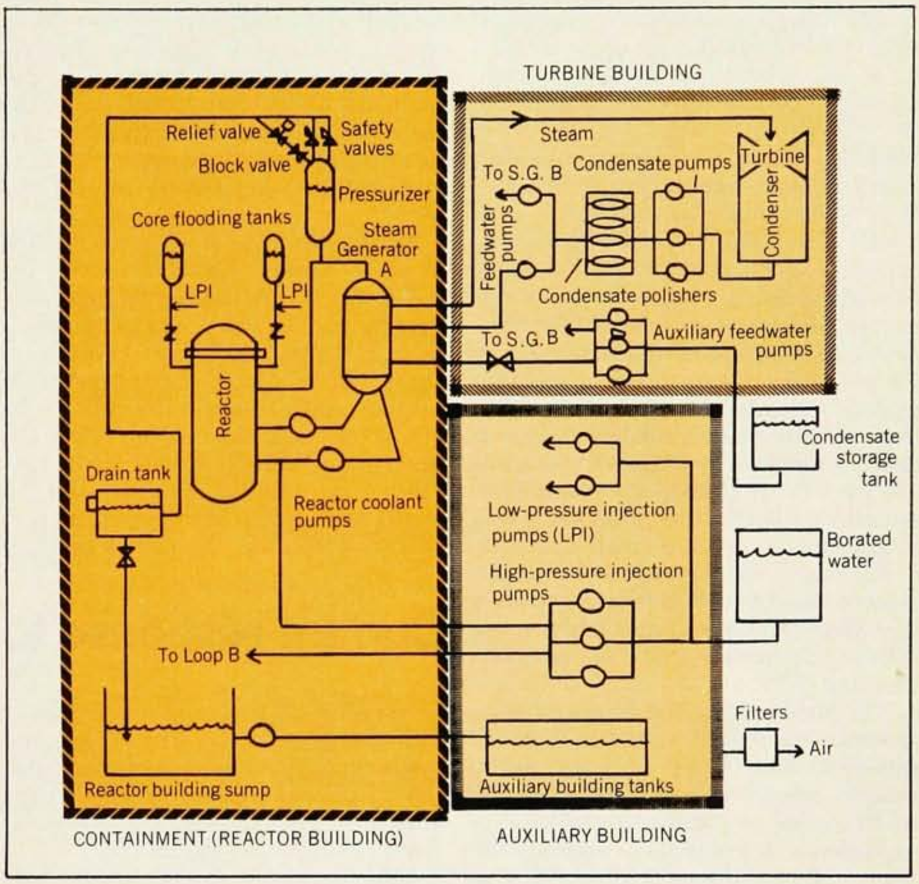
What went wrong with the Three Mile Island reactor?



Pressurized-water reactor at Three Mile Island. The diagram illustrates some of the components that contributed to the accident there on 28 March. It began when condensate and feedwater pumps stopped. Auxiliary feedwater valves had been left shut; the pressurizer relief valve stuck open; the pressurizer level indicator misread; the containment building was not quickly isolated; high-pressure injectors were switched off prematurely. Thus, the core of the reactor overheated.

The Three Mile Island nuclear reactor near Harrisburg, Pa. has been cooling slowly after the crisis that began there on 28 March. The feverish activity to decipher this accident and prevent others has not abated, however. Details of the sequence of events that led to the damage of a large fraction of the nuclear core are only gradually emerging. Some answers must wait until the core can be safely approached, and still others may never be forthcoming. The events as understood on 4 April were related that day to the Nuclear Regulatory Commission by its staff. As part of a routine check of this PHYSICS TODAY account, we consulted several groups analyzing the accident. Although given ten days to reply, NRC failed to comment, despite repeated inquiries.

The reactor—only three months old—is one of a pair of pressurized water reactors (PWR's) at Three Mile Island designed for Metropolitan Edison by Babcock and Wilcox. In a PWR the coolant in the primary loop is prevented from boiling by the pressurizer. (See the diagram.) The heat is transferred to the secondary loop through two steam generators that feed a single turbine. The emergency core cooling system consists of a high-pressure injection system with three pumps and a low-pressure injection system with two pumps designed as a backup principally in the case of a loss of coolant.

The complex chain of events that made up the accident began when a condensate pump stopped, and the loss of suction in turn tripped the feedwater pumps. Among the various reasons suspected for the first pump failure are the spillage of ion-exchange resin from the demineralizer into the secondary flow, and the closing of an air-actuated valve because of moisture in the air line. (Just before the trouble began, an operator had been working on this portion of the feedwater system.)

The loss of the feedwater pump resulted in the shutdown of the turbine. As pressure quickly rose in the primary loop, the reactor "scrammed." Nearly simultaneously, three auxiliary feedwater pumps began to operate. The water never entered the steam generators because the two valves had been left closed after a recent maintenance check.

With the primary deprived of an adequate heat sink, its pressure rose above 2250 psi, at which point a relief valve atop the pressurizer opened. The pressure then dropped back through 2200 psi but, when the valve stuck open, the pressure continued to plummet. When the pressure declined to 1600 psi, the high-pressure injection system was automatically switched on, two minutes after the turbine tripped. One high-pressure injection pump was turned off manually two minutes later, and a second ten minutes later. Both were restored again soon after that. The reason why the operator turned them off was probably his concern that a sensor in the pressurizer was registering a high level of water. The NRC staff has subsequently concluded that this level indicator was giving an erroneous reading at the time. (A pressure gauge at the same time was reading low.) The level indicator is a differential pressure transmitter, whose output is proportional to the water level—under steady-state conditions. It may give unreliable readings under transients such as those prevailing during the Three Mile Island crisis. Perhaps the rapidly dropping pressure, the frothiness due to the two-phase system then present, the fluid rushing out the relief valve or other effects could have contributed to the misleading impression of high water level. Alternatively, a high level may really have existed in the pressurizer due to the presence of steam and

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gas in the primary loop.

Once the emergency core cooling system and auxiliary feedwater pumps were both back in operation, things still were not under control. About one hour into the incident, an operator shut off the primary circulation pumps, apparently out of concern that they were badly vibrating, perhaps because of the bubbles in the system. Without circulation and apparently with little convection (a large temperature difference prevailed between inlet and outlet over this time), the core overheated. During the ensuing hours, the temperatures on some thermocouples on the fuel rods went above the computer-readout cutoff point of about 750° F. A large portion of the core was apparently uncovered after this point for an unknown period of time.

Bubble. When the operators restarted the circulation pumps and closed the block valve on the pressurizer, a new trouble developed. A large volume—as much as 1000 cubic feet or more—of noncondensible gas was detected in the reactor. Although no reliable measurement could be made of the composition of the gas in the reactor vessel, it was suspected to contain hydrogen. Air samples from the containment building registered concentrations of hydrogen of about 2%, and some sharp spikes in the containment building pressure—one of 28 psi—were interpreted as possible small hydrogen explosions. The hydrogen within the reactor vessel would come largely from a high-temperature oxidation reaction between the water and the zircalloy cladding.

The highly publicized concern that a growth of oxygen concentration from the radiolytic disocciation of water might produce an explosive mixture within the reactor vessel now seems unjustified. As explained to us by Milton Levenson of the Electric Power Research Institute, who led an Industrial Advisory Group at the site, the very presence of a hydrogen overpressure in a closed system helps the oxygen recombine with the hydrogen and remain in the water. In fact, PWR's normally operate with an extra charge of hydrogen in the water to scavenge oxygen.

Nevertheless, any noncondensible gas bubble (or bubbles?) within the reactor vessel posed a problem for the safe cooling of the reactor. If the pressure were reduced too low, the bubble would perhaps expand enough to expose the tops of the fuel rods again. The gas was removed by spraying it out of the pressurizer relief valve to the containment building. The procedure worked slowly, and by 4 April the process had virtually eliminated the bubble.

Within the containment building, the additional hydrogen in the atmosphere already present there *could* produce a flammable (at 4% hydrogen) or explosive (at 6 to 8%) mixture. These percentages could be slightly higher in the presence of water vapor, according to Levenson. To reduce this danger, two hydrogen recombiners were installed in the auxiliary building outside the containment.

The reactor continued to cool through most of the month of April with primary pumps and one steam generator in operation. (Steam Generator B had been isolated when primary-to-secondary leaks were suspected there.) On 27 April, the primary pumps were turned off and the core left to cool by convection, with both steam generators operating. After two days, Generator B was isolated and at this writing is being equipped to run with all water and no steam. The decay-heat removal system normally employed to cool the reactor is not being used, partly because it would pump the radioactive primary coolant into the auxiliary building and might cause leakage around the seal.

Radioactivity. The accident has resulted in some releases of radioactivity to the environment. With the fuel rods overheating and cracking, fission products such as iodine, xenon and krypton escaped. These elements contaminated the primary coolant while it was still flowing out of the stuck relief valve. When the seal ruptured on the quench drain tank (15 minutes into the accident), this hot liquid spilled onto the floor of the containment building. The pump sent this fluid into an auxiliary housing that is shielded and equipped with air filters. Releases occurred because the liquid volume was too large for the system to handle. The containment building was not designed to isolate automatically when the emergency core cooling system comes on. It was isolated only after five hours, when the pressure in the containment building rose above 4 psi over atmosphere.

The resulting cumulative dose equivalent from 28 March to 7 April is estimated to be from 2000 to 5000 person-rem (that is, the number of people exposed times the average dose per person) within a 50-mile radius and about half that in a 10-mile radius, according to an NRC spokesman. The average dose equivalent to a person in the smaller-radius region amounts to 10 millirem during that time, he said. This may be compared to the average dose equivalent per person per year from natural sources (in that region of Pennsylvania) of 85 to 90 millirem, according to Mark Mills of the Atomic Industrial Forum.

A massive cleanup job lies ahead to dispose of the radioactive water from the reactor core, and the estimated 400 000 gallons of liquid on the floor of the containment building. A more difficult task will be to decontaminate the inside of the building, where radioactive cesium may have been deposited. —BGL

Current response to Orlov jailing

A year after the trials and sentencings of high-energy physicist Yuri Orlov and computer scientist Anatoly Shcharansky, the US physics community is still grappling with the question of scientific exchange with the Soviet Union.

SOS. Over 2400 US scientists recently signed one of two statements—either withholding or severely restricting cooperation with the Soviet Union until Orlov and Shcharansky are released. The statements were circulated by a group known as Scientists for Orlov and Shcharansky, which a year ago took up the cause of those scientists and other oppressed scientists in the USSR. Of the six members of the SOS Executive Committee, three are physicists—Owen Chamberlain (University of California, Berkeley), Malcolm Derrick (Argonne National Laboratory), and Kurt Gottfried (Cornell University). While SOS does not feel that all contact between the US and Soviet scientific communities must cease, they are opposed to expanding involvement at this time and to the essentially one-way transfer of technology in areas in which the US enjoys a considerable lead.

An international radio broadcast from the Soviet Union recently attacked the SOS statements. According to the broadcast, SOS has been misinformed about the Orlov and Shcharansky cases by "American propaganda." It also went on to denounce the "chauvinism" implicit in the SOS statements, saying that American contributions are not essential to the advancement of Soviet science.

Cooperation. Many US physicists do not feel that prolonged isolation from the Soviet Union is the most productive form of protest. The Working Group on Physics of the US–USSR Joint Commission on Scientific and Technical Cooperation, for example, is continuing to encourage members of the US physics community to participate in its program of meetings, symposia, seminars and exchanges (see box). The activities of the working group fall under the purview of the National Academy of Sciences. David Pines (University of Illinois), US chairman of the working group, told us that although there is a "broad spectrum of opinion" within the group on what is the "most appropriate response," the entire group agreed that "organized boycotts are not the most suitable response" to the current situation. He noted that in the past several individuals in the group have attended, as individuals (not in an official capacity), dissident and re-

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