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CONTAINMENT AND RELEASE MANAGEMENT*

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ABSTRACT

Reducing the risk from potentially severe accidents by appropriate accident management strategies is receiving increased attention from the international reactor safety community. Considerable uncertainty still surrounds some of the physical phenomena likely to occur during a severe accident. The USNRC, in developing its research plan for accident management, wants to ensure that both the developers and implementors of accident management strategies are aware of the uncertainty associated with the plant operators ability to correctly diagnose an accident, as well as the uncertainties associated with various preventive and mitigative strategies. The use of a particular accident management strategy can have both positive and negative effects on the status of a plant and these effects must be carefully weighed before a particular course of action is chosen and implemented.

By using examples of severe accident scenarios, initial insights are presented here regarding the indications plant operators may have to alert them to particular accident states. Insights are also offered on the various management actions operators and plant technical staff might pursue for particular accident situations and the pros and cons associated with such actions. The examples given are taken for the most part from the containment and release phase of accident management since this is the current focus of the effort in the accident management area at Brookhaven National Laboratory.

1. Background

Although severe accidents in nuclear power plants are viewed as very unlikely events, history has shown that their occurrence cannot be ruled out completely. In recent years there has been an increased international interest in the risk arising from potential severe accidents and the role management of such accidents can play in reducing risk.

A useful way of grouping accident management strategies is by their emphasis on preventing core damage, arresting core damage (in-vessel management), or preserving containment integrity (ex-vessel management). The

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latter, termed containment and release management is the focus of our present discussion and is concerned with maintaining containment integrity as long as possible and minimizing the consequences of offsite releases. Usually containment and release management strategies apply to situations where core debris has penetrated the reactor vessel so that the containment is the only barrier between fission products and the environment. However, some containment strategies involve measures to be implemented before vessel failure and even prior to core damage.

2. Objective

The objective of this paper is to highlight some of the important considerations regarding severe accident management that need to be addressed by the NRC research program in this area. While specific examples of management strategies cited here deal for the most part with the containment and release phase, in-vessel and ex-vessel strategies are of necessity closely coupled and often dependent on each other. Therefore many of the insights cited here apply to preventing or arresting core damage as well as to preserving containment integrity.

A significant amount of uncertainty still limits our understanding of many of the physical processes associated with severe accidents. This is especially true of phenomena occurring at reactor vessel penetration and subsequent stages of the accident. High pressure melt ejection, core-concrete interaction, and debris coolability are a few prominent examples of events where comprehension remains limited by uncertainty.

Despite this uncertainty, there is a wide consensus in the reactor safety community that a significant benefit can be obtained by carefully developing accident management strategies and preparing reactor personnel for implementing them. However, the use of a particular strategy can have negative as well as positive effects on the status of the plant. Both the developers and the implementors of a strategy must be aware of the pros and cons associated with it and have confidence that, in the specific situation in which the strategy is applied, the benefits outweigh the disadvantages. The previously mentioned uncertainties make such an assessment more difficult and can themselves influence the selection of a strategy. (For instance a more costly or less efficient strategy, but one with less uncertain "side-effects," may be preferable to a less costly or more efficient strategy which has more uncertainty attached to it.)

Two key questions for conceiving and evaluating any accident management strategy are, first, what will the operators and other responsible plant personnel know, and second, what can they do based on the information available? Often, when the progression of a theoretical severe accident is analyzed and various outcomes postulated, the implicit assumption is made that the status of the core, the conditions in the primary system, the reactor cavity, and the rest of the containment are all known and various safety systems can be called on to fulfill their function at the appropriate time. In reality, lack of information, or erroneous information regarding the status of plant systems may be the biggest obstacle in arresting or mitigating a severe accident.

Therefore, to adequately address the two questions stated above, an accident management research program must focus on the following items:

1) information the operating staff can acquire during a severe accident with the instruments and information systems currently existing within the various containment types;
2) how these symptoms can be correlated to different severe accident phenomena and plant damage states;
3) preventive and mitigative actions that are possible, contingent on the functioning engineered safety features and other available systems;
4) which among these options is the optimum choice under particular containment conditions, and
5) any obviously cost-effective enhancement of instruments and other systems or procedural changes which could improve the accident management response.

In addition, human factors involving the training, staffing and performance of operational and technical personnel, as well as plant organization and lines of responsibility will affect accident management, but in the present discussion we will restrict ourselves to presenting some initial insights related to the first four items listed above. Many of these insights are based on the work done in assembling the five volumes of NUREG/CR-4920[1] and some of them have previously been discussed in NUREG/CR-5132.[2]

By means of examples we want to illustrate how a particular severe accident scenario can be diagnosed from the information the operating staff is likely to have, what strategies could be implemented, and the positive and negative aspects of each strategy.

3. Insights

As a number of studies have shown, one way in which containment integrity can be impaired is via an isolation failure or bypass. Therefore, as a first example illustration we want to consider the situation where an interfacing systems LOCA occurring during a severe accident causes the containment to be bypassed.

An interfacing systems LOCA can occur in both BWRs and PWRs due to a failure of the barriers between the high-pressure reactor coolant system and connected low-pressure systems, resulting in the failure of some components outside of primary containment. Although such sequences have been found to be relatively low frequency events, they may lead to potentially high radiological releases because these events provide a direct path for release of fission products to the atmosphere.

The symptoms of an interfacing systems LOCA that an operator is likely to see on his control panel indicators are several. Primary system pressure level will drop. A loss of primary system inventory will occur without a corresponding increase in containment sump level indication. Since the breach of the low-pressure system outside of the primary containment boundary will occur in the reactor building of BWRs or the auxiliary building or safeguards building in PWRs there may be an indication of water level in these buildings. Furthermore, if some fuel damage has occurred, radiation levels in the auxiliary or reactor building may also provide strong indication that an interfacing systems LOCA is taking place.

Assuming the plant operators have received some of the signals mentioned, have interpreted them correctly, and have realized what is happening, what actions can the operators and plant technical staff take to arrest this accident or mitigate its consequences?

If an interfacing systems LOCA is in progress the operator may be able to arrest it by isolating the component or section of piping where the failure occurred. In many cases adequate additional valves exist to isolate the affected section of the low-pressure system if it can be located precisely. If isolation of the failed component is not feasible it may be possible to flood the location of the break in the auxiliary or reactor building with water and mitigate the consequences of the LOCA by scrubbing any fission products which are being released. If flooding is not possible, the operator may be able to turn on fire sprays in the BWR reactor building or the PWR auxiliary building to reduce the pressures and temperatures and decontaminate the atmosphere. Finally, in some situations it may be feasible to depressurize the high-pressure system to reduce the driving force and thereby the flow and amount of fission products bypassing the containment.

However, there are serious concerns associated with all these strategies except isolation of the affect low-pressure system component, and even in this case, if the system is an essential one, its isolation may solve the immediate problem but have detrimental implications for the future progress of the accident. Trying to flood the location of the break can lead to excessive flooding and impair other systems. The use of fire sprays can have very detrimental effects on electrical apparatus or other sensitive equipment. Deliberate additional depressurization of the high-pressure reactor coolant system will lead to further depletion of the primary system inventory and may, in some accident scenarios, hasten the onset of core damage or aggravate the progression of core melt.

As further examples of the kinds of information operators can expect and the actions plant personnel can take when faced with a severe accident we will describe a severe accident progression in a PWR and identify operator actions which may reduce the severity of such an accident but we will also indicate the risks that may accompany such actions. Both high-pressure sequences as well as situations where the reactor coolant system has been depressurized will be considered and the accident will be followed from core damage to reactor vessel penetration and through the ex-vessel phase.

Many studies have predicted that most severe accidents would be started by transients or small breaks in the primary system pressure boundary. Under these circumstances, the primary system would remain at high pressure unless the plant operators take actions to reduce the pressure. If such an accident starts and high-pressure injection is not available, and heat removal through the steam generators is not effective, then core damage will occur unless the plant operators restore high-pressure injection, reestablish heat removal through the steam generators or depressurize the primary or secondary systems to take advantage of any available low-pressure injection systems.

As long as the primary system has not been breached a major objective of plant personnel must be to maintain water flow to the core. If coolant injection can be restored before core damage the accident is terminated, but it is also possible that plant operators may restore the coolant injection systems only after the start of core damage. The water will cool the reactor core, prevent further degradation, and could prevent the core from melting through the reactor pressure vessel. While supplying water to the damaged core is a major objective of the plant operators, there are phenomena associated with mixing water and high temperature molten core materials that are difficult to predict. It is possible that by adding water additional steam will be produced which in turn could generate more hydrogen before the core materials are cooled. It is also possible that more violent interactions may occur between the hot core debris and water and additional fission products may be released. In addition, adding relatively cool water to hot fuel could shatter the fuel into rubble, impeding further coolant flow through the core.

If high-pressure injection cannot be restored depressurization of the reactor coolant system will allow low-pressure systems to inject. The preferred way of accomplishing this would appear to be depressurization using the steam generators. After the primary system has been depressurized via secondary heat removal, the accumulators will inject and the low-pressure injection systems can be actuated. To attain success in this procedure, the operator must open the steam generator atmospheric steam dump valves, maintain auxiliary feedwater, main feedwater, or special makeup (e.g., fire pumps) to the steam generators, and have one of the low-pressure injection systems available. Although these procedures may improve cooling capabilities, the secondary side depressurization and reflood may induce thermal shock and hence increase the possibility of steam generator tube rupture, which may aggravate the accident sequence. In addition, depressurization of the steam generators will cause loss of steam that could otherwise be used for the steam-driven pumps. Both the nuclear industry and the NRC are studying this emergency procedure further.

If primary system depressurization cannot be achieved by heat removal through the steam generators, direct depressurization may be possible by opening relief valves in the primary system. If successful, the procedure will allow the accumulators to inject, and available low-pressure injection systems can be actuated. Although this procedure has obvious advantages, it is not clear to what extent existing systems in various reactors are capable of meeting such an objective. Depending on the particular strategy, it is also possible that for some accidents the time to core damage could be reduced relative to time that it would have taken with the primary system at high pressure. In addition, pressure relief will also vent hydrogen to the containment atmosphere early in the accident, with the possibility of a burn or detonation. Therefore before implementing this procedure the advantages and disadvantages have to be carefully assessed. It is also being investigated by both NRC and the nuclear industry.

If water flow to the core cannot be restored and the primary system is not depressurized, then core relocation (into the lower plenum) and subsequent lower vessel head failure at high pressure will follow. Upon vessel failure, violent melt ejection could produce large-scale core debris dispersal. The containment integrity could be threatened by any or all of the following: direct containment heating, large, energetic releases of hydrogen, and direct melt-through from contact with core debris. Which, if any, of these threats apply depends on the exact scenario and the particular containment design.

In general, if the accident has progressed to this point there appears to be very little that can be done by the plant operators to mitigate the effects of a high-pressure failure of the reactor vessel during the blowdown phase. However, it is possible for the plant operators to manage containment-related safety features prior to reactor vessel penetration to minimize the effects of high pressure melt ejection. If fan coolers or sprays are available they will keep the containment pressure low so that any pressure increase generated at the time of reactor pressure vessel failure will have less impact than if these containment systems were *not* operating. In addition, if fan coolers are able to maintain a low containment pressure, spray operation could be saved until the plant operators have an indication of core damage. Spray operation after core damage and fission product release could aid in removing aerosol fission products from the containment atmosphere. However, it has also been suggested that it is an advantage to have water in the reactor cavity prior to the release of the core debris from the reactor pressure vessel. For some containment designs, water will only be available in the reactor cavity after the sprays have injected all of the water from the refueling water storage tank into containment. Thus, the advantages and disadvantages of early or late spray operation depend on the containment design.

If the accident sequence is one which causes a reactor coolant system pressure drop (such as a large LOCA) or if the system has been depressurized by one of the techniques mentioned above a number of additional systems can be made available to inject water into the core. Even if no low-pressure injection systems can be made available and core damage eventually occurs, depressurization may still be advantageous because vessel failure with the primary system depressurized represents much less of a challenge to containment integrity. However, it has again been suggested that it would also be an advantage to have water in the cavity prior to vessel failure for low-pressure accidents to mitigate core-concrete interactions. It is also an advantage to have spray operation during core degradation and vessel failure. Therefore, it is again necessary to optimize spray operation to ensure the most effective mitigation of the accident.

In our discussion so far we have skipped over the question of how the plant operators will know that core damage has occurred. With the present instrumentation in commercial nuclear reactors there are not very many indicators of core damage and those that exist are not very precise. Readings of prolonged low water level in the reactor vessel should alert the staff that damage may have occurred. The same is true of high temperature readings from exit thermocouples. Abnormal containment radiation levels are another sign that fuel has been damaged. Beyond such circumstantial evidence however the operators information regarding core damage is very limited. Not only is it difficult for the operating staff to determine if core damage has occurred and the extent of damage, the operators may not know whether the core is still essentially in the vessel or whether some or all of it has penetrated the primary system. The indicators of vessel meltthrough seen in the control room are ambiguous: Rapid depressurization of the primary system may be caused by the core melting through the vessel or by a high temperature failure somewhere in the primary system boundary. High containment temperatures may be due to core penetration but could also be caused by other phenomena such as a hydrogen burn. Likewise high radiation levels in containment and large quantities of noncondensibles may be due to an ex-vessel core which is reacting with concrete, but may also occur if the primary system has failed but the core still remains in the vessel.

Once the core debris has exited the reactor vessel the principal objectives of the plant staff must be to flood the debris with water and to maintain or restore containment heat removal systems. Even if the containment has failed, it is advantageous to flood and cool the core debris to prevent further fission product release from the damaged fuel and to keep the containment atmosphere at a low pressure to minimize the driving force for fission product release to the environment. Although these objectives are well defined, in practice they may be difficult to achieve and may have side effects that have to be carefully considered.

When trying to flood the core debris with water, the plant operators may have to decide to restore water flow to the primary system or directly to the containment atmosphere via the spray system. If the core debris has been released from the reactor vessel, there are advantages and disadvantages to using either system. However as just discussed above, the plant operators will probably not be able to determine whether or not the core debris has actually been released from the vessel or know the extent to which it is dispersed within the containment. Thus, the first priority would be to restore water flow to the primary system in an attempt to retain the core debris in the vessel. If the core debris has already penetrated the bottom head, the water would flow through the break onto the top of the core debris in the reactor cavity. The subsequent interactions between the water and core debris depend on the containment design and the details of the accident prior to vessel failure.

If the core debris melts through the vessel with the primary system at high pressure, it is possible that a large fraction of the core debris could be blown out of the reactor cavity. It is therefore possible that limited quantities of core debris would be left in the cavity and thus minimum concrete attack would occur. However, at the other extreme, if the primary system is depressurized when the core debris melts through the vessel, most if not all the core debris would likely be retained in the reactor cavity. If the cavity is initially dry and the core debris forms a deep bed, it could remain hot for a relatively long time and extensive concrete attack would occur. Under these circumstances, pouring water on top of the core debris may have the effect of rapidly cooling the core and stopping concrete attack. However, experiments have shown that a crust can form on top of the molten core debris and effectively prevent the water from mixing with and cooling the core. These experiments were performed at small scale and the stability of the crusts under the conditions of a severe accident in a power plant have not been established. Thus, the effect of pouring water on top of the core debris is uncertain. Therefore, even though water flow is restored to the core debris continued concrete attack with the generation of more combustible gases and fission products is still possible. The presence of water above the debris does have the advantage, however, of trapping a fraction of the fission-product aerosols generated during the concrete attack, which would otherwise have reached the containment atmosphere.

Core debris attack of concrete in a dry cavity will pressurize the containment relatively slowly. However, concrete attack will generate large quantities of aerosols (nonradioactive and radioactive), combustible and noncondensible gases, all at relatively high temperatures. If water cools the core debris and all the decay heat goes to boiling water, containment pressurization will be significantly faster. However, containment temperatures will remain relatively low and concrete attack will be slowed or prevented.

Restoration of containment heat removal systems such as containment sprays after significant amounts of steam and hydrogen have entered the containment must also be approached with caution. Condensation of the steam by the spray system in a previously steam-inerted containment could result in the formation of a combustible mixture of possible detonable gases in containment and, if an ignition source is available, a potentially damaging combustion event could occur.

If containment heat removal cannot be restored, containment pressurization may very well continue until structural failure. Under these circumstances, controlled containment venting has been suggested as a way of preventing the uncontrolled release of radioactivity that would accompany structural failure of the containment. However, there are questions regarding venting that must be answered prior to implementing such a procedure. Combustion could occur in the vent line, which in turn could produce an uncontrolled release. Venting at some predetermined pressure level significantly below the containment ultimate capacity means that radioactivity release is certain whereas if the accident had been allowed to proceed structural failure may not occur. Isolation valve performance during venting is also uncertain and, if the valves fail open, could result in an uncontrolled release. Finally, restoration of containment heat removal to a vented containment could condense residual steam, and produce a vacuum in containment, with the attendant possibility of implosion.

4. Summary

Initial insights were presented here regarding the information available to plant operators and technical personnel during a severe accident and the interpretation of that information. Insights were also given regarding some of the preventive and mitigative actions plant personnel might take when confronted with a severe accident and the benefits and concerns associated with these actions.

More detailed insights will be developed under the NRC sponsored accident management program now under way as part of an integrated approach to severe accident resolution.

5. References

1. "Assessment of Severe Accident Prevention and Mitigation Features," NUREG/CR-4920, Volumes 1 through 5, Brookhaven National Laboratory, July 1988.

2. "Severe Accident Insights Report," NUREG/CR-5132, Brookhaven National Laboratory, April 1988.