Source Terms: The New Reactor Safety Debate

Whether revised estimates of radioactive releases that could escape a severely damaged reactor should lead to immediate relaxation of some nuclear power regulations is the subject of growing controversy

By JANET RALOFF

Though not widely publicized, there is a major reexamination under way of a fundamental risk factor underpinning a number of nuclear power regulations. It involves the "source term"—a best-guess calculation of the radioactive releases that might escape a severely damaged nuclear power plant.

Two major studies addressing the adequacy of the research base that had been used to calculate source terms were published late last year, one by an industry group, the other by the American Nuclear Society. Both studies concluded that source terms generally had been greatly overestimated when first calculated for the 1975 Reactor Safety Study, also known as WASH-1400, or the Rasmussen Report. Over the last decade, the Nuclear Regulatory Commission (NRC) has based many of its regulations in such important areas as reactor design, reactor siting and emergency planning (including evacuation zones) on those 1975 severe-accident source terms.

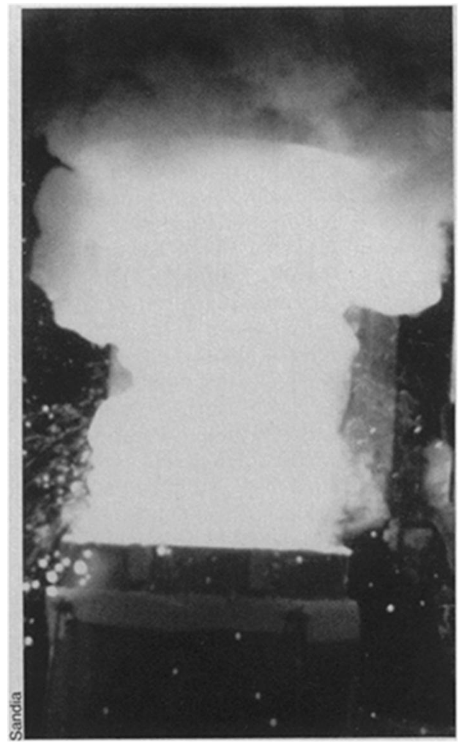
According to a long-range research plan NRC published last year, the agency's policy is to revise regulations whenever research shows they are too stringent or lax. And at a November 1984 briefing before NRC's commissioners on the American Nuclear Society's two-year source term review, William Stratton, the study's director, explained that research data developed during the last decade support a reduction in the source term of somewhere between a factor of 10 and 1,000. When NRC Commissioner James Asselstine asked how widespread this conviction was, Stratton responded that it was the virtually unanimous opinion of the entire nuclear research community.

Floyd Culler, president of the Palo Alto, Calif.-based Electric Power Research Institute (EPRI), urged NRC to commence action immediately in this area. "Sufficient evidence now exists," he said, "to initiate the process of establishing a new source term for regulatory purposes." Moreover, he added, "We suggest that public safety is not increased by maintaining the excessively large source term," because it forces NRC and the nuclear industry to spread their limited resources over too broad an area.

Stratton, Culler and others, however, may have overstated the unanimity of opinion regarding this issue. On Feb. 21, an American Physical Society study group briefed NRC's commissioners on yet a third analysis of research supporting source term calculations. Conducted under NRC contract, this study agreed that in most cases, new source term calculations indicate significantly smaller quantities of radionuclides could reach the environment than the Reactor Safety Study had indicated. However, it also found that for some accident scenarios, calculated radioactive releases "have not changed dramatically." In fact, it said current research suggests there are even some types of accidents that might yield radioactive releases exceeding those in the Reactor Safety Study.

The latter point, if accepted by the NRC staff and commissioners, could put on hold any immediate consideration of changes in nuclear regulations based on the current spate of new source term studies. It also sets the stage for a volatile new technical debate over nuclear safety.

Severe accidents of the type addressed in these studies are considered very unlikely events, emphasizes Richard Bogel, a senior scientific adviser with EPRI's source term program. "A *high*-probability accident," he says, "would be in the neighborhood of 10^{-7} — that would mean that an accident might occur [once in] every 10 million years for a single reactor." Because consequences of such a low-probability event could be extremely serious, however, NRC's office of regulatory research made source term studies its top priority.



Generation of flammable gas during concrete/molten-core material interactions.

This whole reassessment of nuclear source terms began immediately following the Three Mile Island (TMI) accident in 1979, explains Susan J. Niemczyk, a Washington-based nuclear safety consultant. Until last year she had been working under NRC contract on source term analyses at Oak Ridge (Tenn.) National Laboratory. Many people in the safety community, she says, were surprised when radioactive releases from TMI turned out to be only a fraction of what the source term would have predicted for a presumedly less serious accident. Reasoning that the source term must be overly conservative to have been so far off in predicting what TMI emitted into the environment, NRC and the nuclear industry began reexamining the technical basis for source term calculations. What resulted are these three new studies.

Among their new findings:

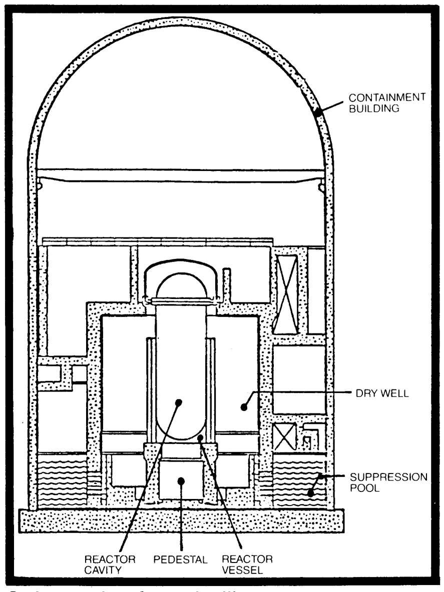
• *Reactor containment buildings are stronger than assumed by the Reactor Safety Study, and therefore if they fail, it will be much longer into the accident than had been originally expected.* That's important because in the first hours to days after an accident is initiated, many of the more biologically hazardous radioactive aerosols will settle out, adhering to surfaces in the reactor vessel — and, if the vessel breaches, onto structures within the surrounding containment building. Since these aerosols are the primary contributor to source terms, it's expected that the later a containment breaches, the less radioactive material will escape.

• *Physical and chemical phenomena, previously neglected, can lead to a scavenging or retention in the reactor of important radioactive materials — preventing their escape into the environment.* For example, new data suggest that much of the iodine previously expected to escape as gaseous molecular iodine will in fact react with cesium to form a relatively nonvolatile salt that could either dissolve in water or condense as an aerosol onto reactor building surfaces. In fact, it was the near absence of the iodine in the releases from TMI that initially focused attention on the source term issue.

• *There may be additional potential fission-product retention sites within a reactor complex.* These include the pressure "suppression pools" (wells in boiling water reactors where steam can condense during an accident, but which might also filter out some fission products); ice condensing systems in some pressurized water reactors; and auxiliary buildings.

The American Nuclear Society report says that such technological advances since the Reactor Safety Study in 1975 have eliminated concern that steam explosions and short-term overpressures might breach reactor containment buildings. Similarly, Tony Buhl, director of the four-year-old Industrial Degraded Core Rulemaking (IDCOR) program, admits that there are still some "open issues" in the technical arena, but says, "I don't see any big unknowns."

Regarding hydrogen generation, for instance, and its potential for detonation, he says, "This is an area that we [at IDCOR] spent a lot of time looking at"—even to the point of scrutinizing the results of large-scale experimental tests by the industry. IDCOR, a consortium supported by more than 60 organizations in the United States, Finland, Sweden and Japan, now has its own severe-accident computer codes for generating source terms. Buhl says that these codes include hydrogen explosions —where the scenarios suggest they would occur — or the melting of fuel, even the ejection of melted fuel from a pressurized reactor vessel onto a concrete mat. So these issues are no longer in the realm of the "big unknowns," he says. Moreover, in an interview he suggested that even though uncertainties remain in some of these areas, source terms could probably be reduced somewhat.



Schematic of one boiling water reactor and its containment.

Niemczyk disagrees. Having worked on the modeling of releases for nuclear accidents, she believes that the uncertainty associated with several of these technical issues is still quite high. It's her contention, in fact, that still-unknown factors associated with several potential accident effects might, in the worst case, actually contribute to source terms exceeding those calculated in the new industry studies. Among the potential problem areas she cites are hydrogen explosions, steam explosions, the high-pressure ejection of molten fuel from a reactor vessel, and interactions between molten fuel and the concrete base mat (floor) beneath the reactor vessel.

To gauge how much radioactive material might escape in an accident, researchers have to model that accident. What makes this problem so difficult, Niemczyk explains, is that there isn't just one type of accident that can occur, one type of plant that can be affected or one scenario for how an accident might develop; there can be hundreds of possible variables for each.

"Technically," she says, "it's one of the most complicated problems we've had to look at." Although better and better computer codes exist to model severe reactor accidents, each requires the inclusion of some critical numerical values that define the accident and initial condition of the reactor. However, Niemczyk points out, "in a lot of these things, our level of ignorance is such that we just don't know what will happen. So we guess." That's why, she says, "if you talk to 10 different people you get 10 different answers." Morever, she contends, severe-accident computer codes are so enormously complex that relatively few people are able to use them knowledgeably.

Authors of the Reactor Safety Study, and of the NRC regulations that have been based on its source terms, had been concerned by the degree to which their analyses had relied on this guessing. To account, in part, for the possibility that their best engineering judgment (these guesses) undervalued or ignored critical factors, these authors deliberately wrote a conservative "fudge factor" into their calculations — an extra factor of 10 or 100 here and there to allow for errors in their original assumptions.

The American Physical Society (APS) study group shares some of these concerns about the computer codes used to model accidents. In academia, notes APS study chairman Richard Wilson, any computer codes that a graduate student develops must be tested, reviewed by faculty advisers and held up to several levels of empirical scrutiny before they are accepted as valid. But, says Wilson, who is a Harvard University physicist, for the many important computer codes used to model source term features, "that process has only just begun."

There is near-universal agreement that more experimental work could be carried out in the areas Niemczyk mentioned, and that peer review should continue on the computer codes to which Wilson refers. Where agreement breaks down is over the potential in these areas for increasing source terms above the levels estimated by the American Nuclear Society and by the nuclear industry's IDCOR program.

Like Niemczyk, Marshall Berman is among those who challenge the assertion that enough is known to claim that source term codes account adequately for several of the more important potential accident sequences. At Sandia National Laboratories in Albuquerque, N.M., Berman supervises NRC-sponsored work in the experimental investigation of both steam and hydrogen explosions, and the writing of nuclear-accident computer codes that model these for use in source term analyses.

Modeling of the events leading up to hydrogen detonation and of detonation itself "is almost absent," Berman says. "And there aren't any models of it at all in the reactor safety codes." Similarly, he contends that the modeling of steam explosions "is very primitive, or absent." In fact, he says, "there are no mechanistic models that have been experimentally verified of steam explosions in *any* code. Either the code user assumes that they don't occur, or there's some branch point [in the logic] and some assumptions made." For instance, Berman is familiar with an IDCOR code, called MAAP, which deals with steam explosions; "that model assumes that large steam explosions never occur," he says. Berman concedes IDCOR may be correct in assuming that these won't occur. But right now, he says, "we don't know that."

The term "steam explosion" is a bit of a misnomer. It's not a chemical process, but a physical one. "In fact, it's just boiling," Berman explains, "but boiling at such a fast rate that it's similar to an explosion, in the sense that shock waves can form." These melt/water interactions, occurring when melted fuel drops into relatively cool water, or vice versa, create a reaction somewhat analogous to the violent interaction that occurs between hot oil and water.

Berman believes that "uncertainty concerning the nature and violence of such [steam] explosions is very high." On the one hand, he explains, "We have shown that at the scales at which we study these phenomena—20 to 25 kilograms—explosions occur. And [computer] models have been developed that in fact explain observations at this scale." But these same models predict that as the scale increases—that is, as the mass of material involved increases — the energetics of the explosion will go down. If that is true, Berman says, "then there's very little threat to reactors, because reactors are big and could easily take the kinds of explosions that we see here."

"My concern," he says, "is that fluid mechanics is very complicated, and people have frequently been wrong in the past." Therefore, he refuses to accept the models' predictions until there has been experimental validation of the phenomena at higher scales. "We have proposed some experiments up to the 2,000-kg scale — that's about 2 tons," he says. "Most researchers believe that's large enough to demonstrate the validity or lack of it in the models." To date, however, NRC has not provided funds for these tests.

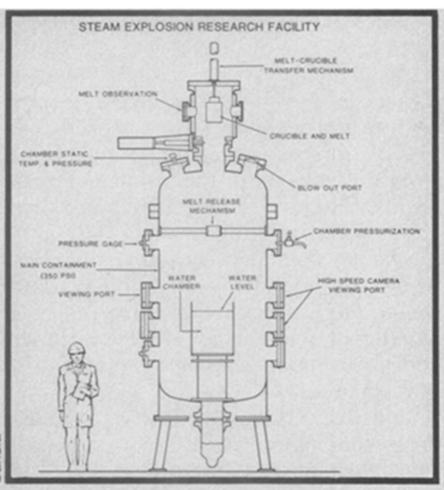
Berman is also trying to make modeling of hydrogen combustion more realistic. Of the several forms of hydrogen combustion that could occur during a reactor accident, detonation—the type of combustion that takes place so fast that shock waves form — poses the most serious source term risk. A large pressure spike initiated by the detonation could weaken or rupture a reactor's containment building, allowing radioactive aerosols to spew into the environment. What's more, the violence of these events means that there's always a possibility that high-velocity missiles — from piping to shards of concrete — might be hurled at the containment building's walls.

Combustion experts once scoffed at the idea that major detonations might occur under the conditions that could be present in a nuclear accident. (Although it's now generally conceded that such detonations are physically possible, many safety engineers still discount the possibility that the specific conditions necessary to cause them will ever develop.) "But here's where the conventional wisdom was quite wrong," Berman says. Through a series of combustion experiments at Sandia, he says, "we showed that there's a close link between the probabilities of detonation and the size of the gas cloud that you're dealing with." As a result, under the severe conditions that might be present in a core-melt accident, he says detonations in large volumes — like a reactor containment building — may be possible. In fact, Berman admits that experiments in this area fuel his skepticism over large-scale effects that the models predict for steam explosions. "If there's an analogy between combustion and steam explosions," he explains, "then the opposite of the conventional wisdom might occur."

Dana Powers, also at Sandia, supervises NRC-sponsored experiments and computer-code building in three other areas of severe-accident effects influencing source terms: fission-product revaporization, the high-pressure ejection of melted fuel from a reactor's pressure vessel, and interactions between melted fuel and concrete. Because there is still so much uncertainty about the science governing these effects, he, like Niemczyk, feels it is probably too soon to advocate a factor of 10 reduction in source terms.

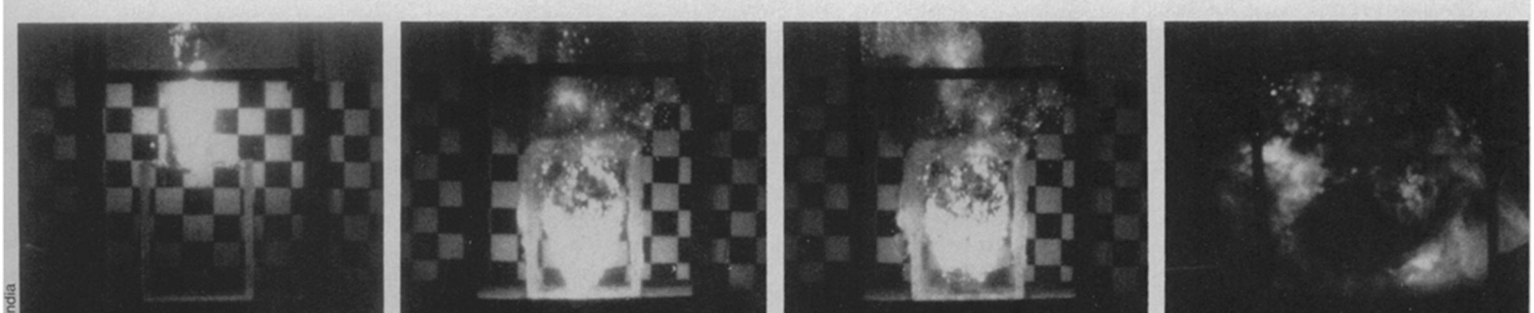
Take revaporization, a phenomenon that's been recognized only since the Reactor Safety Study. Aerosols that form when fission products vaporize will, as they decay, deposit heat onto whatever they've become attached to. Their decay heat, explains Powers, raises the temperature to the point where vapor pressure is sufficient to revaporize — and, therefore, remobilize—aerosols late in the accident sequence.

In some calculations, most of the source term is composed of this revaporized ma-



Sandia

Left, Sandia's steam explosion facility is used to conduct not only steam explosions but also hydrogen combustion tests. The latter focus on studies of deflagrations, a relatively slow form of combustion, involving mixtures of steam, hydrogen, air and water droplets. Below, a steam explosion: Left frame records 5 kg of melted fuel falling into a tank of room-temperature water. Three remaining frames (l to r) record their interactions at 0.05-second intervals beginning at 0.15 second. Among recorded measurements is the conversion of heat into the kinetic energy imparted to exploded debris.



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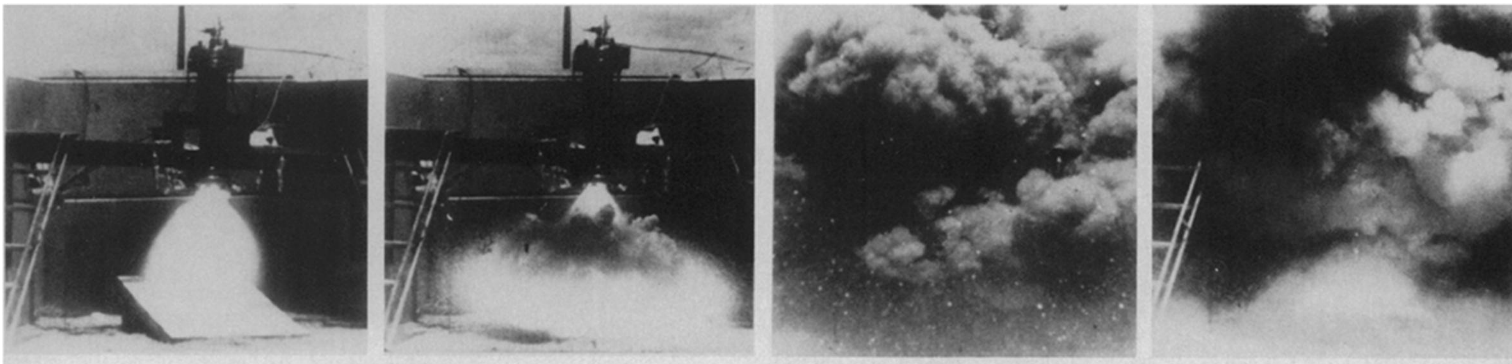
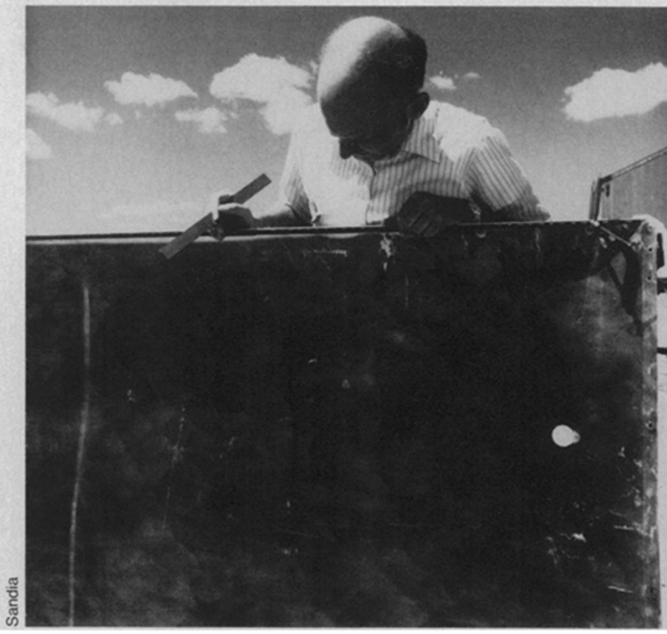


Sandia

Above, series of photos (l to r) recording high-pressure (600 lb/in²) ejection of melted reactor-core material onto a concrete slab, beginning (far left) at 0.05 second into the experiment. Second frame, at 0.1 second, shows vapor condensation. Third frame, at 1.15 seconds, captures the maximum aerosol cloud. In the final frame, at 1.95 seconds, the ejection is completed. These experiments quantify production of aerosols and flammable gases. Right, Martin Sherman measures irregular diamond-shaped detonation cells (barely detectable in photo) left on the surface of a sooted metal sheet that had lined the inside of Sandia's Heated Detonation Tube. The larger the cells, the less detonable the mixtures.



Sandia

terial. "But nobody has actually observed this process, Powers notes. "So while we've identified and named the phenomenon, we don't have experimental verification of its magnitude or importance. We only have computer codes. And if you've never seen something," he asks, "how good can your modeling of it be? I have to be a little suspicious." He notes, however, that experimental verification of this phenomenon is currently under way, both at Sandia and Argonne National Laboratory, near Chicago.

Another concern recognized only recently, he says, is the possible high-pressure spritzing of melted fuel through small holes in the bottom of a reactor vessel — a phenomenon that could spray radioactive material throughout the containment building much the way a carbonated drink will erupt from a shaken bottle. A lot of high-temperature aerosols would form. If zirconium, a metal in the fuel's cladding, were exposed to air, it would oxidize, creating a tremendous amount of additional heat. "Such high temperatures in an enclosed volume means you get high pressure that might break containment," Powers explains.

At this time, the primary unknowns are what the heat load might be and whether any support structures in the containment building might serve either as a heat sink or as an obstruction to limit the aerosols spraying up from under the reactor vessel. "In fact," Powers told SCIENCE NEWS, "it should be a relatively easy phenomenon to model once we understand what it is we're trying to model and what kind of parameters to put into our models." Obtaining the data to do that, he says, "is constrained right now only by the fact that our researchers have to sleep and that all our equipment has not arrived."

Finally, regarding the interactions between melted fuel and concrete, Powers notes that "one of the things we've observed fairly recently is that there is a release of radioactive material occurring during the melt/concrete interaction that people had not anticipated. They had thought that the releases would be short in duration and not very large in magnitude. In fact, we find quite the opposite." The interaction would also release a class of very hazardous radioactive materials that, in terms of source terms, had previously been all but discounted. Called nonvolatile fission products, they do not vaporize except at extremely high temperatures. Moreover, as the high-temperature melted fuel interacted with the water in the concrete, it would generate copious amounts of steam—carbon dioxide too, if there had been much limestone in the concrete.

"So we not only have the temperatures necessary to vaporize materials, but we also have the force to carry them up out of the melt and into the reactor containment," Powers says. Yet to date, he adds, few analyses have recognized the radioactive releases that could result from this phenomenon in their source term calculations — not because their authors haven't looked at it, but because "they used models that were just incorrect." Sandia's models are based on some of the few actual experiments conducted in this area. Typically involving about 200 kg of melted uranium dioxide and zirconium dioxide, "our experiments are not small," Powers says. They show that temperatures of the melt, its composition and the types of concrete used can all have a profound effect on both the type and amount of gases and fission products formed.

According to Powers and Berman, their research could resolve uncertainties associated with the phenomena they are investigating within two years. Some, like Niemczyk, argue that NRC should wait out the results of these studies before considering changes to many important power plant regulations. Others, like Stratton and Culler, have suggested that the wait isn't necessary. In the next few weeks, NRC is expected to begin deciding which tack it will take. □