

Radionuclide releases from severe accidents at nuclear power plants

Releases for many accidents are now predicted to be much lower than previously calculated, but an APS study group cautions against extending that conclusion to all scenarios.

Barbara G. Levi

Regulations governing siting and evacuation procedures for a nuclear power plant rely heavily on estimates of the quantities and types of radioactive fission products that might be emitted in the most severe accident. These estimates are called source terms. The most conservative approach to analyzing accident consequences is to assume that a severe accident might release the entire inventory of fission products within the core just before refueling. Most current regulations rely on a slight modification of that source term—100% of the noble gases, 50% of the iodine and 1% of the remaining fission products. Recent emergency procedures are based on lower, although still conservative, estimates of iodine releases.

The nuclear industry has recently begun to hope that these assumed values might be considerably reduced. That hope was stimulated by the observations that, during the 1979 accident at the Three Mile Island nuclear power plant, the damaged reactor leaked only about one ten-millionth of its inventory of iodine. Although one would not expect large releases from a containment building that, like the one at Three Mile Island, has not failed, the observations at TMI still caused many to ask whether the releases might be lower than previously calculated for more severe accidents at other reactors. The analytical tools to study this

question were also reexamined in the wake of TMI: That episode refocused attention on analyses of severe reactor accidents and stimulated far more extensive application of an analytical methodology that had been used by the Reactor Safety Study, WASH-1400, published¹ in 1975 (often called the Rasmussen study after its chairman).

Reassessments

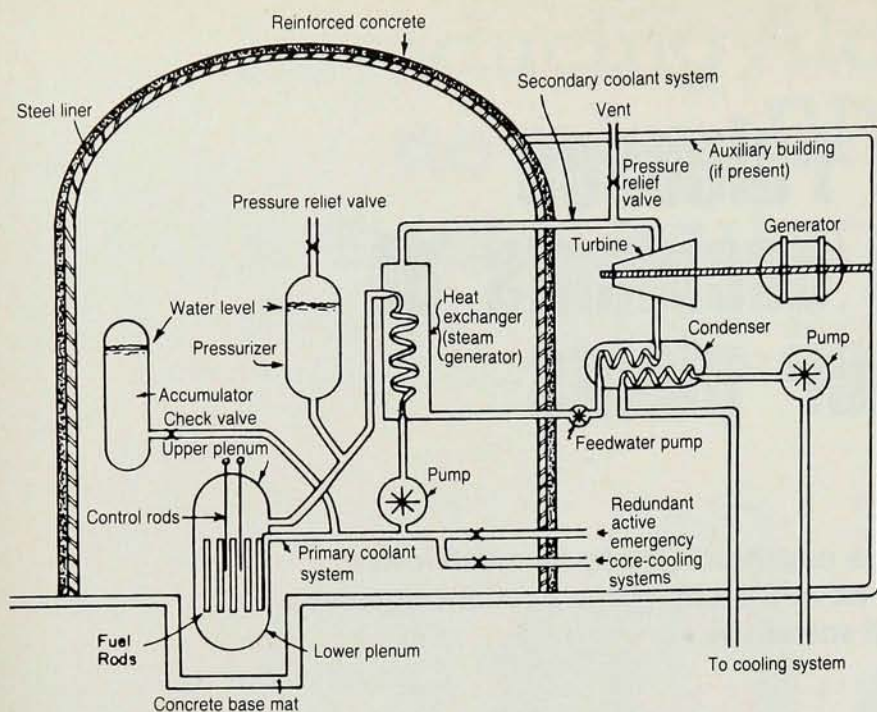
To assess the progress made by such studies to date, the Nuclear Regulatory Commission asked The American Physical Society in the summer of 1983 to create a study group on the radionuclide releases from severe accidents at nuclear power plants. NRC asked the group to conduct an independent, broad-based peer review of the science underlying the source term estimates. Their charter was specifically to "review the adequacy of the technical base upon which the phenomenological models for radionuclide release from postulated severe reactor accidents are constructed, the adequacy of the models themselves, and the current use of the complex computer codes that incorporate these models in the analyses of accident sequences." Richard Wilson of Harvard University headed the study group, and Kamal Araj, of Brookhaven, served as its executive secretary (as a visitor to Harvard). The other members were: Augustine Allen (consultant, now retired from Brookhaven), Peter Auer (Cornell University), David Boulware (University of Washington), Fred Finlayson (Aerospace Corporation), Simon Goren (University of Cali-

fornia, Berkeley), Clark Ice (consultant, retired from Savannah River Plant), Leon Lidofsky (Columbia University), Allen Lee Sessoms (Department of State), Mary Shoaf (Princeton University), Irving Spiewak (Institute for Energy Analysis, Oak Ridge) and Thomas Tombrello (Caltech).

The report released² by this APS study group on 21 February was probably both good news and bad news for the nuclear-power industry. The good news was that three important factors apparently lead to significantly lower predictions of how much radioactive material might be released to the environment during many of the postulated severe accident scenarios. The bad news was that "it is impossible to make the sweeping generalization that the calculated source term for any accident sequence involving any reactor plant would always be a small fraction of the fission product inventory at reactor shutdown." The study group highlights several scenarios where the releases might be even higher than currently predicted, and calls for more experimental and analytical work to improve knowledge in certain critical areas.

In general, the report both praises and prods: It finds "considerable progress in developing both a scientific basis and computational ability for predicting the consequences of hypothetical nuclear reactor accidents since the [Rasmussen study]," while at the same time it strongly encourages continued development in the same direction.

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A large, dry containment building surrounds the primary cooling system in this schematic of a typical pressurized-water reactor. The containment building, along with the reactor pressure vessel and fuel cladding, are barriers to release of radioactive fission products from fuel to environment. Figure 1

The APS report covers most of the same ground as two other recent reports that appeared last fall: One was written³ by the American Nuclear Society's Special Committee on Source Terms, and the other was⁴ by the Industry Degraded Core Rulemaking Program, called IDCOR, an independent, industry-funded program. Like the APS, the ANS committee was asked to examine the state of knowledge relative to the source term, but in addition it was to provide a summary of source-term results obtained by various investigators and to compare these methods, assumptions and results to those in WASH-1400. The ANS report also includes a parametric investigation done by Stone and Webster Engineering Corporation of factors affecting the retention of fission products in the containment and auxiliary buildings.

Although the ANS report agrees in many details with the APS report, it is more sanguine in its conclusions. The ANS committee states that, "In general an ample foundation has been provided to warrant reductions of the source-term estimates in WASH-1400 by more than an order of magnitude to as much as several orders of magnitude." Even though the committee recognizes that some uncertainties remain in the understanding of the phenomenology of severe accidents, it does not feel these will have any major impact on their assessment. Rather, the committee feels that sufficient conservatism exists in most analyses so that source terms will in general be lower when improved data become

available. They also feel that "a substantial basis exists for knowledgeable analysts to calculate light-water reactor source terms with a high degree of confidence in the results."

The IDCOR study, like the other two recent studies, recognizes areas where knowledge is uncertain and further research is warranted. The IDCOR group developed new models and computer codes to analyze accident sequences. Its report considers to some extent probabilities of accident occurrence—a topic that fell outside the charter of APS. The IDCOR report concludes that the source terms are likely to be much lower than have been calculated in previous studies. The group also investigated whether or not any major design or operational changes are warranted in existing nuclear plants and concluded that they are not.

Possible accident sequences

One difficulty in predicting the quantities of radionuclides that might escape from a reactor containment building in an accident is that many paths lead to the same end. Depending on the route taken, the mix of fission products could be very different. The reactor diagrams in figures 1 and 2 indicate some of the major barriers that radionuclides must penetrate to reach the environment. Figure 1 is a schematic view of a pressurized-water reactor, typical of roughly two thirds of the nuclear reactors in the US, while figure 2 pictures a boiling-water reactor, the other major reactor type. The first barrier in each is the solid fuel itself

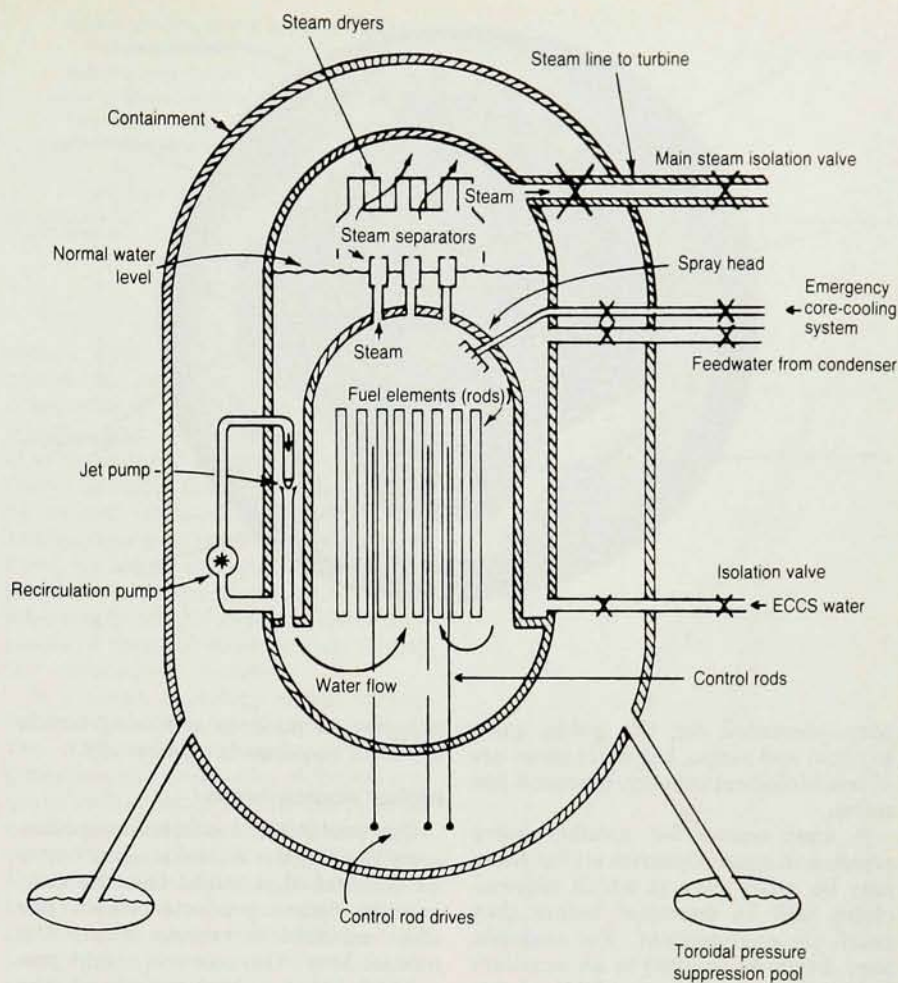
and the zirconium or stainless-steel cladding that surrounds it. If fuel rods crack or melt because they are no longer cooled (see figure 3), the fission products can escape into the reactor pressure vessel or into the water circulating through it. If this vessel in turn is either ruptured or bypassed (because of a pipe break, for example), the radionuclides can escape to the surrounding containment building, which in turn must either fail or be bypassed before its contents escape to the environment. At each step, many safety features are designed to prevent these barriers from being breached. Those features include the control rods for slowing the reaction, containment sprays, several redundant cooling systems, including the emergency core-cooling system, and other heat sinks.

The Rasmussen study was the first attempt to assess the risk of failure in such a complex system. That study delineated many accident sequences and tried to identify those with the greatest potential consequences, using as the basis of analysis two specific plants—the Surry pressurized-water reactor in Virginia and the Peach Bottom boiling-water reactor in Pennsylvania. Partly guided by this work, NRC has selected its own, smaller set of sequences believed to be representative of most severe accidents as a basis for current source-term analyses. In its evaluation of this selection, the APS study group felt the choices had been made fairly well but cautioned that "several of these sequences no longer appear to be risk dominant, and other sequences have become relatively more important." They urge another iteration of the accident sequence selection in light of new understanding.

Lower source terms

Many of the accident sequences for which the Rasmussen study calculated severe consequences are now associated with lower predicted releases, primarily because of three factors. The

Containment structure of a typical boiling-water reactor is smaller than that of the pressurized-water reactors. It features suppression pools to condense steam and reduce pressure in the containment building. Figure 2



first is the recognition that containment buildings are likely to fail, if at all, at later times in the accident sequence. More precisely, the APS group anticipates that, "for those sequences that proceed to containment failure, such failures are likely to occur after tens of hours in the form of seal leaks, base mat penetration, or cracks in the liner." The delay in failure could buy time for operators to mitigate the accident if possible, and allow time for deposition of airborne radionuclides on surfaces within the reactor.

The containment structures were built according to standard construction practices, with a large safety factor, partly to account for wide variations in such factors as the properties of concrete. Calculations and tests at $1/6$ to $1/3$ scale now indicate that the containment building can withstand pressures up to about 2.5 to 4 times the nominal design pressure. The tests confirm structural analyses begun about three years earlier that use new, sophisticated analytical methods. Wilson agrees that, in now assuming the containment building to be stronger, the study group is essentially taking credit for the safety margin. However, he believes that deformations measured during tests of each containment building at 1.15 times design pressure should reveal any structures with insufficient strength. The APS group did not investigate questions of quality control in construction. They mentioned but did not study the intentional venting of the containment building through filters as a possible mechanism for prevention of catastrophic failure.

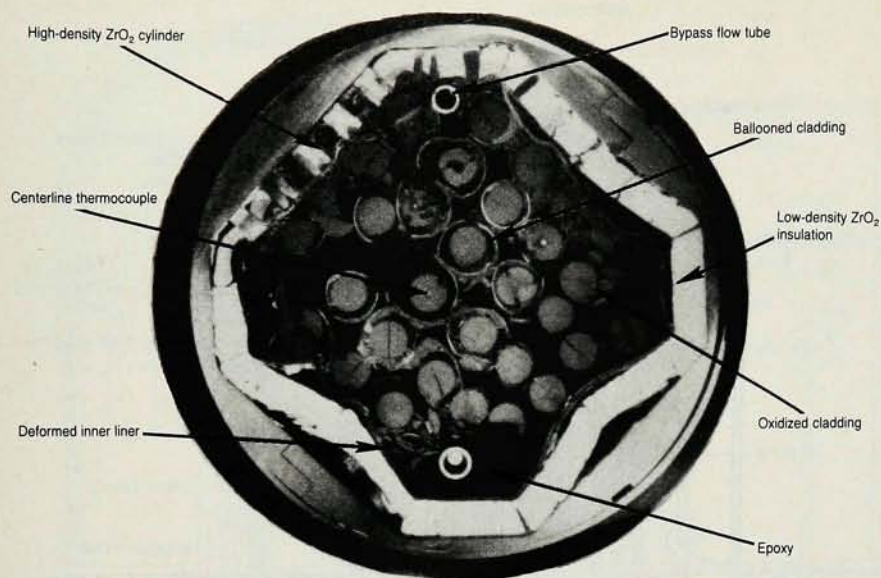
The APS group also asserts that steam explosions large enough to challenge the containment directly are now considered very unlikely. The major concern with steam explosions has been the possibility that, if the molten core dropped suddenly into the water in the lower plenum of the pressure vessel, a steam explosion might blow the top off that vessel, driving it against the

outer containment building and perhaps penetrating it. The APS study group feels that it is improbable that conditions would meet the three criteria for a large steam explosion: very large surface area between the hot liquid (molten core) and the cold liquid (water), a hot liquid above the spontaneous nucleation temperature of the cold liquid, and absence of the vapor blanket that often develops at the interface. However, smaller explosions might occur, some possibly initiating chains of adverse events.

As distinguished from the rapid hydrogen burning that occurred at TMI, a hydrogen detonation, with development of a shock wave, is also deemed unlikely in the large, dry containment buildings of pressurized-water reactors. In such buildings, the amount of steam is high and the water molecules absorb some of the energy, preventing propagation of the shock wave. Hydrogen explosions pose a relatively greater risk for some boiling-water reactors (which have smaller containment buildings) and for those few pressurized-water reactors equipped with ice condensers. Smaller containment

buildings are protected from hydrogen explosions by igniters or by atmospheres filled with nitrogen. In all containment types, local hydrogen burning is possible, however.

Low radionuclide releases require not only that the containment fail late, but also that the major radionuclides of health concern be retained once it does fail. Investigators now believe that the chemical form of some important fission products—iodine, cesium and tellurium—favor retention rather than release. The Rasmussen study assumed that these elements were present as volatile elemental species that could readily escape, whereas evidence now indicates that, in the presence of steam, cesium exists predominantly as the hydroxide, while iodine preferentially forms cesium iodide. The cesium hydroxide can react with metal surfaces to produce a very adherent cesium deposit. Cesium iodide is a salt of low volatility that is now expected to dissolve in water or to condense as aerosols. Tellurium (which decays to iodine) tends to form nonvolatile compounds with zirconium or stainless steel. No retention mechanisms have



Damage to fuel bundle that might occur during accidents is illustrated by photograph taken during tests at the Power Burst Facility of the Idaho National Energy Laboratory. (Photograph courtesy of EG&G.) **Figure 3**

been identified for the noble gases krypton and xenon, but these gases are of less biological concern beyond a few miles.

A final reason for possibly lower releases in some scenarios is that there may be many sites at which radionuclides may be deposited before they reach the environment. For example, they might be trapped in an auxiliary building, as some were at TMI. A few pressurized-water reactors have incorporated ice beds within the containment building to condense the steam. In these reactors the ice might also condense the fission products. In some boiling-water reactors the fission products might dissolve in the suppression pools. The APS does caution, however, that the effectiveness of ice beds or

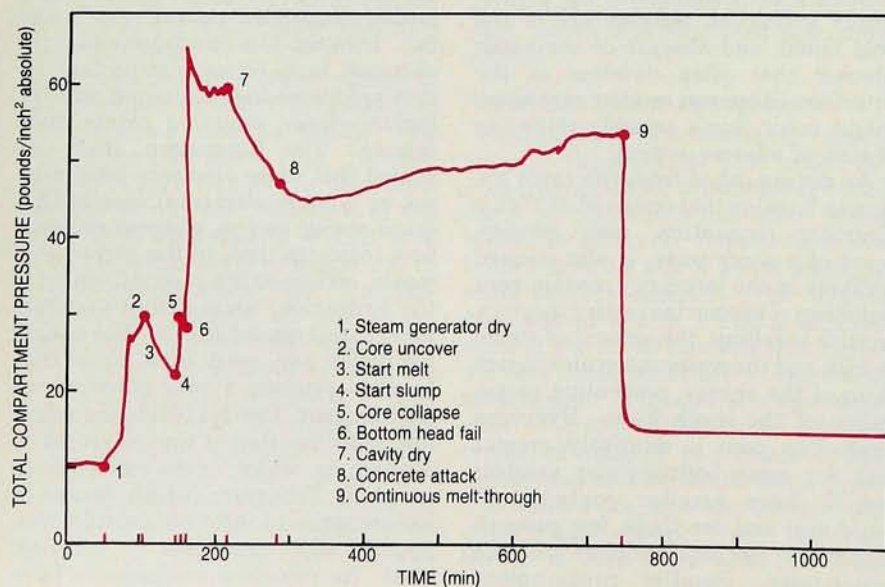
suppression pools in removing fission products requires further study.

Higher source terms

One potentially troublesome scenario outlined by the Wilson study group is an accident that might free the non-volatile fission products, which are often assumed to remain within the molten core. The scenario might proceed as follows: All power is off, the primary coolant is lost and the high pressure in the primary system prevents initiation of passive emergency cooling. The core, due to the decay heat of the fission products, melts to the bottom of the pressure vessel. There it proceeds to melt through the lower plenum until it penetrates to the floor of the containment building. The sud-

den loss of pressure as the primary vessel ruptures would cause the accumulator to flood the depression at the bottom of the containment building, quenching the core. The hot core would evaporate this water until it is gone. At that point, the core would melt again and begin to interact chemically with the concrete floor (base mat). The pressure of the containment building as a function of time for this scenario, calculated for the Surry reactor design, is shown in figure 4.

The interaction between this molten core and the concrete floor is quite complex and still poorly understood. The reactions there would produce carbon dioxide and water that could bubble through the molten mixture, releasing some nonvolatile elements by the agitation of the bubbles. Some fraction of these two gases might be reduced to carbon monoxide and hydrogen by the metals, which in turn might reduce some of the more refractory oxides of lanthanum in the molten core to a more volatile form (more likely to escape). If the reactor containment building failed at this point in the accident sequence, it could emit these nonvolatile aerosols to the atmosphere. The study group points out that "releases depend critically upon the temperature achieved in the core-concrete



Development of pressure within the containment building in the minutes following a transient has been modeled for a hypothetical severe accident sequence in a pressurized-water reactor. Numbered points on the curve correspond to events listed in key. The APS study group recommended more study of the possibility that the core-concrete interaction might free some of the more refractory radionuclides at a time when the containment might fail (point 9). **Figure 4**

Some mechanisms for deposition of radionuclides within the containment building are shown for the hypothetical case of forced flow of air through a tube. Deposition rates may vary sharply with such factors as particle size, as illustrated here. The APS group encouraged continued efforts to understand these mechanisms.

Figure 5

interaction and other parameters that are poorly understood. Moreover, the calculations are only in a preliminary stage." Although some calculations indicate potentially greater releases than in the Rasmussen study, the Wilson group feels that more experiments and analytical work are still required.

One reason for the APS group's interest in the nonvolatile elements such as lanthanum is their recognition that some of these elements have large "dose-conversion" factors, that is, even small releases can lead to relatively large radiation exposures. For example, a release of 4% of the iodine present can deliver the same whole-body dose to someone 5 miles downwind as 100% of the noble gases, assuming two-hour decay prior to release. By comparison, only 0.1% of the lanthanum delivers the same dose. Hence, the study group argues, as some accident sequences are found to produce lower quantities of the volatile gases, they ought to be examined for their potential to release even small amounts of more refractory elements.

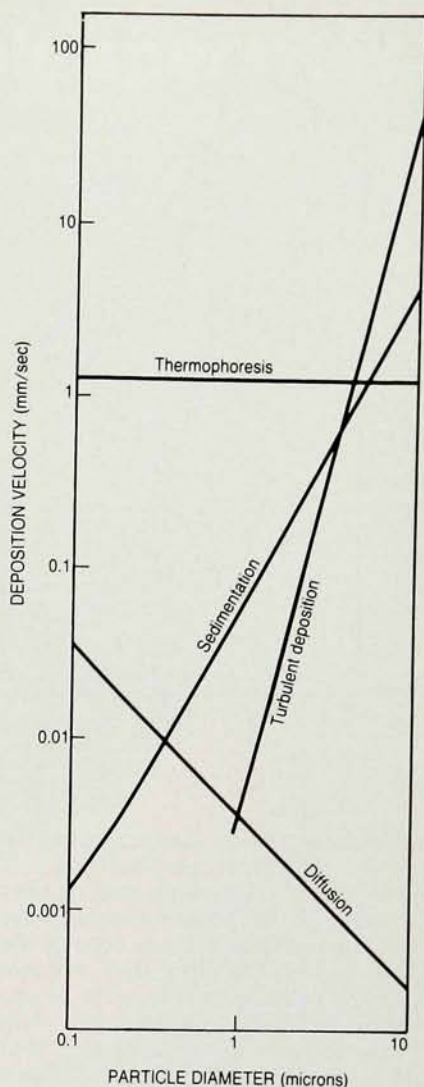
The APS report points out several other accident sequences that warrant attention. In some scenarios the containment might be bypassed entirely. For example, in some pressurized-water reactors, the low-pressure injection system that is part of the emergency cooling system extends outside the containment wall. A failure of the check valve between this system and the primary circuit could rupture the pipe and release radionuclides to the outside. In many cases, however, this possibility may be reduced by reactor-specific design corrections. In other scenarios, the containment building might not be sealed, perhaps because a door or valve is left open. Another worrisome scenario for pressurized-water reactors is the possibility that the steam generator would fail during a sequence in which both auxiliary feedwater and power are lost because of external causes, such as an earthquake, fire or flood.

Although they now strongly discount early containment failure, the members of the APS study group cite some factors that could increase the aerosols in the containment building at some later time when the rupture might

occur. Some of the fission products plated on containment walls might reevaporize from their own decay heating at a point when the concentration of aerosols is too low to scavenge them. Other aerosols might be resuspended by the rush of gases associated with the sudden depressurization of the containment building, or with steam explosions or hydrogen combustion. Still others may simply deposit slowly as a result of thermal stratification within the containment building.

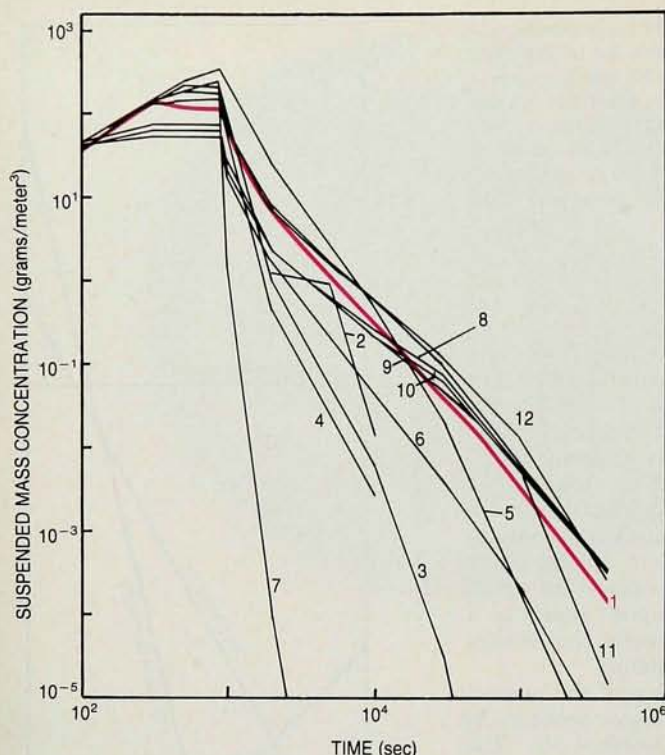
In general, modeling of the aerosol behavior is a very complex process. As the ANS report describes it, "The transport and deposition of fission products and aerosols within the [reactor containment building] is a transient convection problem of a multicomponent, multiphase mixture with simultaneous heat and mass transport, chemical reactions, and aerosol kinetics." As one example of the sensitivity of behavior to particular factors, figure 5 indicates the deposition velocity as a function of particle size for just four of many mechanisms of removal: Particles are moved about by thermal gradients (thermophoresis), concentration gradients (diffusion), gravitational force (sedimentation) and by inertia to changes in fluid flow (turbulent deposition).

The APS report surveys the state of research underlying the analysis of the source terms. In every area—thermal hydraulics, fission-product chemistry, aerosol behavior, containment loads and containment integrity—the research activity is extensive, including experiments both in the US and abroad to test various aspects of reactor behavior, and analytical work to model this behavior. The Wilson group calls for close coordination of these parallel efforts so that the experiments "provide data to validate the computer codes under conditions as close as possible to those occurring in reactor accidents." The APS study group further recommends "that the theoretical and experimental studies be published in archival, peer-reviewed journals and that the computer codes, together with a clear and complete technical description of the models and the assumptions, be made available to interested parties." Currently the results from different computer codes



applied to the same phenomenon, or even of results from the same codes by different users, can vary greatly, as illustrated by figure 6.

The APS findings echo those of ANS and IBCOR—with a few exceptions. William Stratton (retired from Los Alamos), chairman of the ANS study, described to us some of the similarities and differences between the two societies' reports. ANS delineates the same three factors that might now reduce earlier estimates of radionuclide releases. However, ANS assigns a low probability to other accident sequences that APS feels still warrant further study. Sequences involving the release of nonvolatile elements require the core, as it interacts with the concrete floor, to rise above its melting temperature. Although the temperature is not yet well modeled, Stratton believes that earlier estimates have been too high. Furthermore, even if the refractory elements were released from the core, they still might be scavenged by other aerosols produced



Numerical simulations of reactor behavior are compared here with a test result (colored curve). Variations indicate that the same input can produce markedly different outputs. Curves 5-7 result from the same code applied by different users. Curves 8-12 are more representative of current source-term methodology. The APS study group called for careful, fully documented intercomparison of such codes. Figure 6

at the same time, or they might remain within the containment building if it never failed. Regarding containment bypass by an open valve, Stratton says that the parametric study done in the ANS report indicates that releases from an opening on the order of one square foot would be much less than predicted ten years ago. He feels that the probability of steam-generator failure needs to be studied more quantitatively.

The INCOR group does not agree with APS that high releases of radionuclides might still result even if the containment does not fail for many hours. According to Tony Buhl and Mario Fontana (Energex Corp), who directed the INCOR study, their group finds that resuspension of aerosols is not a problem. Buhl and Fontana also said that containment atmospheres tend to be vigorously mixed, rather than stratified. The INCOR group does agree with APS that late containment failure allows time for an operator to intervene. Buhl feels, in fact, that operator action might mitigate circumstances leading to the release of refractory elements.

Steve Sholly of the Union of Concerned Scientists told us that he would like to have seen more emphasis placed on the possibility of bypassing pressurized-water-reactor containment buildings through the rupture of steam-generator tubes, a problem that has already plagued existing reactors.

Reactions to the studies

While the APS group examined basically the same evidence as the other

two studies, it was not yet ready to close the case. It may therefore have applied a brake to the movement towards reduction of the estimates of the source terms. The APS study group carefully avoided judgements about how its assessment might affect NRC regulations, however, for that was not in its charter. NRC Commissioner Fred Bernthal told us he believes one of the primary impacts of the report would be to strengthen efforts already underway to coordinate research efforts and focus them toward the remaining areas of uncertainty. He noted that the report largely supported assessments made by the NRC staff in 1981 for the large, dry-type pressurized-water reactors.

The official reaction of the NRC should be reflected in its task-force report, referred to as NUREG-0956, which was scheduled to be released for public comment in May, as this article went to press. Melvin Silberberg, who is responsible for that report, said that it will not only describe NRC's own assessment of source terms, but will also relate the new knowledge about source terms to different aspects of the regulations. Silberberg commented that he agrees with APS that one cannot yet make any sweeping generalizations about the source terms. He and several others commented that the APS report points in a direction in which NRC was already heading, that is, that there is no one source term.

The source term, as currently used in the regulations, affects several aspects of a nuclear power plant. One defini-

tion of source term is the quantity of radionuclides expected to be released to the containment building but held there. That definition is used in determining standards for equipment to be located in the containment building and for estimating radiation doses for siting requirements. The source term that is the subject of the current intensive studies is the amount that might escape from a failed containment building. That quantity affects emergency planning procedures. Currently, preplanning for emergency response must extend to a radius of ten miles beyond the reactor and must include preparations to move residents in the case of a severe accident. That regulation is of special interest in the controversy over the Shoreham Reactor on Long Island. A key question is whether a reduction in the source term would justify a corresponding reduction in this ten-mile guideline. Robert Bernero, NRC's director of systems integration, told us that a reanalysis of the planning radius using the new source-term understanding, with due caution, might shrink that ten-mile radius to about five or six miles.

In a hearing on 14 March to review progress on their report, the NRC staff urged the commissioners to be cautious in any revisions based on new source-term results. NRC chairman Nunzio Palladino stressed that "any action to revise the regulations must be supported by a sound scientific basis. Where there is a basis for action, we should move forward."

References

1. *Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants*, WASH-1400 (NUREG-75/014), U.S. NRC, October 1975.
2. *Report to the APS of the Study Group on Radionuclide Releases from Severe Accidents at Nuclear Power Plants*, February 1985, to be published in Rev. Mod. Phys., July 1985.
3. *Report of the Special Committee on Source Terms*, ANS, LaGrange Park, Ill., September 1984.
4. *Nuclear Power Plant Response to Severe Accidents*, Technical Summary Report of the Industry Degraded Core Rulemaking Program, Technology for Energy Corp, Knoxville, Tenn., November 1984. □