BNL-NUREG-41964

CONF-881014--16

ACCIDENT MANAGEMENT FOR SEVERE ACCIDENTS*

R. A. BARI, W. T. PRATT, J. LEHNER
(Brookhaven National Laboratory, USA)
M. LEONARD† and R. DISALVO
(Battelle Columbus Division, USA)
B. SHERON
(U.S. Nuclear Regulatory Commission, USA)

BNL-NUREG--41964

DE89 004899

ABSTRACT

The management of severe accidents in light water reactors is receiving much attention in several countries. The reduction of risk by measures and/or actions that would affect the behavior of a severe accident is discussed. The research program that is being conducted by the U.S. Nuclear Regulatory Commission focuses on both in-vessel accident management and containment and release accident management. The key issues and approaches taken in this program are summarized.

INTRODUCTION

The objective of this paper is to present the current status of research by the U.S. Nuclear Regulatory Commission and its contractors in the area of accident management for severe accidents. Severe accident management refers to measures and/or actions that can lead to the reduction of risk posed by a potential severe accident by either preventing or mitigating specific events or conditions that would otherwise occur as part of a severe accident scenario.

Over the past several years there has been an increased interest, worldwide, in the risks posed by potential severe accidents in light water reactors. The Reactor Safety Study[1] (WASH-1400) showed how severe accidents determine the risk profiles of light water reactors in the U.S. This study was followed by many others, in several countries and for specific plants, and these also showed how specific accident sequences and phenomenological conditions contributed to the risk profiles for these plants. The current NRC-sponsored study[2] of risk (NUREG-1150) incorporates some recently identified severe accident phenomena that strongly affect risk uncertainty. Much research has been done on the thermal hydraulic behavior of the reactor and containment during a severe accident and on the resultant behavior of fission product releases. This work has

---

*This work was performed under the auspices of the U.S. Nuclear Regulatory Commission. Views expressed in this paper do not necessarily represent official NRC policy.

†Present Address: Science Applications International Corporation, Columbus, Ohio.

advanced our knowledge of the diverse phenomena (e.g., core debris interactions with concrete, hydrogen combustion in the containment, etc.) that contribute to severe accident scenarios. The accidents at TMI and Chernobyl have provided specific focus on the role of the human in determining the course of events of a severe accident. Both the positive and negative aspects of human interactions during a severe accident have been demonstrated by these events.

While much work has been done over the last several years on accident (and risk) assessment, relatively little has been done on accident management. It is now widely held in several countries that there can be a significant safety benefit from the development and implementation of a severe accident management program for each light water reactor. Thus, programs are underway in several other countries (e.g., Sweden, France and the Federal Republic of Germany) which are aimed at the management of severe accidents through enhanced measures and/or actions that would lead to risk reduction. In the U.S. an Accident Management Program has begun as part of an overall Integrated Program for Closure of Severe Accident Issues[3].

In this paper, we summarize the key features of the U.S. program and provide some initial insights from our knowledge of severe accident behavior to approaches to accident management. While the U.S. program places major emphasis on both in-vessel and containment and release accident management areas, this paper, for the purpose of illustration, gives relatively more emphasis to containment and release accident management.

KEY FEATURES OF SEVERE ACCIDENT MANAGEMENT

The objectives of the NRC accident management program[4] are:

a) To provide a technical basis for the review of accident management programs to be developed by utilities.

b) To assure that adequate guidance (developed from such sources as previous PRA studies, the NRC Severe Accident Research Program and the nuclear industry-sponsored IDCOR program) will be distilled, disseminated to the operating/technical support staff and integrated into utility training programs.

c) To increase the emphasis on accident management as a part of annual emergency preparedness exercises.

d) To develop strategies for dealing with prevention and mitigation of accident sequences based in part on input from NRC programs on Containment Performance Improvement and on Individual Plant Examinations.

The NRC program focuses on three aspects of accident management. These are termed prevention of core damage, in-vessel accident management, and containment and release accident management.

For the prevention of core damage the emphasis is on the investigations of whether cost effective measures may be available to either prevent core melt or significantly delay it and on ensuring that severe accident management strategies that are implemented early during an accident are properly encompassed in procedural guidance so that the strategies do not conflict with the current emergency operating procedures. In-vessel accident management focuses on strategies to maintain core materials within the vessel after damage has occurred to the core. Particular emphasis is given to strategies for water addition to the reactor coolant system (and to the secondary system of PWRs). For accident sequences for which the reactor vessel is at high pressure, emphasis is also given to strategies for depressurization such that low pressure coolant injection could become available to arrest further core damage.

Containment and release accident management refers to strategies that are aimed at preserving the integrity of containment. These strategies include the management of core debris after it is ejected from the reactor vessel. However, some containment strategies involve actions or measures that would be taken prior to ejection of debris from the vessel and even prior to the initiation of core damage. Other containment strategies involve restoration of safety systems after vessel failure has occurred.

It is important to all aspects of accident management that information on the status of the core, containment, safety systems and support system be known to the extent needed to reliably implement the various strategies. Following the TMI-2 accident, the environmental qualifications of important monitoring and control instrumentation were upgraded. In order to assure that the operating crew is capable of managing a severe accident it will be important to determine the types of plant information systems (including control room displays, remote displays, safety parameter display-type systems, and computerized decision aids) that will be needed for such events. Also of importance to all categories of the accident management program are human factors and organizational issues. Some areas that are being considered in the program are (1) methods of assuring the adequacy of operational/technical staff performance, training, and staffing for severe accident situations, (2) identification of unique training requirements for the operating/technical staff, in coping with severe accidents, and (3) development of criteria and guidelines for assessing the contribution of licensee management and organization as related to coping with severe accidents.

INITIAL INSIGHTS

This section describes severe accident progression for pressurized water reactors (PWRs) and boiling water reactors (BWRs) and identifies possible operator actions which may reduce the severity of a severe accident. The material presented is, in part, a summary of a recently published BNL report.[5]

PWR Severe Accident Progression

If an accident occurs in which the primary system is at high pressure, 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.

One potentially effective way of making up core inventory if the high-pressure injection systems are unavailable (either for injection or recirculation) is to depressurize the primary system 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. This emergency procedure is being investigated by both the nuclear industry and the NRC. 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. This procedure is also being investigated by both the nuclear industry and the NRC. If successful, the procedure will allow the accumulators to inject, and available low-pressure injection systems can be actuated. 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 than if the primary system is allowed to remain at high pressure. 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 the 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.

If the primary system cannot be depressurized and the core cannot be adequately cooled, then core damage will eventually occur. The initial stages of core degradation involve coolant boiloff and core heatup in a steam environment. At high pressures natural circulation of the primary loops could be set-up between the core and the remaining cooler components of the primary system. As a result of this energy redistribution, the primary system pressure boundary could fail prior to the occurrence of large-scale core melt. The location and the size of failure, however, remain uncertain. In particular, concerns have been raised about the possibility of steam generator tube failures and associated containment bypass.

In a recent study[6], Battelle Columbus Division compared calculated estimates of core melt progression for various accident sequences and reactors. A general observation[6] is that the operating crew would have at least one hour available in which to preserve the integrity of the pressure vessel once core uncovery starts. The study shows that more slowly developing sequences offer proportionately more time for operators to act. Therefore if the operators are able to restore the coolant injection system after the start of core damage, the water will cool the reactor core, prevent further degradation, and prevent the core from melting through the reactor pressure vessel. Although 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 coolant flow through the core. This was speculated to have occurred at TMI-2 when the coolant pumps were turned back on.

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 dispersal of the core debris into the containment atmosphere, which could result in a very rapid pressure pulse causing containment failure.

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 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 produce 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 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 is initiated by a large break LOCA or the operators are able to depressurize the primary system, core damage would occur at low pressure. At low system pressure, decay heat redistribution due to internal natural circulation flow is negligible and core degradation occurs with very little heat loss to the remainder of the primary system. Limited availability of steam ensures low hydrogen generation rates.

Throughout this core heatup and meltdown process the potential to significantly pressurize the containment is small. In the very unlikely event of complete loss of all emergency cooling functions and a large break in the primary system, core damage could begin 30 minutes or sooner after the start of the accident. If core cooling is not restored, the core could relocate to lower regions of the reactor vessel and penetrate the vessel lower head within 2 hours of the start of the accident. Thus, the time frame for operator action for this type of accident is relatively short if core damage is to be prevented or the core is to be retained within the reactor vessel. However, with the primary system at low pressure, the plant operators have a number of additional systems that could be made available to inject water into the core.

If water flow to the core cannot be restored, the core materials will eventually penetrate the reactor vessel. Failure of the vessel at low pressure does not generally present an immediate threat to containment integrity. However, it has again been suggested that it would also be an advantage to have spray operation during core degradation and vessel failure. Thus, it is again necessary to optimize spray operation to ensure the most effective mitigation of the accident.

Possible actions that operators might take prior to the release of the core debris from the vessel have been discussed above. Actions that might be taken after the vessel has failed are presented below.

Whether or not the containment fails early, the long-term objectives are the same, namely to try to flood the core 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, more fundamentally, 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 containment heat removal systems are not working, it should be noted that pressurization of the containment due to core debris attacking concrete is a relatively slow process. However, concrete attack does generate large quantities of aerosols (nonradioactive and radioactive) and combustible and noncondensable gases, all at relatively high temperatures. If water cools the core debris and all the decay heat goes to boiling water, containment pressurization is significantly faster. However, the containment temperatures are relatively low and concrete attack is slowed or prevented.

Also, if the containment heat removal systems are not working, high steam (above 50 volume percent) and noncondensable gas concentrations in containment can prevent burning of combustible gases. If containment heat removal is restored under these circumstances, steam condensation could result in the formation of a combustible mixture of possibly detonable gases in containment and, if an ignition source is available, a potentially damaging combustion event could occur. Therefore, the decision to restore containment heat removal systems after extensive core damage has occurred must be made with caution. If containment heat removal cannot be restored, containment pressurization might 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.

BWR Severe Accident Progression

The in-vessel accident management objective for BWRs is the same as for PWRs, namely to restore water to the reactor core. However, in BWRs there are numerous ways of injecting water into the reactor vessel and in addition, BWRs have an automatic depressurization system (ADS) which lowers the potential for core damage at high pressure. Additional details on the various in-vessel procedures are given in Reference 5.

If the core materials cannot be cooled in the reactor pressure vessel, they will eventually penetrate the vessel head. The long-term objectives after vessel penetration are the same for BWRs as for PWRs, namely to try to flood the core debris with water and to maintain or restore containment sprays. However, there are differences between the containment designs that are worth noting.

The corium presents more of a direct threat to containment integrity for some BWRs than it does for PWRs. For example, if it is assumed that a large mass of molten corium is released from the vessel in a BWR with a Mark I containment, then the corium could be postulated to flow across the drywell floor and melt through the primary containment resulting in early containment failure. This potential failure mode remains uncertain, but is possible. It is not known if water on the drywell floor (or in the reactor cavity) will preclude core debris from flowing across the floor and interacting with the drywell shell. However, flooding the drywell cavity is beneficial because even if liner melt-through occurs, fission products will pass through water prior to release and will be thereby attenuated. Alternative strategies are being investigated which address the consequences of core debris reaching the containment pressure boundary.

If the sprays or vessel injection cannot be restored, containment pressurization will continue until structural failure becomes a possibility for all BWR containment designs. Under the circumstances, wetwell venting has been suggested as a way of preventing structural failure, provided that the venting path is hardened to withstand the blowdown loads.

Finally, Mark I and Mark II containments are enclosed in a secondary containment structure (reactor building). This building is very large in volume and contains a large amount of structural surface area. Depending on the location at which materials released from the primary containment enters the reactor building, fission products may have to be transported through a tortuous path and over a great distance to be released to the environment (typically via "blowout panels" in the refueling bay). As a result, the reactor building can serve as an effective barrier to fission product release. Events such as the combustion of released hydrogen in the reactor building can significantly reduce the effectiveness of the reactor building in filtering released fission products and, conversely, manual operation of building fire spray systems can significantly enhance fission product scrubbing.

SUMMARY

The status of the research program on severe accident management that is sponsored by the U.S. Nuclear Regulatory Commission has been discussed. The program is part of an overall NRC integration plan for closure of severe accident issues. The results of the research effort will provide a basis for utility programs that will be aimed at maintaining a low level of severe accident risk. In addition, insights on severe accidents that have direct implications for accident management have been discussed.

REFERENCES

1. The Reactor Safety Study, WASH-1400, NUREG 75/014, October 1975.

2. Reactor Risk Reference Document, NUREG-1150, February 1987 (draft).

3. Integration Plan for Closure of Severe Accident Issues, SECY-88-147, U.S. Nuclear Regulatory Commission, May 25, 1988.

4. Accident Management Program Plan (draft), Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, May 1988.

5. Severe Accident Insights Report, NUREG/CR-5132, April 1988.

6. A Characterization of the Time Available for Interaction During Severe Reactor Accidents, Battelle Columbus Division, to be issued.