MANAGEMENT OF SEVERE ACCIDENTS

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ABSTRACT

The definition and the multidimensionality aspects of accident management have been reviewed. The suggested elements in the development of a programme for severe accident management have been identified and discussed. The strategies concentrate on the two tiered approaches. Operative management utilizes the plant's equipment and operators capabilities. The recovery management concentrates on preserving the containment, or delaying its failure, inhibiting the release, and on strategies once there has been a release.

The inspiration for this paper was an excellent overview report on perspectives on managing severe accidents in commercial nuclear power plants [1] and extending plant operating procedures into the severe accident regime [2]; and by the most recent publication [3] of the International Nuclear Safety Advisory Group (INSAG) considering the question of risk reduction and source term reduction through accident prevention, management and mitigation. The latter document concludes that "active development of accident management measures by plant personnel can lead to very large reductions in source terms and risk", and goes further in considering and formulating the key issue: "The most fruitful path to follow in reducing risk even further is through the planning of accident management."

The INSAG document acknowledges the increasing attention worldwide to preventing severe nuclear power plant accidents by all available means, but also stresses the importance of accident management. This would, consequently, lead to a further risk reduction.

In seeking to clarify and define the actual and practical meaning of aspects of accident management it is useful to review the definitions as a starting point. This review reveals and emphasizes the multistructural and multidisciplinary aspects of accident management. As was - correctly - concluded [2], the term 'accident management' means 'different things to different people"; and the challenge today is to define an acceptable programme of accident management, especially its relation and application to unique aspects of the design and operation of nuclear power plants.

The 'different things' that accident management means actually reflect the many dimensions of accident management (which strongly depends on 'who' and 'what' is the subject of discussion), and derive from terminology which refers to 'emergency management', 'risk management', or 'hazard management', and ' accident management'. The integration of these three elements is also termed 'safety management'.

The multidimensionality of accident management for nuclear power enterprises further complicates the formulation of a broadly acceptable definition of (and, most importantly, the practical means of) accident management, since it relates to the interplay between accident prevention and mitigation, on-site and off-site countermeasures, and emergency preparedness actions and responses. Further complication arises from an operational definition of accident management as "a set of actions taken by the plant operating crew to gain control of the outcome of an abnormal event at the earliest possible time and with the minimum consequences". One may argue that this is prevention. Further proposed definitions* and modifications add the 'totality of measures' aspect, 'ad hoc plans' [4], consideration of unexpected developments

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* 'Accident management' refers to the totality of measures, both short and long term, taken to control the course of an accident in progress and to mitigate the consequences of an accident during its occurrence. Examples of such measures are procedures, communications, analyses, ad hoc plans, the use of outside specialist help, special equipment, etc., developments (additional features), unforeseen events, and severe accidents [5].

(additional failures), unforeseen events and severe accidents [5] *.

In general, risk management is the management of uncertainity. In business, 'risk' management is used to optimize profits. In its simplest form, the businessman attempts to maximize the expected value of benefits (profits). This is anologus to minimizing risk in reactor safety if we treat risk simplistically as the probability times the consequences (the first moment or expectation value of the probability density function for consequences). The more cautious businessman worries, however, about major losses that can lead to bankruptcy. He, therefore, uses weighting factors ('risk aversion factors) in his optimization process. Over the long run he can't expect to make as large a profit, but he provides additional assurance that he won't be wiped out by a major loss. In the case of nuclear safety not only do we want to keep the 'expectation value' of risk low, but even more important, we want to control the likelihood of extraordinary accidents [7]. Continuously maintaining the risk 'expectation value' low prevention is the only answer, and the first priority in reactor nuclear safety is to prevent severe accidents from occurring.

Accident prevention is primarily beyond the scope of accident management. Once an accident has occurred, however, the first role of accident management is to limit the accident from reaching severe accident conditions. There is a major pitfall in the use of conventional PSA results for this purpose [7]. PSAs tend to single out 'dominant' accident sequences more than they deserve. Real accidents just don't happen like their PSA counterparts. Real accidents tend to always involve multiple failures, operator errors and unanticipated plant behaviour. Accident management must recognize those uncertainities and assure that protection is provided for a much broader set of conditions than a literal interpretation of a PSA would indicate. Given that the accident has progressed to the point that the core can't be contained within the reactor vessel, the focus of accident management shifts to the preservation or delay of containment failure. Uncertainity phenomena play a key role here.

So, what is 'accident management' and what does it really mean?

In attempting to clarify the real meaning of severe accident management and its practicability [and viability] in relation to the nuclear industry, it is suggested that it is necessary to recognize and consider the following elements in the development of an acceptable and responsive programme for accident management.

These elements are:

(1) Acceptance of the possibility of an extraordinary nuclear accident;
(2) Recognition and acceptance of large uncertainities in the present state of knowledge of developments arising from the evaluation of severe accidents and their predicted consequences;
(3) A willingness to develop accident management strategies based on Elements (1) and (2).

1. ACCEPTANCE OF THE POSSIBILITY OF AN EXTRAORDINARY NUCLEAR ACCIDENT

Severe nuclear accidents are a reality, as it is a reality that many other extraordinary industrial accidents occurred in the past. Nuclear accidents of this kind are a possibility which should not be dismissed or taken lightly; nor should we dismiss public apprehensions about such a possibility. The question, therefore, is not whether a severe nuclear accident will occur again, but rather when, and how severe it might be. The history of nuclear accidents - due to errors in design and construction, or mechanical or human failures - has confirmed this.

The accident at Windscale in the United Kingdom in 1957 occurred during routine maintenance and was partly due to inadequacies in the instrumentation provided for the maintenance operation being performed and partly due to errors of judgement by the operating staff [8].

The fire at the Browns Ferry plant in the USA in 1976 was started by a workman checking for air leaks with a candle. The fire nearly caused a very serious accident which could have resulted in radiological releases to the environment from the two units [9].

The Three Mile Island (TMI) accident in the USA in 1979 led to a partial uncovering of the core which damaged the fuel elements. Hydrogen generated by metal-water reactions was subsequently ignited and the combustion process resulted in a pressure spike. This has given rise to concern about containment integrity, and prompted a review of approaches to safety at nuclear power plants worldwide.

The Chernobyl accident in the USSR in 1986,

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* The commonly used [6] term 'severe accident' refers to an accident which exceeds the design basis sufficiently to result in the failure of structures, materials, systems, etc., without which core cooling cannot be properly ensured by normal menas. The severity of an accident depends on the degree of fuel damage and on the degree of loss of containment integrity, The phrase 'severe core damage' refers to the condition in which a substantial degree of rupturing and oxidation of fuel cladding and possibly some melting of the fuel has occurred, or is intended to define all final states of reactor elements in which cladding integrity has been breached either by melting or by chemical reaction.

the worst in the history of the nuclear industry, caused significant damage to the reactor core, reactor vault an other structures of the plant, leading to loss of life and significant land contamination [10, 17].

Severe nuclear accidents are therefore a reality. An overstatement? Hardly. The astounding sequence of events and processes leading to and during the two explosions at Chernobyl dramatically shows that the avoidable and unpredictable can happen and did happen. The 'lessons learned' still remain to be seen.

The acceptance that an extraordinary nuclear accident might occur is the fundamental first prerequisite in the development process for effective accident management.

2. RECOGNITION AND ACCEPTANCE OF LARGE UNCERTAINITIES

The uncertainity-hypotheticality dilemma in the area of risk or hazard has been recognized for a long period of time. The 'hypotheticality' aspects of severe accidents in nuclear power plants have shifted considerably over the past 13 years.

Nuclear power plants, like any other human enterprise, cannot be designed to take account of all envisaged possibilities so as to lead to the elimination of all accidents. Obviously, this is impossible. A nuclear power plant is therefore designed to ensure its capability of undergoing a specified range of operational events, accidents and external hazards with strictly limited radiological consequences. The defence in depth concept combined with the analyses of accidents and transients constitute the philosophy and methodology for ensuring that plant operation will not result in undue risk to the health and safety of the public.

Through this process the concept of a design basis accident (DBA) has evolved. DBAs are a set of non-mechanistic hypothetical accidents which have been chosen to include the anticipated most credible conditions in what was perceived to be a very conservative manner. Thus these accidents do not represent expected or realistic conditions but have been judged to encompass any credible accident. DBAs, therefore, formed a basis for the design of nuclear power plants.

In estimating risks for nuclear power plants the US Nuclear Regulatory Commission (USNRC) WASH-1400 Reactor Safety Study (RSS) considered a range of possible events from the benign to the most severe hypothetical accidents. This study and the accident at Three Mile Island have led to many changes and improvements in design and operation, shifting the emphasis from DBAs to 'beyond design basis accidents'. The consideration given to accidents beyond the DBAs and the changes subsequently introduced vary from country to country on the basis of regulatory, licensing and national policies and pratices.

The most important improvements in design and operation are in the diagnostic instrumentation in the control room, in critical safety functions and in the preservation of containment integrity by inerting, deliberate ignition, venting and filtration. These changes have been made despite the recognized large uncertainities in accident phenomenology and methodology of evaluation.

The major advance in the quantification of uncertainties in the risks of severe accidents is due to the significant progress over the years in understanding the phenomenology of severe accidents and the source term for fission products [11, 12] as a result of research and more reliable methods of analysis. The US report recently published [6] summarizes the advances achieved over the past 13 years since the RSS was published. It discusses the question of risk based on the re-evaluation of major factors related to internally initiated events* contributing to severe core damage and identifying the primary sources of uncertainities.

From the concept of accident management there follow two very important conclusions. Firstly, early containment failure, in general, cannot be ruled out with high confidence for any of the plants studied. Secondly, the determination of the radioactive source term for the release following a severe accident is perhaps the most difficult and uncertain area of risk analysis.

The acceptance of an early containment failure and the large uncertainities in the quantity, form and timing of radioactive releases are the second fundamental prerequisite in the developement of a comprehensive concept for the management of severe accidents.

Essentially, the uncertain aspects in the development of accident management follow the four basic themes [13, 14]:

(1) An unwillingness or inability to accept limitations or potential limitations imposed by uncertainity;
(2) Uncertainity cannot be eliminated and assumptions to the contrary are not only ineffectual but also dangerous;

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* Excluding fires, floods and earthquakes.

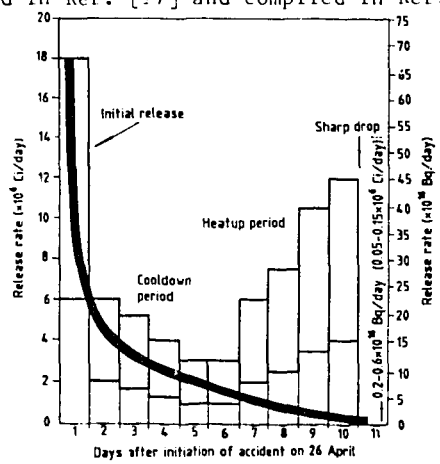
(3) An increased ability to cope with accidents is the essence of good management; and
(4) Even an increased ability to cope is of only limited help if it is restricted to predicted 'dominant' accident sequences.

An illustration of the correctness of the themes is provided by the evaluation of the management approaches in the TMI accident. It was concluded at that time [9] that "plans should concentrate on uncertainity rather than expecting to fit the preconceived patterns, and plans have to be flexible enough to cope with the major uncertainities and unpredictable events that management faces in accident situations."

An incomplete and preliminary evaluation of management strategies in the Chernobyl accident [15, 16] has revealed many peculiarities associated with the ad hoc methods chosen and their influence on the release pattern. The use of water in an attempt to cool the core debris proved ineffectual and was quickly abandoned. The release occurred in two stages: an early intense release and a prolonged release over a period of nine days.

Although it may not be possible to explain all the details of the intense release, it was not inconsistent with expectations for these violent events. The cooldown stage and the reduction in the release was due to the deposition of dry inorganic materials onto the core. The prolonged second stage of the release, and especially the sudden drop on the eleventh day, are not yet understood. The aforementioned actions combined with gas blanketing of the reactor vault had apparently stabilized the core debris, quenched the fire and prevented further releases.

Consider the time dependent release curve for the Chernobyl accident. The values shown are calculated for 6 May 1986 taking into account radioactive decay up until then. The radioactivity released was 20-22 x 10^6 Ci. The range of uncertainity for all releases is $\pm$ 50%, as reported in Ref. [17] and compiled in Ref. [10].



Time dependent release curve for the Chernobyl accident

The superimposed line could represent a hypothetical 'release curve' if the release were continuously decreasing as a result of other earlier actions. Achievable? Perhaps. This hypothetical 'release curve' actually represents the ultimate effectiveness of accident management given a sudden and fast event (e.g. early containment failure).

3. DEVELOPMENT OF ACCIDENT MANAGEMENT STRATEGIES

It is suggested that the development of accident mangement strategies concentrate on the two tiered approaches:
(1) Operative management; and
(2) Recovery management.

The first approach is a fundamental one, and actually represents the enhancement of the powerful operational measures and techniques; the second one is a backup if the operative action proves to be ineffective, or if the rapid progression of an accident could preclude the full utilization of all the possibilities offered by the plant.

Operative Management

The analysis of severe accidents and the insights gained from most of the work done do not invalidate the current existing designs of nuclear power plants. Rather, the information confirms that the defence in depth concept is technically sound.

The engineered safety features in the plant would retain at least some of their effectiveness for accidents beyond the design basis, and the flexible use under abnormal operation (and in accident situations) of those systems and their components should be anticipated [18]. The engineered safety features in the plant provide numerous such possibilities, as do many auxiliary systems designed for normal operation. It is important that the possibilities for use of these systems be understood and taken into account of in the development of plant-specific concepts of how best to use the systems available to halt the progression of an accident. This would permit plant operators and regulators to concentrate their attention even more on operational practices for emergencies that can provide real benefit in realistic evaluation of the plant capabilities.

Needless to say, however, the types and numbers of such systems differ from plant to plant, so that the non-conventional use of them (safety and non-safety related use) requires exploration on a plant specific basis and detailed review of the design specification.

The goal, therefore, for such a plant-specific comprehensive evaluation would be to provide an additional protection of the primary system boundary, protection of the containment and the utilization of any systems and structures that augment the confinement of fission products

in order to maximize the length and complexity of the pathway through which radionuclides would have to pass to escape to the environment. Even if containment protection cannot be maintained, reductions in radionuclide releases can be achieved by maximizing the retention in any structures and attempting to route, for example, air flow paths through any available filtration systems.

These considerations imply the need for plant-specific studies which would offer more realistic methods of analysis that can dependably guide emergency actions offering real benefit.

Operator actions are presently guided by the procedure guides and are country specific. The event-oriented procedures are normally included in the original operating instructions and are applicable to accidents considered within the original design. The plant operation based on event-oriented procedures ought to be cross-checked by a functional analysis of critical safety functions commonly separated from operational functions.* This procedure includes the choice of optional mitigating actions. The state-oriented or symptom-oriented procedures currently under extensive development concentrate on severe (and late) accident stages when the critical safety functions may not be applicable or the information needed is unavailable. Basically, however, there is little explicit guidance given to the operator on how to deal with severe core damage [1].

The outcome, therefore, should be a symptom-based set of responses to provide a direct and rapid link between the state of the system and measures using all available plant systems, which offer many possibilities for plant protection.

The nuclear industry has generally been moving in this direction.

Recovery Management

The next tier would be the development of strategies and measures as an emergency backup if the operative management actions did not lead to the arrest of an accident, but its further progression leading to containment failure and resulting in a large release from the plant.

Operative management actions would differ substantially from recovery management interventions. The first one utilizes primarily the plant's equipment and operators' capabilities. The second one should mainly rely on measures directing towards preserving the containment, or delaying its failure, and inhibiting the release in the shortest possible time, and on strategies and techniques once there has been a release. The containment preservation methodology is at an advanced stage; the ultimate measures and techniques to inhibit the release or to apply these measures effectively once there has been a release are still in their infancy.

On site, the development of strategies and methodologies should concentrate on: (1) provisions and plans to have appropriate materials in sufficient quantities readily available; (2) provisions and plans for external heat removal systems; (3) consideration for alternate fire fighting techniques given the differentiations of materials involved; (4) availability and reliability of special instrumentation in high radiation and high temperature environments, special equipment for personnel involved in recovery and remedial actions, and remotely controlled and operated robotics including heavy equipmnet; (5) manpower resources both from within the establishment and from outside, including redundancy and identified expertise and responsibilities, and backup resources for prolonged events; and (6) possible implications for the safety of other operating units in the case of multi-unit site. These are just a few examples.

Once there has been a release, the strategies, therefore, should be targeted to inhibiting the further release and transport of radionuclides, which could contribute significantly towards mitigating the consequences for plant personnel and the population, and for land and water contamination. Obviously, management of the iodine, caesium, strontium, ruthenium, and tellurium is of prime importance.

Science and modern technology could offer many possibilities once recognized and considered in relation to reactor nuclear safety.

* Variation depends on the type of reactor, manufacturer etc.

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