SPECIAL REPORT

SEVERE ACCIDENT SCENARIOS AT ISSUE IN DOE PLAN TO RESTART REACTOR

By the end of this year the US Department of Energy, which inherited from the old Atomic Energy Commission the anomalous assignment of producing the nuclear weapons for the US arsenal, plans to restart one of the three production reactors at the Savannah River Site in South Carolina. Critics of the restart decision have argued that new material for weapons is unneeded at this time and that more public discussion is needed of some important safety issues. The Bush Administration has insisted on the reactor restart as a point of principle: The government's position is that so long as the United States relies on nuclear weapons as its deterrent of last resort, it must have the operational capacity to replenish the nuclear arsenal at all times.

During the last three years all the reactors that the government traditionally has used for production of plutonium and tritium for US nuclear weapons have been closed. Following reviews prompted by the Chernobyl accident, the N-Reactor at Hanford was shut down, first temporarily in 1987, and then permanently the following year. (See PHYSICS TODAY, February 1987, page 63, and November 1988, page 49.) In August 1988 the three remaining production reactors, at the Savannah River Site, were turned off after an incident in which operators continued to manipulate a reactor even after it began to behave unexpectedly.

The SRS reactors now have undergone an extensive program of modifications, and staff have been put through an almost equally demanding program of training and retraining. DOE's current policy is to restart one reactor soon, maintain one on standby (to be used if the first is unavailable) and keep the third permanently shut down.

The focus in this report will be on a number of important safety issues bearing on the future of the SRS reactors, in particular the danger of explosions, both nuclear (recriticality and prompt criticality accidents) and chemical (fuel, fuel cladding, moderator and coolant interactions). While the probability of explosions is almost certainly very small—much smaller than the probability of a meltdown, which is estimated at 1 in 10 000 reactor years—the possible severity of such "worse than worst case" accidents makes them worthy of special attention. What follows is a summary of how such accidents might unfold, along with a range of expert opinion on their potential magnitudes and probabilities.

While the most severe conceivable accident in the SRS reactors might be of the same order of magnitude as Chernobyl, the probability of any such accident is enormously smaller. This summer a panel of reactor experts meeting in Moscow issued a statement saying that an accident like Chernobyl was "inevitable" given the known defects of the reactor type and the poor training that operators received. Nobody would make the same kind of claim about the SRS reactors.

Reactor characteristics

The three reactors at Savannah River were built in the 1950s, primarily to produce materials for nuclear weapons. Moderated by heavy water, each reactor has positions for 600 fuel and target assemblies, plus 162 secondary positions for neutron-absorbing control rods and instrument rods. Compared with commercial power reactors, the SRS reactors operate at low temperatures and pressures, a significant safety feature.

When the reactors are operated for tritium production, the fuel consists of uranium enriched to 80% in ^{235}U and the targets consist of lithium. The fuel–target lattice is "uniform," meaning that each assembly is made up of concentric rods containing uranium and lithium. (When the reactors are operated for weapons-grade plutonium production, the targets consist of ^{238}U; resumption of plutonium production, however, is not anticipated.)

Each reactor is equipped with an emergency core cooling system that draws on river water in the event of a loss-of-coolant accident and meltdown threat. In addition, a supplementary safety system can inject a neutron poison, gadolinium nitrate, to scram the reactor in the event the control rods fail.

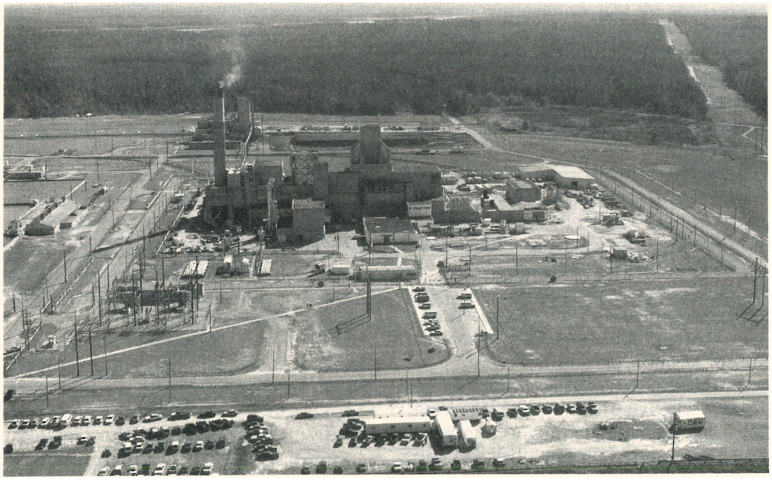
Like the Chernobyl-type RBMK reactors, the SRS reactors do not have containments in the normal sense. Instead they rely on a confinement system designed to capture and filter potentially dangerous gases in the event of accident (see the illustration, on page 83). The part of the confinement above the core in the SRS reactors is much sturdier than the comparable part in the RBMKs, and the RBMKs do not maintain negative air pressure, which is an important feature of the SRS safety system. Control rods enter the SRS core through a massive lid, but it may be the case, as at Chernobyl, that surprisingly little excess pressure would suffice to lift the lid.

When the lid lifted at Chernobyl, one effect was that all the water coolant immediately blew off. This was an especially serious matter because the RBMKs have a positive feedback mechanism in certain operating regimes such that when water voids, the reactivity of the reactor increases. The SRS reactors do not have a positive void feedback mechanism in any regime, and in the event of a reactivity transient, a number of factors—thermal expansion, Doppler broadening of absorption spectra and negative feedback from moderator voiding—would dampen the excursion.

The SRS reactors have, however, certain instabilities not found in the RBMKs. The aluminum-clad highly enriched uranium metal fuel in the SRS reactors has a low melting point relative to the standard zirconium-clad oxide fuel used in power reactors, so that the SRS reactors are more vulnerable to meltdowns or to even more severe accidents initiated by core melts. And because the SRS core contains a large quantity of highly enriched uranium—about a thousand pounds—the reactors are much more vulnerable to severe recriticality accidents than the standard power reactor.

Recriticality, prompt criticality

Conceptually, the SRS reactors re-



K-Reactor at Savannah River Site in South Carolina. What would most effectively mitigate the consequences of a severe accident, such as an explosion, is the site's size, an environmental impact statement for the three SRS reactors recently observed. The minimum distance from any SRS reactor to the nearest site boundary is 7 kilometers.

semble breeder reactors (reactors in which neutrons from highly enriched uranium or plutonium bombard ^{238}U, producing new plutonium), except that breeders are unmoderated and operate on fast neutrons. Like breeders, the SRS reactors are vulnerable to reactivity transients and prompt critical bursts—well-known risks in the breeder safety literature. In the event of an SRS meltdown, for example, a portion of the highly enriched uranium fuel could slump to the bottom of the reactor, collect and go recritical.

The difference between normal criticality and prompt criticality, as explained in a report on a study of the nuclear weapons complex that the National Academy of Sciences sponsored several years ago, is as follows: "The term *critical* in this context means that the assembly uses all neutrons, including those delayed, to maintain criticality. The delayed fraction, under this condition, permits convenient control because small changes in the reactivity of a system are manifest with times characteristic of the delay periods. If, however, only the prompt neutrons are necessary for criticality, the system does not have this controllability. Such a system is said to have achieved 'prompt criticality,' and the power output will rise very rapidly."

A prompt criticality by definition is very difficult to control and is likely to end only when the reacting nuclear materials disassemble, which can occur violently. A prompt criticality was the initiating cause of the Chernobyl accident, and a second prompt criticality probably was what destroyed the reactor's core and dispersed its contents into the atmosphere (see below).

This kind of prompt critical burst is from a purely physical point of view a species of nuclear explosion, and so it is important to be clear that this is not the kind of nuclear explosion that makes a mushroom cloud or destroys a city. Theodore B. Taylor, a former weapons designer and a leading independent expert on criticality, proposes a useful rule of thumb: Unless the destructive yield from a criticality is, say, an order of magnitude greater than what one gets from an equivalent quantity of chemical materials, one should not say that the explosion is "like an atomic bomb." From this point of view, Taylor feels it is essentially accurate to say that *no* reactor can blow up like an atomic bomb.

Letter and Meserve report

The danger of a Chernobyl-type explosion at the SRS reactors was first drawn to our attention in a letter that probably was written by a nuclear engineer at Hanford. "Down in South Carolina," the letter said, "there are three heavy-water reactors operated by DOE that certainly could never be licensed [commercially] because they do have the potential to blow up. These low-temperature, low-pressure reactors are highly efficient producers of nuclear materials but potentially are among the most dangerous in the world."

The letter proceeded to list nine specific points about the reactors, many of which already were being addressed in the safety-enhancement programs DOE inaugurated after the reactors were shut down in 1988. The three final points, however, concerned features of the reactors that did not appear to be easily fixed. The letter said that the emergency core cooling system was ineffective; that in a loss-of-coolant accident, steam–aluminum reactions could release large amounts of hydrogen, which could then explode; and that in the event of a core melt, the reactors could go recritical, releasing large amounts of energy and reactive fission products.

At the time the letter arrived it was not immediately apparent how seriously it should be taken. But in due course an opportunity arose to show the letter to Richard Meserve, a physicist-turned-lawyer who had headed a special panel that the National Academy of Sciences established to evaluate the defense production reactors in light of Chernobyl. Meserve confirmed that the issues raised in the letter deserved attention, categorically. On the subject of the emergency core cooling system, for example, Meserve explained that the defect at issue had to do with the fact that the system injects water from the top, but that if the reactor were exploding or blowing off steam, the steam might prevent the water from entering the core.

The report that Meserve's committee produced on the defense production reactors in 1987 already was very critical of the SRS machines, and it was indeed true, as Meserve indicated, that the key points contained in the letter were made in the report—albeit not always prominently. On the question of recriticality, the report said: "1958 melting experiments performed on Savannah River fuel tubes in the SPERT reactor in Idaho led to the identification of a potential mechanism by which positive reactivity insertion could occur in the Savannah River reactors in a severe accident.... In a recent DOE technical appraisal of the Savannah River reactors it was recommended that analyses be made of the 'potential recriticality from a molten fuel mass slumping to the tank bottom.'" The committee went on to say that although the probability of such an event might be remote, further study was warranted.

System upgrades

The Meserve committee recommended establishment of an independent, external safety committee for the production reactors, and it recommended that "the bulk of the committee's work should be unclassified and available to the public." These recommendations helped lead to a restructuring of safety management in DOE and to the establishment of the Defense Nuclear Facilities Safety Board, which is headed by John Conway, an experienced scientist from the nuclear industry. In addition, a massive environmental impact statement has been prepared in connection with the SRS restart, and since its release last December it has gone through a standard public review process.

Since the Meserve report came out and the SRS reactors were shut down in August 1988, far-reaching modifications have been made to the reactors, new training programs have been inaugurated, emergency procedures have been clarified, and very thorough safety reviews have been carried out, both on site and off site. The total cost of the programs has been reported to be greater than $2 billion; the safety review effort alone has involved hundreds of person-years of effort and has cost $100–150 million, according to top DOE and Westinghouse officials at the site.

The most important hardware modifications have included addition of a fourth emergency core cooling line to ensure that at least two paths always would be available in a loss-of-coolant accident; addition of an entry point for the supplementary safety system; a modification of the design for the tubes housing the control rods to prevent excessive heating of the rods in a loss-of-coolant accident; extensive seismic upgrades to approximate commercial standards for resisting earthquake damage; and addition of a seismically qualified diesel pump to power the recirculation system that is to be used to remove decay heat in the event the flow of river water is interrupted.

Probably the most important single reform is an operating rule—which has yet to be endorsed by the Conway panel—saying that when the initial reactor is restarted for tritium production (the K-Reactor), power will be limited to 30% of the normal maximum operating level, which is 2500 MW for tritium. DOE believes it may be safe to operate the reactor at up to 50% of its normal maximum upon completion of all upgrades and safety reviews.

The point of the power limits is to make it extremely improbable that bulk boiling of the moderator or coolant could occur, in which case steam could interfere with effective operation of the emergency cooling system. As long as the fuel does not melt, the thinking goes, the issues of cladding–coolant or fuel–coolant interactions, hydrogen generation and recriticality or prompt criticality never arise.

Studies indicate that the risk of a meltdown in one of the SRS reactors, given the new power limits, would be no greater than in a commercial nuclear reactor. Nevertheless, in the unlikely event a meltdown did occur, there would remain the residual danger of fuel-cladding-coolant, recriticality or prompt criticality events.

Referring to studies done for the Conway board on the prompt criticality issue, Herbert Kouts (a member of the board) said it looked like it would be "very hard to prove that prompt criticality could not occur in a meltdown." It is Kouts's belief, however, that the risk of a prompt criticality is really only significant when the fuel is in the process of slumping, when it still is mixed with heavy water (its most reactive state), *not* when the fuel has slumped to the bottom of the reactor.

Even though the reactor contains a thousand pounds of highly enriched uranium, and a sphere of just 25 kg of pure ^{235}U could in theory form a critical mass, Kouts points out that the slumped fuel would form a pancake, not a sphere, and it would be contaminated. "There would not be as much there as you might think," Kouts claims.

In addition, Kouts points out, any recriticality would have a low yield because of the innate tendency of the reacting materials to disassemble. The most energetic criticality ever recorded in a US reactor incident, Kouts says, was 35 megajoules.

Argonne and Sandia reports

In a series of conference calls with SRS management in mid-August and early September, PHYSICS TODAY discussed safety issues with Savannah River's top managers and safety experts, who are led by Frank McCoy, director of DOE's SRS special projects office, which is responsible for the restart. In addition to the points raised in the letter that first alerted us to the severe accident possibilities at Savannah River, the Meserve report and the environmental impact statement, the interviews covered two particular concerns coming out of special reports done at Sandia and Argonne.

The massive Argonne report refers primarily to a proposed new production reactor that would be moderated by heavy water (see PHYSICS TODAY, September 1988, page 47), but because such a reactor would be fundamentally similar to the SRS machines (albeit with many improved features and minus the effects of aging), much of what the report says is relevant to SRS restart issues. Most relevant here is a scenario the report describes in which fuel would separate from target assemblies in a meltdown (because the fuel has a higher heating rate than the target), slump to the bottom of the reactor, go prompt critical and explode.

From data presented in the Argonne report, one can obtain a work-energy estimate of 60 GJ (equivalent to 15 tons of TNT) for a prompt criticality accident, on the conservative (and unrealistic) assumptions of no Doppler coefficient (no drop in reactivity with increase of temperature) and isotropic expansion of the core. L. Walter Deitrich, director of engineering research for the new production reactor at Argonne, stresses that this is a bounding calculation based on pessimistic assumptions, not a physics prediction. Using a reasonable conversion ratio for thermal to work energy, Deitrich says, the destructive yield of such an extreme-case explosion might be about 1 GJ.

(As a point of reference, the energy from fuel vaporization associated with a prompt criticality in the Chernobyl accident is estimated at 32 GJ, according to a DOE study team. While the fuel vaporization accounted for only a fraction of the total energy released, the DOE researchers concluded that it was by far the most violent of the events and that it—not the steam explosion or the fuel–coolant interaction—caused the destruction and dispersal of the Chernobyl core.)

The Sandia report, which also was done in the context of the new production reactor program, concerns the results of an experiment in which molten aluminum was dropped into a vessel containing water. This caused a much more violent explosion than expected. Energy from chemical reactions between aluminum and water is believed to have accounted for most of the work energy released, which came to 3–4 MJ per kilogram of aluminum. A uniform reaction of this kind scaled up to an SRS core obviously would be a very serious event, but people at Sandia stress that the experiment involved small quantities of aluminum and warn that it would not be realistic to scale up linearly from such an experiment. "A distorted picture of plant safety can be created if the results concerning one particularly energetic scenario are singled out, without regard for its low probability," they say.

SRS management's position

Responding to questions about the Sandia report, the SRS managers and safety experts said first of all that the Sandia findings have been incorporated into the second-stage Probabilistic Risk Assessment for the SRS reactors, which is currently in progress.

Probabilistic risk assessment is an analytic procedure widely applied in the US nuclear industry after the Three Mile Island accident, which involves tracing out every conceivable accident sequence in a branching scheme. The Level-1 PRA for the SRS reactors, which was completed in June 1990, concerned the probability of core-melt accidents; it has been peer reviewed and will be released in about four months. Level 2, which has just gone out for peer review, covers severe accidents with multiple failures.

The SRS representatives said that in an actual accident it would be very hard or indeed virtually impossible to get the amount of superheat needed to melt the aluminum cladding, suspend a mass of it and drop it into the water, on the model of the Sandia experiment.

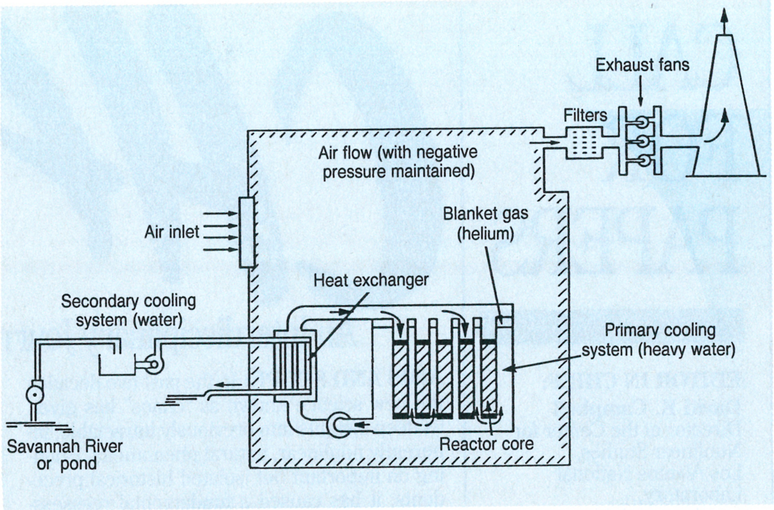
Concerning the scenario in which uranium fuel melts faster than target assemblies and slumps to the bottom of the reactor, inducing a large reactivity burst because neutrons no longer are absorbed by the target, the Savannah River experts said that this scenario also is being addressed in the Level 2 PRA and that preliminary Level 2 findings already were incorporated in the environmental impact statement. In the meantime the Level 2 analysis has been completed (though not fully peer reviewed), previous results have been confirmed, and no new surprises have been identified, they reported.

They said it already is clear that:

▷ When an SRS reactor is used for tritium production, operating at reduced power levels, there is no meltdown process or reactivity effect that could induce fuel–target separation and cause a prompt criticality.

▷ It also is highly improbable that such a scenario could occur when a reactor is used for production of plutonium-238 for use in spacecraft reactors, as foreseen in the near or medium term.

▷ The scenario may be an issue if a reactor is loaded with charges for weapons-plutonium production, which have higher power densities, but this issue will be covered in the Level 2 PRA if it becomes relevant. Meanwhile, there are no plans for the immediate or near term to use the reactors to produce weapons plutonium.



Savannah River reactors rely on a confinement and air filtering system for protection against release of radionuclides into the atmosphere. While the system is an adequate safeguard against consequences of a "design basis" accident (a water break and meltdown), traditionally considered the worst possible case in reactor safety literature, it might not prevent releases in the event of a "worse than worst case" accident such as an explosion.

We asked the Savannah River experts to address the general issue of recriticality, which is mentioned only once in the environmental impact statement, and then only in a way that is confusing, cryptic and obscure. They said the meaning of that reference is that even if a recriticality event were to occur in the course of a meltdown and steam explosion, its effects would be no worse than those of the steam explosion itself.

We pointed out that in the case of the Chernobyl accident, a DOE analysis found that uranium fuel vaporization was what accounted for the destruction and dispersal of the reactor core, not the (much more energetic) steam explosion. They said that their analyses indicated that at the reduced power levels, a meltdown or transient could not generate enough heat to cause significant fuel vaporization in the SRS reactors.

The last word?

The men responsible for the SRS restart answered all questions squarely, without any attempt at evasion whatsoever and without ever claiming that something was too sensitive or too secret to talk about. Nonetheless questions can be raised as to whether what they said represents the last word on Savannah River safety. They themselves stressed that their responses on key issues such as the prompt criticality scenarios depended on analyses that are only now being peer reviewed and that are quite a long way from being publicly disclosed.

"You often find claims about reactor safety not holding up in reviews, even though the claims are sincerely held," comments Gordon Thompson, an applied mathematician who is executive director of the Institute for Resource and Security Studies in Cambridge, Massachusetts. In critical testimony on the draft environmental impact statement for the SRS reactors, Thompson emphasized that "there are inherent difficulties in probabilistic risk assessment."

On the other hand, people also have high praise for the analytic work done for the SRS reactors, and there are those who consider the state of the art in PRA analysis to be very high already. This is true, for example, of George Greene of Brookhaven National Laboratory, who has served on several SRS review panels and who considers the reactors ready for restart. "There has been a lot of research in the past several years for both the K-Reactor and the heavy-water new production reactor," Greene says. "The research on the restart of the K-Reactor has set a high technical standard by which the rest of the DOE nuclear establishment will be judged in the future."

—WILLIAM SWEET ■