Assessing the Effects of a Nuclear Accident

Studies prompted by Three Mile Island indicate radiation released by a severe accident may be less than expected, but uncertainties remain

Six years have now gone by since an obscure little island on the Susquehanna River suddenly became a household word. The accident at Three Mile Island, which began on 28 March 1979, made an indelible mark on public consciousness and on the finances of the nuclear industry as well. It left the industry's public image in tatters and prompted a sheaf of costly new regulations that further depressed the industry's already sinking economic fortunes.

But the accident has also left a mark of a different kind. Some initially puzzling features of the event prompted a massive, worldwide effort to gain a better understanding of just what is likely to happen inside a nuclear plant undergoing a catastrophe. Many of these studies are now coming to fruition, and they indicate a surprising result: the amount of radioactivity likely to be released into the environment from even the most severe accident may be far less than was estimated, even by nuclear experts, 6 years ago.

Needless to say, in an area as uncertain and as highly charged as nuclear accident phenomenology, this conclusion is not universally shared. It could, however, have enormous implications for nuclear regulation, emergency planning, and nuclear reactor design.

The nuclear industry, in fact, is already arguing that some regulations should be changed on the basis of what is known so far. The stakes are high. As William Dircks, the Nuclear Regulatory Commission's chief of operations, recently noted at a commission meeting, estimates of radioactivity release "underlie the basic fabric of how the NRC approaches regulation." Moreover, he added, "most of the industrial countries seem to be holding their breath to see how we come out on this issue."

Nuclear critics are not convinced, however. Steven Aftergood, a physicist with the antinuclear Committee to Bridge the Gap, contends that uncertainties in estimates of what would happen in a severe accident are "so great they amount to little more than a sketch of accident consequences. . . . They provide no basis for altering regulations." Susan Niemczyk, a consultant who spent 8 years working on nuclear safety analyses at Sandia and Oak Ridge National Laboratories, argues that the wide diversity of plant designs in the United States makes it impossible to come up with sweeping generalizations. "Small differences between plants when you get down to the details turn out to be very important" in determining potential radioactive releases, she says.

Much of the reanalysis of severe accident consequences was spurred by the unexpected absence of radioactive iodine in the environment around Three Mile Island. Although the reactor core contained some 64 million curies of iodine, only about 17 curies were released from the plant.

Richard Wilson

"There's still a lot more work to be done."

This was a surprise because earlier analyses had predicted that most of the iodine released from damaged fuel rods during an accident would be in the form of iodine vapor, which would be difficult to contain within the plant. Iodine is especially important because of its propensity to concentrate in the thyroid and give that organ a large dose of radiation. "For 20 years, the critical dose [for nuclear regulation] has been the thyroid dose," notes Robert Bernero, a senior NRC official who had headed the commission's work on potential radioactivity releases from severe accidents.

It is now widely accepted within the nuclear research community that the chemistry underlying the earlier predictions was faulty. In the reducing environment expected to be present during a reactor accident, iodine is likely to be bound to cesium in the form of cesium iodide, which is much less volatile and more soluble in water than iodine itself. This reaction appears to account for the fact that iodine largely remained in the cooling water at Three Mile Island.

This realization prompted a much broader experimental and analytical search for other physical or chemical processes that might reduce—or increase—the amount of radioactive isotopes likely to reach the environment in a major accident. In the arcane jargon of the nuclear research community, the amount and form of radioactive release is known as "source terms."

Three major studies attempting to pull together the results of this source terms research have recently been published in the United States. Two of them, produced by the American Nuclear Society and by an industry-sponsored group called the Industry Degraded Core Rulemaking Program (IDCOR), concluded that source terms have generally been greatly overestimated in the past. The third, a much more cautious document produced by a committee of the American Physical Society under contract to the NRC, agreed with the general thrust of the other two but emphasized that there are still uncertainties in the analyses that must be cleared up before sweeping conclusions are warranted.* The NRC itself is now digesting these studies and is expected to come up with an analysis of its own in May or June.

The analyses are all concerned with events that are calculated to have a very low probability of occurring: a severe accident in which safety systems fail and the reactor core loses all cooling water. In such circumstances, the core would be expected eventually to collapse, melt its way through the thick steel pressure vessel in which it is enclosed, and end up in the containment building that sur-

**Report of the Special Committee on Source Terms* (American Nuclear Society, La Grange Park, Ill. 60525); *Radionuclide Release from Severe Accidents at Nuclear Power Plants* (American Physical Society, New York, N.Y.); *Nuclear Power Plant Response to Severe Accidents* (IDCOR, available from Atomic Industrial Forum, Bethesda, Md. 20814).

rounds the pressure vessel and the coolant plumbing. Volatile radioactive fission products would escape from the fuel as it degraded. Others would be released as the core heats up and as a result of reactions between the molten core and the concrete floor of the containment building. (See box for a more detailed description of the progression of a hypothetical accident.)

The three studies are in general agreement that several factors could be expected to reduce previous estimates of source terms. These are:

• *Increased estimates of containment strength.* Once the fission products and molten core have breached the pressure vessel, the only remaining barrier preventing release of radioactive compounds into the environment is the containment building. This is a massive structure made of reinforced concrete, usually lined with steel. Tests conducted at Sandia National Laboratory on models of containment buildings have indicated that the structures can be expected to hold up under pressures at least twice as high as those they were designed to withstand. Moreover, a massive breach is considered unlikely; instead, failure would probably occur as a result of small cracks and openings, which would help relieve the pressure without releasing all the airborne elements in the building.

If the containment holds for several hours after the molten core leaves the pressure vessel, there would be time for many of the less volatile aerosols to be deposited on surfaces within the containment building, further reducing releases to the environment even if the containment is eventually breached.

Critics argue, however, that construction defects and quality assurance problems may reduce the theoretical strength of the containment. The calculations, Aftergood maintains, "presume an ideal quality assurance." Moreover, the NRC has issued many notices of violation to utilities for failing to ensure that the containment is isolated, for example, by leaving valves or doors open.

• *The possibility that some plant features will retain fission products.* Boiling water reactors contain a large pool of water, known as a suppression pool, through which gases and vapors released during an accident bubble before they enter the containment building. The purpose of this feature is to condense steam to prevent pressure buildup in the containment, but they may perform the additional function of scrubbing out many airborne radionuclides. In addition, a few pressurized water reactors contain columns filled with ice, which are de-

Anatomy of an Accident

For a nuclear accident to progress to the point at which large amounts of radiation are released to the environment, a variety of safety systems would have to fail or, as happened at Three Mile Island, be rendered ineffective by human errors. Such an accident would start with an event such as a system failure or an operator error and progress through several stages. The American Physical Society report suggests the following general sequence.

First, cooling water, which normally floods the core, would be lost, either through a pipe break or a pressure relief valve. An emergency cooling system should keep the core flooded, but this is presumed to fail. As the core becomes exposed, it heats up because the heat generated by the radioactive decay of fission products is not adequately removed. The zircalloy cladding surrounding the fuel pins then begins to react with steam, producing hydrogen and more heat. Eventually, the cladding fails, releasing volatile fission products, which are deposited on the primary system and are also carried into the containment along with steam forced out of pipe breaks or through the relief valve.

As the core continues to heat up, it will release more fission products and will eventually reach high enough temperatures to start melting. Finally, it will slump to the bottom of the pressure vessel, set off small steam explosions as it hits any water remaining there, and eventually melt through the thick steel base of the vessel. This event, which occurs about an hour after the core is uncovered, is an especially critical point in the accident sequence.

If the primary system is still under pressure, it is conceivable that the molten core could be ejected rapidly through a small hole in the pressure vessel into the containment. If this were to happen, the core could be fragmented, which would provide a large surface area for zirconium and iron to react with steam, giving off large amounts of heat and rapidly raising pressure in the containment building to the point at which it could fail. The American Physical Society study considers such a process unlikely, but recommends that it be given further study.

An equally alarming sequence would be for the primary system to fail in the heat exchanger (see diagram), which would put the full primary pressure on the secondary cooling system. This excess pressure would then be relieved through a valve, which in some plants leads directly into the environment, thus providing a pathway out of the containment for volatile fission products. Again, the Physical Society study considers this unlikely, but recommends further study.

A more likely occurrence would be for the core to fall in a molten mass to the floor of the containment building, where it would set off steam explosions with any water present. Pressure in the containment would rise, but is not expected to be sufficiently high to cause it to fail. The pressure would then fall gradually as steam condensed. This pressure drop would be enhanced if sprinklers in the containment building were working.

Once water on the containment floor has evaporated, the molten core would begin to react with the concrete. Although there is a great deal of uncertainty about this process, large amounts of steam, hydrogen, carbon monoxide, and carbon dioxide would be produced, which would cause containment pressure to rise again. In addition, some radioactive compounds could be released into the containment volume as aerosols. Eventually, the containment pressure could increase to the point of failure. The Physical Society report also says there is some "residual uncertainty" over the possibility that pressure from burning hydrogen in some types of reactors could cause containment failure.

If the containment survives these insults, the molten core could continue to erode the concrete base until it reached the soil beneath the reactor—the so-called China syndrome. The molten mass would penetrate only about 10 feet into the soil before reaching equilibrium with its surroundings, according to the report. The immediate threat to public health from this would be small, but there would be some long-term potential for contamination of ground water.—**C.N.**

signed to condense steam to hold down pressure in the containment. Like the suppression pools, they may also retain fission products. The Physical Society report noted that these features are likely to reduce the release of radioactivity, but said this expectation has not been adequately tested.

All three reports also note that fission products may be released from the containment building into auxiliary buildings, where some would be deposited on walls and equipment or trapped in water.

- *The chemical form of several fission products may favor retention rather than release.* In addition to the reassessment of iodine chemistry, researchers have taken a close look at several other radioisotopes and concluded that they are likely to exist in a form that would favor their retention in the plant. For example, cesium, in addition to forming cesium iodide, will exist as cesium hydroxide, which binds to many surfaces. Tellurium also tends to form nonvolatile compounds with stainless steel and zirconium. Radioactive forms of noble gases, which constituted virtually all the radioactive release from Three Mile Island, will, however, be exempt from these retention processes.

As a result of these studies, the American Nuclear Society report concluded that "in general an ample foundation has been provided to warrant reductions of the source term estimates . . . by more than an order of magnitude to as much as several orders of magnitude." And the IDCOR report concluded that "the fission product source terms . . . are likely to be much less than had been calculated in previous studies."

This has put growing pressure on the NRC to change some of its regulations. "Regulations should be based on valid science. They should not be based on assumptions that are wrong," argues William Stratton, a consultant who chaired the American Nuclear Society committee.

The American Physical Society was much more cautious, however. Although it noted that for "most sequences and most radionuclides," the source terms are expected to be lower than previously estimated, "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."

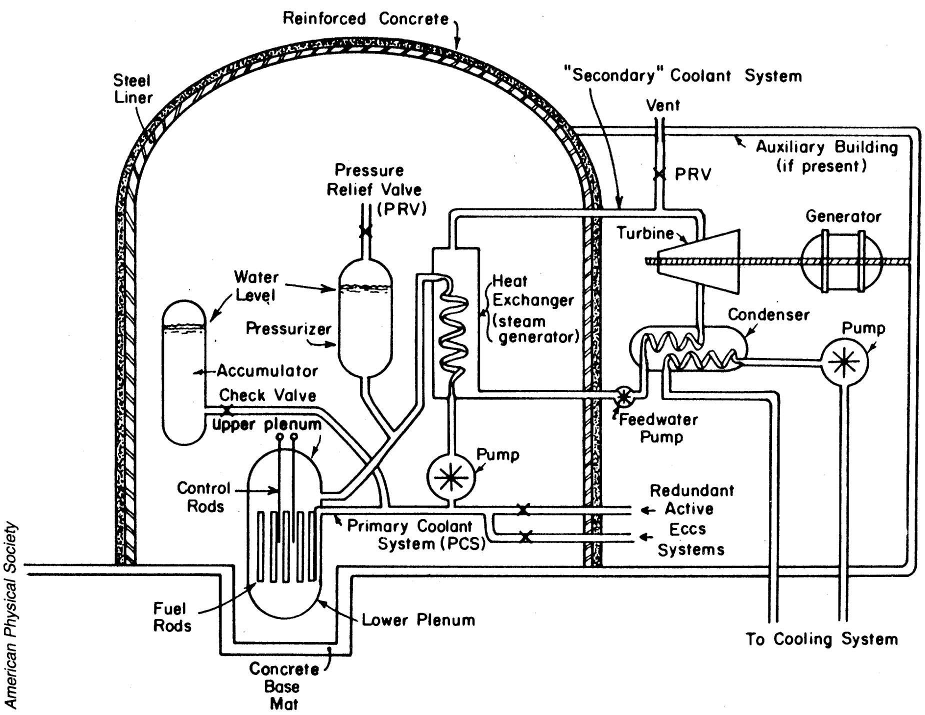
The Physical Society's caution was based on several uncertainties. For example, it suggested that there is not enough information to be able to state conclusively that the containment would not be breached by a large pressure surge when the core melts through the pressure vessel (see box). It also said there is "residual uncertainty" over the pressure generated by burning hydrogen in a reactor with a small containment volume, such as a pressurized water reactor with an ice condenser.

The largest question mark identified by the committee, however, concerns the reaction generated between molten core and the concrete floor of the containment building. In addition to generating gases such as hydrogen and carbon monoxide, which could eventually build up sufficient pressure to breach the containment, the core-concrete interaction may cause the release of nonvolatile radionuclides, such as lanthanum. This could actually raise source term estimates above earlier predictions.

When will some of these uncertainties be cleared up? Richard Wilson, a Harvard physicist who chaired the American Physical Society committee, says he thinks it will take 2 years to complete the necessary work, another year to publish it, and a year after that to digest the data. "Things look pretty much better than they did 10 years ago, but there's still a lot more work to be done," he says.

Running through all the debate about possible reactor accidents is the fact that there is a huge variety of basic reactor designs in the United States, and even within designs there are important differences between individual plants. For some types of accidents, such differences could be crucial.

For example, in one postulated event, the containment could be bypassed through a break in a pipe outside the containment. In some plants, the break would occur under water, which would scrub out some fission products, in others it could vent into an auxiliary building. Moreover, the American Physical Society report notes that accident sequences for pressurized water reactors have been subjected to much more detailed analyses than those for boiling water reactors.



American Physical Society

Schematic diagram of a pressurized water reactor

This is just one of five basic types in operation in the United States.

The fact that the American Physical Society declined to endorse the sweeping conclusions of the other groups will make it politically difficult for the NRC to make major regulatory changes until some of the uncertainties are cleared up. Moreover, notes Susan Niemczyk, when source terms are estimated conservatively, differences between plants are not so important, but if an attempt is made to reduce the estimates, individual plants and individual accident sequences should be studied in detail.

This point appears to have been accepted by the NRC staff. "You can't go around talking about a factor of 10" reduction in source terms, says Bernero. "You have to be plant-specific and even sequence-specific." He adds, "I wish I were in France," where there is only one basic plant design.—COLIN NORMAN