Commentary

Discussion on Station Blackout

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The safety of nuclear power plants is ensured by the concept of defense in depth. The impact that the Great East Japan Earthquake (March 11, 2011) had on nuclear power plants, as examined under this concept, testifies to the indispensability of power supplies in any circumstances. It is important to implement the measures required to deal with events such as a station blackout caused by a complete loss of external and emergency AC power (SBO) and a complete station blackout (loss of all electric power) in accordance with their respective probabilities and the risks involved. Even a small-scale power supply can help gain some time. It is important to reduce the overall risks posed to each power plant by classifying events and conducting comprehensive assessments.

I. Introduction

Nuclear power plants produce a large amount of radioactive materials in return for a large amount of energy through nuclear fission. These radioactive materials contain nuclei resulting from the fission of uranium nuclei. Some of these fission products stabilize themselves instantly, while others may take 30 years or even longer to do so. During this process, the unstable fission products emit hazardous radiation such as gamma rays, thereby resulting in a continuous release of heat.

Nuclear safety is primarily aimed at protecting human health and the environment from such hazardous radiation [1]. Defense in depth −or multi-level protection− has been incorporated as a concept to achieve this purpose. IAEA NS-R-1 defines the five levels of defense as follows [2].

(1) Prevent abnormal operations
(2) Prevent the escalation of abnormal operations
(3) Mitigate the impact of abnormal operations and prevent them from escalating into severe accidents
(4) Ensure suitable measures against severe accidents
(5) Protect human life even in the event of a failure to respond properly to a severe accident

The concept of defense in depth advocates the protection of human health by assuming

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that the preceding level of defense may fail. For example, Level 2 is intended to prevent deviations from escalating if the defense provided under Level 1 fails, while Level 3 is intended to mitigate the impact of any failure of the defense provided under Level 2. Similarly, Level 4 prepares for severe accidents to prevent them from escalating and mitigate their impact, while Level 5 seeks to protect human life from any radioactive materials that may be released in the event of a severe accident.

The Great East Japan Earthquake affected 14 units at nuclear power plants located along the Pacific coast: three units at the Onagawa Nuclear Power Plant, six units at the Fukushima Daiichi Nuclear Power Plant, four units at the Fukushima Daini Nuclear Power Plant, and one unit at the Tokai Daini Nuclear Power Plant. At the Fukushima Daiichi Nuclear Power Plant, which is operated by the Tokyo Electric Power Company (TEPCO), an enormous amount of radioactive materials was released after its defense in depth was overwhelmed by the magnitude 9.0 earthquake and the subsequent tsunami.

The Fukushima disaster underlines the importance of reliable power supplies [3, 4]. This commentary discusses station blackouts while also considering them in relation to defense in depth.

II. Defense in Depth and Station Blackouts

1. Level 1: Preventing Abnormal Operations

With the exception of Fukushima Daiichi Units 4, 5, and 6, which were being subjected to a regular inspection, all of the 14 reactor units mentioned above were in operation. Onagawa Unit 2 had just entered startup mode when the earthquake triggered an automatic cold shutdown. The full-output operation of the remaining ten units was automatically interrupted by the insertion of control rods to stop nuclear fission reaction.

Many external power supplies were rendered inoperable by the earthquake. The major reason for this was the damage that the seismic shaking caused to the insulators, etc. Each power station is equipped with multiple external power supply systems. At the Fukushima Daiichi Plant and the Tokai Daini Plant emergency diesel generators were employed to supply power when their external power supplies were lost. At both the Onagawa Plant and the Fukushima Daini Plant, one external power supply system remained operable although a few other systems were damaged.

External power supplies tend to be relatively unreliable. On September 8, 2011, for example, the San Onofre Nuclear Power Plant lost its external power supplies during a major blackout in California. Based on the lessons learned from an earlier large-scale blackout in New York, the station was designed in anticipation of a possible loss of external power supplies, so its emergency generators were automatically activated to supply electric power.

Owing to this emergency power, the pumps were able to release the decay heat from the reactor into the ocean. In Fukushima Daiichi Units 2 and 3, isolation cooling systems were employed to remove this heat. They supplied water to the reactors by operating turbines with the steam generated by the reactors. This heat was ultimately released into the ocean by using heat exchangers and seawater pumps, which was exactly how the Kashiwazaki-Kariwa Nuclear Power Plant had responded to the Chuetsu Offshore earthquake. The operators presumably expected the continued cooling to remedy the deviations and safely return the reactors to their normal cold shutdown conditions.

At Fukushima Daiichi Unit 1, the decay heat was removed using an isolation condenser that cooled the steam generated by the decay heat from the nuclear reactor through natural circulation before releasing the steam into the atmosphere.

Challenge: Ensuring reliable power supplies

The large pumps needed for the cooling process used at nuclear power plants are designed to operate with multiple external power supply systems and emergency generators. The necessary power supply remains intact as long as at least one of them is operational. All of the emergency generators operated properly to at least ensure a reliable power supply. In any assessment, external power supply systems should be assumed unreliable during emergencies. During the disaster, two external power supply systems (Fukushima Daini and Onagawa) remained intact to mitigate the risks.

Notably, an aftershock that occurred on April 7, 2011, led to a station blackout (SBO) at the Higashidori Nuclear Power Plant caused by both the shutdown of emergency generators and the loss of external power supplies. Greater reliability for external power supplies should certainly be pursued to some extent, but enhancing the overall reliability of power supply systems, including emergency generators, is more important.

2. Level 2: Preventing the Escalation of Abnormal Operations

A fire broke out at Onagawa Nuclear Power Plant Unit 1 when a power panel was damaged by the shaking. This regular power panel was not important to safety, but the resulting fire made it difficult to enter the building. Efforts were made to extinguish the fire and implement the necessary response. The emergency power panel was intact and did not compromise safety.

Incidentally, a fire also broke out at the Kashiwazaki-Kariwa Nuclear Power Plant when a transformer was damaged by the Chuetsu Offshore earthquake. The fire posed no threat to safety, but the substantial media coverage gave rise to harmful rumors.

Challenge: Protecting power supply systems from earthquake-induced fires

With respect to preventing the escalation of abnormal operations, one of the lessons that have been learned is that sufficient consideration must be given to the risk of earthquakes causing fires. Responses to fires can be hampered by problems with equipment that is not crucial for ensuring safety. Measures to prevent earthquake-induced fires will prove particularly effective with power supply systems.

3. Level 3: Mitigating the Impact of Abnormal Operations

About an hour after the earthquake, a massive tsunami hit four nuclear power plants. The wave height marked at each station −13 m at the Onagawa Nuclear Power Plant, 14 m at the Fukushima Daiichi Nuclear Power Plant, 7 m at the Fukushima Daini Nuclear Power Plant (run-up height: 14 m), and 6 m at the Tokai Daini Nuclear Power Station− was greater than the level postulated in the respective station designs. This tsunami triggered various different types of abnormal circumstances at these stations.

Tables 1 − 3 compile how the tsunami affected the power supply systems, which comprised external power supplies, emergency power supplies, power panels (metal-clad switchgear and power centers), and DC power supply. A circle indicates complete availability, while a cross indicates complete unavailability. Any partial availability was indicated by recording how many of the total number of systems were available.

The Onagawa Nuclear Power Plant sunk 1 m due to earthquake-induced subsidence. However, the station was not directly affected very much because it was still about 1 m above the tsunami. Inadequate measures led to water leaking through trenches, thereby rendering two emergency generators unusable for Unit 2. Fortunately, the resulting abnormality was not a serious one.

Similarly, inadequate measures at the Tokai Daini Nuclear Power Plant led to water leaking and rendering one of the seawater pumps unusable for cooling an emergency generator. As a result, one of the emergency generators could not be used in addition to the external power supplies having failed. Safe cooling could be continued using the two remaining emergency generators in combination with the still functional and available seawater pumps, power panels, and other electrical systems.

Challenge: Ensuring that the power supply systems are watertight

One of the lessons that have been learned is that channels by which water may infiltrate power panels and emergency generators must be eliminated, since electrical systems are incompatible with water. Sufficient water-tightness must be ensured to protect the seawater pumps. Air-cooled emergency generators must be deployed alongside the implementation of

Table 1 Conditions at the Fukushima Daiichi Nuclear Power Plant immediately after the tsunami

	#1	#2	#3	#4	#5	#6
External power supply	×	×	×	×	×	×
Emergency diesel generator Air cooling system (A/C) * Damage to cooling pump	× ×	× × A/C	× ×	× × A/C	× * × *	× * ○ A/C × *
Metal-clad switchgear (emergency)	×	×	×	×	×	3/3
Metal-clad switchgear (regular)	×	×	×	×	×	×
Power center (emergency)	×	2/3	×	2/3	×	3/3
Power center (regular)	×	2/4	×	2/2	2/4	×
DC power supply	×	×	○	×	○	○
Seawater cooling pump	×	×	×	×	×	×

Table 2 Conditions at the Fukushima Daini Nuclear Power Plant immediately after the tsunami

	#1	#2	#3	#4
External power supply	○	○	○	○
Emergency diesel generator Air cooling system (A/C) * Damage to cooling pump	× × ×	× * × * × *	× * ○ ○	× * × * ○
Metal-clad switchgear (emergency)	1/3	○	○	○
Metal-clad switchgear (regular)	○	○	○	○
Power center (emergency)	1/3	2/3	2/3	2/3
Power center (regular)	6/7	4/5	7/7	4/5
DC power supply	○	○	○	○
Seawater cooling pump	×	×	1/2	×

Table 3 Conditions at the Onagawa Nuclear Power Plant and the Tokai Daini Nuclear Power Plant immediately after the tsunami

	Onagawa			Tokai Daini
	#1	#2	#3	
External power supply	O	O	O	×
Emergency diesel generator	O	O	O	O
Air cooling system (A/C)	O	×	O	O
* Damage to cooling pump	O	×	O	× *
Metal-clad switchgear (emergency)	O	O	O	O
Metal-clad switchgear (regular)	×	O	O	O
Power center (emergency)	O	O	O	O
Power center (regular)	O	O	O	O
DC power supply	O	O	O	O
Seawater cooling pump	O	O	O	O

other necessary measures in anticipation of any possible failure of the seawater pumps.

4. Level 4: Countermeasures Against Severe Accidents

Abnormal conditions that cannot be mitigated may lead to a severe accident. Even if the lines of defense in the design have been broken up to Level 3, all of the resources available at a station must be utilized to prevent the occurrence of a severe accident or mitigate the impact of a severe accident. Such measures are collectively referred to as “accident management (AM).”

In accordance with existing design guidelines, this commentary classifies short station blackouts (SBOs) as Level 3 (design basis) and long SBOs as Level 4 (beyond design basis).

(1) Loss of ultimate heat sink with available power supplies

This section discusses the loss of ultimate heat sink (LUHS) in Level 4, which is an event that is closely related to SBOs even though it is not actually classified as one. At the Fukushima Daini Nuclear Power Plant, a seawater pump in the cooling system was damaged by the tsunami. One of the seawater pumps for removing decay heat from Unit 3 could still be used, along with some of the pumps for the cooling emergency generators used for Units 3 and 4. The power panels for Units 1 to 4 were still operational, although part of the power panel for Unit 1 was damaged. The power supply systems could be operated normally because the external power supplies, the emergency generators for Units 3 to 4, and the power panels for all of the units were still available for use.

The damage suffered by the seawater pump for Fukushima Daiichi Unit 6, which was shut down at the time, led to the loss of ultimate heat sink. Fortunately, the power supply systems were still available because no damage was sustained by the air-cooled emergency generator deployed high above the ground and by the emergency power panel inside the reactor building.

As a result, both the Fukushima Daini Nuclear Power Plant and Fukushima Daiichi Unit 6 managed to avoid a station blackout. Despite the loss of ultimate heat sink, the power supplies enabled accurate monitoring of the conditions inside the reactors. Prearranged procedures—namely, the depressurization of reactors and alternative water injections into the reactors and primary containment vessels—were conducted to gain some time. The cooling system was successfully restored three days after it had been struck by the tsunami while in operation, thereby allowing the Fukushima Daini Plant to be safely shut down. This experience demonstrates that power supplies can provide a gain margin of about three more days.

(2) Station blackouts (SBOs)

Station blackouts have already been experienced around the world. This section takes as an example an SBO experienced in 2001 at the Maanshan Nuclear Power Plant (Taiwan)[5]. On March 17, 2001, Unit 1 was in a hot standby condition after its operation had been stopped due to salt-bearing sea fog. About one day later at 0:35 am on March 18, the station's external power supplies were lost when both power lines suffered an insulation degradation due to the salt-bearing sea fog. Under the station's design, such a problem should have prompted the automatic activation of the two emergency diesel generator systems (A and B). However, System A failed to supply any power because its bus had been damaged by a ground fault in the distribution panelboard, while System B could not supply any power either as the emergency diesel generator failed to activate. The resultant station blackout led to the core being cooled using the auxiliary feedwater system and other such means.

In Taiwan, nuclear power plants had been backed up by a swing diesel generator in order to increase the reliability of power supplies, since the reliability of external power supply system had been poor. Two reactor units shared such a generator, which was also referred to as the fifth diesel generator. At 2:47 am, the fifth generator was connected to System B, which was still electrically intact, to end a station blackout that had lasted for nearly two hours. The temporary loss of ultimate heat sink caused by the station blackout did not trigger a major problem as the recovery took only two hours and the reactor had been shut down a day earlier.

This accident is a good example of an SBO being caused by damage to a bus or a power panel even though the generators and external power supplies are intact. It also demonstrates that the reliability of power supply system can be enhanced by the adoption of backup generators (i.e., generator redundancy). The DC power supply system also proved important as its availability ensured the proper functioning of the measurement control systems as well as the cooling of the core using the auxiliary feedwater system and other such means.

(3) Station blackout and loss of power panels

Fukushima Daiichi Unit 5 suffered a station blackout when its external power supplies were lost due to the earthquake and its emergency generators failed to operate after the tsunami. Furthermore, both of the emergency power panels were damaged by the tsunami. Fortunately, DC power supplies could still be used to operate the measurement control systems properly. Nonetheless, the batteries could last eight hours at most even with disconnected loads. On March 12, the batteries for Unit 5 were charged as an accident management measure by connecting its power panel to the undamaged emergency power panel for Unit 6, which still had one functional emergency generator. The power panel for Unit 5 was badly damaged, but it was charged by using a small part that had escaped damage. On March 13, temporary cables from the power panel for Unit 6 were connected to the standby gas treatment system and make-up water system for Unit 5 to supply power. On March 18, power was supplied directly to the seawater pump from a power supply vehicle and to the pump for removing decay heat through a temporary cable from Unit 6 so that the necessary cooling operation could be performed. These accident management measures proved effective. Fortunately, the reactor had been shut down for a periodic inspection, so it reached a cold shutdown state safely owing to the relatively small amount of decay heat.

Challenge: Protecting power supply hubs and power panels from damage
Crucial task for ensuring the redundancy and independence of AC power supplies
Crucial task for charging DC power supplies

In contrast, Fukushima Daiichi Unit 3 suffered not only an SBO, but also total damage to its power panel. Fukushima Daiichi Unit 5 experienced the same problem. In both cases, part of the measurement control systems still functioned properly using the only available DC power supplies. However, unlike for Unit 5, the batteries for Unit 3 could not be charged and a large amount of decay heat remained because the core shutdown had taken place only an hour before the station blackout. Measurement control systems could no longer be used when the batteries were depleted and the DC power supply was lost. The resultant core damage led to a hydrogen explosion that released a large amount of radioactive materials into the environment.

(4) Station blackout, loss of power panels, and loss of DC power supplies

When Fukushima Daiichi Units 1 and 2 were struck by the tsunami, they lost their DC power supplies (125 V) in addition to suffering SBOs and losing their power panels. Although the facts have yet to be ascertained, DC power supplies with voltages of 250 V and 24 V were presumably rendered inoperable. These units experienced complete station blackouts with absolutely no power supplies remaining operable. The resultant core damage led to a hydrogen explosion that released a large amount of radioactive materials into the environment.

The two most serious challenges posed by the loss of power supplies are the resultant failure to control the cooling systems and to operate the measuring instruments to gain key information from the reactor cores. Adequate control of a cooling system can gain some time until the core suffers any damage. Any available measuring systems can help keep track of the core conditions so that appropriate measures can be implemented. These systems do not require much power. It is vital to ensure a continued supply of power to important measuring and control systems.

Challenge: DC power supplies are the last bastion

If DC power supplies are lost, it is extremely likely that the core will be damaged and a massive release of radioactive materials will occur.

III. Counter Measures for Complete Station Blackouts

As explained above, SBOs occur on various levels. The pace of escalation into a more serious problem also depends on the amount of decay heat; in other words, the time between the core shutdown and any subsequent SBO. This chapter classifies the approaches to be taken in the event of an SBO.

1. Station Blackouts

A station blackout is defined as a failure to supply power to emergency equipment due to the loss of external and emergency AC power supplies (power generation units, such as emergency generators). An emergency power supply consists of multiple (usually two) independent systems to enhance its reliability. It is assumed that the power panel and the bus of at least one system will always be available for use. This type of SBO is considered most likely considering the dense fog and other such factors that cause it. Therefore, reliable measures should be implemented in advance to reduce the risk of this SBO.

If we take the Maanshan Plant as an example, we can see that the preparation of an extra power supply facilitates the necessary recovery. Various options are available for restoring power generation units, such as the restoration of external power supplies, the restoration of emergency generators, the establishment of a connection to an alternative emergency generator, and the establishment of a connection to a power supply vehicle. These options commonly enhance the reliability of power generation units. Given that the time constraints are increased by a larger amount of decay heat, reliability can be enhanced by preparing alternative power generation units in advance.

2. Complete Loss of AC Power Supply Systems

This condition is defined as a failure to supply power to emergency equipment due to the complete loss of the buses or power panels (metal-clad switchgear or power centers) for emergency power supplies with multiple lines. Due to the loss of power lines, power cannot be supplied even if external power supplies or emergency generators are available. For this reason, the power supply is lost regardless of the availability of power generation units. Similarly, the power supply will be disabled even if one type of power panel (e.g., power center) is still available downstream as long as another type (metal-clad switchgear) is unavailable upstream. In general, it is highly unlikely that multiple lines will suffer simultaneous damage due to a common cause. Therefore, it is not reasonable to deploy any permanent equipment in an attempt to prevent such a problem. Instead, accident management measures should be prepared in advance. It is important to adjust the design to enhance the independence and diversity of power supplies to eliminate any chance of failures resulting from common causes. Possible common causes include earthquakes, tsunamis, and other natural disasters, and terrorism.

In such an event, alternative emergency generators and the like cannot be expected to help because the power supply buses for the connected systems are damaged. Given the need to prepare for many kinds of triggering events, it is not realistic to eliminate common causes, although reliability could possibly be enhanced by preparing independent buses and power panels for alternative emergency generators.

Instead, accident management measures can be implemented to gain the necessary time. More specifically, DC power supplies should be used to remove the decay heat, while cables should be prepared to connect alternative emergency generators and power supply vehicles to the chargers for the DC power supplies in order to ensure that they are charged properly in the event of an emergency. It is also important to prepare the necessary temporary cables and organize regular training. Furthermore, it is necessary to estimate the possible duration of the cooling operation and make sure that it can last longer than the time required to restore the power supply lines.

3. Complete Station Blackouts

This condition is defined as the complete loss of AC power supply systems compounded by the unavailability of DC power supplies. Fukushima Daiichi Units 1 and 2 experienced this immediately after they were struck by the tsunami, as was Unit 3 after its batteries ran out. Similar to the complete loss of AC power supply systems, a complete station blackout is triggered by common causes of failures. The implementation of accident management measures is crucial, but this type of blackout is deemed slightly less likely to occur than a complete loss of AC power supply systems.

Possible accident management measures involving the use of equipment include enhancing the reliability, redundancy, and diversity of DC power supplies. For example, alternative DC power supplies or dedicated charging equipment could be deployed. In addition, backup power supplies could be prepared for measurement control systems and venting systems, both of which play essential roles during a severe accident.

4. Combinations of Different Types of Station Blackouts

The conditions involved in a station blackout, a complete loss of AC power supplies, and a complete station blackout are sometimes more complex than the simple definitions given above might suggest. For example, alternative AC power supplies may fail to activate during a station blackout. The necessary response should be taken by assessing the probabilities and risks of different combinations. It is generally believed that these different combinations can be enveloped by complete station blackouts. Nonetheless, further detailed assessments are probably required.

IV. Conclusions

The safety of nuclear power plants is ensured by the concept of defense in depth. In practice, the crucial tasks involved in the shutting down and cooling of reactors, and containment of radioactive materials must be performed. Fail-safe designs enable reactors to be shut down and contained to a certain extent even without power supplies. However, a supply of power is essential for the cooling operation, so it is vital to ensure that one is available in any circumstances. Even a small amount of power can gain some time. Appropriate measures must be considered for each level of defense in accordance with the relevant occurrence probabilities and risks. The overall risks for nuclear power plant should be reduced by classifying possible events and assessing them in a comprehensive manner. A scalded dog may understandably fear even cold water, but excessive caution can do more harm. The situation that we face today requires a clear-headed response and a comprehensive assessment.

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