AN INTEGRATED ACCIDENT MANAGEMENT FRAMEWORK FOR MITIGATING BEYOND DESIGN BASIS EXTERNAL EVENTS

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The objective of this paper is to provide an integrated accident management framework to mitigate beyond-design-basis external events (BDBEEs). The framework is named an integrated, RObust Coping Strategy (iROCS). The iROCS approach is characterized by the various plant damage conditions (PDCs) that might be impacted by BDBEEs, and corresponding integrated coping strategies to mitigate BDBEEs. The PDCs considered in the iROCS approach include combinations of the states of major critical safety functions such as (1) an extended loss of all AC power (and/or a loss of ultimate heat sink), (2) an extended loss of all DC power, (3) a loss of the reactor coolant system (RCS) inventory, and (4) a loss of the secondary heat removal (SHR) function. The loss of all DC power consequently leads to a loss of all instrumentation and controls at a main control room and local control panels. A loss of the RCS inventory is considered to reflect an uncontrollable loss of reactor coolant such as the reactor coolant pump (RCP) seal break LOCA. Lastly, a loss of the SHR function is considered to reflect the possibility of the failure of the SHR system including a rupture of the condensate storage tank, a failure of the TDAFW system, and a failure in associated pipings and instrumentations and controls. And then, it provides coping strategies for each categorized plant damage condition with an aim to preserve or restore core cooling and to maintain the integrity of the reactor pressure vessel and the reactor containment. Evaluation of candidate strategies under a postulated PDC has been conducted to provide valuable insights for making accident management provisions more feasible and effective against extreme hazards. The PDC under a case study includes both the loss of all AC power and the loss of the SHR function due to an extreme external event. From the case study, it turned out that both strategies such as 'the restoration of the SHR function using the ADVs and portable equipment' and 'the primary feed and bleed strategy using the SDS and portable equipment' are not easily achievable under the current status of design and plant condition due to a limited time available compared with the time required for completing necessary actions including deployment and connection of portable equipment. An innovative way such as pre-staging of necessary portable equipment or installation of independent power sources to improve the feasibility of candidate strategies are also suggested.

I. INTRODUCTION

Severe accidents occurred at multiple units of the Fukushima Daiichi nuclear power station due to an extended loss of all electric power and loss of ultimate heat sink induced by a large earthquake and tsunami, March 11, 2011. Beyond-design-basis external events (BDBEEs) are natural extreme events that exceed a plant design basis. There are several approaches to cope with BDBEEs. In the U.S., even before the Fukushima Daiichi accident, they have already had the extensive damage mitigation guideline (EDMG) to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities to cope with the loss of large areas of the nuclear facility due to large fires and explosions from any cause including beyond-design-basis aircraft impacts.[1,2] After the Fukushima accident, another set of mitigation strategies to cope with beyond design basis external events, diverse and flexible coping strategies (FLEX), were requested by the USNRC and are currently being implemented with developing FLEX Supporting Guidelines (FSGs) in most U.S. nuclear power plants.[3,4]

EDMG is developed to provide strategies and guidelines to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the loss of large areas of the nuclear facility due to large fires and explosions from any cause including beyond-design-basis aircraft impacts.[1,2] Due to the nature of the security threat, prediction or predefinition of precise damage states is not possible and of little value in assessing and enhancing plant capabilities.[2] Nevertheless, the guidelines for responding to the security threats are generally developed on the basic assumptions that includes disruption of normal command and control structure, loss of access to the control room, loss of all personnel in the control room, loss of all AC and DC power required for the operation of plant systems, minimum site staffing levels, and so on. Therefore, most of the plant-specific EDMG start from establishment of initial command and control structure, and then local activation and control of the turbine-driven auxiliary feedwater system (TDAFW) and monitoring of plant status via local instrumentation measurements, by any available personnel at the plant or site, in addition to the reactor scram and turbine trip.

FLEX aims to provide indefinite coping capability to prevent damage to the fuel in the reactor and spent fuel pools and to maintain the containment function under both an extended loss of AC power (ELAP) and a loss of normal access to the ultimate heat sink (LUHS) which could arise following external events.[4] In order to achieve the indefinite coping capability, FLEX provides a phased approach that utilizes installed equipment, on-site portable equipment, and pre-staged off-site resources. Similar to the EDMG, the baseline coping strategy of the FLEX starts with normal cooling and depressurization of the RCS by operation of the TDAFW and the steam generator (SG) power-operated relief valves (PORV) or atmospheric depressurization valves (ADV), but all these operations are not necessarily required to be initiated in local places like EDMG because the baseline coping strategy assumes that DC power is normally available. And the continuing strategies of FLEX to cope with an extended loss of electric power include the DC load shedding, deployment of portable generators, makeup of secondary cooling water, connection of portable pumps, makeup of primary coolant, and so on.

The objective of this paper is to provide a more integrated and extended framework and strategies to cope with BEBEEs adequately. The framework is named an integrated, RObust Coping Strategy (iROCS), which is built upon the basic concept of EDMG and FLEX employing temporary and portable equipment.

II. THE iROCS APPROACH TO MITIGATION OF BDBEE

The iROCS framework provides an *integrated* framework including a loss of the secondary heat removal function (e.g., due to the loss of the TDAFW system or rupture of the condensate water storage tank) and a loss of the RCS integrity (e.g., due to the RCP seal degradation), in addition to an extended loss of AC power (ELAP), a loss of normal access to the ultimate heat sink (LUHS), and a loss of DC power and instrumentation and control for preparing and analyzing accident management plans and strategies to cope with an extreme event. And the iROCS framework also provides an *extended* feature that provides successive strategies for each combination of damage conditions, aiming to prevent core damage as well as to preserve the integrity of the reactor pressure vessel, and further to be extended to preserve the integrity of the reactor containment. For each combination of damage conditions, the iROCS framework provides a platform to evaluate whether currently available candidate strategies referenced from the present EOP and SAMG would be effective or not in preventing or mitigating a severe accident as well as whether they could be feasible or not when considering extreme damage conditions of the plant site such as the flood-in and fade-away of the tsunami and the spreading of the debris on the site, and so on. If needed, the evaluation may result in revision of the candidate strategies including modification of necessary equipment, change of the implementation priority between strategies under a given damage condition, and so on.

Figure 1 provides an overall framework of the iROCS approach. It firstly defines plant damage conditions (PDCs) in the way that BDBEEs may have an impact on the major plant systems in view of critical safety functions.[5] The PDCs considered in the iROCS approach include combinations of the states of major critical safety functions such as (1) an extended loss of all AC power (and/or a loss of ultimate heat sink), (2) an extended loss of all DC power, (3) a loss of the secondary heat removal (SHR) function, and (4) a loss of the reactor coolant system (RCS) inventory. The loss of all DC power consequently leads to a loss of all instrumentation and controls at a main control room and local control panels. Reactivity control is assumed to be met at an early phase of an event through a normal reactor trip. A loss of the SHR function is considered to reflect the possibility of the failure of the SHR system including a rupture of the condensate storage tank, a failure of the TDAFW system, and a failure in associated piping and instrumentation and controls. Lastly, a loss of the RCS inventory is considered to reflect the possibility of the reactor coolant pump (RCP) seal break, the pressurizer safety valve (PSV) being stuck-open, and so on. Fundamental coping strategies for each of the defined plant damage conditions are described in more detail in the following sections.

II.A. Mitigation Strategy for PDC-1

PDC-1 may represent the baseline coping strategy of U.S. FLEX.[4] This condition is an extended loss of AC power with all the other critical safety functions including DC power, RCS inventory, and SHR system being intact. The fundamentally required action under this condition may be a restoration of all possible AC power sources including mobile diesel-generators and connection to the plant safety-grade or non-safety grade AC power buses, if possible. The next required task is to extend the lifetime of the DC battery by stripping the DC power supply to non-essential instrumentation and controls (I&Cs), while DC power supply to the essential I&Cs required for monitoring and controlling the critical safety functions under extended loss of AC power should be maintained (This task is also called 'DC load shedding').

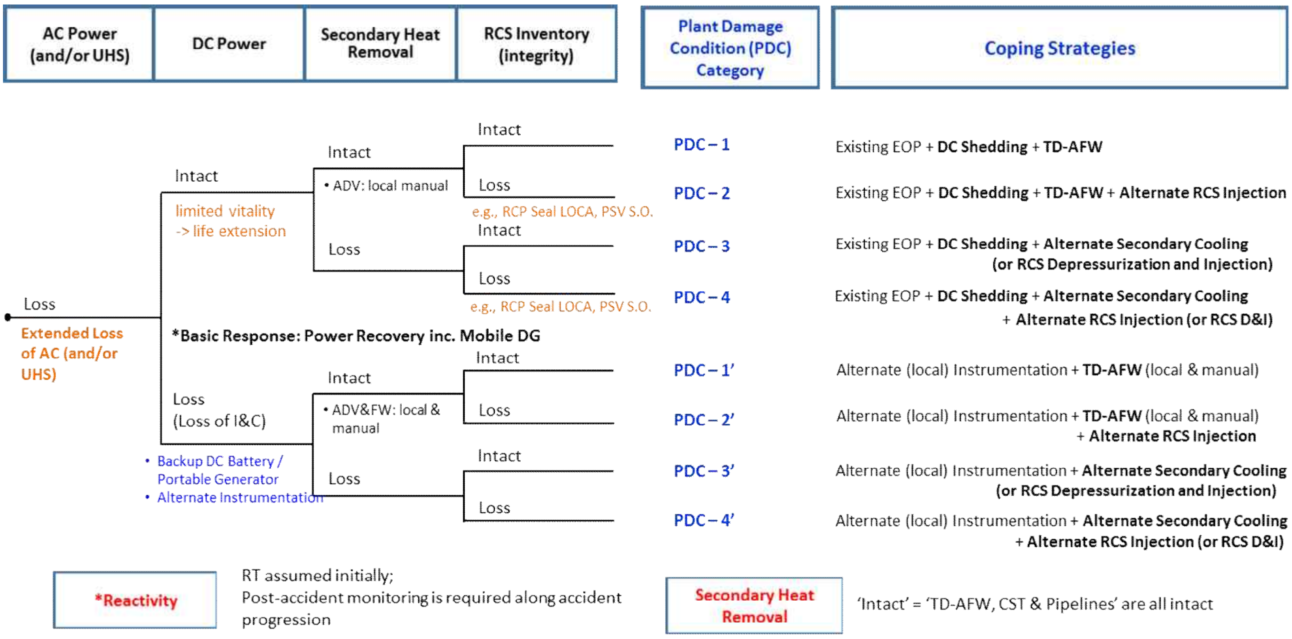

Fig. 1. The iROCS approach to cope with beyond-design-basis external events (BDBEEs)

The only way to cool down the RCS under an extended loss of AC in most of the pressurized water reactors (PWRs) is to use the TDAFW system. When DC power is available, control of feedwater to the steam generators (SGs) is possible in the main control room (MCR), but removal of the heated steam should be performed through a manual manipulation of the ADVs at a local place. If the DC load shedding is successfully implemented, DC lifetime can be extended to several to tens of hrs depending on the capability of DC battery and the degree of DC load shedding. During this extended time the RCS can be cooled down continuously using the TDAFW system and the ADVs, and this also increases the time available for restoration of AC power and supply of external resources. Additionally, DC battery should be recharged by connecting portable AC power to the DC charger. For long-term RCS cooling, the condensate storage tank (CST), or the auxiliary feedwater storage tank (AFST), which contains feedwater for the SGs, should be refilled from any available water sources including the fire protection water, the site pond, or river or sea water; or those water sources should be directly supplied to the SGs by using portable pumps. Preparatory actions such as deploying portable pumps and connecting hoses are required to supply water to the SGs at the appropriate time.

II.B. Mitigation Strategy for PDC-2

This damage condition includes a loss of RCS integrity, i.e., a loss of RCS inventory, in addition to an extended loss of AC power. The events associated with a loss of the RCS integrity may include a loss of coolant accident (LOCA) and a steam generator tube rupture (SGTR). The LOCA event may include small/medium/large sizes of a rupture along with the RCS pressure boundary, and it also includes an RCP seal rupture (i.e., the RCP seal LOCA) and stuck-open PSVs. Generally, the piping structure of the RCS pressure boundary is known to have strong durability against a seismic event, however, there may be vulnerable points attached in the RCS structure such as the injection part of the safety injection tank (SIT), in addition to the RCP seal break and the stuck-open PSVs.

Under even this condition, existing EOPs can still be useful for monitoring major plant safety functions but provide no means for injecting borated water into the reactor core. The basic actions required for an extended loss of AC power would be restoration of essential AC power and extension of DC lifetime through DC load shedding, which is the same as described in Section 3.1. To restore the reactor coolant inventory, high-pressure or low-pressure portable pumps can be connected to the RWST or the fire protection system water or any other alternate water sources. Under the loss of the RCS inventory, the SHR function needs to be maintained at the same time with the restoration of the RCS inventory to prevent core damage for the case of a leakage event or very small LOCA event, but it has a negligible impact for the case of a beyond small LOCA event, in other words, recovery of the RCS inventory is of utmost importance to restore the core cooling function for that case.

On the other hand, it may take about 2 hrs or more to deploy high-pressure or low-pressure portable pumps to inject borated water into the RCS depending on the site damage condition. In most loss of RCS inventory accidents except for a small LOCA,[6] this duration may sufficiently lead to a SAMG entry condition, e.g., CET > 650ºC, while preparing portable or mobile equipment in an extreme event. When the operating personnel enter the SAMG, SAG actions such as 'SAG-1: Inject into the SGs,' 'SAG-2: Depressurize the RCS,' 'SAG-3: Inject into the RCS,' and so on, are checked against critical plant parameters for their need for implementation, in accordance with the SAMG instructions. The strategy of 'Inject into the SGs' is expected to continue from the stage of EOP, and the strategy of 'Depressurize the RCS' is expected to have been accomplished for some larger sizes of the LOCA events, but may not have been accomplished enough for small sizes of LOCA for sufficient water to be injected into the RCS when using the portable diesel-driven pump. On the other hand, the strategy of 'Inject into the RCS' should be initiated and achieved well before the failure of the reactor pressure vessel occurs. According to the accident analysis results using the MAAP code, it has turned out that the reactor vessel failure occurs at approximately 3.8 hrs into the event for a small loss of coolant accident (SLOCA), and it occurs at approximately 2.6 hrs into the event for the large loss of coolant accident (LLOCA).[6] Therefore, an activity to depressurize the RCS and to inject borated water into the RCS using high-pressure or low-pressure portable pumps should be prepared from an early stage of a loss of the RCS inventory to maintain the integrity of the reactor pressure vessel under an extreme external event. An alternative strategy for using portable equipment is to install diesel-driven safety injection pumps, which are independent of electric power, or to pre-stage required portable pumps at a proximate place so that a prompt deployment might be possible under an extreme event.

II.C. Mitigation Strategy for PDC-3

This damage condition includes a loss of the SHR function in addition to an extended loss of AC power. The loss of the SHR system means the system is in a failed condition such that it cannot perform the heat removal function for the RCS cooldown due to the damage to the related structures, systems, and components (SSCs) from external events; such cases might include the structural failure of the CST, the rupture of the pipelines such as a steam-line or a feed-line, the damage to the TDAFW system, or the functional failure of ADVs, and so on. Under this condition, existing EOPs are still available for checking overall plant conditions but provide no means to cool down the reactor core.

The basic actions required for an extended loss of AC power would be the restoration of essential AC power and an extension of the DC lifetime through the shedding or stripping of unnecessary supply of DC power, which is the same as in the PDC-1. In addition to these, the restoration of the SHR function is also required. If the TDAFW system fails, an activity to recover feedwater to the SGs using a fire protection pump or portable equipment will be required. If the water sources to the SGs such as the CSTs (or the demineralized water or the raw water) rupture and lose all the contained water, due to the damage from an external event such as an earthquake, then the fire protection system water can be drawn to the SGs first if available, and in a long-term phase, other available water sources from a pond, river, or sea can be used as feedwater sources to the SGs.

On the other hand, it may take 2 hrs or more in deploying portable equipment or establishing alternate water sources, depending on plant damage conditions.[7,8] In addition, according to accident analysis results, the time from a reactor trip to core damage is known to be around 2 hrs if the SHR function fails under a total loss of AC power.[9] This means the core condition can lead to an entry condition of SAMG, for example, CET > 650ºC for the case of the WOG SAMG, while the operators and plant personnel try to recover the SHR function by deploying portable equipment and/or connecting alternate water sources to the required systems. When the operating personnel enter the arena of SAMG, they are required to perform severe accident guidelines (SAGs) associated with unsatisfied plant parameters in view of severe accident management. The strategies to be implemented include 'SAG-1, Inject into the SGs,' 'SAG-2, Depressurize the RCS,' 'SAG-3, Inject into the RCS,' and 'SAG-4, Inject into the Containment.'

If AC power is not recovered yet even after entering into SAMG, the operators or plant personnel have to use portable equipment and/or alternate water sources to implement the required SAMG strategies. Given the condition of a loss of the SHR function under an extended loss of AC power, the 'Inject into the SGs' strategy of SAG-1 can be continued from a previous stage of implementing an alternate strategy using the fire protection system or portable equipment to restore the SHR function.

For the 'SAG-2, Depressurize the RCS,' the RCS depressurization can be achieved by using the following valves, according to the SAMG of the reference plant, such as the safety depressurization system (SDS) valves, the power-operated relief valves (PORVs), the pressurizer vent valves, or the reactor vessel gas vent valves. To open these valves, DC power or both AC and DC power should be supplied. Pneumatic back-ups are equipped for some valves; they can be opened using portable air bottles.

For the 'SAG-3, Inject into the RCS,' which is required after successful depressurization of the RCS, the high-pressure or low-pressure safety injection system, or the charging system, can be used if AC power is recovered, or portable equipment with sufficient capacity should be deployed to inject borated water from the RWST into the RCS, if AC power is not recovered. When the RWST is unavailable because of the rupture of the tank or the depletion of the water, alternate water sources such as seawater or raw water should be drawn to the RCS using a high-capacity portable pump.

II.D. Mitigation Strategy for PDC-4

This damage condition includes both a loss of the RCS integrity and a loss of SHR function, in addition to an extended loss of AC power. As stated in the previous sections for postulated damage conditions, the existing EOPs can still be useful for monitoring major plant safety functions, but provide no means for alternative strategies to cope with these damage conditions. Basic actions under an extended loss of AC power will be the restoration of essential AC power and an extension of the DC lifetime through DC load shedding, which have also been addressed in the previous sections.

The required actions to recover RCS inventory are to deploy high-pressure or low-pressure portable pumps and connect those pumps to borated water sources such as the RWST. When an RWST rupture occurs due to an earthquake, the plant personnel need to make boric acid water by mixing boron with available water sources to supply borated water through portable pumps to the RCS. At the same time while they make an effort to recover the RCS inventory, they also have to try to recover the SHR by deploying portable equipment or by accessing alternate water sources, depending on the causes of the failure of the SHR function.

As stated repeatedly in the previous sections, since it may take about 2 hrs or more to deploy portable equipment, depending on the damaged situation of the site, the core state may lead to the SAMG entry condition, e.g., CET > 650^{o}C, while preparing recovery actions using portable equipment. Therefore, the required actions for a recovery of the RCS inventory and the SHR function using portable equipment should be prepared from an early stage of events in order to succeed in maintaining the integrity of the reactor pressure vessel under an extreme event. An alternative strategy for using portable equipment needs to be considered, for example, to install diesel-driven safety injection pumps, or to pre-stage required portable pumps at a proximate place so that prompt deployment may be possible under an extreme event.

II.E. Mitigation Strategy for PDC-1'~4'

This damage condition includes an extended loss of DC power as well as an extended loss of AC power. The loss of essential DC power can result in a loss of all instrumentation and control in both the main control rooms and local control panels. One of the fundamentally required actions for this situation is the recovery of essential DC power or the connection of temporary or portable DC battery to the essential DC bus lines. Furthermore, in preparation for a prolonged failure in the recovery of DC power, an alternative method for acquiring the requisite information should be prepared such as the use of DC-powered portable instrumentation, as adopted in the U.S. EDMG. In this case, the plant personnel need to be deployed to local places to measure critical plant parameters and to report measured data directly to higher decision-makers or other emergency response staff members by using communication equipment.

The high-level actions required under the condition of a loss of all AC and DC power are very similar to those required under the condition of an extended loss of all AC power except the shedding of unnecessary DC power. Additionally required actions may include the acquirement of critical parameters using alternate instrumentation methods, manual operation of the required systems and components at local places, and cooperation and coordination between plant personnel and (on-site and off-site) emergency response staff members.

In the base case in which both the RCS inventory and the SHR function are intact under the loss of all AC and DC power, the basic strategy to cooldown the reactor core is the operation of the TDAFW system and the ADV at the appropriate locations. The TDAFW system can be operated initially by heated steam from the SGs or restarted by manual operation by supplying instrument air and/or portable DC power when it fails to start. The SG water level needs to be controlled within an appropriate range to maintain continued operation of the TDAFW system. Manual operation of the motor-driven isolation valve at a local place, when no AC or DC power is available, can be used as a method to achieve the control of the SG water level. The ADV should also be opened and manually controlled locally to cooldown the reactor core. Furthermore, requisite information for an adequate control of the RCS cooldown should be acquired from the local instrumentation. Therefore, for all of these activities to be achieved successfully toward the safe shutdown of a plant, coordination and cooperation with other plant staff members and emergency response organizations are essential. Appropriate communication equipment should also be provided.

Mitigating strategies for the other accident conditions such as a loss of the SHR system and a loss of the RCS inventory are basically the same as those for the accident conditions under an extended loss of AC power, except the need for a local measurement of the critical plant parameters, special equipment such as portable instrument air or portable DC power for manipulation of motor-operated or air-operated valves, and special effort for the coordination and cooperation between plant staff members using communication equipment. Simplified mitigating guidelines composed of major critical parameters and clear rules for decision-making and deploying mobile or portable equipment will be helpful for emergency response staff members or plant personnel to make a prompt decision under the condition of a loss of all instrumentation resulting from a loss of all DC power.

III. EFFECTIVENESS AND FEASIBILITY ANALYSIS

A case study for evaluating candidate accident management strategies was performed for the iROCS PDC-3 condition, i.e., the loss of the SHR function following an extended loss of AC power due to a beyond-design-basis external event. Due to an extreme event, both the loss of all AC power (including both offsite power and emergency diesel power) and loss of the SHR function are assumed to occur from an early stage of the event, following a reactor trip and turbine trip at T=0.

Under the loss of all AC power and SHR functions, basically required actions are the DC load shedding to extend the DC life time and the restoration of the SHR function using the ADV and portable equipment or the primary-side feed and bleed strategy using the SDS and portable equipment. The DC load shedding activity can be conducted in the instrumentation and control panel inside the control room at an early phase of the event progression, without being affected or impacted by an external event. However, restoration of the SHR function and the primary-side feed and bleed strategy using portable equipment must be affected by an external event because these activities should be conducted locally and manually outside the control room. To identify the feasibility associated with these actions, effectiveness of both strategies according to initiation times were analyzed using the MAAP 5.03 code.[10]

The accident progression for the unmitigated base case scenario for the loss of both all AC power and the SHR function is as follows. After a reactor trip at T=0, the RCS temperature and pressure rise due to the loss of the SHR function, and at around T=1 hr, the pressurizer safety valve (PSV) starts the first opening operation. The RCS loses its inventory to the containment through repetitive open and close operations of the PSV, and finally leads to a core uncovery at about 2 hrs after the reactor trip. The core starts to melt at about 3.16 hrs after the reactor trip. At about T=3.42 hrs, the hot leg creep rupture occurs due to the high temperature and high pressure condition of the RCS, and as a result of the RCS depressurization due to the hot leg creep rupture, the safety injection tank (SIT), which is a passive safety injection system, begins to inject borated water into the RCS. At about 5.45 hrs into the event, the molten corium relocates to the lower plenum, and eventually the reactor vessel failure occurs at about T=7.06 hrs. A summary of the timepoints for the major events is given in TABLE I.

TABLE I. Timeline for Unmitigated Event Scenario under a Loss of AC Power and a Loss of the Secondary Heat Removal

Event	Time (hr)
PSV 1st Opening	1.07
Core Uncovery	1.99
EOP-SAMG Transition (CET=650^{o}C)	2.86
Core Melt (Start)	3.16
Hot Leg Rupture	3.42
SIT Injection	3.43
Corium Relocation to Lower Plenum	5.45
Reactor Vessel Failure	7.06

From the evaluation of two candidate strategies, it is implied that if implementation of the restoration of SHR using ADVs and portable pumps can be achieved within 2 hrs or so, then this strategy is preferred to the primary feed and bleed strategy using the SDS and portable pumps because the latter induces a forced loss of coolant accident. However, completion of deployment and connection of portable equipment within 2 hrs or so under an extreme external event seems to be very uncertain. For example, under an extreme earthquake or tsunami, the path from the portable equipment storage facility to the connection point of the portable equipment may be broken or covered with all kinds of debris scattered by the external event. Therefore, in order to implement required accident management strategies, maintenance of the broken paths and clearing of the scattered debris on the travel path for deploying portable equipment should first be preceded. If we take into account these kinds of preparative actions in addition to deploying and connecting portable equipment, the required time to complete a given accident management strategy can be more than 3~4 hrs or so, according to the consultation with an expert who has knowledge and experience in implementing U.S. FLEX. Furthermore, if we consider the intrusion of a tsunami into the site, the initiation time at a local place by the operating staff must be delayed, for the operating staff can take required local actions only after tsunami has removed away.

The other candidate strategy is the primary feed and bleed using the SDS and portable pumps. As described in the above accident analysis result, the SDS valves should be opened prior to the hot leg creep rupture, i.e., within around 3 hrs into the event, to prevent the hot leg creep rupture, and the RCS injection using the portable pump should be achieved prior to 6~7 hrs after the reactor trip. Also as noted above, both the 125VDC and 480VAC power should be supplied to open and control the SDS valves. Therefore the 480VAC portable generator should be deployed and connected to the power supply system of the SDS control valves at a minimum prior to the hot leg creep rupture. In the same way as in the restoration of SHR using ADVs and portable pumps, it may take more than 3~4 hrs or so to complete all required actions, including plant damage assessment and debris removal and deployment and connection of the 480VAC portable generator, to achieve the opening of SDS valves. If we consider those actions under an intrusion of a tsunami, the initiation of a local accident management action must be delayed until the tsunami has fade away.

A rough timeline was constructed for the required actions associated with the primary feed and bleed strategy using the SDS and portable equipment under an intrusion of a tsunami, as shown in Fig. 2. The time required vs. the time available for preventing the hot leg creep rupture as well as the reactor vessel failure seems to be very competing with each other. The timeline is constructed on the basis that a minimum number of emergency staff are available at the time of an extreme event according to the emergency plan of the site, and therefore conductance of multiple actions in parallel by the minimum available staff is very limited.

Under the given evaluation of the candidate accident management strategies, both strategies turned out to need remediation to achieve a required goal within an available time. For the strategy associated with restoration of the SHR function using ADVs and portable equipment, a way of pre-staging portable equipment nearby the connection points is required to achieve the goal of preventing a reactor vessel failure as well as core damage. In the other way, if such a way as pre-staging is not plausible in a given plant, the plant can choose the primary-side feed and bleed strategy using the SDS and portable equipment, by modifying the electrical supply system connected to the SDS control valves or devising other driving mechanism which is robust against external events.

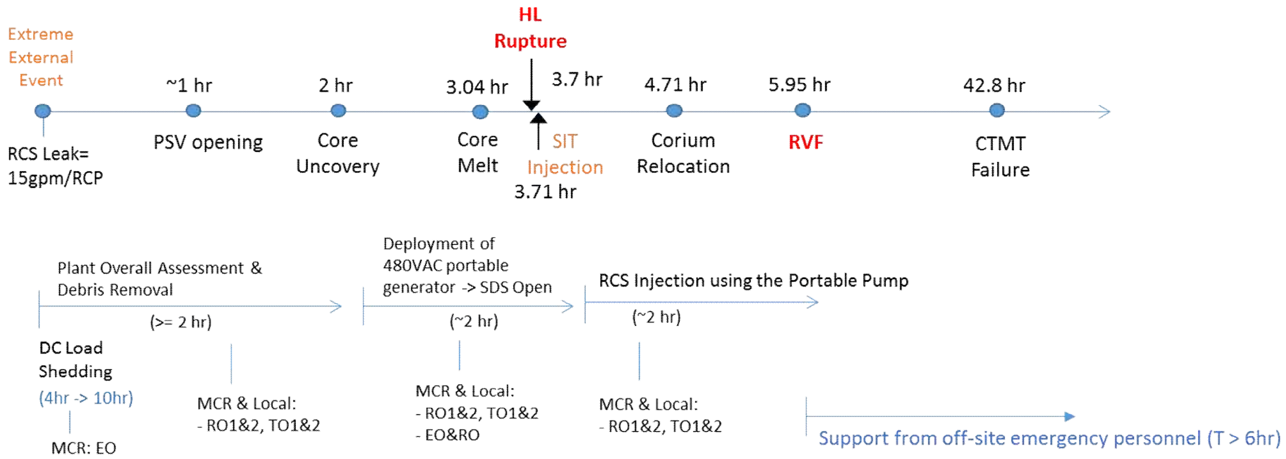

Fig. 2. Timeline of accident management actions against accident progression when considering a minimum number of emergency operating staff

IV. CONCLUSION

In this study, the iROCS approach was proposed to cope with BDBEEs. The iROCS approach provides an integrated view of the potential plant damage conditions that might be impacted to the plant's safety functions by BDBEEs. It also provides candidate mitigation strategies for each of the impacted plant conditions aiming to maintain core cooling as well as to preserve the integrity of the reactor pressure vessel. From a case study under both the loss of all AC power and the loss of the SHR function due to an extreme external event, it turned out that both strategies such as 'the restoration of the SHR function using the ADVs and portable equipment' and 'the primary feed and bleed strategy using the SDS and portable equipment' are not easily achievable under the current status of design and plant condition due to a limited time available compared with the time required for completing necessary actions including deployment and connection of portable equipment.

Likewise this case study, existing strategies adopted in EOPs and SAMGs should be reevaluated for their effectiveness and feasibility against accident scenarios under plausible extreme events. In these evaluations, they should basically consider the timing aspects, i.e., the time available vs. the time required, in employing mobile or portable equipment under an extreme event, cognitive capability of the emergency operating team such as for information gathering, situation assessment, and decision-making, including the time required to gather the status of critical parameters and judge the critical plant status under the loss of instrumentation due to the loss of all DC power, appropriateness of the role and responsibility of the emergency response staff, especially the initial response organization, as well as effectiveness of the candidate accident management strategies.

ACKNOWLEDGMENTS

This work was supported by Nuclear Research & Development Program of the National Research Foundation (NRF) of Korea grant, funded by the Korean government, Ministry of Science, ICT & Future Planning (MSIP) (No. NRF-2012 M2A8A4025989).

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