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PHENOMENA OCCURRING IN THE REACTOR COOLANT SYSTEM DURING SEVERE CORE DAMAGE ACCIDENTS¹

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INTRODUCTION

The reactor coolant system (RCS) of a nuclear power plant consists of the reactor pressure vessel and the piping and associated components that are required for the continuous circulation of the coolant which is used to maintain thermal equilibrium throughout the system. In the event of an accident, the RCS also serves as one of several barriers to the escape of radiotoxic material into the biosphere.

The physical and chemical processes occurring within the RCS during normal operation of the reactor are relatively uncomplicated and are reasonably well understood. When the flow of coolant is properly adjusted, the thermal energy resulting from nuclear fission (or, in the shutdown mode, from radioactive decay processes) and secondary inputs, such as pumps, are exactly balanced by thermal losses through the RCS boundaries and to the various heat sinks that are employed to effect the conversion of heat to electrical energy. Because all of the heat and mass fluxes remain sensibly constant with time, mathematical descriptions of the thermophysical processes are relatively straightforward, even for boiling water reactor (BWR) systems. Although the coolant in a BWR does undergo phase changes, the phase boundaries remain well-defined and time-invariant.

Moreover, much of the focus in normal operation is on the performance of the fuel and the characteristics of the coolant; transport processes involving other species, such as fission products (from leaking fuel rods) or oxidized debris ("crud"), are of secondary importance and their effect on the thermalhydraulics is negligible.

In contrast to normal operating conditions, severe core damage accidents are characterized by significant temporal and spatial variations in heat and mass fluxes, and by eventual geometrical changes within the RCS. Furthermore, the difficulties in describing the system in the severe accident mode are compounded by the occurrence of chemical reactions. These reactions can influence both the thermal and the mass transport behavior of the system. In addition, behavior of the reactor vessel

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internals and of materials released from the core region (especially the radioactive fission products) in the course of the accident likewise become of concern to the analyst.

SEVERE CORE DAMAGE ACCIDENTS

Severe core damage accidents are believed to result typically from the failure of an engineered safety feature (ESF) to respond to a reactor upset condition, either because of failure of the ESF to perform its intended function, or because of its deliberate disablement. As a consequence, a mismatch occurs between the thermal power production of the core and the rate at which the thermal energy is transported by the coolant from the core of the reactor to the appropriate heat sinks. This mismatch may be sudden (such as in the case of a reactivity insertion accident), or it may proceed over a prolonged period of time (a station blackout sequence, for example).

Several stages of a severe core damage accident which involve the RCS can be identified. The first of these is the power-coolant mismatch, i.e., the inability of the coolant to adequately remove the heat being generated within the core region. This results in the heatup of the coolant and its consequent loss through either a breach in the RCS or relief or safety valves. The second stage involves uncovering of the core, heatup of the uncovered portions of the fuel elements, the onset of steam-cladding chemical reaction, and the eventual loss of fuel cladding integrity. It is thus at this point that fission products begin to escape from the fuel rods. The initial releases, however, primarily involve only that fraction of the fission product inventory that is associated with the interconnected void volumes within the rods, that is, the so-called "gap inventory." Hence, the initial releases consist of a small amount of fuel fines and their associated fission products, and small fractions of the inventories of the noble gas and volatile fission products (primarily nuclides of cesium and iodine). Should the accident be terminated at this stage (a "controlled loss-of-coolant accident"), the amount of radioactivity introduced into the environment would be inconsequential [1].

The third stage of a severe core damage accident is characterized by the appearance of molten material and the relocation of core components into the bottom head of the reactor pressure vessel. It also includes interaction of the molten core debris with residual water in the bottom head. Major fractions of the inventories of the risk dominant radionuclides (^{131}I , ^{134}Cs , ^{137}Cs) are introduced into the RCS at this time, and a dense aerosol (comprised mostly of control rod and structural material) is formed.

The fourth stage involves failure of the reactor pressure vessel and the introduction of molten material into the reactor containment. This was previously regarded as the terminus for considerations of phenomena occurring within the RCS. More recently, however, it has been realized that decay heat from radioactive materials that had become deposited on the RCS surfaces during the earlier stages of the accident could heat these surfaces to sufficiently high temperatures that revaporization of some of the deposited material could occur. This, then, is an additional stage of a severe core damage accident that involves the RCS. Moreover, since this stage represents the delayed release of radioactive material from the RCS, its neglect may lead to non-conservative estimates of the consequences of several accident scenarios.

SEVERE CORE DAMAGE ACCIDENT PHENOMENA

The degree of mathematical complexity that is required to describe the physicochemical processes occurring within the RCS, even under steady-state conditions, is determined by the temporal and spatial scales that are of interest, and by the accuracy of the results that are desired. Thus, for example, estimates of the average core exit temperature of the coolant that are adequate for most purposes can be had using only the power rating of the core, the flow rate of the coolant through the core, its core inlet temperature, and the specification of a small number of thermophysical properties of the coolant and RCS structural materials.

The problem would become considerably more complex, however, if the complete specification of the temperature distribution throughout the core were desired. Moreover, the calculational method would have to be extended to include an interdependence between fission product transport within the uranium dioxide fuel matrix and the thermal performance of the fuel elements, since the thermal performance of the fuel rods degrades with time due to the release of fission products into the fuel-cladding gap region. Furthermore, the resultant decrease in gap conductance increases the operating temperature of the fuel, and this promotes additional transport of fission products into the gap region.

In slowly developing accidents (i.e., those not associated with reactivity transients), a mathematical description of the thermophysical processes in the early stages presents no additional complexities relative to their description under normal reactor operation. In fact, if decay heat represents the major mode of energy production (the reactor has been tripped), some simplification results, since the temperature gradients within individual fuel pellets are reduced significantly. Later into the accident, however, the appearance of a second coolant phase in the covered portion of the core does result in considerable complication. As core uncover occurs, the complexities multiply. One source is due to the initiation of steam-cladding chemical reaction. This reaction has a two-fold effect; first, it introduces a new and significant source of thermal energy, and second, the hydrogen produced in the course of the reaction alters the thermophysical properties of the coolant.

Other complications arise when the fuel rod claddings are breached and fission products are released, and again when reactor vessel temperatures become sufficiently high that structural and control rod materials begin to relocate. This alters the problem from one involving purely thermalhydraulics considerations to one concerning the interdependence of thermalhydraulics and materials behavior.

The initial release of fission products from the fuel rods is almost inconsequential. As the accident progresses, however, their further release and subsequent transport, which are determined by thermalhydraulics factors, begin to influence the thermalhydraulics. An example of this is evident from a consideration of the data presented in Table 1. At reactor shutdown, elements which form volatile or moderately volatile species under severe accident conditions (Kr, Xe, I, Br, Cs, Rb, Te, Se) constitute more than a third of the total decay heat generation of the core. These species are essentially completely released into the RCS as the fuel forms low temperature melting eutectics with other core components or attains temperatures in excess of about 2000°C [2]. One hour into the accident (after reactor shutdown), the radionuclides in volatile form still contribute about a third of the total decay heat generation, and the total

power production due to decay heat decreases to less than a quarter of its value at shutdown. Thus, the thermalhydraulics models must account both for a decrease and a redistribution of the thermal power sources over time.

As temperatures in the core continue to rise, less volatile fission product species, such as those which include the nuclides of Ba, Sr, Sb, Ru, etc., likewise begin to be released in significant amounts and thus further deplete the thermal energy production of the (now molten) fuel. These releases are accompanied by the formation, by both mechanical and thermal processes, of a dense aerosol. In the case of most pressurized water reactor (PWR) systems, major components of the aerosolized mass are the constituents of the control rods, i.e., Cd, In, and (possibly) Ag. In addition, for both BWR and PWR systems, a large fraction of the aerosol is comprised of structural components (Fe, Cr, Mn, Sn) [3]. These aerosols present new surfaces for fission product interaction and provide additional modes of transport and deposition of radioactive material within the RCS. Throughout the accident, the coolant and the hydrogen produced from the steam-metal reactions represent the primary motive fluids for aerosol and fission product transport.

Because of the wide variations in temperature that occur within the reactor pressure vessel in the course of a severe core damage accident, materials behavior is influenced by a number of competing processes. Molten species can flow downward in the vessel and resolidify in cooler regions; moreover, the process can be repeated many times, so long as parts of the vessel remain covered with water. Some of the molten material is unoxidized metal (Zr, Fe, Cr, Ni), which can act as a trap for some of the fission products (Te, Sb, Ru), and thus delay their release until the metals become oxidized.

Materials that become airborne may nucleate to form aerosols; a fraction of these aerosols will fall or be driven back into the core region, where they may revolatilize to repeat the release process. The remainder of the aerosol mass may impact stationary surfaces or other particles in the course of their transit through the RCS. Other airborne material may become attached to aerosol particles as a result of physical or chemical processes, become sorbed by stationary surfaces, undergo chemical reaction, or simply be transported by the motive fluid through the RCS.

The chemical processes are no less complex. The presence of metallic zirconium during the early stages of a severe core damage accident, and of hydrogen in the later stages, does result in generally chemically reducing conditions for many species of interest. However, the elevated temperatures involved and the large gradations in temperature throughout the RCS permit the possibility (from a thermodynamics standpoint) of many types of chemical reactions. For example, thermodynamics considerations of the gaseous phase chemical reaction,

indicates that CsI could decompose in a steam-hydrogen environment at temperatures characteristic of the core region in a severe accident, provided that there is a preponderance of steam relative to iodine. But as the temperature of the system is reduced, as would occur ex-core, the reaction can be reversed; re-formation of CsI could then occur [4]. In the interim, however, the CsOH may react with other species (such as boron oxide neutron poisons or with RCS metal components) and thus may no longer be available for CsI formation.

The number of chemical reactions that can be identified for the highly complex chemical system provided by the contents of the reactor pressure vessel in a severe core damage accident is prohibitively large. Moreover, most considerations of the chemical aspects tacitly assume rapid kinetics and no limitations on transport, and the latter has recently been shown to have a significant effect on even vaporization processes [5]. Thus, a rigorous, complete mathematical formulation of the chemical processes appears to be intractable; the use of carefully selected experiments, designed to identify those interactions that have major impacts on the consequences of severe accidents, seems to be the more appropriate solution to this problem.

The appearance of molten materials adds another degree of complication, viz., a time dependence of the geometrical parameters. This becomes particularly bothersome when it includes the heat source (i.e., the fuel). And as the molten material falls into residual water in the lower head of the reactor pressure vessel, a new set of phenomena must be considered. These phenomena include core debris-coolant interactions, the possibility and consequences of steam explosions, the release of mechanically-generated aerosols, and an enhancement in the processes causing release of materials from the RCS.

Even prior to this phase, in a PWR, natural circulation patterns are predicted to develop within the primary circuit [6]; these can have a significant effect on the course of the accident, since they provide a process for the loss of RCS integrity at an elevated location relative to the lower head of the pressure vessel. If such a breach in the RCS were to occur, it would preclude the possibility of core melt ejection under conditions of high RCS pressure.

Natural circulation patterns can lead to highly localized heating in the upper regions of the core; this is obvious from examination of the upper gridwork of the Three Mile Island Unit 2 Reactor.

Once the debris falls into the lower plenum of the reactor pressure vessel, and the water that had been present there is removed through vaporization and chemical reaction, ablation of the pressure vessel occurs. This would eventually result in failure of the pressure vessel due to the combined effects of the weight of the debris and the melting of the vessel metal. Alternately, loss of pressure vessel integrity could result from failure of one or more penetrations in the lower head. The manner in which the vessel fails, the nature of the debris, and the mode in which the debris is ejected from the vessel can significantly impact events which occur afterward outside the RCS (and are thus not considered in this paper).

Phenomena occurring within the RCS even after the pressure vessel has been breached can influence the consequences of the accident if they result in additional releases of radiotoxic materials after the reactor containment has been breached. Paramount among these phenomena is the revaporization of material that had become deposited on the RCS surfaces in the earlier phases of the accident. This can occur if the decay heat from the deposited radioactive material is sufficient to elevate the temperatures of the areas of deposition to the point at which significant re-vaporization results. However, the extent to which re-vaporization can contribute to overall accident consequences will depend upon the magnitude of the motive forces at the time re-vaporization occurs. For example, the phenomenon would probably have little impact if gaseous diffusion or (for aerosols) Brownian motion or thermophoresis were the primary modes of transport (as

would be the case if the only breach in the pressure vessel were failure of the bottom head). If, on the other hand, the RCS were breached in such a manner as to promote a chimney effect, the re-volatilized material could be more efficiently released into the containment.

Re-volatilization also serves to illustrate how an apparently "conservative" approach can in fact underestimate the consequences of a severe accident. For example, at first glance it would appear to be conservative to ignore deposition in the RCS altogether. While this would certainly maximize the amount of radioactive material introduced into the reactor containment, it would also maximize those removal processes whose rates vary directly with concentration, and would preclude re-vaporization from RCS surfaces from ever occurring. Thus, should the accident involve a breach of the reactor containment at a time late into the accident, this apparently "conservative" approach would overestimate removal processes occurring within the containment prior to its loss of integrity, and underestimate radioactive material concentrations within the breached containment afterwards.

It has been tacitly assumed throughout this paper that intervention of the accident does not occur, i.e., that none of the systems, such as coolant injection systems, which are designed specifically to mitigate severe core damage, could perform their intended functions. Considerations of the operation of these systems, or of other mitigative actions, such as the deliberate depressurization of the RCS, provides additional levels of complexity, and their impact is not always clear even in a global sense.

CONCLUDING REMARKS

It is obvious that sophisticated computational programs are necessary in order to describe the course of a severe core damage accident in sufficient detail that reasonably accurate assessments of its radiological consequences can be made. Consequently, a number of computer codes have been developed to describe the various physicochemical processes that occur in a severe accident. Several of these, and their limitations, are described elsewhere in these Proceedings and will not be discussed in this paper. We conclude, however, with some general observations concerning these computer codes.

First, none of the codes has been developed solely on the basis of "first principles;" nor does such an approach appear to be practical or warranted. As a consequence, however, it has become necessary to rely upon experimental data to guide code development and to obtain values for input parameters. Moreover, some of the input data (constants in constitutive relations, for example) are devoid of physical meaning, whereas others, because they lack an adequate experience base, are left as parameters to be adjusted at the discretion of the code user.

The validity of the results of most of the severe accident computer codes therefore rests primarily with the experience and capabilities of the code user, and not necessarily with the codes themselves; the codes lack rigidity. Code flexibility is of course desirable while the code is in an evolutionary stage and while sensitivity studies are of interest, but the codes should become less flexible in their employment of user-adjusted parameters as the computer programs mature.

A related concern involves code "completeness." Since the codes are semi-empirical in nature, elements of the computer program necessarily reflect

only the experimental data base available. In many cases this data base is limited, and extrapolation beyond the base of experience becomes necessary. At the other extreme is the tendency to include all possible physical and chemical processes in developing the computational model, without regard to their significance. This approach, while more rigorous mathematically, can complicate the problem unnecessarily. In both cases, an acceptable solution appears to be an appeal to experiment, i.e., the conduct of carefully selected integral-type experiments, which could test the extrapolation assumptions on the one hand, and the significance of selected phenomena on the other.

Lastly, a major criticism is that virtually all of the computer codes lack a pedigree. As the computer programs were being developed, they were distributed, at various stages in their development, to potential users. In many cases these users developed the codes further, often in parallel and independent of each other. There has thus become a proliferation of modified versions of certain computer codes, with little or no indication that modifications had been made. This renders code verification exercises as suspect.

Some recognition of the problem has occurred, and attempts toward rectification are underway. One of these has been the formation of the International Code Assessment and Applications Program (ICAP), whose purpose is to provide independent assessment (and, hopefully, provide a pedigree as well) of three major thermalhydraulics computer codes: RELAP5, TRAC-PWR, and TRAC-BWR [7]. Such activities should be extended to all of the computational programs currently being used to assess the course and consequences of severe core damage accidents.

TABLE 1. Decay Heat Generation in a 1000MW(e) PWR^a

Element	Decay Heat Generation (MW)	
	At Shutdown	1 Hour Post-shutdown
Kr	6.50	1.13
Xe	7.65	0.53
I	15.75	7.96
Br	4.92	0.13
Cs	13.87	1.69
Rb	12.87	1.05
Te	6.92	1.79
Se	1.71	0.01
Sb	6.38	0.76
Ba	8.25	1.27
Sr	11.00	2.02
Actinides	9.20	5.30
All others	91.98	19.50
Total	197.0	43.14

^aCalculated using ORIGEN2 [8, 9].

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