for design basis accident conditions, additional methods may be used for qualification for DEC when justifiable. Capability to withstand internal and external hazards is confirmed by analysis and/or testing.

The design of storage areas provides an adequate margin against levels of natural hazards more severe than those to be considered for plant design taking into account the site hazard evaluation. In order to protect the equipment (alternate AC power source, portable pumps, motors, etc.) dedicated for coping with an extended SBO event, the equipment may be permanently installed at the site or remotely located.

It is advised that the environment and postulated external events such as earthquakes, hurricanes, tornados, flooding, etc. are taken into consideration for the storage location and the connection points to ensure that the equipment is available when required.

4.2.2. Hazards to be considered

The alternate AC power supplies and the associated auxiliaries are qualified for their intended application. The independency, diversity, testing and maintenance, and the qualification requirements for external hazards (e.g., seismic, site ambient conditions, storms, heavy snow, icing, flooding, etc.) ensure availability and reliability.

Reference [2] requires that the design of structures, systems and components (SSC) important to safety should prevent large or early radioactive releases and provide an adequate margin against levels of natural hazards than those selected for the design basis.

The following hazards are considered in the design of alternate AC power system:

- Internal events;
- Extreme external event;
- Localized external event (such as flooding).

The following natural events (or their credible combination) are examples of those that are considered:

- Seismic events typically affect a wide area and can cause collapse of the grid system and can damage the plant switchyard. Grid recovery and the power distribution through the plant switchyard may not be possible for an extended period of time. The alternate AC power source is qualified to withstand the anticipated seismic event with sufficient margin considered in the design basis of the plant. In order to qualify the alternate power source, it is necessary to determine seismic spectrum at the equipment location.
- Flooding may be either an area wide external event or a localized internal / external event. In both cases, the flooding may cause significant damage to power sources located onsite as well as AC/DC distribution systems. The alternate AC power source, including the connection points and power distribution systems inside the plant, is protected against flooding.
- Extreme wind, hurricanes, tornados, heavy snow, combination of wind and rain or snow and icing conditions are examples of events which may challenge the grid systems, plant switchyards and open air distribution systems. The alternate AC source and other equipment required to cope with an extended SBO event is protected against severe weather conditions.
- Aircraft crash is an example of a human induced event. It may cause plant wide structural damage which may eventually lead to an SBO. Alternate AC power sources are protected against human induced events.

The external events and plant site events discussed above have the potential to deteriorate site access; alternate means of accessing the plant site and building are typically considered in the plant emergency operating procedures (EOP), and accident management guidelines.

4.2.3. Protection against hazards

While the same hazards are considered for alternate AC power sources as for standby AC power sources, the design of alternate AC power source may consider additional safety features to better protect the source from the specific external hazard as well as to ensure its operation under degraded site conditions.

An important lesson learnt from the Fukushima Daiichi accident is that an air-cooled diesel generator survived flooding, but could not be connected to the plant AC distribution system which remained flooded by seawater. Alternate AC power sources as well as AC/DC distribution system should be protected, to the extent possible, against internal or external events in accordance with the applicable IAEA guidance.

Some power plants have implemented 'bunkered systems' which house the alternate power supply system as well as diesel driven feedwater pumps to ensure controlled state of the plant. The bunker is designed to be more resilient against external hazards that exceed the plant design basis.

The IAEA Safety Guides NS-G-1.5 [7], NS-G-1.6 [8], NS-G-1.7 [9], NS-G-1.11 [10], and SSG-3 [11] discuss internal and external hazards and the measures for qualifying or protecting structures, systems and components against these hazards.

4.3. ESTABLISHING QUALITY ASSURANCE CRITERIA

Requirements, design, and development activities for alternate AC power supply systems are documented in sufficient detail to support verification, validation, inspection and regulatory review. This documentation includes details on procurement specifications, installation, commissioning, operation and modification. This documentation is maintained under a configuration management programme. The alternate AC power supply source should be designed and maintained in accordance with the requirements for Management Systems, GS-R-3 [12] and supporting Guides GS-G-3.1 [13] and GS-G-3.5 [14], and Safety Assessment for Facilities and Activities GS-R-4 [15].

5. DESIGN AND IMPLEMENTATION OF EQUIPMENT FOR SBO

5.1. DIFFERENCES FOR NEW AND EXISTING PLANTS

The integration of alternate AC power systems at a new plant is less onerous and can be accomplished without compromise when compared to a retrofit application at an existing plant. If the design and performance criteria are taken into consideration in the conceptual design phase of the new plant, identifying a suitable place for the installation of alternate AC power systems is easier.

In existing plants, the complete design of the standby AC power systems requires reassessment to incorporate the necessary modifications.

The evaluation for existing plants typically includes:

- The assessment of vulnerabilities under different plant conditions (from operational states to design extension conditions);
- The development of accident management strategies and the establishment of a systematic process to ensure that strategies exist to deal with all identified vulnerabilities; and
- The implementation and validation of these strategies in the form of procedures and guidelines.

Note: Plants considering upgrades for SBO coping and recovery can obtain information from operating experience and research through the IAEA or other national / international organizations.

5.2. SBO DESIGN CONSIDERATIONS

Plant safety features available to cope with a loss of offsite power and an SBO event vary for different plant designs and are often dependent on the age and the specific threats that the plants were designed to cope with.

Some of these safety features are inherent in the design (e.g., large volume of water in the SGs, multiple defense in depth layers of power sources, etc.), while others have been added as safety improvements over the years.

Some safety improvements have been introduced after the Fukushima Daiichi accident to address identified design deficiencies resolving the findings of individual plant vulnerability analyses or responding to new regulatory requirements.

The following robust safety features and practices were identified during the 'Stress Tests' performed for NPPs in the European Union Ref. [16], US NRC Mitigation Strategies [17], and Japanese New Technical Standards for Commercial Power Reactors and their Auxiliary Facilities [18]. These features may also be applicable to other NPPs:

- Capability of the turbine island to handle large load rejection and stabilize for house load operation;
- Multiple grid connections at different voltage levels including secure connections (e.g., underground cable) to a switchyard located near the plant;
- Nearby hydro or a gas power plant, having a black start capability, with a dedicated direct connection (separate from the grid or the plant switchyard);
- Dedicated small AC power sources for specific functions such as battery charging;
- Multiple dedicated portable and stationary AC power sources to supply power to safety buses;
- Station batteries that have been shown to supply power for at least 8 to 12 hours with load shedding. Run time or DC power availability can be extended for longer duration with deep load shedding procedures or removing a single battery train/division from service then restoring that battery train/division when the opposite train/division battery has depleted.
- Trailer mounted fuel tanks, hoses, fuel transfer pumps, and cable spools for generators and portable pumps;
- Procedures to connect and power specific buses, operate switches and breakers to disconnect non-essential loads;
- Drills that encompass full sequences (i.e. from bringing a mobile diesel generator trailer to a location, to connecting and powering essential loads);
- The practice of storing mobile equipment in areas which are protected from seismic, flooding or other internal or external events.
- Portable battery or diesel powered lights.
- Multiple connection points for portable generators and pumps.
- Debris removal equipment that is stored in areas which are protected from seismic, flooding or other internal or external events.
- Establishment of procedures for coordinating, accepting, and deploying offsite resources.
- Staging areas to receive equipment from offsite resources.
- Coordination with local and federal authorities to establish guidelines for responding to extended SBO events.

To cope with SBO scenarios resulting from beyond design basis events, some plants have installed:

- A 'hardened core' of equipment and organizational measures; or
- Bunker-based systems having their own power sources with dedicated fuel reserve; and/or
- Dedicated pumps with independent sources of water and their own instrumentation and controls.

5.3. RECOMMENDED DESIGN PRACTICES

The SBO design provisions are evaluated from the perspective of the initiating event or the combination of events that can lead to SBO conditions while bearing in mind the following:

- Protection against effects of the initiating event;
- Availability of alternate AC power supplies with pre-installed connection points, which are qualified;
- Availability of portable power generating means that can be deployed considering possible site wide disruption;
- Availability of portable equipment (electrical or non-electrical) such as pumps, compressors, and the connecting hardware (e.g., hoses, cables, connectors, etc.).

5.3.1. Increasing SBO coping capability

Each plant and site has unique design features and for this reason, the evaluation of SBO coping capabilities has to be site-specific. The plant SBO coping capability is evaluated to determine the time required to withstand and recover from an SBO event. The capability to maintain fuel cooling, containment integrity and monitoring is adequately demonstrated. Appropriate procedures and personnel training need also be implemented.

It is advised that the following considerations are taken into account when determining SBO coping capability includes as follows:

- Battery run time;
- Deployment and connection time of alternate AC power source including consumables;
- Reactivity control;
- Reactor coolant system leak rates;
- Available water sources for primary and secondary systems;
- Instrumentation & control;
- Room temperatures, habitability, lighting, communication, etc.;
- Motive power to ensure containment isolation (i.e., AC power to operate motor operated valves and compressed air to operate air operated valves);
- Capability to restore at least one source of offsite or onsite AC power (compressed air for starting standby sources, DC power for operating breakers, etc.).

The above considerations present some of the limitations to extending SBO coping capability. In addition to stationery AC/DC power sources, deployment of portable equipment (i.e. diesel driven pumps, diesel driven generators, portable battery chargers, etc.) may be necessary to maintain cooling for the core, containment and SFP.

5.3.2. Design provisions to minimize SBO probability

Existing plants have implemented provisions in order to minimize SBO probability. These provisions include:

- House load capability of the turbine and generator island;
- Optional backup offsite power sources from a different switchyard;
- Reduced failure rates and common mode failures of standby AC power sources.

5.3.3. Design provisions implemented to cope with SBO

Existing plants have implemented design provisions in order to improve SBO coping capabilities. These provisions include:

- Improved procedures for restoring the offsite power;
- Crosstie capability of AC sources at multi-unit sites;
- Alternate AC power source designed and qualified for anticipated external events;
- Reliable connection to a nearby small power generating plant (such as hydro, diesel generator station or gas turbine) generally used to improve grid reliability may be used to support an SBO;
- Mobile diesel / gas turbine generators (medium or low voltage);
- High capacity station batteries (e.g. 12-24 hours);
- Additional spare battery systems maintained in fully charged condition but not connected to plant loads;
- Dedicated mobile pumps and battery chargers;
- Detailed procedural guidance for SBO coping;
- Database with external resources capable of supporting plant needs.

The above stated measures provide reasonable assurance for preventing fuel damage by providing technical and organizational measures to cope with an SBO event.

In order to cope with an extended SBO duration, the following additional means or provisions are considered to enhance the SBO coping capability of the plant:

- Generators to re-energize safety buses and battery chargers;
- Emergency diesel engine driven pumps to replenish water sources, i.e., EFT or CST make-up or make up directly to the SGs;
- Generators to power injection pumps to restore RCP seal cooling and limited number of pressurizer heaters;
- Improved RCP seal designs to limit seal leakage;
- Pre-planning and pre-staged emergency equipment to make manual actions easier and improve procedures and training.
- Measures to purge explosive gases from the main generator, containment building, battery rooms, spent fuel handling areas, etc.
- Establishment of emergency response center(s) that will supply equipment within a pre-established time period upon notification.
- Establishment of procedures for coordinating, accepting, and deploying offsite resources.
- Staging areas to receive equipment from offsite resources.
  Coordination with local and federal authorities to establish guidelines for responding to extended SBO events.

It may be necessary to use alternative means of cooling including alternate heat sinks for extended SBO durations. Use of other sources of water supply from stored condenser cooling water, alternate tanks or wells on the site, or water sources in the vicinity (reservoir, lakes, etc.) is an additional way of enabling core cooling and prevention of fuel degradation.

5.3.4. Protective measures for SBO coping equipment

Existing alternate AC power sources (installed in response to operating experience before Fukushima Daiichi accident) may not be capable of supplying power to designated SBO mitigation equipment if the AC/DC power distribution system, connection points, cables, etc. are unavailable because they were not protected against the effects of the external or internal events. Hence, additional measures that better protect the electrical equipment from extreme events such as seismic or flooding are implemented. This includes the following design features:

- Protecting storage facilities for consumables and alternate AC power equipment to external natural events such as earthquake, flooding;

- Installing water-proof doors sealing the electrical compartments for standby and alternate AC power sources, DC batteries, and switchgear rooms;
- Sealing external cable raceways to prevent water intrusion into the electrical distribution systems from the outside;
- Dewatering pumps to remove water from areas requiring access or equipment connection;
- Modifying the plant for connecting external power sources, pumps etc., at an elevation which consider sufficient margin for the highest flood level anticipated in the design;
- Providing water transport means to enable personnel to reach connecting points or replenishing usable fluids and materials on site;
- Providing debris removal equipment to enable access after an extreme event (earthquake, mud slides, etc.) and to deploy portable equipment;
- Training the plant personnel for manual actions that may be required as the SBO duration increases.
- Validation of procedures/guidance to ensure they can be accomplished within the expected times.

5.3.5. Design for extended mission time

The objective of SBO coping strategies is to establish an extended coping capability by relying upon installed equipment, onsite pre-staged/portable equipment, and offsite resources to ensure core cooling, containment cooling and SFP cooling can be maintained or restored.

The alternate AC power source mission time may be limited by the availability of consumables onsite (e.g., fuel and lube oil). Current recommendations require onsite storage of consumables to support a minimum operation of 72 hours. Provisions are made to replenish consumables to support extended operation of the alternate AC power source for indefinite operation.

5.4. SBO CONSIDERATION FOR NEW NPPS

There are two different concepts to consider for an SBO event in the design of new nuclear power plants, depending on whether the plant is active or passive.

For active plants, SBO is included in the design basis. The design requires alternate AC power systems which are independent, diverse and physically separated from the standby AC power systems. The design objective of alternate AC power source is to preserve the integrity of the reactor coolant system and to prevent significant fuel damage in the core and the SFP in DEC.

The alternate AC power supply system is typically enclosed in a reinforced building, qualified to withstand extreme external hazards, with autonomy of at least 24 hours. It provides power supply to dedicated plant buses.

For passive plants, SBO is included in the design basis. The design may not require an alternate AC power supply system to preserve the integrity of the reactor coolant system and to prevent significant fuel damage in the core and the SFP in DEC.

A common design feature for active and passive plants is to ensure the continuity of DC power supply by large capacity station batteries to enable monitoring of the key plant parameters as well as providing essential controls for extended duration.

For defense in depth, the design typically includes features to enable the use of non-permanent equipment to provide the necessary electrical power supply to cope with severe accidents. The equipment that is necessary to mitigate the consequences of the severe accident can be supplied by any of the available power sources.

Detailed description of the design provisions for SBO that are considered for the new nuclear power plant designs is provided in Annex II.

6. OPERATING EXPERIENCE

Historically, risk analyses have indicated that the SBO event is an important contributor to overall NPP risk, substantially contributing to Core Damage Frequency (CDF) in many NPPs. The frequency of occurrence of SBO is quite low but operating experience has indicated the consequences are significant. Experience has shown that frequent LOOP events have resulted in near SBO events. Table 2 shows SBO events or near SBO conditions that have been reported by 2014.

The major contributor to SBO is the LOOP as well as its duration. Grid-related, switchyard-related, plant-centered, and weather-related events may initiate LOOP. Natural external events such as weather-related, seismic, etc. have a significant effect on the capability to restore offsite power.

TABLE 2. REPORTED SBO EVENTS THAT OCCURRED AT NUCLEAR POWER PLANTS WORLDWIDE.

1986	Kori 4 (Republic of Korea)	SBO caused by a typhoon.
1990	Vogtle 1 (United States of America)	Offsite power was lost from switchyard work during a refueling outage, the only operable EDG failed to start.
1993	Narora 1 Event (Republic of India)	Ejected turbine blade caused a fire, hydrogen explosion. Due to fire, cables started burning and there was complete loss of power supply in the unit including loss of class I & II supplies. The extended SBO lasted for approximately seventeen hours.
1993	Kola Event (Russian Federation)	LOOP induced by high wind with subsequent loss of EDGs caused SBO event.
2006	Forsmark 1 (Sweden)*	Switchyard work resulted in overvoltage and degraded electrical safety systems performance.
2007	Dampierre-3 (France)	Reactor shut down due to failure on 6.6kV switch boards and protective relay malfunctions resulted in SBO.
2011	Fukushima Daiichi (Japan)	Following a major earthquake of magnitude 9.0 on the Richter scale, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing an extended SBO.
2012	Byron event (United States of America)**	Failure of insulator resulted in open phase conditions on the offsite power source. The failure was not detected by the onsite degraded voltage relays and as a result, EDGs did not start.
2012	Kori 1 (Republic of Korea)	An error in generator protective relay testing resulted in loss of offsite power to shutdown cooling. Consecutive failure of EDG to start resulted in SBO event.
2013	Forsmark 3** (Sweden)	An error resulted in double open phase conditions. The failure was not detected by the onsite voltage relays. As a result, the standby sources did not start.

* Near SBO event

** Degraded voltage conditions resulted in inability to use offsite and onsite AC power sources.

A detailed description of events listed in Table 2 is provided in Annex 3.

7. SUMMARY AND CONCLUSIONS

Prior to the Fukushima Daiichi accident, international operating experience showed that the loss of offsite power concurrent with a turbine trip and unavailability of the standby AC power systems was a credible event. The SBO events or near SBO events that occurred before Fukushima were important precursors, pointing to a vulnerability in the plant electrical power systems.

The power supply systems were historically designed for DBA. Current practices consider SBO events lasting for short duration. Subsequent to the Fukushima Daiichi accident, the Member States recognized the need to include SBO as a part of DEC.

The IAEA has amended the SSR 2/1 [2] Requirement 68: *Design for withstanding the loss of offsite power* to consider LOOP event coincident with loss of standby AC power systems. SSR 2/1 requires "*an alternate power source to supply the necessary power in design extension conditions"*.

SSG-34 provides recommended design practices for the alternate AC power system including classification, sizing, storage and qualification. Other considerations such as connection points, mission time, maintenance and testing, and storage of consumables to ensure reliable indefinite operation of alternate AC power system is also discussed.

Whilst the SSR 2/1 [2] is meant for the new nuclear power plants, the integration of an alternate AC power supply system into the plant electrical power supply system suitable for both DBA and DEC is also recommended for existing nuclear power plants.

This TECDOC discusses recommended practices on SBO coping strategies for short and extended SBO which include:

- The initiating event that resulted in the SBO conditions;
- The plant capability to respond to the SBO condition;
- The robustness of the plant design; and
- The resources available on site or offsite.

The following plant systems that are impacted by SBO are also discussed:

- Inventories in RCS, SG, EFT and CST;
- Prevention re-criticality;
- Integrity of reactor coolant pump seals;
- Battery capacity;
- Alternate AC power source mission time;
- SFP heat removal;
- HVAC.

This TECDOC outlines provisions related to the design, qualification, protection against external hazards, maintenance and testing for the alternate SBO coping equipment such as:

- Alternate AC power systems;
- DC power systems,
- Portable equipment;
- Connection points for the equipment;
- Storage locations.

The provisions described in this publication will assist in increasing the robustness of the plant electrical design for preventing and coping with SBO events and enhance the overall plant safety.

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[20] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, IAEA, Vienna (2007).

DEFINITIONS

The following definitions apply for the purposes of this TECDOC.
Further definitions are provided in the IAEA Safety Glossary:
Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition),
IAEA, Vienna (2007): http://www-ns.iaea.org/standards/safety-glossary.asp

accident conditions. Deviations from normal operation that are less frequent and more severe than anticipated operational occurrences, and which include design basis accidents and design extension conditions.

alternate AC power source. Dedicated power source (mobile or fixed) that could be used as power supply to the plant during total loss of all non-battery power in the safety power systems (station blackout) and other design extension conditions.

controlled state. Plant state, following an anticipated operational occurrence or accident conditions, in which the fundamental safety functions can be ensured and which can be maintained for a time sufficient to implement provisions to reach a safe state.

design extension conditions. Postulated accident conditions that are not considered for design basis accidents, but that are considered in the design process of the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. Design extension conditions include conditions in events without significant fuel degradation and conditions with core melting.

extreme natural event: External event that exceeds the design basis of the existing nuclear installation.

extended station blackout: SBO event where alternate AC power source is connected within the coping time but is required to continue operating for extended duration (e.g. more than 4 hours).

house load operation: Operation of a unit, isolated from the grid and which provides power supply only to the station loads.

loss of offsite power. Simultaneous loss of preferred AC power to all safety buses. (Note: it is likely that the non safety buses will also lose power).

mission time for SBO equipment: Time for which the SBO equipment is able to perform (maintain) its intended function, considering the re-supply of necessary consumables, and actual environmental conditions.

preferred power supply: The power supply from the transmission system up to the safety classified electrical power system. It is composed of transmission system, switchyard, main generator and distribution system up to safety classified electrical power system. Some portions of the preferred power supply are not part of the safety classification scheme.

Short term SBO: Generally accepted to be an SBO event that lasts less than 4 hours.

standby AC Power Source. The AC electric power supply source(s) important to safety located within the nuclear power plant and controlled by the nuclear power station operators (e.g., diesel or gas turbine generators).

station blackout: Plant condition with complete loss of all AC power from the preferred offsite AC sources, from the main generator, and from standby AC power sources important to safety to the essential and nonessential switchgear buses. DC power supplies and uninterruptible AC

power supplies may be available as long as batteries can supply the loads. Alternate AC power supplies are available.

station blackout coping time: Time available from loss of all AC power to the safety bus until onset of core damage if no counter measures.

Note: Credit can be taken for equipment which operates automatically without need of AC power, e.g. turbine driven Emergency Feedwater Water (EFW) pump, turbine driven generator for cooling RCP seals, as well as diesel driven FW pump that starts automatically following SBO.

station blackout coping capability: All measures and equipment that are necessary to extend the time available to mitigate the consequences of an SBO event.

ABBREVIATIONS

AC	Alternating current
ACC	Alternate AC power
AOO	Anticipated operational occurrence
APWR	Advanced pressurized water reactor
BDBA	Beyond design basis accident
BDBE	Beyond design basis event
BWR	Boiling water reactor
CANDU	Canada deuterium uranium
CCF	Common cause failure
CNSC	Canadian Nuclear Safety Commission
CST	Condensate storage tank
CTG	Combustion turbine generator
DBA	Design basis accident
DC	Direct current
DEC	Design extension condition
DUS	(French) Ultimate additional backup diesel
ECR	Emergency Control Room
EDF	Electricite de France
EDG	Emergency diesel generator
EFT	Essential feedwater tank
EFWDG	Emergency feedwater diesel generators
EFWP	Emergency feedwater pumps
EME	Emergency mitigating equipment
EOP	Emergency operating procedure
FARN	(French) Nuclear rapid response force
FCVS	Filtered containment venting system
FST	Feedwater storage tank
HPCS	High pressure core spray
HSC	Hardened safety core
HVAC	Heating ventilation and air conditioning
I&C	Instrumentation and control
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
KINS	Korea Institute of Nuclear Safety
LLC	Local crisis centre
LOOP	Loss of offsite Power
MCC	Motor control centre
MCR	Main control room
NO	Normal operation
NPP	Nuclear power plant
NSA	Nuclear safety authority
OLC	Operating limits and conditions
OPC	Open phase conditions
PHTS	Primary heat transport system (CANDU PHWRS)
PHWR	Pressurized heavy water moderated reactor
PSA	Probabilistic safety analysis
PWR	Pressurized water reactor
QA	Quality assurance
RCIC	Reactor core isolation cooling system
RCP	Reactor coolant pump
RCS	Reactor coolant system
RHR	Residual heat removal
RPS	Reactor protection system

RPV	Reactor pressure vessel
RSC	Reactor safety commission
RWT	Reserve water tank
SAMG	Severe accident mitigation guideline
SBO	Station blackout
SFP	Spent fuel pool
SG	Steam generator
SSC	Structures, systems and components
TLACPS	Total loss of ac power supply
TMI	Three Mile Island
TOI	Generic optimized computerized reactor design
TSC	Technical support centre
UHS	Ultimate heat sink
US NRC	United States Nuclear Regulatory Commission

ANNEX I

CONFIGURATION OF ALTERNATE POWER SOURCES TO ENSURE POWER SUPPLY DURING SBO CONDITIONS

I–1. INTRODUCTION

With respect to the plant electrical systems, the alternate power supply (AC and DC) constitute the fourth level of defense in depth. The fact that systems and components important to safety are dependent on power supplies to perform their intended safety functions implies the importance of design considerations for SBO scenarios.

This annex discusses example of configurations and connection options for alternate AC/DC power sources. It further details characteristics and performance criteria for dedicated power source as follows:

- Alternate power source(s) is capable of supplying the necessary power to prevent significant core and spent fuel degradation in the event of the loss of the offsite power combined with the failure of the standby AC power source.
- Alternate power source(s) is independent and physically separated from the standby AC power source. Terminal characteristics, capacity, connection time, and stock of consumables ensure the necessary service time to bring the plant in to and maintain it in a controlled state in the event of loss of the offsite power combined with the failure of the standby AC power source.
- Equipment necessary to mitigate the consequences of a core melt accident can be supplied by any of the power sources.
- The design includes the necessary features to enable the use of non-permanent power sources which may be available at the site or a remote location.

In summary, the primary purpose of alternate AC power source(s) is to ensure that cooling for the core, containment and SFP is maintained or restored by supplying power to essential equipment. The intent of plant modifications that support connection and operation of alternate power sources (such as necessary connecting points, fuel oil reserves, etc.) is to provide counter measures against the simultaneous failure of offsite and standby AC power supplies that are normally used for these functions. The AC power sources are diverse in design and not susceptible to the external or internal events that caused the loss of onsite and offsite power sources.

I–2. EXAMPLE OF LAYOUT AND CONNECTIONS

I–2.1 Alternate AC power source

The design of alternate AC power supplies ensure its capacity and capability to supply the required loads within the time specified in the plant safety analysis and the plant SBO coping analysis.

In order to meet this criterion, the alternate AC power source has pre-installed connection points to be capable of supplying loads within the required time period. Some NPPs have very little margin (maybe less than 10 minutes) for responding to an extended SBO event. Plant operators must make the determination quickly to maintain core cooling, containment, and SFP cooling. Restoring AC power as soon as possible after a SBO restores a degree of defense in depth to the electrical power systems, restores safety systems that depend on AC power and restores support systems (e.g. lighting systems and habitability systems) that significantly enhance the ability of the operators to respond to an event.

Figure I–1 shows an example of the configuration and connection points of alternate AC power sources. A dedicated alternate AC power source may be stationary or mobile. There may be different options to connect alternate AC power sources either to a dedicated bus which is the connected to the plant safety bus or directly to a designated safety bus. At multi-unit sites, a designated bus for alternate

AC power source(s) may provide connection to the safety buses of other units. As a rule, the alternate AC power source is connected to the plant buses after all loads and power supplies have been disconnected.

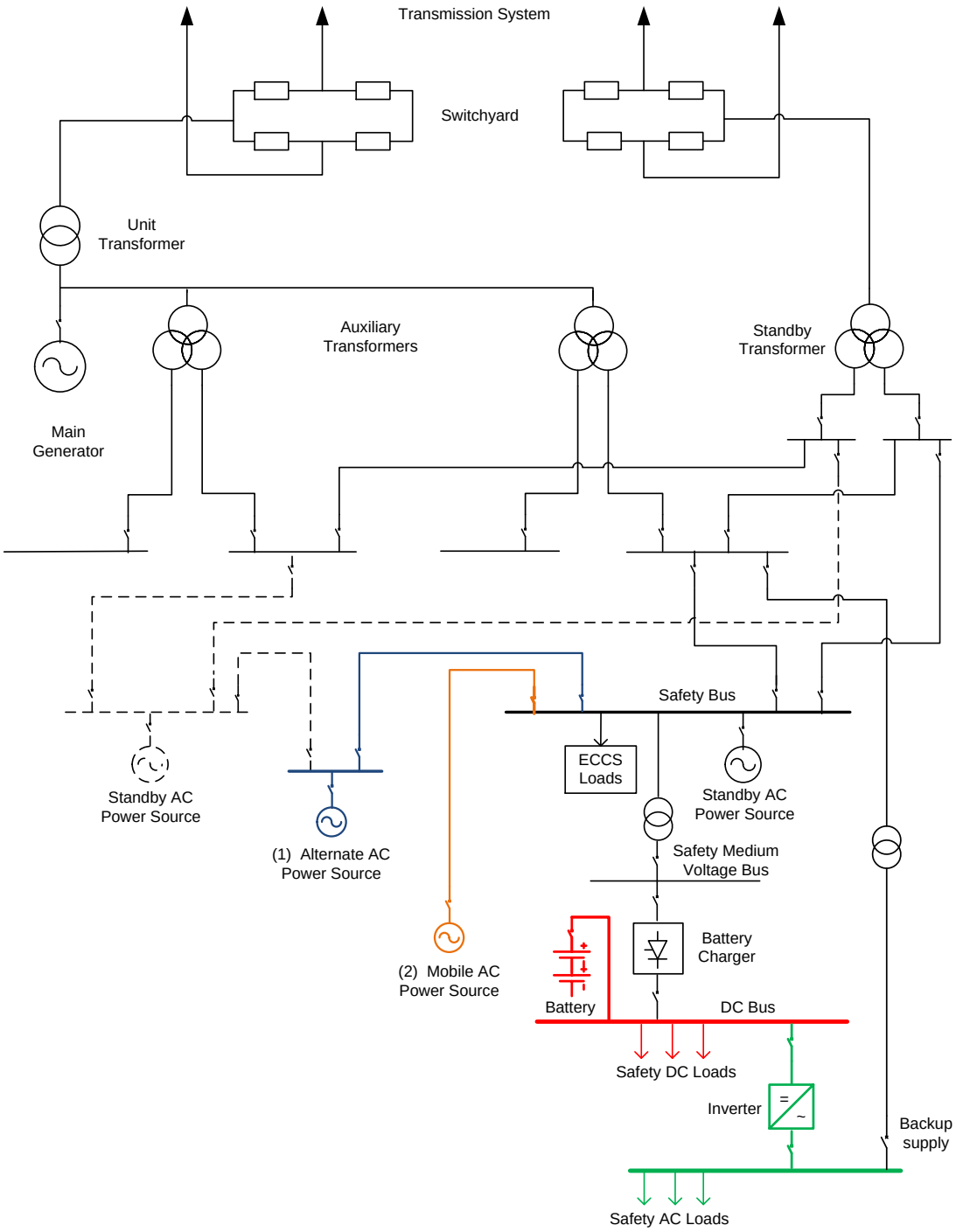

FIG. I–1. An example of schematic representation of alternate stationary and mobile AC power supply connection.

I–2.2 Alternate DC power source

In the event of a severe accident, the alternate electrical power supply may be used to power loads needed for implementation of severe accident management strategies. As a defense in depth measure, it is essential to ensure continuity of DC power supply because it provides vital control power to

operate equipment needed to implement severe accident management strategies, e.g. line up valves, operate electrical circuit breakers, provide power to associated electrical protection systems and accident monitoring (I&C) equipment. Figure I–2 shows an example of configuration and connection points of alternate DC power sources.

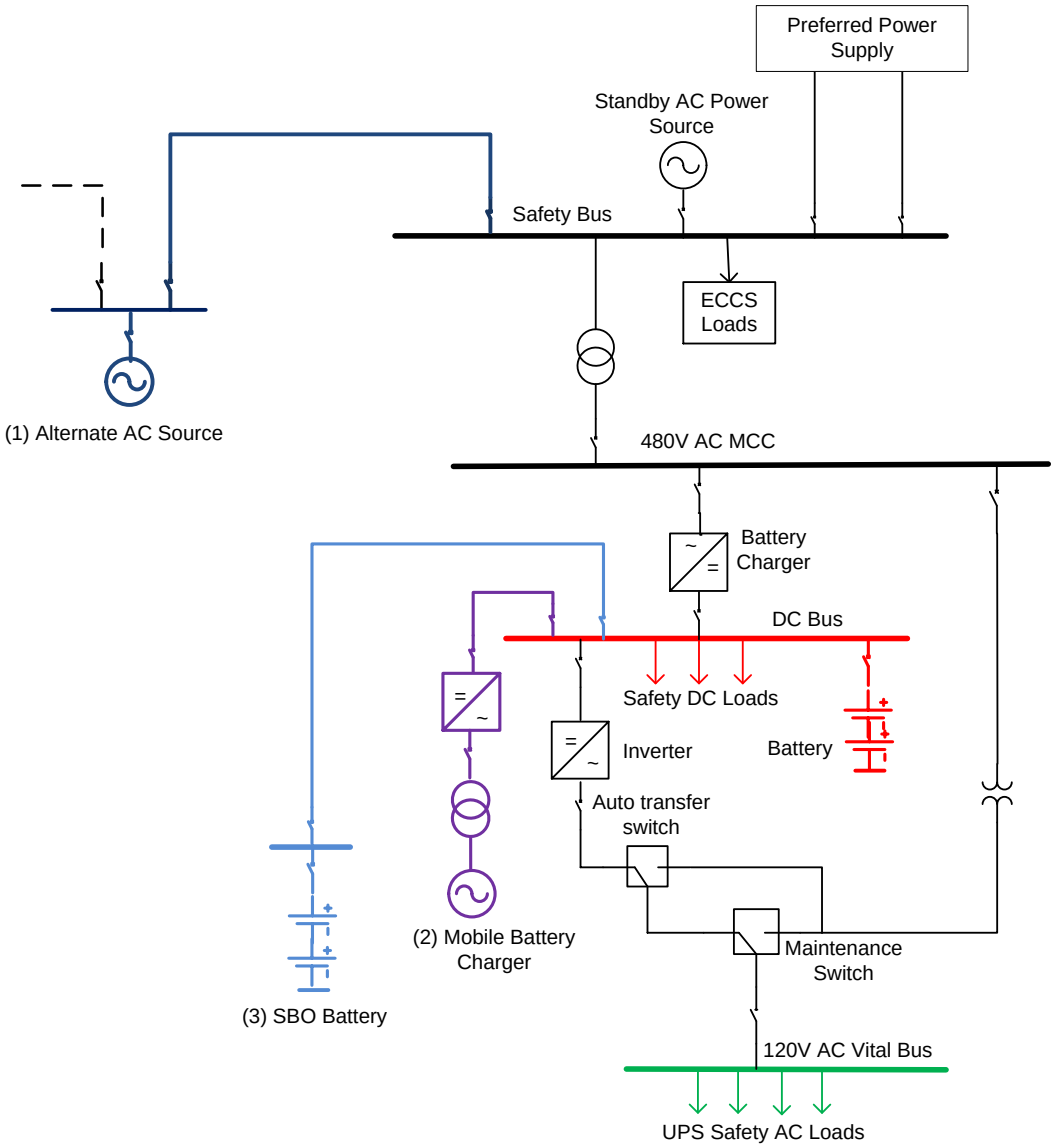

FIG. I–2. An example of schematic representation of external DC power supply connection.

Portable electrical generators may be provided to power the battery chargers, as well as operate critical instrumentation and coping equipment. It is essential to have associated connection points and electrical distribution systems, sized to minimize voltage drop, to ensure sufficient power (voltage and current) is supplied to specific loads.

Continuous operation of DC loads can be ensured from alternate power source(s) by one of the following methods:

- Supplying the DC bus from the alternate AC power source (1); or
- Connecting a mobile battery charger (2) to the DC bus(es); or
- Connecting a reserve SBO battery (3) to the DC bus.

If a reserve SBO battery is used, then it is critical to minimize the distance between the battery location and connection point to the DC loads. A large voltage drop may result in inadequate voltage at load terminals even though the battery capacity may be available for continued operation. Multiple heavy duty conductors are generally connected in parallel to reduce voltage drop. In all cases, pre-installed connection points have to be available.

I–2.3 Alternate AC power supply to buses of different voltage levels

Figure I–3 shows an example of alternate power supply to essential DC and AC buses at different voltage level. The alternate power source (1) which requires high voltage (higher than 4 kV) can be aligned to the safety bus via alternate AC bus and electrical circuit breakers.

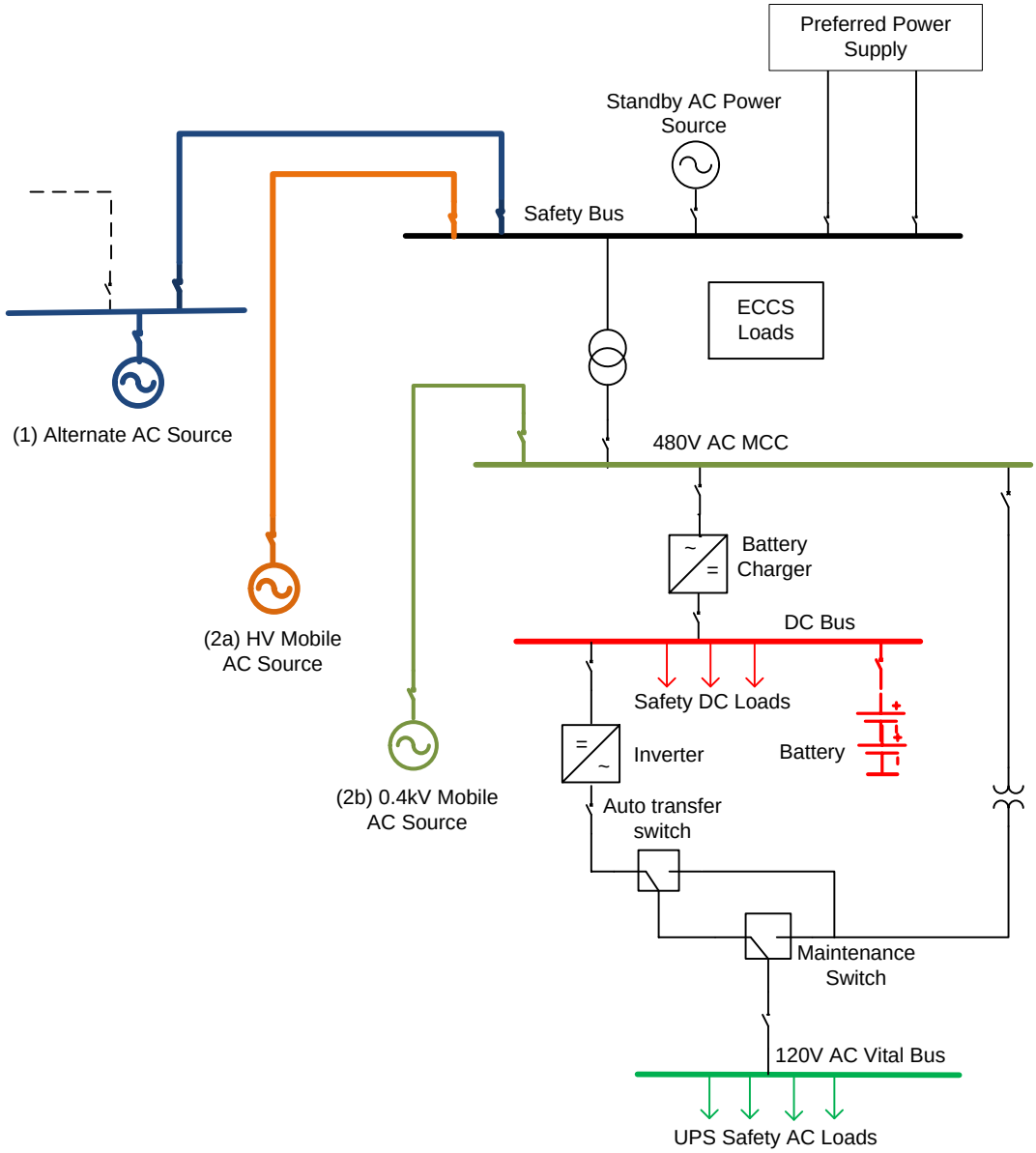

FIG. I–3. An example of alternate power supply to essential AC buses of different voltage levels.

In this example, the alternate AC power source, its AC bus electrical circuit breakers, connecting cables as well as connecting points are already pre-installed in order to minimize the impact of SBO conditions.

Some plants implemented modifications to allow connection of a mobile medium voltage diesel generator (2b) to the plant buses. In this case, a mobile diesel generator is moved to the required location and connected to pre-installed connecting points. This arrangement requires more time when compared to stationary alternate AC power source design.

An adequately sized alternate AC power source (1 and 2a in Figure I–3) has the following advantages:

- It can power all the critical large AC motors.
- It can be connected directly to the station safety busses.
- It can charge station batteries and UPS powered loads.
- Requires minimum operator actions to connect during an emergency
- Simplifies operational, maintenance and procedural requirements.

Another option is to provide a mobile low voltage (e.g., 0.4kV) diesel generator (2b) which can be smaller in size and therefore easy to move to a designated location. It can be connected to a 0.4 kV bus and provide power to charge batteries, critical loads and maintain UPS loads. Pre-installed connections are necessary for this configuration. The capability to power loads by this mobile power source is limited, but may be adequate for some plant designs where only a small set of critical I&C equipment is needed.

Loads that require an uninterruptible power supply are typically supplied from DC bus via an inverter. Figure I–4 shows an example of power supply to a UPS safety bus operating at 120V AC (220V AC at some plants). The essential bus can be supplied either from DC bus via inverter or the bypass source. In the case where the inverter or battery is fails, an automatic transfer switch changes the power supply from the motor control centre (MCC) AC bus. This option is also used for preventive/corrective maintenance in which case a procedurally controlled manual transfer or maintenance switch is used.

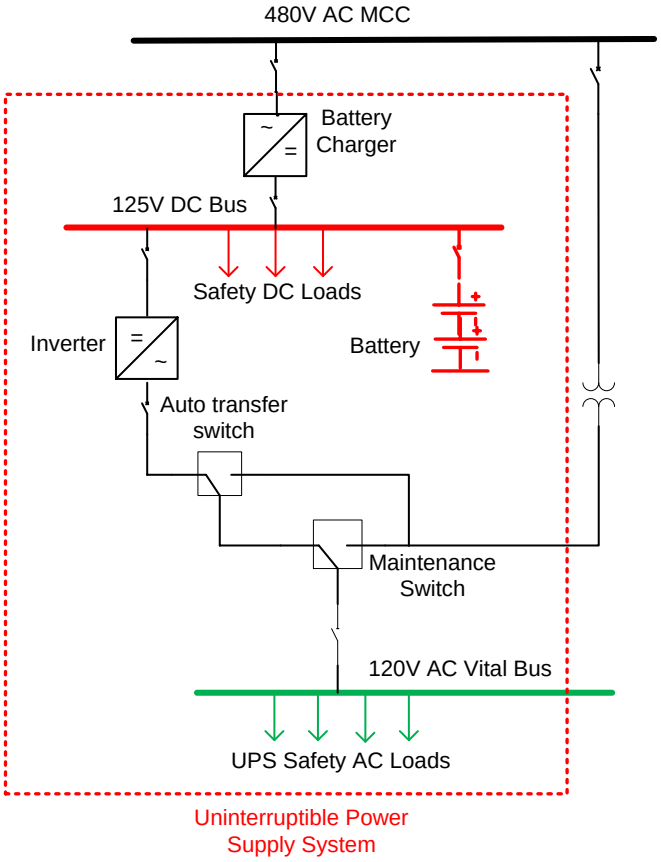

FIG. I–4. An example of different ways of power supply to UPS AC bus.

The transfer switches allow bypassing the inverter and are a useful option in case of inverter malfunction or in case of preventive/corrective maintenance. The UPS powered safety bus remains energized for the duration needed to perform the maintenance or repair without loss of critical control or instrumentation functions.

I–2.4 The bunker system

The design for some NPPs includes an extra layer of protection for the equipment required to function during an SBO or loss of heat sink event. This bunker system is especially relevant for events caused by external hazards that are generally beyond the original design basis of the NPP.

The bunker based systems include AC power sources with dedicated fuel reserves, dedicated pumps with independent sources of water and instrumentation and controls required for plant shutdown. The example in Figure I–5 shows redundant systems. Other designs may have several such systems for greater defense in depth. Bunkers are generally resistant to a range of external threats and have dedicated water supplies allowing for long term independent operation. In all cases, bunker based systems are separate and independent from plant safety systems.

In the example below, a compact practical system for bunker designs is illustrated. The motive power in each redundant loop is ensured by a diesel engine which powers an emergency generator and an emergency feedwater pump - both installed on a common shaft.

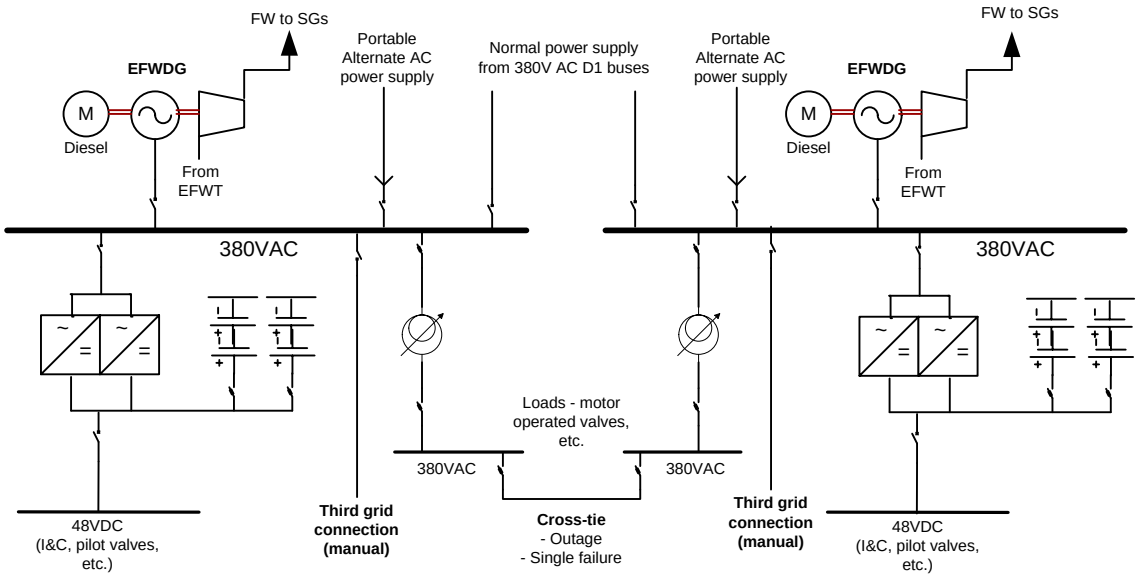

FIG. I–5. Example of a power supply and feedwater system in emergency feedwater building.

The bunker system buses are normally energized to assure reliability and availability. Several power feeds from the grid system are available. Manual actions are needed to operate the system in accordance with the emergency operating procedures.

Some of the equipment that is stored in bunkers for achieving and maintaining safe shutdown conditions is identified below:

- Additional borating pump;
- Spent fuel pool cooling pump (can also be used for emergency core cooling);
- Emergency component cooling pump;
- Emergency service water pump;
- Dwell pump (e.g. for long term emergency feedwater supply when the tanks in the building will be empty);

- Rectifiers for the batteries;
- Circulation pump for autonomous cooling system for the emergency feedwater water diesel generator (EFWDG) and rooms in the EFW building;
- Ventilation system for the EFW building;
- Auxiliary equipment for the EFWDG;
- Fire protection system dampers from the EFW building;
- Reactor vessel and SG level indication system;
- Lighting in the EFW building;
- Drainage pumps in the EFW building;
- Communication system.

Some designs have emergency component cooling pump and the emergency service water pump form two redundant loops, i.e. each loop contains an emergency component cooling pump and an emergency service water pump in order to assure SFP cooling is maintained. The EFWP may be disconnected from the shaft of the EFWDG to avoid overloading the diesel in such a design.

ANNEX II

SBO CONSIDERATION FOR NEW NPPS

II–1. ADVANCED BOILING WATER REACTOR (ABWR)

The AC power system design for ABWR is divided into three divisions. Each division is fed by an independent 6.9 kV safety bus, and each division has access to one onsite and two offsite power sources. An additional power source is provided by the combustion turbine generator (CTG). The design uses three safety grade DGs as standby AC power supplies to provide a separate onsite source of power for each safety division when normal or alternate preferred power supplies are not available. The Division I, II, and III standby AC power supplies consist of an independent 6.9 kV safety grade DG, one for each division. The ABWR design utilizes an Alternate AC (AAC) power source to comply with SBO requirements and the recommendations for advanced light water reactors. The ABWR design AAC power source will supplement and compliment the current offsite AC power connections, the onsite normal AC power sources (the unit auxiliary and reserve auxiliary transformers), the onsite emergency AC power sources (DGs) and the onsite DC power sources. The ABWR AAC CTG power source is expected to be rated at a minimum of 9 MW(e) and be capable of accepting shutdown loads within 10 minutes.

The normal design function of the CTG is to act as a standby, non safety-related power source for the plant critical non safety loads during loss of preferred power (LOOP) events. The CTG can be manually configured to provide power to a selected safety-related emergency bus within 10 minutes of onset of an SBO event. The CTG design has an automatic start, accelerates to required speed, reaches required voltage and frequency and is ready to accept critical loads within two minutes of the receipt of start signal. The CTG is diverse, self-contained unit (including its auxiliaries) and is independent of the plant preferred and emergency power sources.

The CTG has a limited number of design interface requirements. Fuel oil is initially supplied from a local tank, and then transferred from a fuel oil storage tank, both of which are independent of the DG fuel oil tanks. A seven day oil supply for the CTG operation is available onsite. The local CTG I&C is powered by the unit itself or supplied from station batteries. Other auxiliary functions are an integral part of the CTG unit.

The CTG is provided with an immediate fuel supply that is separate from the fuel supply for other onsite standby AC power systems. The AAC power source is capable of operating during and after a station blackout independent of other AC power support systems such as preferred power supply or the blacked-out units safety class power sources. The CTG is capable of powering all of the critical and/or safety grade shutdown loads necessary within 10 minutes of the onset of the station blackout, such that the plant is capable of maintaining core cooling, spent fuel pool cooling and containment integrity.

The AAC power source is capable of providing the necessary core, containment and equipment services (e.g. makeup and cooling water, I&C power, etc.) to bring the reactor to hot shutdown and then to cold shutdown conditions. In addition to maintaining core cooling and primary system inventory, the CTG is capable of recharging the plant batteries during SBO scenarios while supplying safe shutdown loads. It is capable of restoring environmental conditions (temperature) for safe shutdown equipment and maintaining the Main Control Room environment within its design basis temperature even during a prolonged SBO event.

For a typical ABWR, the expected sequence of events during an SBO event is as follows; the loss of preferred AC power will automatically cause reactor scram, main steam isolation valve closure, and initiation of the Reactor Core Isolation Cooling System (RCIC). Coincident failure of the standby AC sources will provide an automatic start signal for the CTG. The AAC power source will re-energize the shutdown loads (emergency makeup water, heat removal and HVAC services) within 10 to 60

minutes, depending on the specific design conditions. The condensate storage tank is used during the first ten minutes and throughout the hot shutdown transition period. A significant amount of water (in excess of 2271 cubic metre) is available from the CST. After restoration of power via AAC, other plant makeup and cooling water sources are also available. The CST provides primary makeup water via the RCIC or HPCS. The suppression pool serves as a secondary water source. The AAC also powers reactor water building cooling water system and the reactor building service water system pumps to provide heat removal service to the plant systems including chillers and HVAC cooling subsystems.

II–2. PASSIVE PWR PLANT (AP 1000)

The AP 1000 design relies on a coping strategy using onsite DC power and available water sources for the first 72 hours of a SBO event. The loss of offsite power results in an immediate reactor trip with gravity assisted insertion of control rods upon loss of power to grippers holding the control rods.

The DC systems typically consists of several banks of safety grade batteries that power vital DC loads and UPS which power vital AC loads. Part of this battery bank is designed to last 24 hours and power loads such as isolation valves. The rest of the batteries last 72 hours and provide lighting for the main control room as well as critical monitoring instrumentation. After approximately 72 hours, all batteries are expected to be expended.

A low SG level signal from the Protection and Safety Monitoring System activates passive core cooling system and passive heat removal system. A passive heat exchanger is automatically placed in service by fail open valve operation. Natural circulation through the reactor core and the heat exchanger removes decay heat. No pumps are required for this process. The heat sink for decay heat is an in-containment refueling water storage tank.

Sufficient amount of water inside the in-containment tank absorbs heat from the heat exchanger and will eventually begin steaming, causing the decay heat to be transferred from the water in the in-containment tank to the steam. The in-containment tank is vented to the containment. The steam rises and is condensed back to water as the containment vessel is cooled by the passive containment cooling system. This condensed water is then returned via gutters and gravity to the in-containment tank and the cycle continues.

As the in-containment tank continues to steam and release energy to the containment, the pressure inside containment steadily increases. When the containment ‘pressure high’ setpoint is reached, the passive containment cooling system is actuated by opening the isolation valves associated with containment cooling tank. This tank is located in the roof structure of the shield building and provides cooling water to the containment shell for a period of 72 hours.

Opening of isolation valves results in water being distributed to the outside of the containment shell. Water is dispersed via gravity to the top of the containment vessel from the containment cooling tank on top the shield building. The decay heat is ultimately transferred to the cooling air and the evaporation of cooling water from the containment cooling tank.

The flow rate of the water from the containment cooling tank is passively controlled through the use of standpipes of decreasing heights. At the onset of a SBO event, full flow is released through the standpipes to provide maximum water cooling to containment and match the decay heat rate from the reactor. As the water level in the containment cooling tank lowers over time, fewer standpipes will remain covered by water thereby reducing the water flow rate to match the decay heat rate. After approximately 36 hours, the passive operation of the passive systems ensures the reactor coolant system will be able to transition to a long term controlled state.

The battery system is designed to last for 72 hours and prior to complete depletion, plant operators have to start the onsite power systems or standby DGs to provide power for control room lighting,

instrumentation and the passive containment cooling recirculation pumps. The onsite storage capacity of diesel fuel oil tanks is enough to allow operation of the DGs for 7 days.

Additional water for cooling of the containment vessel is available in ancillary water storage tanks. The passive cooling system recirculation pumps are used to pump water to cool the containment shell. This water is enough to maintain satisfactory temperatures in the containment for 7 days. If the SBO event lasts longer than 7 days, additional sources of water are available onsite in order to continue the operation of containment cooling indefinitely.

II–3. ADVANCED PRESSURIZED WATER REACTOR

Advanced pressurized water reactor (APWR) has 4 sets of emergency standby AC power source (i.e. 50% capacity per set). This configuration provides additional margin on the capability of safety AC power supply system in case of LOOP. These 4 standby AC sources are located in two separate buildings (2 sets each). This design concept can reduce the potential possibility of total loss of standby AC sources due to extreme external hazards or internal fires.

APWR has 2 sets of alternate AC power sources which are located inside nuclear island building. This alternate AC system is diverse from safety grade emergency power sources and is protected against extreme external hazards, such as the earthquake, tsunami, and tornado. The APWR can cope with extended SBO by using only one of the two alternate AC power sources. The onsite storage of consumables will allow operation of the alternate AC power source for 7 days without replenishment.

In addition, APWR can keep the plant in hot shutdown condition without alternate AC power source for 8 hours by using turbine driven auxiliary feedwater pump (TDAFWP) and DC batteries. This provides sufficient safety margin until the alternate AC power source is connected to the bus. APWR design also includes measures to cope with loss of ultimate heat sink (UHS) via secondary chiller system that can be used as an alternate UHS system.

Technical data of the APWR alternate AC power source include:

- Capacity: 2 sets each rated at 4600kW
- Rated Voltage: 6.6kV
- Redundancy: There is no requirement for redundant trains of AAC source to support SBO event. However, the current design proposal has two AAC sources, and each source is sized to support the required SBO loads.
- QA requirement: There is no safety grade QA requirement for this system, but industry guidelines such as those recommended by International Organization for Standardization (ISO) for reliable operation are used.
- Equipment Qualification:
    a. Seismic requirement; as a minimum, the same level of seismic requirement as the safety systems is recommended.
    b. Environmental Qualification; this equipment is not expected to be exposed to harsh radiological or environmental conditions. Hence, requirements for mild environment are considered.

Technical data of the APWR DC power supply system include:

- Capacity: 4 trains of battery systems expected to support 8 hours operation without recharging.
- Rated Voltage: 125V DC
- Redundancy: DC system has 4 redundant trains.
- QA requirement: DC system is a safety grade system.
- Equipment qualification:
    a. Seismic requirement; this system is one of safety systems, the seismic requirement is applied.

b. Environmental qualification for mild environment is required for the equipment located in protected area.

II–4. SBO PROVISIONS FOR EPR™ PLANTS

The EPR™ design provides a high level of robustness against extreme hazards. Safeguard function comprises four separate, protected and redundant trains, located in four dedicated safeguard buildings.

In order to cope with the LOOP event, each train is supplied with an EDG with 100% power capacity for its safety train.

Diversity and redundancy are further reinforced with two additional station blackout DGs (SBO DG) using different technologies from the EDG to prevent common cause failures. These SBO DGs, which constitute the alternate AC power sources, are associated with the safety trains 1 and 4.

The EDG and SBO DG buildings of trains 1 and 2 are spatially separated from the trains 3 and 4 DG buildings. Therefore, an external event such as an airplane crash or blast wave can potentially impact only two trains (out of 4) of safety systems.

In case of SBO event, both SBO DGs will start and require manual actions to connect to plant loads to prevent total loss of AC power supply.

In the unlikely event of the failure of standby AC power sources and SBO DG coupled with a LOOP, resulting in a total loss of AC power supply, emergency measures such as secondary bleed & feed of steam generators can be performed to remove decay heat.

Fuel storage capacities for EDG and SBO DG are designed according to plant specific requirements providing sufficient time to enable external re-supply. The standard fuel capacity is 3 days for each EDG and one day for each SBO DG. Onsite fuel storage capacity is more than 12 days. The tanks are designed to withstand external hazards.

The DC supply is guaranteed by 220V Main Batteries for two hours of full DC load according to the four safety train concept. Additional Severe Accident Batteries located in the trains 1 and 4 ensure 220V DC supply for 24 hours for essential loads.

During SBO conditions, the steam generators are supplied by electrical EFW Pumps of train 1 and 4. Each EFW pump provides sufficient water inventory for decay heat removal for 24 hours. The large volumes of water available onsite can ensure the cooling functions for a minimum of 7 days before the requiring replenishment external sources. Existing connections and lines provide the possibility to feed the EFW tanks with alternate onsite water sources including the seismic-resistant firefighting tank.

Pre-installed connection points for supplementing the available resources of water and diesel fuel using mobile means are available to support decay heat removal beyond 7 days.

Additional alternate mobile AC power sources and emergency feed water pumps may be deployed according to the requirements of the plant and national safety authorities.

Double shell containment is designed to withstand a core melt event with reactor pressure vessel failure. In addition, a filtered containment venting system can be installed to prevent uncontrolled release of radioactivity due to Containment overpressure failure.

II–5. CANDU 6

The Enhanced CANDU® 6 (EC6®) is the new Generation III CANDU reactor design that meets the most up to date regulatory requirements. EC6 builds on design and the defense in depth features of

CANDU 6 units and has made improvements to safety and operational performance, and has incorporated operational feedback including lessons learned from Fukushima accident.

In the event that all engineered safety features are unavailable, the inventories in the steam generators, the reserve water tank (RWT), the calandria vessel and the calandria vault will slow event progression. At any stage of the event, onsite and offsite water supplies may be established using provided connections to halt event progression. Following a SBO event, with make-up from the reserve water tank fed by gravity to the steam generators, there is sufficient capacity to keep the fuel cool for several days before emergency power and emergency water are needed. The EC6 design has implemented a three-phase approach to address an extended SBO event, as the one experienced in Japan:

- During the initial phase of the event, permanently installed engineered safety features are relied upon to maintain or restore core cooling.
- During the interim phase, portable onsite equipment and consumables are provided to maintain or restore these functions until they can be accomplished with resources brought from offsite.
- In the final phase, offsite resources are obtained to sustain the functions indefinitely.

An SBO is considered beyond design basis accident (BDBA) according to Canadian regulations, but there is potential for severe core damage (SCD) if the event is prolonged and all cooling systems and backup provisions for water makeup to the steam generators (SGs) become unavailable.

EC6 has large inventories of water within or connected to the reactor building that are available to provide passive cooling, even during accidents in which electrical power is not available and that involve earthquakes and flooding, such as was the case in the Fukushima event.

In the EC6 design, for example, different water sources together come to over 3,000 metric tonnes of water available for passive heat removal. The large water inventories surrounding the fuel can passively remove decay heat from the fuel and the reactor core for many hours after an accident, providing time and opportunity for operator intervention. This is an important inherent safety feature of the CANDU reactors.

In addition to the existing EC6 passive systems, the following safety features have been incorporated in the EC6 design to meet the regulatory requirements and at the same time address the lessons learned from the Fukushima accident. These features (listed below) also increase the robustness of the EC6 design for SBO:

- Design to seismic level (0.3 peak ground acceleration (pga) for UHS) and higher internal pressure (400kPa(g)) of containment;
- Internal steel liner to reduce leakage rate below 0.2% volume per day;
- Refractory layer on top of the calandria vault concrete to delay molten core debris interaction with structural concrete;
- Severe accident recovery heat removal system with dedicated emergency power supply to provide make up water to the RWT, calandria vessel and calandria vault;
- Connections for onsite and offsite emergency water supply;
- Connections for onsite and offsite emergency power supply;
- Passive autocatalytic recombines (PARS) working in conjunction with existing igniters for improved hydrogen control;
- Filtered containment venting system to prevent uncontrolled release of radioactivity due to Containment overpressure failure.

II–6. WWER TOI™

The new reactor design of 1200 MW(e), known as WWER TOI™ is a generic, optimized reactor entirely designed by computerized tools. The WWER TOI™ design has evolved from a standard

WWER 1000/320 model. It contains several passive features (e.g. 4 stages large capacity hydro accumulators, passive heat removal systems from SG, large capacity station battery, etc.), which ensure the integrity of the reactor coolant system and prevent significant damage to the fuel and spent fuel under DBA as well as DEC. The plant is able to cope with a large break LOCA with simultaneous loss of all AC power to safety buses (SBO).

In order to manage an SBO event, the plant is equipped with an alternate AC power system, which consists of one air-cooled diesel generator (0.4kV, 2000kW), and can be connected to either of two safety divisions. The alternate AC power system is manually operated and connected to the safety bus within two hours.

The AC safety bus can be split into two parts via two electrical circuit breakers; one part of the bus supplies DC power system for SBO coping, while the second part of the bus supplies power to the loads such as the containment spray pump (130 kW), emergency boron injection pump (350 kW), DC system, a heat removal pump (131 kW) and air-cooling tower ventilators which are required in DBA conditions. Additional loads such as HVAC equipment can be connected to the bus.

The air-cooled diesel generator can power the following essential loads:

- Boron injection pumps;
- Component cooling water pump;
- Ventilator in a component cooling water tower;
- Containment isolation valves;
- Containment spray pump;
- Dedicated motor operated valves;
- Instrumentation for safety feature actuation system equipment;
- Plant process information and technological protection;
- Radiation control equipment.

Loads are connected manually in sequence as required by the emergency operating procedures.

The continuity of DC power is ensured by two station batteries with a capacity of 2 hours and 72 hours. The DC system bus can be divided by circuit breakers into two sections; one section contains a high capacity battery which can power essential loads for 72 hours without recharging. The other section contains a low capacity battery which can power loads needed for the first two hours.

The following AC essential loads, that require an uninterruptible power supply, are powered from the 72 hours battery bus:

- Air louvres of the passive heat removal system from steam generators (passive system);
- Emergency gas removal from SG collectors and reactor pressure vessel heads;
- Pressurizer relief valves;
- Valves enabling to discharge third stage hydro accumulators into the reactor coolant system;
- Accident and post-accident monitoring system.

ANNEX III

EXAMPLE OF MEMBER STATE GUIDANCE ON SBO

III–1. CANADA

Canadian Nuclear Safety Commission (CNSC) regulatory document REGDOC-2.5.2 entitled Design of Reactor Facilities: Nuclear Power Plants sets out the requirements and guidance of the CNSC for the design of new water-cooled nuclear power plants. It establishes a set of comprehensive design requirements and guidance that are risk informed and align with accepted national and international codes and practices, including the IAEA SSR-2/1 entitled Safety of Nuclear Power Plants: Design.

The design of alternate AC electrical power system design includes provisions for mitigating the complete loss of onsite and offsite AC power. This is accomplished by the use of onsite portable, transportable or fixed power sources or offsite portable or transportable power sources, or a combination of these.

The alternate AC power source is available and located at or nearby the NPP, and:

- Is connectable to but not normally connected to the offsite or onsite standby and emergency AC power systems;
- Has minimum potential for common mode failure with offsite power or the onsite standby and emergency AC power sources;
- Is available in a timely manner after the onset of a SBO;
- Has sufficient capacity and reliability for operation of all systems required for coping with SBO; and for the time required to bring and maintain the plant in a safe shutdown state.

It is required that the design includes provision for periodic capacity testing of the alternate power supply to confirm its capability to cope with a station blackout event.

The capability of the plant to maintain critical parameters (reactor coolant inventory, containment temperature and pressure, room temperatures where critical equipment is located) and to remove decay heat from irradiated fuel is analyzed for the period that the plant is in a SBO condition.

III–2. FRANCE

The design to cope with operating conditions with multiple failures is managed when they likely lead to consequences beyond those of reference operating conditions. Accumulations can be grouped to define a limited number of reference combinations so that the consequences of each reference combination envelop those in the corresponding group; conditions defining these combinations are the multiple failures operating conditions.

Studies of multiple failures operating conditions are used to define the additional design measures to reduce their frequency or to reduce their consequences at the level of those of the reference operating conditions. Probabilistic safety assessments are used, if relevant, to verify the adequacy of provisions for preventing and limiting the consequences.

The plant operator specifies a method for determining the list of multiple failures operating conditions in the demonstration of nuclear safety, which may include use of the results of probabilistic safety assessments made at the design stage. A justification that this method is appropriate is provided.

The multiple failures operating conditions to consider are for example the following, as far as they are plausible enough:

- Complete loss of AC power: the cumulative loss of normal electrical power supply and standby AC power supplies;
- Loss of intermediate cooling systems;
- Loss of the main heat sink source;
- Total loss of normal cooling system of the reactor in a shutdown state;
- Total loss of the steam generators feed water systems (loss of main feed water system, startup and shutdown feed water systems and emergency feed water system);
- Breach of the reactor cooling system combined with the loss of the low pressure or high pressure safety injection system;
- Breach of the reactor cooling system combined with the simultaneous loss of the intermediate cooling systems and uninterruptible raw water;
- Transients with failure of reactor automatic emergency shutdown;
- Failure of more than two tubes of steam generators;
- Total loss of the normal cooling of the spent fuel storage pool;
- Internal event combined with the loss of an emergency system required for the long term cooling of the reactor;
- Cumulative operating conditions with the failure of a family of complex digital equipment.

The licensee is obliged to specify rules and assessment criteria of the results used for the multiple failures operating conditions in an analysis. These rules (absence of single failure, realistic assumptions) and the assessment criteria of the results can be adapted from those used for the reference operating conditions.

III–3. GERMANY

The Federal Ministry for Environment, Ambient Protection and Reactor Safety published new Safety Requirements for Nuclear Power Plants in January 2013. These requirements consider the current state of science and technical knowledge and in particular the lessons learned from the Fukushima accident. General requirements for protection against events due to internal and external impacts and emergency cases also apply to the emergency power supply systems.

General requirements for the emergency electrical power supply can be summarized as follows:

- The electrical power supply of NPP has to ensure the supply of the consumers, which fulfill functions at the defense in depth levels 1 to 4a, according to the specified conditions also in case of events with internal and external impact as well as in cases of emergency. The electrical power supply is reliable and does not determine statistically the availability of the consumers.
- At least two grid connections of the NPP are in place. These two grid connections have to be functionally separated and equipped with independent protection systems.
- In addition to the energy supply from the grid connections and the unit generator, all safety systems, emergency means and safety related equipment have to be supplied in reliable manner from an emergency power supply system consisting of emergency diesel generators, batteries, rectifiers and inverters in case of loss of offsite and unit generator power supply.
- The emergency power supply system is redundant, spatially separated, functional independent and one redundancy protected from the other. The number of electrical redundancies is at least consistent with the redundancy of the supplied technical systems and consumers.
- The battery capacity of each redundancy has to be designed at least for a discharge time of two hours for all events.
- In addition to the aforementioned provisions, one independent electrical supply system with power capacity for a residual heat removal chain has to be foreseen.
- The potential of systematic failures has to be analyzed during the design phase of all components, which contains electrical, electromechanical or electro-magnetic parts and

devices. Provisions have to be taken in order to reduce the frequency of a systematic failure so that it must not be considered or its consequence can be limited and controlled.
- Complex electronic devices have to be designed under consideration and implementation of failure preventing or failure self-controlling provisions.
- Necessary electrical power supply for the execution of all planned plant internal emergency measures and procedures has to be ensured without external support for a time frame of 10 hours.
- The electrical power supply has to be restored with onsite emergency measures and means after an event with loss of all not battery buffered power supply.

The Fukushima lessons learned as well as results from the European Union Stress tests resulted in further increase of a robustness of the plant electrical systems. The AC power supply required for the vital safety functions is ensured even when grid connection in unavailable for up to one week. The emergency AC power generators, stocks of fuel and lubricating oil as well as their auxiliary systems are sufficient to maintain continuous operation after extreme external event.

German design requirements for AC power supply system provide for a robust design consisting of four redundant standby AC diesel generators and four additional stationary emergency feedwater diesel generators physically separated and enclosed in a bunkered building protected against external hazards. An SBO event is included in the design basis of German NPPs. The design also includes at least one mobile emergency power generator, which is protected against external hazards, with sufficient capacity for supplying one redundant residual heat removal train. Predesigned standard connection points, which are protected against external hazards outside of the buildings, allows supplying the safety buses via external (portable) power supply source(s).

III–4. JAPAN

Japanese Nuclear Regulation Authority (NRA) issued new technical standards for nuclear power plants in 2013. Article 14 and 57 contain requirements for withstanding a station blackout.

Article 14 stipulates that in addition to the electric power supply systems for design basis accidents, a nuclear power reactor facility has batteries with sufficient capacity to safely shut down the reactor, to power systems to cool the reactor after reactor shutdown and to power systems/equipment to maintain integrity of the reactor containment during station blackout until an AC power source becomes available.

Article 57 stipulates that a nuclear power reactor facility is provided with the necessary systems/equipment to ensure electric power supplies that are required for preventing significant damage to the reactor core, failure of reactor containment, significant damage to fuel assemblies in the spent fuel pool and significant damage to the fuel assemblies in the reactor in shutdown state when a serious accident occurs.

In addition to the emergency power supply systems required by the Clause 1 of the Article 33 (i.e. requirements for safety power supply systems), a nuclear power reactor facility has permanently installed DC power supply systems to prevent significant damages to the reactor core, failure of reactor containment, significant damages to fuel assemblies in the spent fuel pool and significant damages to the fuel assemblies within shut-down reactor, when serious accident occurs.

Necessary systems/equipment to ensure electric power required in the Clause 1 mean systems/equipment (or any other systems/equipment with the same or improved effectiveness) which are provided for the purpose of coping with station blackout:

- Deployment of transportable alternative power supply systems/equipment (e.g. power supply vehicle and batteries).

– Installation of alternate current power supply system as a permanently-installed alternative power supply system.
– Systems/equipment are independent of and spatially separated from the systems/equipment to cope with design basis accidents.
– The permanently installed DC power system with battery capacity of 8 hours without load shedding[3]. After 8 hours, the system can supply loads for subsequent 16 hours (i.e. 24 hours in total) provided that loads which are not required for safety purpose are disconnected (load shedding).
– Mobile DC power supply is provided that can supply for 24 hours systems/equipment required for the response to serious accidents.
– In case of multiple unit sites, necessary cables are laid in advance to allow electrical interconnection among the units. The power supply to specific unit is connected manually.
– Loss of functions of plant electric equipment (e.g. motor control centers, power centers and metal clad switchgears, etc.) due to common cause failures is avoided by, for example, providing alternative electric equipment.

One simplified one-line diagram that illustrates a composition of alternate AC and DC power systems for coping with station blackout is showed in Fig. III–1.

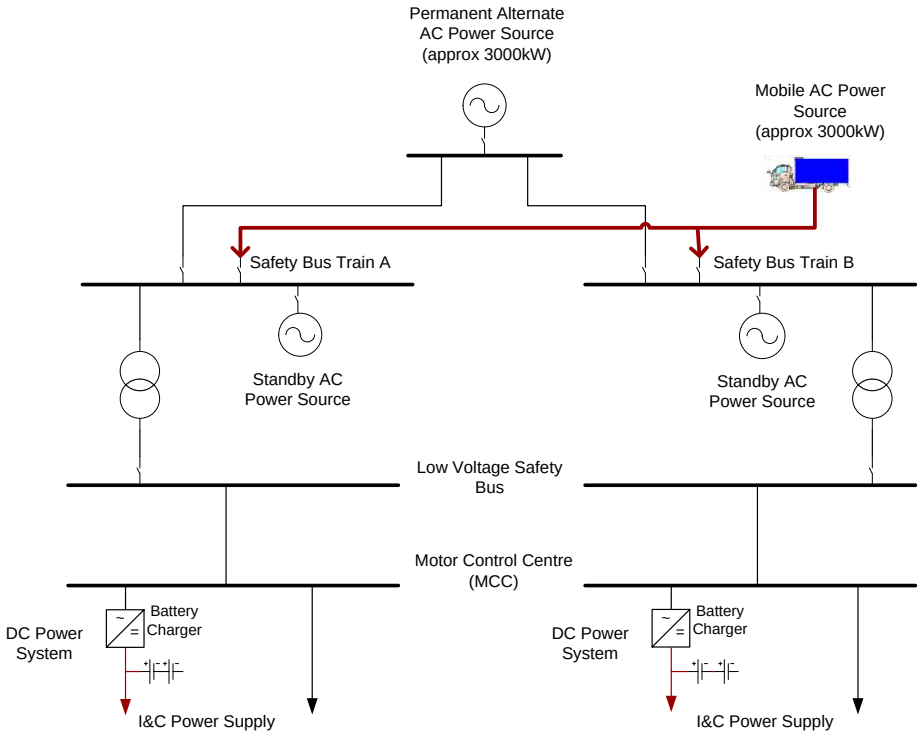

FIG. III–1. Recommended design of post Fukushima electrical power supply (one-line diagram).

In order to increase reliability, one additional permanently installed DC power supply system (the third DC power supply system) is provided. This system supplies DC power to the systems/equipment required for coping with severe accidents for 8 hours without load shedding (except for those loads which can be easily switched off in the main control room or adjacent rooms such as electric rooms)

[3] The load shedding does not include the loads that can easily be switched off from the main control room or adjacent rooms such as electric rooms.

and for subsequent 16 hours (i.e. 24 hours in total), with shedding the loads that are not required for safety.

III–5. REPUBLIC OF KOREA

The SBO requirements are stipulated in the following documents:

- Regulations on Technical Standards for Nuclear Reactor Facilities, Article 24. Electric Power Supply Systems
- Standard Review Guidelines, 8.4 Station Blackout
- KINS Regulation Standard, 9.4 Station Blackout
- KINS Regulatory Guide, 9.13 Station Blackout

In accordance with SBO requirements, all NPPs have to withstand and recover from SBO conditions for a specified duration. According to Standard Review Guidelines 8.4 and KINS Regulatory Guide 9.13, NPPs are provided with SBO coping measures which meet the following considerations:

- SBO coping time
- SBO coping capability
- Procedures and training
- Quality Assurance for SBO coping equipment

A specified SBO coping time is determined by the analysis of site and plant specific factors such as redundancy and reliability of emergency diesel generators, expected LOOP frequency, and probable time needed to restore offsite power.

The SBO coping capability is evaluated to determine the capability of NPPs to withstand and recover from SBO event. The capability to maintain core cooling and containment integrity is also adequately demonstrated. Additionally, the appropriate procedures and training is implemented.

Procedures to cope with SBO and recover from SBO are developed and integrated into the plant specific technical guidelines and emergency operating procedures. These procedures specify necessary actions to attain shutdown or necessary equipment during the SBO event. These procedures identify the portable lighting and communication equipment and also consider the locked entry area where local equipment operation is necessary.

The SBO coping equipment does not require safety classification, but some quality assurance activities for the equipment is implemented as appropriate.

III–6. SLOVAKIA

Regulatory guides include considerations for an SBO event at nuclear power plants. A regulatory guide I.11.1/2013 entitled Requirements for deterministic analyses specifies the structure of analyses for basic design, Design Extension Conditions, and Severe Accidents. An SBO event belongs to the beyond design basis events.

The stress tests performed on European nuclear power plants resulted in additional improvements that are included in the National Action Plan of Slovak Republic for implementation post Fukushima upgrades. This includes the following improvements of the plant electrical power systems:

- Interconnection of safety buses between units;
- Long term management of SBO scenarios;
- Greater flexibility for management of faults of electrical equipment (transformers, etc.);
- Installed alternate AC source(s) common for SBO and severe accident management;

- Provision of mobile DG for charging of batteries and supplying systems and components necessary for core subcriticality and core cooling;
- Provision of technical solutions and cable pre-preparation in order to facilitate interconnection of batteries between systems;
- Reducing emergency illumination levels in order to extend battery run time (subdivision into sections with the possibility for switching off unnecessary loads, use of energy saving bulbs, etc.);
- Provision of monitoring systems capable of operating on batteries;
- Provision of mobile measuring instruments which use measuring sensors without power supply;
- Provision of vital power supply for valves on the bubble steam condenser tower and for hydro accumulator isolation valves.
- Provision of controlling selected valves without vital power supply by using portable 3-phase generators operating at 0.4 kV;
- Development of operating procedure for possible uses of diesel generators installed in a nearby open switchyard;
- To assure long term operation of communication means for main control room operators and operational personnel.

III–7. UNITED STATES OF AMERICA

The current US Nuclear Regulatory Commission (NRC) rules on SBO for Light Water Reactors are formulated in Title 10 of Code of Federal Regulations (10 CFR 50). Section 50.63 is related to Loss of all alternating current power [III–1].

10CFR50.63 requires that each light water cooled NPP licensed to operate must be able to withstand for a specified duration and recover from a SBO, which is defined as the complete loss of AC electric power to the essential and nonessential switchgear buses in a NPP. SBO does not include the loss of available buses fed by station batteries through inverters or by alternate AC sources and does not assume a concurrent single failure or design basis accident. For plants that rely solely on the use of batteries to power essential equipment, the SBO coping time is typically between 4 and 8 hours. These time frames are based on the assumption that at least one source of AC power (offsite or onsite) will be successfully restored within four hours.

The specified SBO duration is based on the following factors:

- The redundancy of the onsite emergency AC power sources;
- The reliability of the onsite emergency AC power sources;
- The expected frequency of LOOP events; and
- The probable time needed to restore offsite power.

The reactor core and associated coolant, control, and protection systems, including station batteries and any other necessary support systems, must provide sufficient capacity and capability to ensure that the core is cooled and appropriate containment integrity is maintained in the event of a SBO for the specified duration.

The capability for coping with a SBO of specified duration is determined by an appropriate coping analysis. NPP operators are expected to have the baseline assumptions, analyses, and related information used in their coping evaluations available for review

The Regulatory Guide 1.155, Station Blackout [III–2] specifies method acceptable for complying with SBO rule. It contains detailed guidance, emergency diesel generator target reliability levels, restoration of offsite power, ability of the plant to cope with SBO, and quality assurance guidance for non safety systems and equipment.

In response to regulatory requirements, the US nuclear industry, under the guidance of Nuclear Management a Resources Council developed Guidelines and Methodologies for Implementing the Station Blackout Initiatives (NUMARC) 8700). This document provides detailed guidance, examples, topical reports, and questions & answers. Other related publications to SBO are:

- US NRC NUREG 0800, Standard Review Plan Chapter 8.4 Station Blackout [III–4];
- US NRC NUREG-1032, SBO technical basis [III–5];
- US NRC Regulatory Guide 1.9 Selection, Design, Qualification, and Testing of Emergency Diesel Generator Units Used as Class 1E onsite Electric Power Systems at Nuclear Power Plants [III–6].

Following the events at the Fukushima Daiichi nuclear power plant on March 11, 2011, the US NRC initiated a Mitigation Strategies order directing licensees to develop, implement, and maintain guidance and strategies to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities in the event of a beyond design basis external event. In particular, NPP strategies needed to be capable of mitigating a simultaneous loss of all AC power and loss of normal access to the ultimate heat sink resulting from a beyond design basis external event by providing the capability to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities at all units.

The NRC also initiated rulemaking to revise Ref. [III–2] to require each operating and new reactor licensee to:

- Establish a minimum coping time of 8 hours for a loss of all AC power.
- Establish the equipment, procedures, and training necessary to implement an extended loss of all AC coping capability for core and SFP cooling and for RCS and primary containment integrity as needed.
- Preplan and prestage offsite resources to support core and SFP cooling, and RCS and containment integrity as needed, including the ability to deliver the equipment to the site in the time period allowed for extended coping, under conditions involving significant degradation of offsite transportation infrastructure associated with significant natural disasters.

In parallel to NRC requirements, the US nuclear industry, under the guidance of Nuclear Energy Institute (NEI), developed document NEI 12-06, ‘Diverse and Flexible Coping Strategies (FLEX) Implementation Guide,’ Revision 0. This is an industry-developed methodology for the development, implementation, and maintenance of guidance and strategies in response to the Mitigation Strategies order. The NRC subsequently endorsed NEI 12-06.

FLEX consists of the following elements:

- Portable equipment that provides means of obtaining power and water to maintain or restore key safety functions for all reactors at a site. This could include equipment such as portable pumps, generators, batteries and battery chargers, compressors, hoses, couplings, tools, debris clearing equipment, temporary flood protection equipment and other supporting equipment or tools.
- Reasonable staging and protection of portable equipment from beyond design basis external event s applicable to a site. The equipment used for FLEX would be staged and reasonably protected from applicable site-specific severe external events to provide reasonable assurance that N sets of FLEX equipment will remain deployable following such an event.
- Procedures and guidance to implement FLEX strategies. FLEX Support Guidelines to the extent possible, will provide pre-planned FLEX strategies for accomplishing specific tasks in support of emergency operating procedures and abnormal operating procedures functions to improve the capability to cope with beyond-design-basis external events.
- Programmatic controls that assure the continued viability and reliability of the FLEX strategies. These controls would establish standards for quality, maintenance, testing of FLEX equipment, configuration management and periodic training of personnel.

The FLEX strategies will consist of both an onsite component using equipment stored at the plant site and an offsite component for the provision of additional materials and equipment for longer-term response.

REFERENCES TO ANNEX III

[III–1] NUCLEAR REGULATORY COMMISSION, Loss of All Alternating Current Power, 10 CFR 50.63, US Govt Printing Office, Washington DC (2007).

[III–2] NUCLEAR REGULATORY COMMISSION, Station Blackout, Regulatory Guide No. 1.155, Washington DC (1988).

[III–3] NUCLEAR REGULATORY COMMISSION, Order on Mitigation Strategies (EA-12-049), Washington DC (2012).

[III–4] NUCLEAR REGULATORY COMMISSION, Standard Review Plan Chapter 8.4 Station Blackout, NUREG 0800, Office of Standards Development, Washington DC (2007).

[III–5] NUCLEAR REGULATORY COMMISSION, SBO Technical Basis, NUREG-1032, Office of Standards Development, Washington DC (1988).

[III–6] NUCLEAR REGULATORY COMMISSION, Selection, Design, Qualification, and Testing of Emergency Diesel Generator Units Used as Class 1E Onsite Electric Power Systems at Nuclear Power Plants, Regulatory Guide No. 1.9, Washington DC (1993).

ANNEX IV

EXAMPLE OF MEMBER STATES DESIGN PROVISIONS FOR SBO

IV–1. CANADA

IV–1.1. SBO considerations

SBO considerations for CANDU PHWRs are based on a multiple barrier concept to event progression and multiple means to supply water or electricity will be used to ensure adequate defense in depth.

Multiple barriers to ensure fuel cooling provides redundancy and also allows the event to be terminated at various stages if one barrier fail or become unavailable. These barriers to fuel cooling are provided using Emergency Mitigating Equipment (EME) consisting of portable water pumps and portable AC power generators.

In the event of a total loss of heat sink event, if the design basis methods of providing fuel cooling cannot be restored, the most effective alternate method of preventing a loss of heat sink event from progressing into a severe accident is to provide emergency cooling water to the SGs. This is achieved by rapid cooldown of the SGs through the boiler safety relief valves and by adding emergency makeup water to the SGs. Rapid cooldown of the SGs serves two purposes.

- First, it provides rapid cooling and depressurization of the Heat Transport System (HTS). This increases the margin to fuel failures, reduces the energy introduced into containment via the heat transport relief system, and allows for EME to inject additional water into heat transport system.
- Secondly, the release of steam from the SGs by the opening of steam relief valves depressurizes the SGs and allows for the injection of water from EME to the SGs so that they can act as a sustainable primary heat sink.

Since the SGs are the primary and most important barrier for prevention of the progression of a beyond design basis event into a severe accident, robust means must be available to provide rapid cool down of the SGs, to enable the SGs steam relief valves to be held open and to provide emergency cooling water into the SGs.

IV–1.2. Survivability confirmation

Necessary systems, structures and components (SSC) will be confirmed to survive rare yet credible conditions for external hazards.

The systems, structures and components (SSC) which are required to function for rare yet credible beyond design basis events must be demonstrated to be capable of operating under the low probability, high consequence conditions for which they are expected to operate. This assurance can be provided by demonstrating that the credited SSCs are capable of surviving relevant external hazards at their credible Review Level Conditions.

An alternative approach is to demonstrate through fragility analysis that the SSCs have substantial margin beyond the design basis condition without specifying a Review Level Condition in advance.

A method to provide protection against hazards such as seismically induced internal fire or flood could utilize diversity and independence which could involve the use of a second connection point for water or power at different locations in order to mitigate the consequence of a lost connection point due to a fire or flood.

The consideration of these approaches is included in analysis, strategies and modifications to ensure EME will add value at the time of the event.

IV–1.3. Irradiated fuel bay water level

Irradiated fuel bay (IFB) water levels are maintained sufficiently above the top of the fuel to mitigate high radiation fields, hydrogen production and fuel damage. Providing an emergency water supply to the SFP in the event of a total loss of AC power is critical to ensuring cooling of the fuel in the SFP. Maintaining an adequate level of water in the SFP will ensure low dose rates in the SFP area through shielding, will prevent hydrogen production due to fuel oxidation and will prevent fuel failures due inadequate heat removal.

Because of the importance of maintaining the fuel covered, it must be possible to provide emergency make-up water to the SFPs using the EME pumps, and corresponding procedures and/or guidelines must be in place to ensure water make-up to the SFP. The target is to maintain water level in the normal range with EME equipment. Hazards are still possible from steaming and water overflowing out of the SFP; however the primary hazard of fuel failures, high dose rates and hydrogen production will be precluded. The time required to respond to a loss of SFP cooling is typically quite long for PHWRs which use natural uranium fuel bundles; therefore, it is regarded as acceptable to have a single method of providing emergency water to the SFPs. It is necessary to ensure that the capacity of the make-up water through EME exceeds the required capacity to make-up for evaporation and conservatively estimated SFP leakage, due, for example, to cracking of the concrete due to elevated temperatures.

The volume of water in the SFP during normal operation is maximized within normal water levels to the extent practicable. This increases the time for heat up of the overall SFP water and therefore increases response time for adding make-up water in a loss of SFP cooling event. Maximizing water within the SFP volume is done by controlling and removal of objects that displace water such as spent fuel and other material such as racking, baskets and flasks.

Typically spent fuel is removed from the SFP to dry storage containers after 10 years of residency in the SFP. At this age the fuel's low decay heat generation allows for adequate cooling by air. The movement of fuel to dry storage is a focus by the utilities by removing fuel as soon as able based on fuel cooling needs. Fuel could be moved sooner than 10 years as studies presently indicate fuel could be moved as early as 6 years to dry storage.

IV–1.4. Emergency mitigating equipment

Emergency mitigating equipment (EME) is robust, readily available, easily deployable within required timeframes, and have adequate redundancy. The EME will be purchased, stored in a suitable location at or near the site and have a planned maintenance and availability testing program to ensure the equipment will operate reliably if required to address Beyond Design Basis Events. This equipment plays an important role in providing defense in depth and a credible response to BDBEs and BDBAs, including severe accidents.

To ensure this equipment is able to function and meet performance requirements the following sub-principles are identified:

- Emergency Mitigating Equipment Principles:
    - The EME Storage facility is at a higher elevation and at a distance from the station to provide separation (minimize common mode event impact) but close enough to allow deployment in a timely manner.
    - The storage facility is either a robust building which can withstand a severe external event at the review level condition or a building that does not impede recovery of EME equipment by personnel if the structure is damaged by external forces.
    - EME deployment is simple, via procedures or operating guidelines.

- EME deployment is not entirely reliant on specialized staff or specific work groups unless that work group has sufficient numbers to provide effective task implementation and redundancy. The rationale is to maximize the number of personnel that could execute the deployment and therefore increase the likelihood of successful deployment. Consideration is given to maximizing the diversity of staff that can deploy EME (i.e., staff not requiring specialized skills) using simple tasks, pre-job briefing and procedures/guidelines.

- Training and practice is provided to staff for the tasks they have been planned to execute.
- EME use proven technology as to reliability, effectiveness and run time.
- A preventative maintenance and availability testing program is defined and executed.
- Unless significant benefits exist, testing of EME is kept separate from station systems (i.e. not connected) to minimize risk of errors and equipment failures that could impact normal system operation and safety.
- Diversity of EME deployment vehicles does not rely on one method or vehicle (e.g., delivery vehicles may include trucks, tractors and security vehicles).
- Onsite fuel supplies are sufficient for at least 72 hour run time of EME to support all reactor units at site and IFBs.
- It is possible to refuel EME in place.
- Pre-staging of EME is an option to events which may impact deployment (e.g., high winds).
- Connections to station systems maintain the same number of pressure boundary barriers as presently exist. For example the boiler feed system typically has an isolation valve plus a threaded cap to contain leakage for piping that allows external flow of water or steam. Any modifications to enable quick connections of EME maintain these two barriers such as a valve and quick connect plug.

Connections do not have no negative impact on the station system in terms of seismic or environmental qualification or compliance with applicable codes and standards.

IV–2. FRANCE

An SBO event was originally considered as beyond the design basis event. SBO is limited to one unit. Current design includes a turbine driven emergency feedwater pump and a permanent turbine driven small alternate AC power supply, which is designed to power loads such as minimum I&C, emergency lighting, associated DC sources and a volumetric pump for the RCPs seal injection.

Maintaining the integrity of RCP seals is a primary issue in SBO condition. Électricité de France (EDF), the French power generation company, performed a test to assess the time that RCP seals will remain leak tight without cooling. Although test results were satisfactory, it was difficult to conclude whether RCPs seals were reliable enough to maintain their integrity without any cooling (loss of the cooling of the thermal barrier combined with the loss of the injection to the seals).

A full scale test with the goal of forming a steam bubble under the reactor pressure vessel head was performed at one unit of the Gravelines NPP: All RCPS were shutdown (core cooling by natural circulation) and the reactor was operated with maximum pressure and temperature (P and T) conditions to facilitate the formation of a steam bubble. The test showed that it was not easy to create a steam bubble.

A decision was made to make available to the plants an additional mobile AC power source to cope with SBO combined with a loss of the integrity of RCS (failure of the RCPs seals/small LOCA). One mobile diesel generator is provided for several units located in the same region. The required mobile diesel generator is located at one site and could be moved to another site as soon as a SBO event occurs. Nevertheless feedback has revealed that this shared equipment was ignored by the operators (poor maintenance), so a decision was made to install one per site. Currently, permanent pre-aligned alternate power sources are installed to reduce connection time.

IV–2.1. The hardened safety core

The hardened safety core (HSC) of limited key functions provides means to cope with extended SBO scenarios. Examples of HSC arrangements at French NPP design are shown on Fig. IV–1 and IV–2. It consists of physical and organizational provisions that are robust enough to cater to extreme situations by preventing or limiting the progression of an accident with fuel melt, mitigating large-scale radioactive releases, and allowing the operator to perform the required crisis management missions. The preferred design of the HSC is independent and diversified Structures, Systems and Components (SSCs) as compared to the existing SSCs to minimize common-mode failure.

For EDF, the HSC constitutes an ultimate safety net which will be used only in the event that the established comprehensive approach to safety is not sufficient:

- Conservative design of the plant with built in design margins remains the cornerstone of nuclear safety,
- Margins and additional features which enable an improvement in behaviour in DEC. EDF recalls that parts of the Post-Fukushima actions includes improvements in this area.

As a result, only a limited number of key functions are included in the HSC which makes it possible to achieve robustness against high levels of hazards while taking into account possible impacts of installing these components.

The perimeter of the HSC has been proposed by EDF and may be subject to additional prescriptions from the Nuclear Safety Authority (ASN):

- Ultimate additional back up diesel (DUS), batteries, electrical connections;
- Instrumentation to diagnose the state of the plant, assess and predict the radiological impact of releases on the workers and the public (weather and environmental measures) and control the HSC;
- Diversified EFW to the SGs:
- Depressurization of the RCS, and sufficient injection capacity to maintain vessel integrity;
- Reinforced water make-up supply to SFP and reactor pool;
- Containment isolation;
- New local crisis centre (LCC);
- Mobile devices and means of communication essential to emergency management; and
- Means to control containment pressure.

Implementation of the DUS is one of the main requirements. The objective is to implement it by 2018, but the first improvement will be operational by the end of 2013 with lighter generator sets and mobile devices for make-up water.

New LCC will be deployed between 2016 (Flamanville) and 2020. The standard building will be large enough and equipped to manage the crisis on a long term basis, taking into account all its aspects. It will include a plant data supervision room with essential data, intervention facilities, crisis management equipment, mobile equipment storage and offer living conditions (rest, food, hygiene). It is designed for a capacity of 100 people (multiply by two during shift turn-over), to remain accessible and habitable at all times and to handle a multi-unit crisis.

The proposed loading cases for HSC are derived from those considered in CSA (complementary safety assessment). SSCs belonging to HSC are to be protected from effects induced by these extreme situations, either internal like load falls, fires, explosions, or dangerous installations located in the vicinity of the plant that can cause fires, explosion, or toxic gases releases.

For earthquake, EDF has decided to take into consideration, in addition to the improvements already considered for the CSA, the rules applicable to other dangerous classified installations. This decision leads to the application at some sites of an increase up to 100% in the amount of Seismic Monitoring

Systems) SMS (for instance nuclear power plants in Fessenheim, Bugey and Blayais) or even 200% (St Alban). Spectral shapes associated with these acceleration levels remain defined according to fundamental rules of safety.

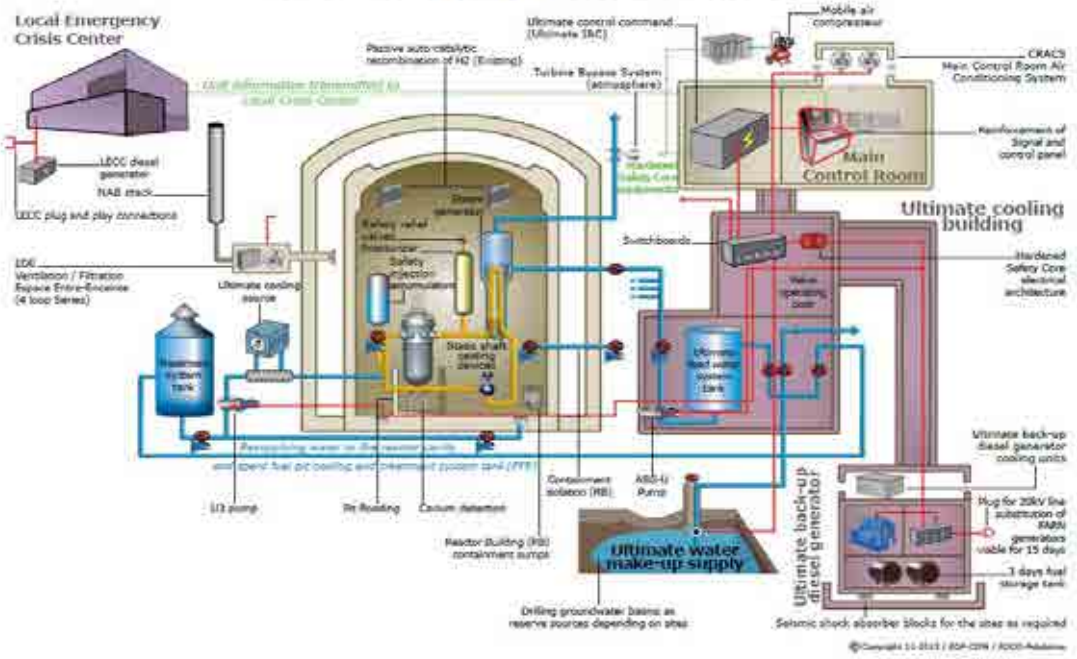

FIG. IV–1. Example of hardened safety core (photo courtesy of EDF).

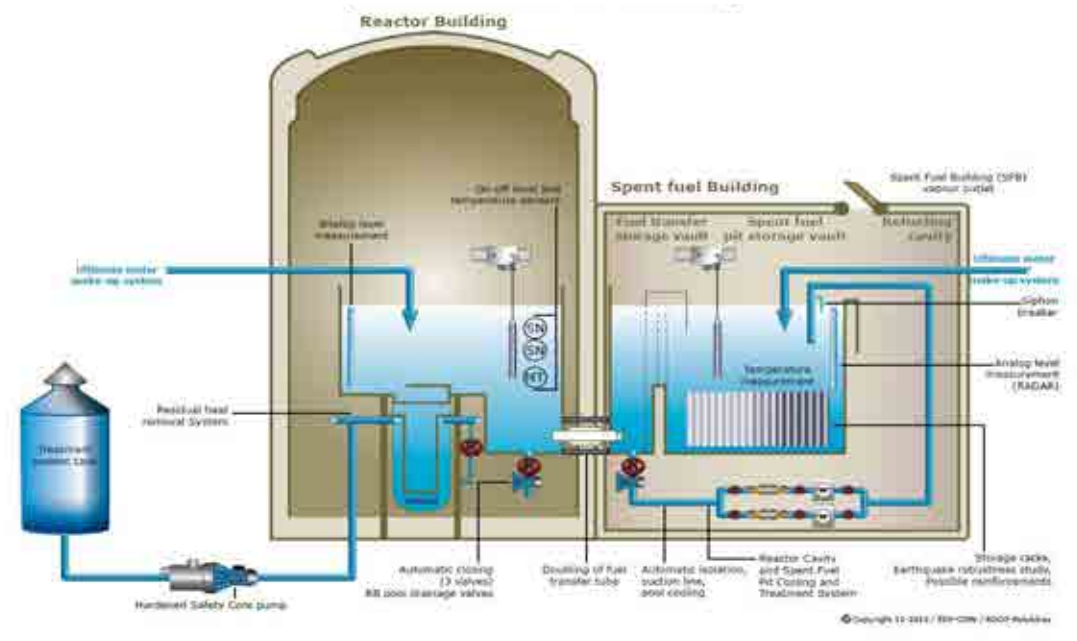

FIG. IV–2. Hardened safety core focusing on spent fuel pools (photo courtesy of EDF).

For flooding hazards, a study is in progress to check if for some sites a severe earthquake upstream of the site could cause the break of more than one dam (the most limiting dam break is already considered in the design basis).

The HSC will also take into account other natural phenomena, namely lightning (maximum load of 300 kA with a specific energy of 45 MJ/Ohm), hail (50 mm diameter with a speed of 32 m/s and a density in the range of 0.9), and an F4 tornado.

IV–2.2. Nuclear rapid response force

Less than two months after the Fukushima event, EDF decided to implement a deployment of a nuclear rapid response force (FARN); which able to provide quick assistance to a plant facing difficulties. Deployment began late 2012 and will be completed in the year 2015. The objective of the FARN is to be able to get to the site of a NPP undergoing an accident, within 12 hours, in order to provide skilled operators onsite to support the local shift, and provide relief staff for auxiliary duties. If onsite equipment is not functional or unavailable, the FARN will supply mobile equipment to re-establish or maintain core and SFP cooling, to minimize core melt or significant release and contain the release. The FARN ensures supply chain and technical support. The autonomy goals are as follows:

- Use of the existing fixed equipment remained available and implementation of local mobile equipment to be deployed by the teams on site will allow site autonomy of at least 24 hours.
- After 24 hours, the FARN, with its own dedicated human resources and dedicated mobile equipment, will supply the site to guarantee autonomy of at least 72 hours.
- After 72 hours, additional resources from the EDF Group, and if necessary from partners, will guarantee the continuity of maintaining the affect NPP(s) in a safe stable condition.

The FARN design considers that only one site out of the 19 sites faces a severe accident, that the infrastructures may have experienced major destructions, including access to the site, and that the work environment may include radiological and/or chemical hazards.

FARN is fully encompassed into the EDF national crisis organization. The decision to alert FARN is made by the nuclear fleet Director, at the request of the NPP management, advised by a FARN headquarters member.

IV–3. GERMANY

All nuclear power plants have their main grid connection to the 380kV transmission network. In addition, the plants have a connection to the 110kV auxiliary transmission system. In individual cases (GKN II), this auxiliary grid connection is diversified by transmission lines and an underground cable connection. Furthermore, the auxiliary grid can be supplied by a gas turbine with black start capability.

In case of loss of the 380kV and 110kV systems, the expected sequence of the event is as follows:

- After opening the 380 kV circuit breaker the house load will be supplied by the unit generator. The plants have load rejection capability from full load to house load without actuation of reactor scram. The turbine generator is designed for operation on low power to accommodate this mode of operation. During house load operation, turbine protection limits will not be exceeded and as such house load operation is not restricted in time. Real load rejection tests have proven this capability.
- The four emergency diesel generators (EDG D1) will start, when the house load cannot be supplied from the unit generator and the plant buses are transferred to the auxiliary grid. The four Emergency Power supply trains are associated with four redundant shutdown trains according to the 4 x 50% (n + 2) concept. Each EDG has a power capacity between 5 and 6 MW(e), depending on the individual plant.
- The four EDG D1 are located in spatially separated trains in the EDG building which is designed to withstand site specific earthquake and flooding requirements. The switchgear for the normal and emergency D1 loads is located in the switchgear building with the same

protection level. The EDG D1 is water cooled by the secured component cooling circuit which transfers the heat to the Secured Service Water System.

– In case of SBO, the essential AC power supply will be automatically provided by four emergency feedwater diesel generators (EFWDG D2) located in the fully protected bunkered emergency feedwater building (EFWB).

IV–3.1. Offsite Power Restoration

Prior to restoration of offsite power, it is assumed that the emergency power is being supplied by the EDG D1. The offsite power can be restored from either the 110kV or the 380kV systems. The preferred sequence is to start with the 110kV source. In this case, the sequence detailed below:

– Energize the auxiliary transformer from the 110kV source,
– Energize the 10kV normal power buses from the auxiliary transformer. The normal power loads have to be loaded sequentially and not simultaneously.
– Synchronize the 10kV emergency power buses fed by the EDG D1 to the normal power buses.
– Shutdown of the EDG D1 and return to standby mode.
– Energize the station transformers from the 380kV source.
– Energize the house load transformers, prepare house load transfer to the 380kV system
– Transfer to the buses to house load transformers and the 380kV power source.

IV–3.2. SBO management

The objective of SBO management is to prevent the total loss of AC power supply (TLACPS) at the NPP. In case of SBO (loss of offsite power, the house load cannot be supplied from the unit generator and all four EDG D1 failed to start), the reactor protection system (RPS) will automatically start the four emergency feedwater diesel generators (EFWDG D2) located in the fully protected bunkered emergency feedwater building. Load sequencing will occur automatically by the RPS.

The EFWDGs D2 also have the four train redundancy concept and are rated at 1.2 MW(e) each. Therefore, the classic SBO event (loss of offsite power and loss of onsite standby or emergency EDGs) does not result in a TLACPS.

The emergency feedwater building is shown on Fig. IV–3 is designed to withstand airplane crash (APC), blast wave, earthquake, flooding and extreme weather conditions.

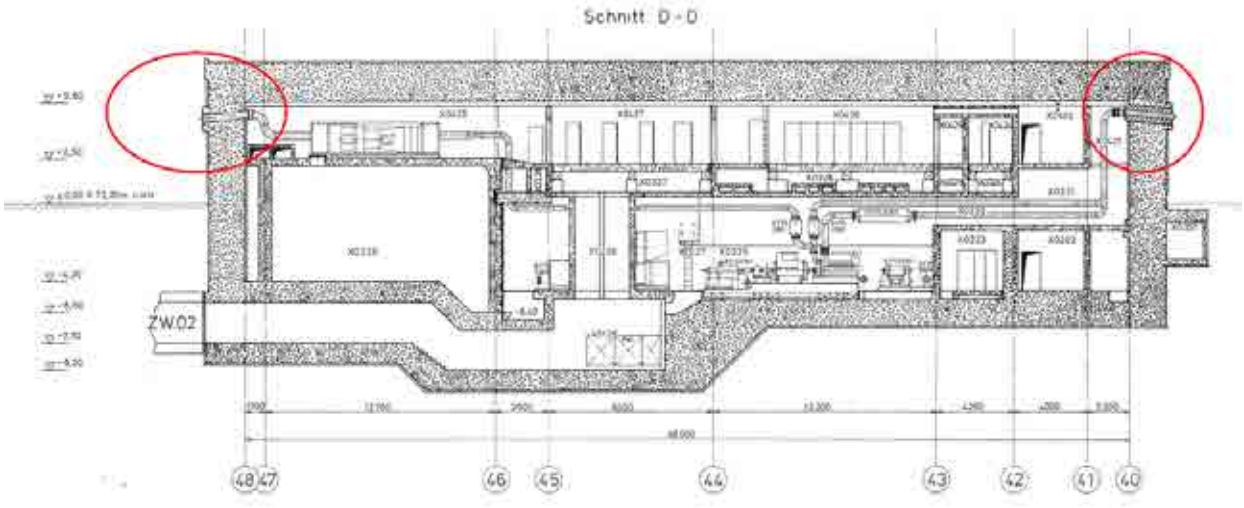

FIG. IV–3. Sectional drawing of one redundancy of the emergency feed water building.

The building contains four physically separated redundancies:

- Four emergency feedwater diesel generators and the required fuel tanks;
- Four emergency feedwater pumps (EFWP) on the same shaft of the EFWDG D2 and the emergency feedwater system;
- Four demineralized water tanks, each of 360 m³ capacity for supplying the SGs and providing the heat sink during emergency operation condition of the systems located in the building;
- The necessary systems for HVAC and internal cooling of rooms and components;
- The parts of the RPS, which has to be protected from external events and further safety-related I&C;
- The switchgear for all components supplied from the EFWDG D2 including rectifiers and 48 V batteries for DC supply;
- The emergency control room.

Figures IV–4 and IV–5 show composition of internal equipment in the feedwater building.

FIG. IV–4. Emergency feedwater diesel D2 with 1.2 MW(e) power emergency feedwater pump on the shaft of the EFWDG set (photo courtesy of AREVA).

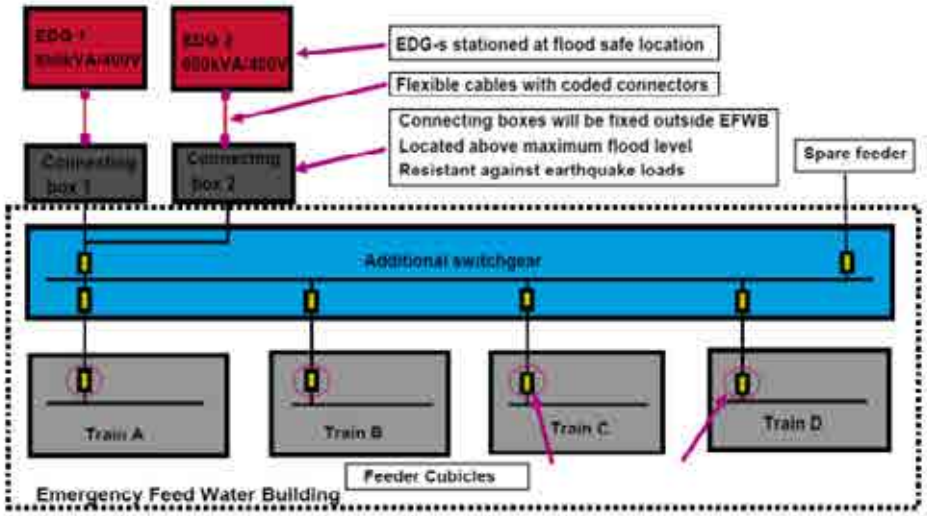

FIG. IV–5. Electrical diagram for connecting two mobile EDG.

Makeup to the reactor coolant system will be guaranteed by extra borating pumps which are located in the reactor building annulus and have power supply from the EFWDG D2.

The diesel fuel and demineralized water resources in the EFWB are estimated to last for 24 hours. Within this time, the plant may be cooled down to conditions which allow decay heat removal by the two emergency heat removal chains supplied by the EFWDG D2 of the trains 1 and 4.

An SBO with duration of more than 24 hours is considered as an extended SBO. In this case, fuel oil and water resources in the EFW building have to be replenished in order to ensure the long term operation of the EFWDGs until offsite power or the EDGs D1 can be restored. This way, the long term decay heat removal from the reactor core and the spent fuel pool by the emergency heat removal chains will be guaranteed.

The coping duration is therefore only limited by the availability of additional fuel oil and water for the operation and cooling of the EFWDGs.

A probabilistic failure frequency of the TLACPS has been assessed to be less than 10^{-7}/year. Based on probabilistic analyses, the total loss of AC power supply is a postulated DEC with duration of up to 10 hours.

IV–3.3. Management of the total loss of AC power supply

The Total Loss of AC Power Supply will be handled based on emergency operating procedures (EOP) provided within the emergency manual.

German NPPs have a battery capacity for at least two hours of nominal load available (GKN 2 has replaced batteries with new ones with full capacity for 10 hours).

When the TLACPS occurs and AC power supply cannot be restored quickly, preparations for the Secondary Bleed & Feed have to be started (about 60 to 70 minutes for different plant designs). The rectifiers charging the 48V batteries in the EFWB can supply AC UPS buses for at least two hours. A portable diesel generator set (mEDG 1) rated at 200kVA, stored in the floor of the EFW building near the material lock, can be used to recharge the batteries. The mEDG 1 can be positioned on the ramp outside the material lock and connected to a pre-installed connection panel. The mEDG 1 can supply 48V rectifiers in all four redundant trains of the EFW building for another 10 hours. Furthermore, the mEDG 1 can also supply a portable firefighting pump with electrical motor available in the EFW building for feeding the SGs. With these measures, all German NPPs are able to cope with an extended SBO (TLACPS) for 10 hours.

In order to further improve the plant robustness, the plants additionally purchased portable diesel generator sets (mEDG 2) rated at about 1.2 to 1.3 MVA as second alternate AC power sources. These mEDG 2 are stored at the plant in a facility protected against floods and earthquake. Connection panels and switchgear have been installed for connection of these mEDG 2 to the 380V D2 buses in the EFW building. The mEDG 2 is required to be operable and ready for power supply within 10 hours after onset of a TLACPS. It has the capacity to feed one complete emergency train including an emergency heat removal chain and an Extra Borating Pump for feeding and boration of the RCS. Therefore, the mEDG 2 can replace the functions of mEDG 1 after 10 hours.

Dedicated connection boxes, additional switchgear and feeder cubicles to the buses of each train of the EFWB were installed at the plants.

With the alternate power supplies in line, the plants can be cooled down to cold subcritical condition even during TLACPS and maintained in safe condition on long term until recovery of normal power supply.

Some examples of the electrical installations implemented after Fukushima at German nuclear power plants in order to enable alternate AC power supply by mobile EDG are shown on Figures IV–6 to IV–11 below.

FIG. IV–6. Feeder cubicle for alternate power supply inserted into the existing switch gear (photo courtesy of AREVA).

FIG. IV–7. Fixing points for the cable connection box arranged above the maximum flood level (photo courtesy of AREVA).

FIG. IV–8. Water tight Brattberg cable seals (photo courtesy of AREVA).

FIG. IV–9. New switchgear on the diesel floor as interface between the mEDG 2 and four 380 V D2 busbars (photo courtesy of AREVA).

FIG. IV–10. New earthquake resistant cable trays (photo courtesy of AREVA).

FIG. IV–11. Mobile EDG with 650 kVA at its standby position (photo courtesy of AREVA).

IV–3.4. Provisions for SBO resulted in core melt

The core melt frequency due to TLACPS for German NPP has to be considered in the range between 10^{-8}/a and 10^{-9}/a taking into account all provisions of the defense in depth concepts discussed above. Independent from this, severe accident systems are installed in order to prevent significant radiological impact on population and environment in the surrounding of the plants.

In case of core melt, the integrity of the containment has to be ensured and early or significant radioactive release has to be excluded. Therefore, passive autocatalytic recombiners (PAR) have been installed in the containment for reduction of hydrogen concentration and a filtered containment venting system (FCVS) is available. Both systems work without electrical power. The FCVS can be operated manually in a controlled way allowing to optimize the venting strategy and to minimize radioactive releases.

Emergency procedures of the emergency manual and severe accident management guidelines are available or going to be implemented in 2014 to support the work of the onsite emergency response team of the plant.

Recovery from TLACPS is achieved when AC power supply is restored from one of the offsite power resources or at least one of the eight installed E(FW)DGs (5-6 MVA or 1.2 MVA) or the portable mEDG 2 (1.2 MVA) is available to power the requisite buses.

The main control room and the emergency control room are equipped with aerosol filtered ventilation systems in order to minimize the exposure of operating personnel in any case of radioactive release to the atmosphere.

IV–5. JAPAN

The new Japanese regulation defines a power supply recovery strategy for an SBO event. All NPPs are required to demonstrate coping capability for at least 24 hours with DC power sources only. This new regulation is intended to allow plant operators enough time and margin for connecting the alternate AC power source to safety buses and maintain the plant in safe shutdown (i.e. hot shutdown condition), and preclude core damage.

IV–5.1. Coping with short SBO event

IV–5.1.1. No AC power supply systems are available.

Each plant is required to cope with an SBO event (without any AC power sources) for 24 hours. DC power is supplied from plant battery system and is used to maintain the instrumentation and safe shutdown conditions.

Typical DC loads are identified in Table IV–1 A coping strategy for PWR plants includes the following:

- Plant heat removal: SGs are supplied by turbine driven auxiliary feed water pump (TDAFWP). The water source is essential feed water tank (EFWT) which has capacity for 24 hour operation.
- RCP integrity: Robust/improved RCP seal design maintains seal integrity for 24 hours.
- Electrical power: Power is supplied from DC Batteries which are required to run for 8 hours without load shedding and additional 16 hours with non-critical load shedding.
- Plant status monitoring: Monitoring capability in main control room using DC powered instrumentation.
- Ambient condition: Natural air circulation supported by opening doors to keep the room temperatures within the maximum allowable design limit.

TABLE IV–1: TYPICAL DC LOADS AT SBO (EXAMPLE)

Load	0 - 8 hours	8-24 hours
Control system for TDAFWP	x	x
I&C system	x (2 trains)	x (1 train only)
Main Control Board	x	x
Switchgear system	x	-
Control system for EDG	x	-

IV–5.1.2. Relying on support from AC power supply systems.

The AC power is restored from an alternate AC source buses within 24 hours to cope. The alternate AC power system is diverse as compared to the design of standby power supply systems. The alternate AC power systems consist of permanently installed sources and mobile sources.

Typical PWR plants will be equipped with an alternate AC power source from gas turbine generators (GTGs) located inside the NPP building, and mobile AC power source with installed GTGs. The mobile power sources are located near the NPP site.

A coping strategy for extended SBO for nuclear power plants with PWR after 24 hours involves:

- Plant heat removal: SGs are supplied by TDAFWP or motor driven auxiliary feed water pump (MDAFWP). Residual heat removal system can also be used in order to cool down to cold shutdown condition.
- Reactor coolant pump seal integrity: Charging pump starts to support RCP seal cooling system.
- Electrical Power: Alternate AC power.
- Plant status monitoring: Monitoring in the main control room with instrumentation powered from DC and alternate AC power system.
- Ambient conditions: HVAC system powered from alternate AC power to maintain room temperatures.

The alternate AC loads required for the coping strategy are identified in Table IV–2.

TABLE IV–2: TYPICAL ALTERNATE AC LOADS AT SBO (EXAMPLE)

Load	Permanent AAC	Mobile AAC
MDAFWP or RHR pump	x	-
Charging Pump	x	x
Component Cooling Pump	x	x
Essential UHS pump	x	x
HVAC system including essential Chillers	x	-
DC systems	x	x

IV–5.2. Coping with extended SBO event

Based on new regulatory requirements, Japanese NPPs are required to cope with an extended SBO (longer than 24 hours) by using two types of alternate AC power sources which are designed to provide sufficient AC power supply in order to ensure:

– Plant heat removal: Steam generators are supplied by TDAFWP or motor driven auxiliary feed water pump (MDAFWP) in order to maintain hot shutdown condition. Residual heat removal system also can be used in order to cool down to cold shutdown condition.
– Reactor coolant pump seals integrity: Charging pump is started to provide cooling to reactor coolant pump seals.
– Plant status monitoring: Monitoring in main control room with instrumentation powered from DC and alternate AC power system.
– Ambient conditions: HVAC system powered from alternate AC power to maintain room temperatures.

After 72 hours, operators transfer the feedwater pumps to external water storage tanks. Similarly, diesel driven pumps, diesel generators fuel tanks are refilled from external storage tanks.

IV–5.3. Considerations of protective measure for extreme external hazard

Japanese NPPs are required to protect the SBO equipment for extreme events such as seismic and Tsunami. Each site is required to implement series of protective measures for beyond design basis flooding due to tsunami and sealing of NPP buildings against water intrusion.

As a short term countermeasure against the extreme tsunami, several enhancements on sealing of essential rooms and buildings were implemented.

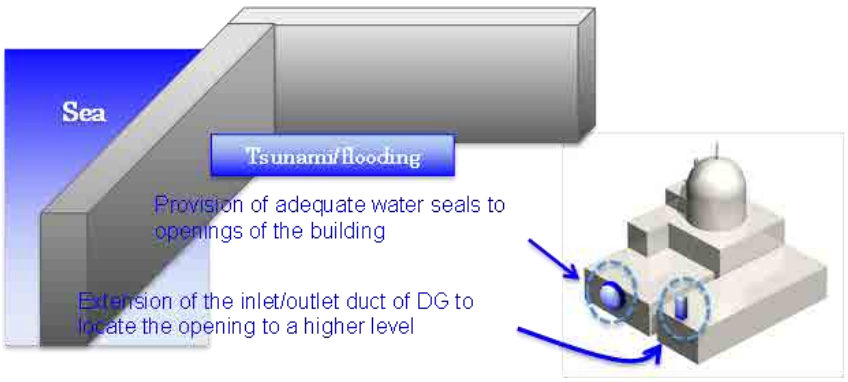

FIG. IV–12. Design provisions to prevent water intrusion through doors and exhaust system of diesel generator (photo courtesy of Mitsubishi Heavy Industries).

As long term countermeasures against the extreme tsunami, protection banks for each site are under consideration. The height of each bank will depend on the postulated magnitude of the extreme external hazard for a specific plant site. Fig. IV–12 shows typical design provisions to prevent water intrusion through doors and exhaust system of an emergency diesel generator.

IV–5.4. Configuration of mitigation systems

Basic configuration of SBO mitigation system consists of an alternate AC power supply system and DC power system. Typical capacity of the permanent and mobile alternate AC is approximately 3500kVA (1800kVA * 2 sets), with rated voltage of 6.6kV. While there is no requirement for redundancy, a permanent alternate AC and the mobile alternate AC are considered as redundant. Although there is no safety grade required for mobile AC sources, but meeting of industry recommended standards for achieving high reliability is needed.

The alternate AC power system is qualified in accordance with seismic requirements. Alternate AC equipment is located in protected area, therefore only qualification to mild environment is required. The design requirement for the cable connection is the same as for alternate AC system.

DC power supply at 125V DC is required to provide power for 8 hours without any load shedding, and additional 16 hours with shedding of non-essential loads. Although there is no requirement for redundancy, typical PWR DC power supply system comprises two trains. Because DC system is safety classified the quality assurance programme for safety systems is applied.

The DC power system is qualified in accordance with seismic requirements. The DC power equipment is located in a protected area, therefore only qualification to mild environment needs to be demonstrated.

IV–6. REPUBLIC OF KOREA

IV–6.1. LOOP coping capability of Korean NPPs

The offsite power systems consist of two physically independent circuits that are defined as the preferred power supply systems from the transmission network to the onsite electrical distribution systems in order to supply offsite power to safety and non safety loads. During normal operations, electric power generated from the main generator is supplied to the onsite distribution system through unit auxiliary transformers.

If the main generator trips, a generator circuit breaker opens and offsite power is supplied from the power grid to the onsite power bus via a main transformer and unit auxiliary transformers. If the main transformer or the unit auxiliary transformers fail, the power transfer is made from the unit auxiliary transformers to the standby auxiliary transformers and offsite power is supplied to the onsite distribution system through the standby auxiliary transformers.

To cope with the LOOP event, redundant safety class EDGs forming two trains which complying with the single failure criteria are installed in separate areas of the auxiliary building and are electrically independent. Fuel inventory is secured for each EDG to supply 100% power to full loads for seven days. The EDGs are water-cooled type using seawater as the heat sink.

The EDGs reach the rated voltage, frequency, and speed within 10 seconds after startup and have sufficient power to supply the safety related loads. The plant technical specifications require recovery from the LOOP event within 24 hours.

IV–6.2. SBO coping capability

The permanently installed alternate AC power source(s) to cope with SBO event has sufficient capacity, reliability, and testability. The alternate AC power source has a physical and electrical independence from the preferred power supply and emergency power source systems. After the onset of SBO, the alternate AC power source is available in a timely manner (typically, available within 10 minutes) and be manually connected to a safety bus to achieve and maintain safe shutdown. The parameters of the alternate AC power source and their circuit breaker position is monitored in the MCR. In case of multi-units at a specific site, the alternate AC power source is able to supply up to maximum of 4 units.

IV–6.3. Extended SBO for Korean NPPs

All NPPs have measures to cope with extended SBO event following unavailability of EDGs and alternate AC power source(s) due to beyond design basis natural events. The following countermeasures which take into account the lessons learned from the Fukushima Daiichi accident have been implemented adequately.

- Securing mobile generators and batteries;
- Upgrading the design basis for the alternate AC generator;
- Fastening transformers with anchor bolts;

- Improvement of the response management and recovery procedures for switchyard facilities;
- Installation of watertight doors on the major electrical rooms.

The secured mobile generators for coping with extended SBO event have sufficient capacity necessary for SAM and are available within 2 hours considering battery depletion. The mobile generators are located in a safe area against extreme natural events and be tested regularly to maintain the target reliability of the inherent design.

A terminal box to connect secured mobile generator is installed in such a way so as to protect it from external events such as seismic, tsunami, and flooding. The terminal box enables the connection cable to be easily connected to the mobile generator to successfully energize a safety bus.

With regard to batteries, extension of duty time of battery by means of load shedding is needed. If battery duty time is shorter than 2 hours, additional batteries are installed. In the cases where the battery rooms are located lower than ground level, measures of protection against inundation or flooding are taken.

The design basis of existing alternate AC generator has been improved appropriately. The alternate AC generator has adequate capacity to cope with simultaneous SBO at multi-units stations and be provided with a fuel supply capacity of at least 24 hours. The existing alternate AC generator has a diverse cooling capability compared to the EDG. The alternate AC power source for new NPPs will be equipped with appropriate protection measures against extreme natural events and dedicated to only one unit, i.e. installed for each unit rather than shared between units.

With respect to offsite power recovery, transformers that are not fixed on the ground are fastened with anchor bolts because they would likely be damaged in the event of a massive tsunami. Switchyard facilities are also vulnerable to external natural events. A protocol has been established to ensure cooperation between the transmission company and the nuclear power generating company for urgent and prompt offsite power recovery.

The installation of watertight doors on the major electrical facility rooms is one measure that could be used to protect the EDGs, alternate AC power sources, battery systems, and distribution systems against inundation due to tsunami or flooding.

IV–6.4. SBO resulted in core melt for Korean NPPs

In the situation where neither EDGs nor alternate AC power source is able to be restored, it will be necessary to take measures to ensure the continuous power supply from the mobile generator(s) by using EDG fuel storage tanks that have sufficient capacity for 7 days of continuous operation.

IV–7. SLOVAKIA

IV–7.1. Power supply recovery

Recovery strategies after SBO event at the WWER 440 type reactors consist of two main parallel approaches ensuring integrity barriers in accordance of defense in depth concept as follows:

- Restoration of power supply from normal, backup, emergency or alternate AC power sources to restore RCS core cooling and secondary heat sink equipment supplied by the available AC power source.
- Deployment of mobile equipment which takes advantage of the longer coping time typical for WEER 440 reactors due to large volume of feedwater in SGs and passive systems (e.g. hydro accumulators, bubble steam condenser tower coolant inventory) which allow additional time for using mobile equipment such as portable FW pumps, and mobile alternate AC power generators for charging of batteries as necessary.

IV–7.2. Concept of SBO management for units currently under construction

Although WWER design is generally very robust to respond to SBO (e.g. large water volume in RCS and SGs, low power density of the core) many improvements in SBO coping strategy and mitigation of severe accidents have also been implemented in a revised basic design. Mochovce Unit 3 and 4 will be the first WWER plant to fully include Fukushima lessons and European Union Stress Tests results into the design before commissioning.

The main design principles that were considered for SBO management involve:

- Minimizing the need of human intervention during the first phases of accident scenarios: preference given to 'passive' or manually operated systems;
- Increasing robustness of defense in depth (further independent sublevels in relation to every detected cliff edge effects);
- Ensuring the plant in safe conditions within 72 hours from the accident onset;
- Ensuring that new safety measures must not decrease performance of design basis safety functions;
- Using the combination of mobile and stationary means; hardened stationary means are essential, mobile means provide a backup and flexibility;
- Enabling the fulfilment of safety functions even upon multiple equipment failures.

A permanent alternate AC power source (6kV 2,5 MW(e)) was already considered in the design; it extends the functionality of AC power systems for SBO conditions. This alternate AC power source can be connected to anyone of the 6kV safety-system buses of two Units (see Fig IV–13).

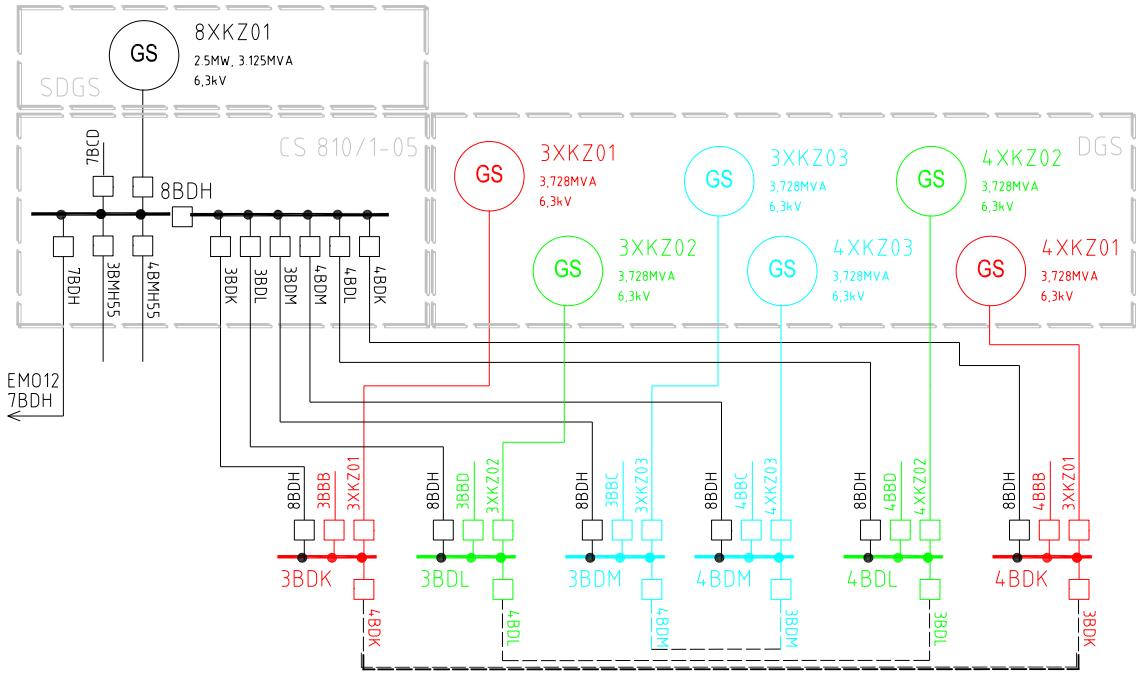

FIG. IV–13. Stationary alternate AC power source connections (diagram courtesy of Slovenské elektrárne, a. s., Enel Group Company).

Two mobile 0.4 kV 600kW alternate AC sources (one for Unit) were installed in addition to alternated AC power source. They are stored in a protected shelter that provides protection against 'mechanical actions' (devastated site) and extreme conditions. The diesel is 'parked and connected' in the shelter because it was considered the best option in order to have it readily available for power supply but it can be transported in other places. Dedicated connection points and distribution network for the mobile diesel were preinstalled (see Fig. IV–14).

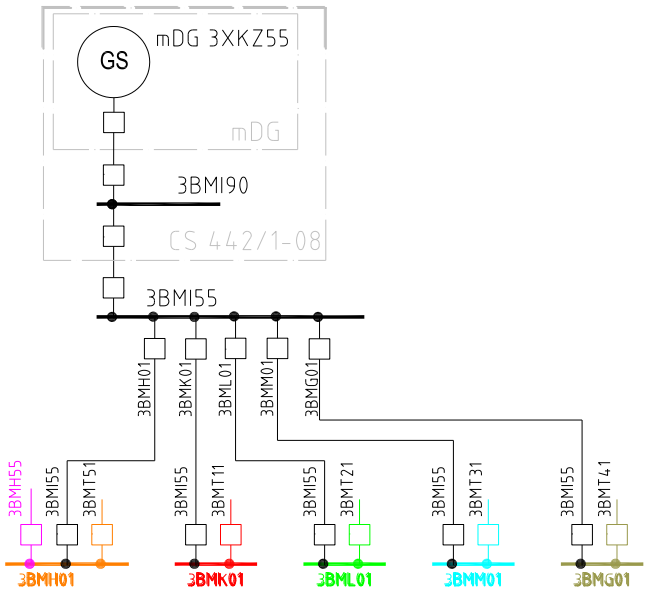

FIG. IV–14. Mobile 0.4 kV 600kW alternate AC sources connections (diagram courtesy of Slovenské elektrárne, a. s., Enel Group Company).

A mobile alternate AC source can power supply all loads needed for successful management of an SBO event in conjunction with mobile means for water injection. Calculation of battery depletion during SBO event and principles for a load shedding strategy were established.

A power supply to selected motor operated valves (e.g. hydro-accumulator isolation valves, valves for fast depressurisation of the reactor coolant system, motor operated valves for flooding the reactor cavity from bubble condenser tower tranches) is provided from uninterruptible power supply systems (i.e. batteries and inverters) in order to increase capability to manage the plant in SBO conditions.

A battery capacity monitoring system was added; it provides essential information to the operators on the state of batteries in order to better manage their discharge time in SBO conditions (e.g. differential load shedding strategies among three different safety divisions).

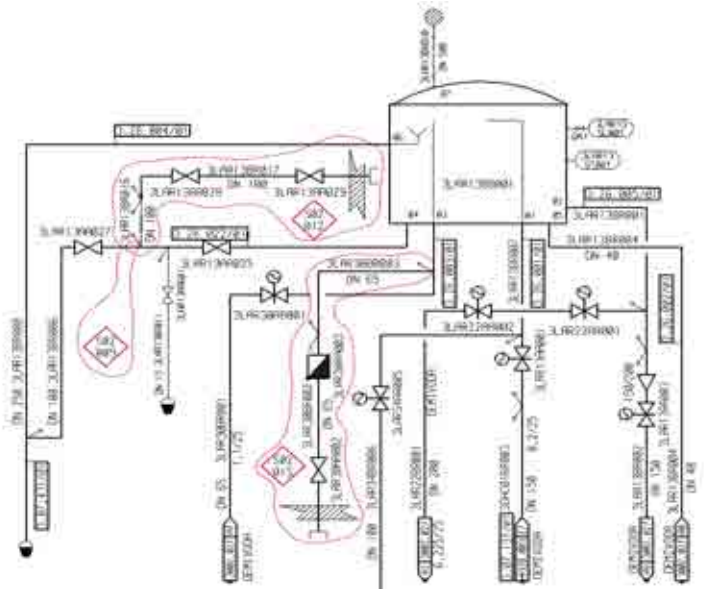

FIG. IV–15. Connection of mobile means to the EFW system (diagram courtesy of Slovenské elektrárne, a. s., Enel Group Company).

A conceptual design of power supply system showing different sources and possible interconnections is provided on Fig. IV–16. During an SBO event, it is assumed that the following sources are sequentially lost:

- NAXS – normal auxiliary supply system (i.e. 400 kV main generator);
- SAXS – standby auxiliary supply system (i.e. 110 kV);
- Unit 1 and 2 interconnection – the 4 units are connected by 6 kV highway between the non safety buses and also between the relevant safety buses (manual connection for beyond design status);
- Standby EDG, 6 kV; there are three EDGs for each unit.

In addition to a common DG (6kV, 2,5 MW(e) alternate AC source, air cooled), a mobile 2 mDG (0.4 kV, 600kW(e) alternate AC source) is also available.

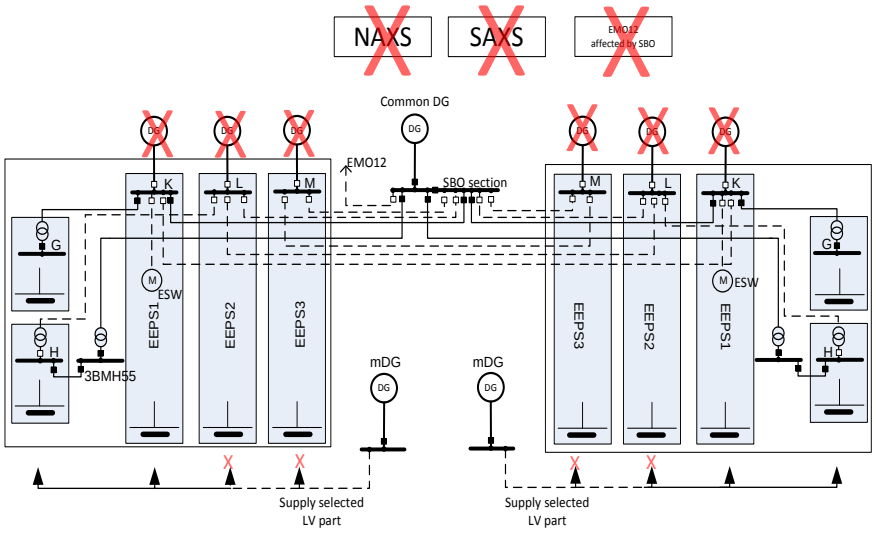

FIG. IV–16. Safety part of the power supply scheme with the different sources and possible interconnections (diagram courtesy of Slovenské elektrárne, a. s., Enel Group Company).

IV–8. SWEDEN

An SBO event was originally considered beyond design basis events; however, several countermeasures for an SBO event were incorporated into the original design of Swedish NPPs. In order to limit the radioactive releases following a reactor core melt, the original plant designs were later enhanced by the addition of containment filtered venting systems and independent containment spray features.

To date, no major plant modifications have been implemented as a result of the Fukushima incident in 2011; Post Fukushima improvements (major modifications) are still under consideration.

The operating Swedish NPP fleet consists of 3 Westinghouse PWR units and 7 ASEA/ATOM BWR units (the design of the ASEA/ATOM plants vary significantly between the plants). The following countermeasures for LOOP/SBO are a collection of features from the whole fleet.

IV–8.1. LOOP/SBO countermeasures

The connection to the grid for Swedish NPPs is via the 400kV transmission system (except one that is connected to the 130kV system). In addition, units have a connection to the 130 kV or 70kV auxiliary transmission systems via the standby transformers. When the units were designed, the possibility of LOOP was taken into consideration, either as an initiating event or as a consequence of an initiating

event. All main turbine generators are equipped with generator breakers and hence are capable of operating the house load after a loss of transmission system. A typical power supply diagram of Swedish NPPs is shown on Fig. IV–17.

All units are designed with the ability to transfer to house load operation if all offsite power is lost. During house load operation the main generators only supply the unit onsite power system with electrical power.

It is advantageous to have an additional source of electrical power to supply safety system equipment for situations where all offsite power is lost. The load rejection capability is 100% of total load.

The ability to transfer to house load operation is required by the Swedish grid authorities. The grid authority requires that a plant be capable of house load operation for a minimum of 12 hours and this requirement aids in ensuring the operational safety of the national grid.

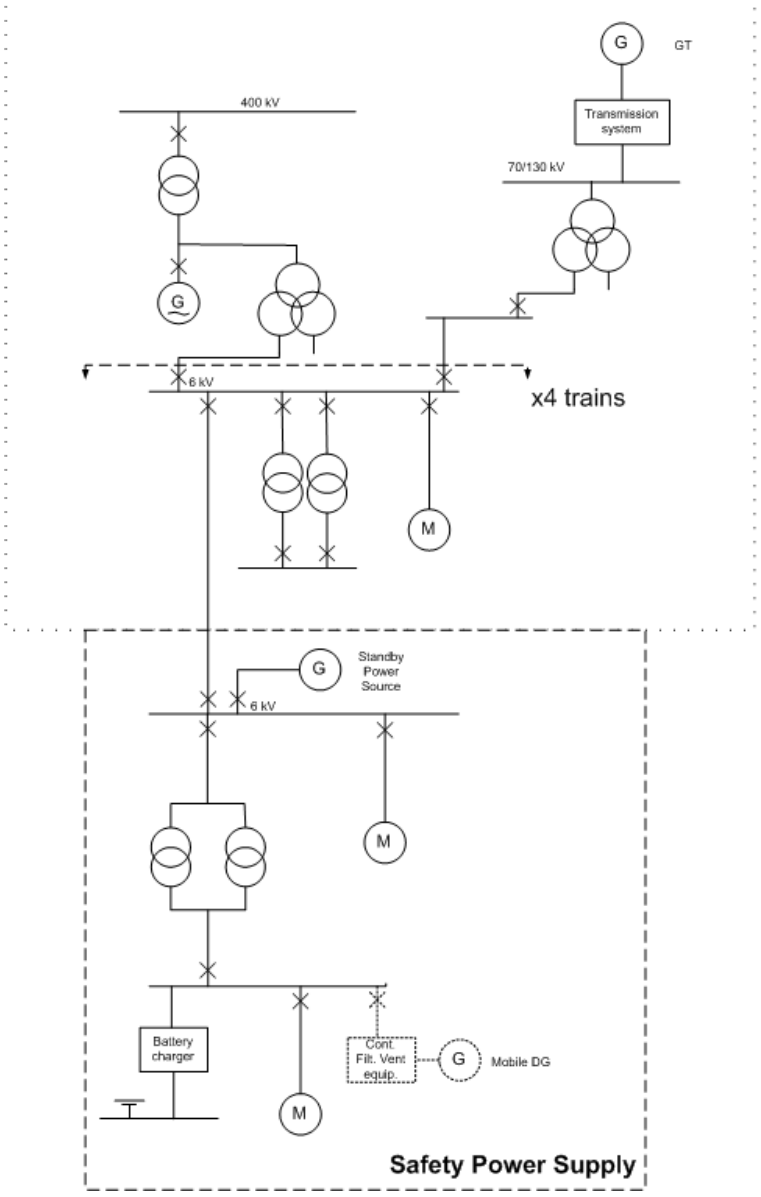

FIG. IV–17. Typical power supply diagram *(diagram courtesy of Vatenfall)*

A high level of operational safety and the ability to restore power on the national grid in a short time is imperative for all NPPs during all modes of operation but in particular during emergency situations.

Actual load rejection tests and operating experience has proven the capability of full load rejection. Operating experience (one affected unit) has demonstrated the capability to successfully operate on house load operation for as long as 6 hours before synchronizing back to the grid.

The standby power sources typically consist of four diesel generators that will start automatically after an unsuccessful transition to house load operation or turbine trip. Most of the diesel generators are water cooled, but some diesel generators are air cooled.

If the offsite power is lost for an extended period of time and the diesel generators are supplying the safety power system, the preferred power supply will not be energized for all units. If the gas turbines (see next paragraph) are operational and the power transmission system is intact, the gas turbines may be used to re-establish the power to the onsite power system.

In the case where all safety standby power sources fail, different arrangements are available at different units. All NPPs in Sweden are equipped with gas turbine driven generator sets, in addition to the diesel generator sets. The gas turbine generators are located onsite or offsite (these offsite sources are generally not part of the classification system) and are dependent on overhead lines in some cases, however they reduce the probability of a total loss of AC power and can reduce the duration of such losses. Those units with gas turbine generators onsite are equipped with connection points from the generator to the 6kV or 10kV voltage level.

Other arrangements such as a mobile diesel generator (the same size as the standby power source), interconnections between units and interconnections within units are also available for some units. In one NPP, a diversified plant section (building) has been constructed. The diversified plant section have been based on its own input signals (independent of the original plant section), initiate safety functions for reactivity control, pressure relief, emergency core cooling (including small line breaks) and residual heat removal. Two diesel generators, DC power supplies and associated switchgear etc. are used to supply power to the functions in the diversified plant section during loss of offsite power. The diversified plant section is hardened and is powered by air cooled diesel generators.

If all AC power sources fail, some units rely on turbine driven feed water pumps, DC power and compressed air in order to operate equipment necessary to achieve safe shutdown in a SBO scenario. Some units are fully electrically dependent and hence are more vulnerable if all power sources are lost.

If all measures fail to recover core cooling, reactor vessel melt-through will occur and the strategy then focuses on maintaining the containment integrity. The containment filtered vent and independent containment spray were installed in Swedish power plants as a result of requirements stipulated by the Swedish government, due to the TMI-2 accident 1979. A decision made by the government in 1986 required Swedish plants to install the mitigating systems before 1989. The concept involved a separate building containing a control room and its own power system, including batteries. The basic design requirement was that depressurization of the reactor containment is possible without relying on operator action during the first 8 hours following an event.

For all PWR units in Sweden it is possible to back feed critical I&C systems in the onsite power systems, with the mobile power supply source used for the filtered containment vent feature. This extended use of steam driven feed water pumps also increases the coping time. Some units have specific guidelines for how the power supply for the unit can be restored after a complete loss of AC power and depletion of batteries. The restoration will be performed manually without the use of control systems, control power, protection relays etc. due to discharged batteries.

The operating procedure describes a number of predetermined power supply paths to the unit and the measures required to restore the power supply using one of the predetermined supply paths with reference to unconventional system configurations. Problems that may occur while connecting to the power supply paths are also identified. Operations in the switchyards will have to be performed in a de-energized condition and operation of breakers and disconnectors will have to be performed

manually. The purpose of the different supply paths is to provide redundant means of obtaining charging voltage to the batteries from the switchyard, or alternatively to restore voltage to the battery systems in the onsite power system and thereafter start to energize the unit in a normal manner.

IV–8.2. A design solution for an extended SBO event for Oskarshamn NPP

The gas turbines will be modernized to increase the defense in depth for all units and to supply power to unit 1-3 during an extended SBO until the grid or onsite power systems has been restored. Unit 1-3 will be able to handle the first 8 hours with only safety classified battery-backed AC and DC power supplies. New independent core cooling systems will be autonomous for the first 8 hours. The alternate AC power supply system will supply the new independent core cooling system after 8 hours.

The gas turbines will be manually connected to unit 1-3 in case of an extended SBO. The gas turbines will be credited to supply power to one, two or all three units 8 hours after the initiating event and to keep the buses energized for a minimum of 72 hours without refueling. The consumables may be replenished from the central storage facility after 72 hours. The alternate AC power supply will have the following tasks during an extended SBO:

- Supply power to permanently installed equipment (pumps, valves, etc.) for core cooling and cooling of the spent fuel pools.
- Supply power to permanent installed equipment (pumps, valves, etc.) for residual heat removal in purpose to establish a stabile end state with secured removal of the residual heat.
- Supply power to installed safety classified battery-backed DC and AC systems in purpose to secure necessary control and monitoring equipment.
- Supply power to auxiliary loads (elevators, overhead cranes, lighting, heating, ventilation etc.) at unit 1-3 including non-operational facilities and interim storage facility for spent nuclear fuel;
- Mobile equipment using temporary cables.

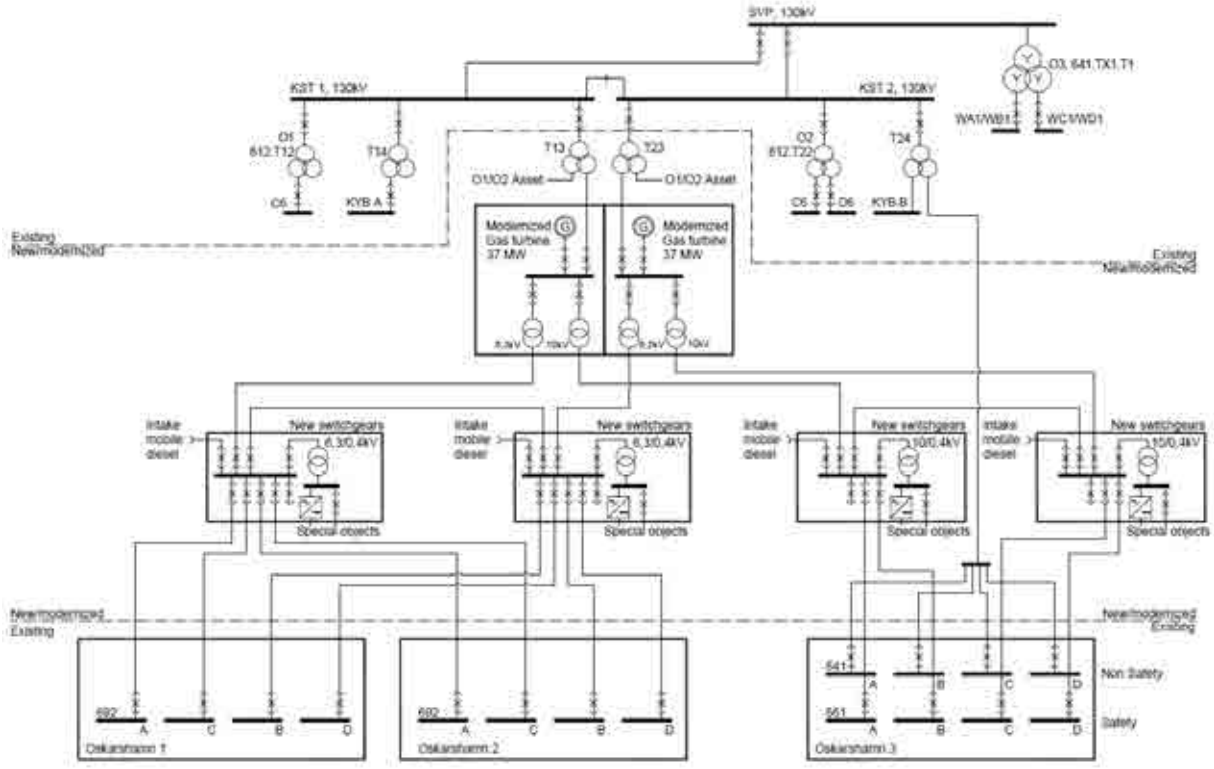

FIG. IV–18. A schematic configuration of a gas turbine plant including electrical infrastructure (diagram curtesy of E.ON/OKG).

A schematic configuration of the new electrical infrastructure including the gas turbines is shown in Fig. IV–18. The alternate AC power supply will be placed inside reinforced buildings. The power supply comprises two redundant gas turbines with a rated power of 43 MVA each at 40° C. These redundant gas turbines are able to supply all three units with sufficient power during an extended SBO.

The power will be generated at a voltage level of 10 kV on the generator buses. The reinforced buildings that contain the gas turbines will also include the generator switchgear and the associated 10/6.3 kV and 10/10 kV distribution transformers.

IV–9. UNITED STATES OF AMERICA

In the United States, Title 10 of the Code of Federal Regulations, Part 50 (10 CFR, Part 50), Appendix A 'General Design Criterion (GDC) delineates the requirements for the design of NPPs. GDC 17, 'Electric power systems,' requires, in part, that NPPs have onsite and offsite electric power systems to permit the functioning of structures, systems, and components that are important to safety. The onsite system is required to have sufficient independence, redundancy, and testability to perform its safety function, assuming a single failure.

The offsite power system is required to be supplied by two physically independent circuits that are 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. One of these circuits is required to be available within a few seconds following a LOCA to assure that core cooling, containment integrity, and other vital safety functions are maintained. In addition, this criterion requires provisions to minimize the probability of losing electric power from the remaining electric power supplies as a result of loss of power from the unit, the offsite transmission network, or the onsite power supplies.

Thus GDC 17 defines the preferred power systems (i) capacity and capability to permit functioning of structures, systems, and components important to safety; (ii) provisions to minimize the probability of losing electric power from any of the remaining supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit, the loss of power from the transmission network, or the loss of power from the onsite electric power supplies; (iii) physical independence; (iv) availability. This criterion provides assurance that a LOOP event will not adversely impact the capability of the onsite sources to mitigate the consequences of an event at a NPP.

However, the offsite source is considered the preferred source of power and the design requirements consider contingencies that minimize the potential for a LOOP event. A robust grid that can withstand severe perturbations reduces the probability of a LOOP at a NPP. The robustness of the grid system determines the reliability and availability of offsite power and is evaluated using the following contingencies:

- The trip of the nuclear power unit is an anticipated operational occurrence (AOO) that can result in reduced switchyard voltage, potentially actuating the plant's degraded voltage protection and separating the plant's safety buses from offsite power. It can also result in grid instability, potential grid collapse, inadequate switchyard voltages, and a subsequent LOOP due to loss of the real and/or reactive power support supplied to the grid from the nuclear unit.
- Grid stability and offsite power availability conditions under postulated transients on the grid system need to be evaluated for grid reliability. The results of the grid stability analysis must show that the loss of the largest single supply to the grid does not result in the complete loss of preferred power. The analysis considers the loss, through a single event, of the largest capacity being supplied to the grid, removal of the largest load from the grid, or loss of the most critical transmission line. This could be the total output of the station, the largest station on the grid, or possibly several large stations if these use a common transmission tower, transformer, or a breaker in a remote switchyard or substation.

IV–9.1. Preventive measures for LOOP

Maintenance activities can often result in inadvertent LOOP for a NPP. The US NRC initiated regulation, 10 CFR 50.65 (a)(4) which requires NPP owners to assess and manage the increase in risk that may result from proposed maintenance activities before performing the maintenance activities. Grid stability and offsite power availability are examples of emergent conditions that may result in the need for action prior to conducting maintenance activities that could change the conditions of a previously performed assessment. Accordingly, NPP owners are required to perform grid reliability evaluations as part of the maintenance risk assessment before performing any grid-risk-sensitive maintenance activities (such as surveillances, post-maintenance testing, and preventive and corrective maintenance). Such activities could increase risk under existing or imminent degraded grid reliability conditions, including (1) conditions that could increase the likelihood of a plant trip, (2) conditions that could increase the likelihood of a LOOP or SBO, and (3) conditions that could have an impact on the plant's ability to cope with a LOOP or SBO event, such as out-of-service risk-significant equipment (for example, a diesel generator used for onsite power, a battery, a steam-driven pump, or an alternate ac power source).

On August 14, 2003, the largest power outage in U.S. history occurred in the Northeastern United States and parts of Canada. Nine U.S. NPPs tripped. Eight of these lost offsite power, along with one NPP that was already shut down. The length of time until power was available to the switchyard ranged from approximately 1 to 6½ hours. Although the onsite DGs functioned to maintain safe shutdown conditions, this event was significant in terms of the number of plants affected and the duration of the power outage. In response, the US nuclear industry developed protocols between the NPP and the transmission system operator (TSO), independent system operator (ISO), or reliability coordinator/authority (RC/RA) and the use of transmission load flow analysis tools (analysis tools) by TSOs to assist NPPs in monitoring grid conditions to determine the operability of offsite power systems. (In the US, after the deregulation of the electric power industry, the TSO, ISO, or regional authority is responsible for preserving the reliability of the local transmission system. The use of NPP/TSO protocols and analysis tools by TSOs assist NPPs in monitoring grid conditions for consideration in maintenance risk assessments and any impending challenges to the offsite power systems. A communication interface with the plant's TSO, together with training and other local means to maintain NPP operator awareness of changes in the plant switchyard and offsite power grid, is important to enable the licensee to determine the effects of these changes on the operability of the offsite power system. Hence, these protocols and communications help NPP operators in making conservative decisions for onsite power systems to preclude SBO conditions in the event of a LOOP.

IV–9.2. LOOP events

DGs are used as onsite standby source of emergency power. The DGs are sized such that the continuous rating of the DGs exceeds the sum of the loads needed at any one time. The typical design of a NPP has two trains of safety grade equipment with each train powered by a 100% rated DG. One DG is capable of satisfying GDC 17 criterion of energizing the safety bus within a few seconds following a LOOP and concurrent loss-of-coolant accident, to assure that core cooling, containment integrity, and other vital safety functions are maintained.

The DGs start automatically in the event of LOOP, attain the required voltage and frequency within acceptable limits and time and energize the auto-connected shutdown loads through a load sequencer. The typical mission time is expected to be 30 days. Typically, onsite fuel oil and lube oil capacities are adequate to support operation of at least one DG for seven days and provisions have been made by most NPP to have additional fuel oil delivered to the plant within 3 to 4 days. The current fleet of power plants use AC motors to drive pumps required for decay heat removal. The light water pressurized water reactor (PWR) designs typically have an additional steam driven pump that can supply water to the steam generators in the event of loss of electric motor driven pumps. The boiling water reactor (BWR) designs typically have additional diesel driven pumps to support decay heat removal capability.

Passive design plants such as the Westinghouse AP-1000 and Economic Simplified Boiling Water Reactor (ESBWR) do not rely on AC power for a period of up to 72 hours to cope with a LOOP event. If the LOOP event lasts longer than 72 hours, onsite power systems are available to support plant shutdown conditions.

IV–9.3. SBO events

SBO coping capability is a measure of the ability of a NPP to withstand a complete loss of offsite and safety grade onsite AC power systems. Per the existing regulations, for a multi-NPP site, an SBO is only assumed to occur at a single NPP unit. Onsite power systems, AC and DC, supported by safety grade plant batteries are generally available to support plant systems required for decay heat removal and maintaining the integrity of radiation barriers including fuel cladding. NPPs are designed to cope with SBO conditions until the restoration of offsite or safety grade onsite AC power to the plant safety buses. The restoration of AC power within the coping time is vital, and depends on many circumstances. Typically, longer coping time affords higher probability that the AC power will be restored in time to preclude fuel damage.

NPP operators have adopted different SBO coping strategies depending on the type of reactor design, the robustness of the local grid, and the defense in depth of permanently installed equipment. Generally the methods can be grouped into two main categories:

- The AC Independent approach. In this approach plants rely on available process steam, DC power and compressed air to operate equipment necessary to achieve safe shutdown conditions until offsite or safety grade onsite AC power is restored.
- The Alternate AC (AAC) approach. This method requires the use of AC power sources not credited for design basis accident mitigation at the SBO unit. With the exception of multi-NPP sites where the SBO unit relies on another NPP unit's emergency DG, the AAC source is normally isolated from the offsite and onsite power sources and manually aligned to the designated shutdown buses upon confirmation of complete loss of offsite and onsite power sources. The coping strategy typically entails a short period of time in an AC-Independent state while the operators initiate power from the backup AAC source(s). Once power is available, the plant transitions to the AAC state and can have extended decay heat removal capability until offsite or onsite safety grade AC-power becomes available.

It is noted that an external event affecting the plant site (e.g. seismic, flooding) can adversely impact the AAC source and degrade the capability to restore power to the plant buses.

The current NRC regulatory framework for SBO (10 CFR 50.63) requires each plant to demonstrate that it can cope with and recover from an SBO that lasts for a specified duration. For plants that rely solely on the use of batteries to power essential equipment, the SBO coping time is typically between 4 and 8 hours. These time frames are based on the assumption that at least one source of AC power (offsite or onsite) will be successfully restored within four hours. The common-cause damage to the emergency power supplies and electrical distribution systems that occurred at Fukushima resulted in an extended condition that ultimately led to core damage in three reactors.

Following the events at the Fukushima Dai-ichi nuclear power plant, the NRC issued Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events. This order directed NPPs to develop, implement, and maintain guidance and strategies to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities in the event of a beyond-design-basis external event (BDBEE). In particular, strategies need to be capable of mitigating a simultaneous loss of all AC power and loss of normal access to the ultimate heat sink (LUHS) resulting from a BDBEE by providing the capability to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities at all units.

ANNEX V

DESCRIPTION OF REPORTED SBO EVENTS

V–1. KORI-4, REPUBLIC OF KOREA, 1986

On August 28th 1986, while the unit was operating at 100% power, a main transformer protective arrester failed due to the effects of Typhoon Vera. The unit tripped, the line arrester failed and station, the standby AC power sources did not start that resulted in SBO conditions. The natural circulation mode of operation was carried out in loss of all off site power conditions without any trouble. After cleaning all the porcelain and replacing the failed arrester, the following corrective actions were implemented: (i) external power reliability improvement; (ii) independence of each unit startup transformer, and (iii) setting the new values of the protective relays.

V–2. VOGTLE-1, UNITED STATES OF AMERICA, 1990

On March 20th, 1990, Vogtle unit 1 experienced a loss of all safety (vital) ac power. The plant was in cold shutdown with reactor coolant level lowered to 'midloop' for various maintenance tasks. Both the containment building personnel hatch and equipment hatch were open. One emergency diesel generator (EDG) and one reserve auxiliary transformer (rat) were out of service for maintenance, with the remaining supplying both unit 1 safety buses. At about 9:20 A.M., a truck in the low-voltage switchyard backed into the support column for an offsite power feed to the rat which was supplying safety power. The insulator broke, a phase-to-ground fault occurred, and the feeder breakers for the safety buses opened. The unit 1 operable emergency diesel generator started automatically because of the undervoltage condition on the safety bus, but tripped after about 1 minute. Nearly 20 minutes later, the EDG load sequence was reset, causing the EDG to start a second time. The EDG operated for about a minute, and tripped off again. The EDG was restarted in the manual emergency mode 36 minutes after the loss of power. The EDG remained on line and provided power to safety bus, and the residual heat removal pumps restarted. During the 36 minutes following the loss of safety bus power, the reactor coolant system temperature rose from about 90 F to 136 F.

The loss of vital AC power at Vogtle was caused by human error during a refueling outage. This occurred typically at a time when: (1) the electrical distribution system is most vulnerable to a single fault causing a loss of power when other equipment is out of service for maintenance; and, (2) more activities are taking place at the plant site that can cause such a fault (e.g., operation of heavy equipment, more vehicles onsite, and construction activities). Therefore, particularly during plant outages, activities and hazardous materials in switch-yards and other protected areas need to be properly controlled to prevent an incident similar to that at Vogtle.

V–3. NARORA-1, INDIA, 1993

Unit 1 of Narora Atomic Power Station was operating at 185 MW(e). At 03:31 AM, a fire incident occurred in the Turbine Building, accompanied by a hydrogen explosion. The reactor was immediately tripped after the turbine had tripped earlier. Due to fire, cables started burning and there was complete loss of power supply in the unit including loss of class I & II supplies. There was an extended station blackout which lasted for about seventeen (17) hours. Core cooling was maintained by the thermo siphoning effect. Manual crash cooldown of the reactor was initiated. Operating personnel started diesel driven fire pumps and aligned them to feed water into steam generators.

Boron poison was added manually using the GRAB (gravity addition of boron) system to maintain the reactor in a subcritical state. The reactor was able to be maintained in a safe shutdown condition, with adequate subcriticality, at all stages subsequently. The major fire was able to be put out in about 1 hour and 30 minutes.

During the incident, control room staff had to evacuate the control room due to ingress of smoke. In emergency control room no indications were available on Unit-1 panel due to loss of control power supply. Of the important parameters had to be directly measured from field. It resulted in the blind operation of the plant.

The event caused a physical disintegration of the turbine blade which behaved like a missile. Examination of the blade no. 51 showed that the crack initiation occurred at the root from both ends of the blade and grew initially to a in depth by fatigue and finally failed by the overload. The analyses indicated that the blade experienced low to high cycle fatigue. Blade 52 had a longer fatigue crack red to blade 51.

The incident has been rated at level 3 on the INES scale. The cause of the incident was attributed to the failure of turbine blades in the 5th stage of low path 2 of the LP turbine as initiating event.

V–4. KOLA, RUSSIAN FEDERATION, 1994

Prior to the event all four units of Kola NPP were in normal operation at the following power levels: Unit 1 - 370 MW(e), Unit 2 – 290 MW(e), Unit 3 - 350 MW(e), Unit 4 - MW(e). Safety systems were in hot standby. Due to the hurricane wind the 'Kolenergo' grid system collapsed, and the 330 kV, 154 kV, and 110 kV high voltage transmission lines were damaged. Spiked voltage oscillations in the NPP unit auxiliary power line resulted in trips of the turbine generators and other main equipment and reactor scrams.

An attempt to supply power to Unit 1 and 2 (WWER-440, V-230 designs) equipment by emergency connections from diesel generators was unsuccessful due to diesel generators failure for the following reasons: Deficiencies in diesel generator control design configuration and deficiencies of work planning and organization by NPP management as regards timely changes of diesel generators control design configuration and ensuring emergency power supply to essential equipment. Total blackout of these units was accompanied by breach of safe operation limits and conditions.

Safety systems at Units 3 and 4 (WWER-440, V-213 designs) are configured as three channels with independent power supplies, service water supplies, compressed air supplies, etc. For this reason total LOOP conditions at Units 3 and 4 passed without serious criticism.

V–5. FORSMARK-1, SWEDEN, 2006

Forsmark 1 was on July 25th 2006, in full power operation when a short circuit occurred in the 400kV switchyard. The transient resulted in an automatic reactor power reduction, through a partial reactor scram, and reduction of the speed of the primary circulation pumps. The unit went shortly into house load operation before signals were received for reactor scram, isolation of the primary containment, and start of the reactor safety systems. The event generated two electrical transients in the onsite power system.

The first one was a load rejection that caused the trip of two UPS-units (Uninterruptible Power Supply) in train A and B (train C and D were not affected). This voltage transient exceeded the UPS design specifications (exceeded in both under and over voltage). The inverter part of the UPS tripped on over voltage at the DC-bus bar, over voltage caused by the quick voltage rise during the isolation of the short circuit. The UPS automatically transferred to bypass operation during the trip of the inverter part.

The second transient was a low frequency transient when the turbine coasted down after the failed house load operation. The under frequency protection of the main generator didn't trip the generator breaker as intended, because it was sensitive to the phase order and two phases were cross connected. (The original under frequency protection was not sensitive to the phase order)

The low frequency caused disconnection of the preferred power supply from the safety bus bars and hence two UPS powered bus bars lost power. The power from the UPS was necessary for connecting the standby power sources to the safety bus bars.

All four standby power sources (diesel generators) started automatically, but diesel generator A and diesel generator B did not connect to their respective bus bar due to loss of UPS power (missing speed measurement).

In this situation two out of four trains in each safety system were operating (auxiliary feed water system, core spray system and containment spray system). The loss of the two 220 V AC bus bars caused however several isolation signals and loss of information in the control room (for example voltage instruments). After 22 minutes the operators reconnected offsite power to trains A and B thus all power was available at the unit. After in total 45 minutes, the operators could confirm that the unit was in a safe and stable shutdown mode.

The event has uncovered weaknesses in the electrical system design, test routines and documentation. Analyses performed after the incident indicate that the transient, that followed the initial short-circuit in the 400 kV switchyard, has influenced and defeated UPS in a manner not analyzed in the unit's SAR. The event has additionally uncovered weaknesses in the 400 kV switch yard and the maintenance of it.

The event also shows the ability of the unit to automatically respond to a severe transient, although the occurrence of several faulty functions caused by the loss of power in two out of four safety system trains. The important safety functions reactor shut down and heat removal were ensured with adequate margins during the transient sequence.

The preferred power supply was lost for two redundant safety buses and the standby power sources did not connect to these two redundant safety buses, i.e. the event in July 25th is to be considered as a near SBO. Detailed description of this event is provided in Ref. [6].

V–6. DAMPIERRE-3, FRANCE, 2007

On 9 April 2007, a relay failure led to the loss of one of the two safety switchboards of reactor unit 3 at the Dampierre nuclear power plant, thereby making it impossible to connect the emergency diesel generator. Electrical power for protective devices and safeguard auxiliaries could only be obtained from the other safety switchboard.

During this incident, the initial situation was made worse by another fault, this time on a generator breaker, as a result of which the line breaker opened, disconnecting unit 3 from the 400 kV main offsite power line. In addition, the instrumentation and control device used to switch over to the auxiliary power supply had been cut, in accordance with the required operating procedures in the event of this type of incident. The loss of offsite power led to a reactor scram, reactor coolant pump shutdown and the automatic startup of the emergency diesel generator on the safety train available.

The loss of one of the switchboards was due to a malfunction on an overcurrent relay. Subsequent expert analysis on this relay revealed that the formation of zinc filaments similar to 'tin whiskers' was the cause of the incident, and that the opening of the line breaker was due to an erroneous command not to open the generator breaker of the main alternator.

Offsite power was restored in the morning on 10 April, providing better conditions for bringing the reactor unit to a safe state.

Investigations carried out by the operator revealed that almost all of the protective relays installed on identical units were affected by this phenomenon while the quantity and size of the filaments varied.

The oldest sites are the most affected by this risk of failure. As a result, a strategy for replacing the relays involved was prepared by the operator for the entire fleet.

The incident also showed that the control procedures in force on the site did not allow the consequences of the sequential occurrence of these two electrical failures at the Dampierre plant to be managed optimally.

V–7. FORSMARK 3, SWEDEN, 2013

Initial state: reactor in cold shutdown with reactor vessel head removed and spent fuel pool gates open to the reactor vessel and most of the fuel removed from the core to the spent fuel pool.

During the outage in May 30th 2013 (with the 70 kV grid disconnected due to maintenance) testing on the main generator caused the relay protection to send a spurious trip signal to the 400kV breaker. The 400kV circuit breaker opened correctly in two phases while the third phase remained in a closed position due to a loose cable connection in the tripping device.

The double open phase condition resulted in a voltage unbalance for the onsite power system. The voltage on safety buses did not drop below the threshold for the loss of voltage relay starting the standby power sources (due to positive sequence measurement of voltage). Train A and B were ready for operation and the standby power sources in C and D train were ready for operation when the double open phase condition occurred.

Operating loads equipped with imbalance protection tripped, whereupon for example residual heat removal and the cooling chain for the standby power sources was lost. Residual heat removal was lost for 17 minutes and the temperature in the fuel pools increased by 0.7 degrees Celsius before the operators started the standby power sources manually and opened the circuit breakers from the preferred power supply to the safety power system. Manual resetting of imbalance protection was required when the safety standby power sources where supplying safety loads. Some non safety motors were damaged during the event.

The only available offsite power source did not have enough capacity (power quality) to power required loads and the standby power sources did not start, i.e. the double open phase event in May 30th is to be considered as an SBO.

V–8. FUKUSHIMA DAIICHI, JAPAN, 2011

Following a major earthquake of magnitude 9.0 on the Richter scale, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a nuclear accident on 11 March 2011.

There were ten reactors at two nuclear power sites in the region, and seven units were under the power-operating condition and remaining three units were in the maintenance mode at the time. All seven operating units shut down automatically when the quake hit. The reactors proved robust seismically, but vulnerable to the tsunami.

Power, from grid or backup generators, was available to run the Residual Heat Removal system cooling pumps at four of the seven power-operating units, and despite some problems they achieved cold shutdown within about four days.

The other three Units 1-3 at Fukushima Daiichi lost power at 3.42 pm, almost an hour after the quake, when the entire site was flooded by the 15 meter high tsunami causing 12 of 13 backup generators inoperable as well as heat exchangers for dumping reactor waste heat and decay heat to the sea.

The three units lost the ability to maintain proper reactor cooling and water circulation functions. Electrical switchgear was also disabled.

All three cores largely melted in the first three days. Thereafter, many weeks of focused work centered on restoring heat removal from the reactors and coping with overheated spent fuel ponds.

V–9. KORI UNIT 1, REPUBLIC OF KOREA, 2012

On February 9, 2012, during a refueling outage, loss of offsite power occurred and emergency diesel generator 'B' failed to start while emergency diesel generator 'A' was out of service for scheduled maintenance, resulting in a station blackout. Offsite power was restored in 12 minutes.

The Loss of offsite power was caused by a human error during a protective relay test of the main generator. The emergency diesel generator 'B' failing to start was caused by the failure of the emergency diesel generator air start system. Further investigation revealed that the utility did not exercise proper control of electrical distribution configuration to ensure the availability of the station auxiliary transformer while conducting test on the unit auxiliary transformer.

After restoring offsite power through the station auxiliary transformer, the operators eventually recovered shutdown cooling by restoring power to a residual heat removal pump. During the loss of shutdown cooling for 19 minutes, the reactor coolant maximum temperature in the hot leg increased from 37° to 58.3° (approximately 21.3° rise), and the spent fuel pool temperature slightly increased from 21° to 21.5°.

There was no adverse effect on the plant safety as a result of this event, no radiation exposure to the workers, and no release of radioactive materials to the environment. However, inconsistent with the requirements, the licensee did not report the SBO event to the regulatory body in a timely manner and did not declare the alert status of the event in accordance with the plant emergency plan. The licensee reported this event to the regulatory body about a month after the event had occurred.

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