Articles

Nuclear Power After Chernobyl

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The causes and progress of the accident at Chernobyl are described, and a comparison between the Chernobyl accident and the 1979 accident at the Three Mile Island nuclear power station is made. Significant similarities between Chernobyl and Three Mile Island include complacency of operators and industry, deliberate negation of safety systems, and a lack of understanding of their plant on the part of the operators, which shows the critical importance of the human element. The Chernobyl accident has implications for nuclear power in the United States; it will affect the research program of the Nuclear Regulatory Commission, regulation of Department of Energy reactors, new reactor designs, and public attitudes.

NUCLEAR POWER PLANTS IN THE SOVIET UNION ARE equipped with pressurized water reactors (PWRs) as well as boiling-water pressure tube reactors, called RBMKs. Fifteen RBMK-1000 plants like those at Chernobyl, each generating 1000 MW of electricity, provide more than half of the Soviet Union's nuclear-generated electrical capacity. The RBMK-1000 is also rated at 3200 MW thermal (the amount of power from the fuel), much of which is released as waste heat.

The RBMK is designed to be constructed with two units connected by a joint turbine-generator hall, but the two independent reactor systems have a number of interchangeable auxiliary systems. The Chernobyl reactor site, with four completed reactors and two additional ones under construction, is located on the Pripyat River, approximately 24 km northwest of the town of Chernobyl and 110 km north of Kiev. The nearest town is Pripyat, which grew up around the Chernobyl power plant (*1*). At the time of the accident, about 45,000 people lived within the immediate neighborhood of the plant and about 150,000 within 30 km.

The first RBMK-1000 went on-line in 1973. The RBMK has on-line refueling, which makes it possible to remove a used fuel assembly and insert a fresh fuel assembly while the plant is running at full power. On-line refueling allows the plant to be available for electricity generation a much higher percentage of the time than the typical U.S. nuclear plant, which must be shut down for refueling every 12 to 18 months.

Figure 1 is a sketch of the major features of this reactor (*2, 3*). The core contains about 2000 tons of graphite blocks that are arranged in the form of a cylinder. The reactor fuel is in 1660 zircaloy (zirconium alloy) pressure tubes embedded in the graphite blocks. Each pressure tube contains two fuel assemblies, each with 18 fuel pins, which are uranium dioxide clad with zircaloy. The entire reactor core is 11.8 m in diameter and 7 m high, including graphite reflectors on the top and on the side. Pumps circulate water up from the bottom of each pressure tube. After rising about a third of the way, the water begins to boil. This steam-water mixture exits from the top and goes to the steam separators; the water portion is returned for reuse, and the steam runs the turbine to generate electricity. The water circulates through the pressure tubes at a temperature of about 270°C, although the temperature increases as the water is heated. The steam pressure is about 70 kg/cm^2.

This plant does have an emergency core cooling system and diesel generators for emergency power. The emergency cooling system was designed in case of a break in the main cooling pipe. It has been "tested and adjusted during operation, and the reliable cooling of the core by natural circulation in the event of a total failure in the electricity supply has been demonstrated" (*4*, p. 389). Power is controlled by 211 control rods made of boron carbide. The effectiveness of a control rod follows an "S" curve: a rod is not as marginally effective in the early or late stages of insertion as in intermediate stages. A reference to "x control rods" inserted means the equivalent of x control rods fully inserted. Many more than x may be partially inserted.

The RBMK reactor has a positive void coefficient, a critical feature that played a major role in the accident. The reactor power in this case increases as the available water through the core decreases, the opposite of the behavior of most reactors. The following is a basic description of the phenomenon.

When uranium atoms fission, the resulting neutrons are inefficient producers of further fissions at the high energy at which they originally are emitted. These neutrons must be slowed down to induce additional fissions efficiently and to sustain the chain reaction. A "moderator" slows down the neutrons by collisions, but it should not capture them. Water in light-water reactors (LWRs) and graphite in the RBMK serve as moderators. The water in the RBMK is not used as a moderator; instead, it is used to transfer heat. Some neutrons are nonetheless captured by the water. Thus the water is a slight "poison," that is, a material that captures neutrons, preventing them from going on to produce further fissions.

In an LWR, such as that at the Three Mile Island (TMI) nuclear power plant, the primary effect of the water on neutrons is as a moderator; capture is a secondary effect. As the water heats up and becomes less dense, less scattering occurs. Consequently, the neutrons are not slowed down as much and are less efficient in producing fissions, and thus the reactivity decreases. If there were no water, there would be no scattering, and almost no subsequent fissioning. Consequently, when the water boils away in an LWR, the fission reactions stop. However, the fuel elements may still melt from the heat generated by decaying fission products. This is in essence what would happen in a meltdown and what undoubtedly happened in a portion of the TMI core. In the RBMK, however, when the water boils and becomes less dense and voids are formed, or if there is a substantial steam-air mixture, neutrons are not captured by the water; they go into the graphite where they are efficiently moderated to cause more fissions. Therefore, in the

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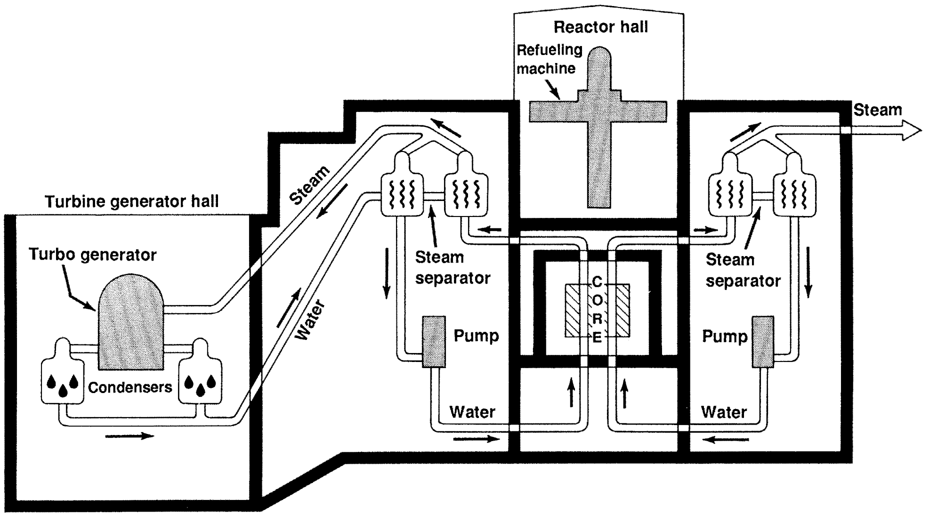

Fig. 1. Schematic diagram of the reactor hall and part of the generating halls at Chernobyl. Arrows indicate the direction of steam and water. Only one of the two 500-MW generators is shown. Heavy lines indicate reinforced concrete.

RBMK, the absence of water increases the rate of fissioning and the reactivity increases (the void coefficient is positive). The RBMK reactors depend on a complex computer-run control system to handle this effect.

Why did the Soviet Union build this type of machine if it does have a positive void coefficient? In the document they presented and during discussions at the International Atomic Energy Agency (IAEA) in Vienna, the Soviets provided an insight. Although they knew disadvantages existed, they saw no alternatives 25 years ago. At that time, the Soviets could not make large pressure vessels or steam generators. This inability led them to the RBMK design, which has neither. The graphite core comes in modules, making this design easy to construct (*5*). The Soviets have described some of the RBMK design characteristics as advantages: "The absence of cumbersome pressure vessels . . . absence of a complex and costly steam generator . . ." (*6*, part I, p. 4). After developing the necessary manufacturing capability, the Soviet Union constructed PWRs. However, the RBMK design remained a mainstay of the Soviet nuclear energy program, which is evidenced by the two additional units under construction at Chernobyl, and by the announcement of two more designs, the RBMK-1500, already in service, and the RBMKP-2400, for 1500 and 2400 MW of electricity, respectively.

The RBMK design problems were known as early as 1977. At that time, Britain examined the best available nuclear technology to decide whether a design other than the gas reactor design that they had used until that time should be developed. (Britain chose a PWR design.) According to a senior British official, the British warned the Soviet Union 9 years ago that the RBMK design had serious defects and that this design gave the operators too difficult a task (*7*).

Most reactors are built with the reactor vessel inside of a structure called the containment. In the United States, this can be a steel shell or a reinforced concrete containment. These structures are designed to withstand large pressures before leaking and to prevent the release of radioactivity in the event of an accident. Design pressures range from 1.9 to 5.4 kg/cm^2, although calculations indicate most containments could withstand much higher than design pressures.

Much discussion after the Chernobyl accident focused on whether the RBMK had a containment structure. The U.S. representatives to the Vienna meeting reported that the design was built to withstand a pressure of 4.2 kg/cm^2 in the outer walls and about 1.8 kg/cm^2 at the reactor room. The large concrete slab on the top of the reactor weighs about 1000 tons. However, much of the concrete slab lies on top of the graphite, which does not incur any pressure buildup. Rather, the pressure tubes (8.8 cm in diameter) are subject to pressure buildup. In addition, the building on top of the reactor is what the United States would call a confinement building. It is equipped with fans and filters so that if radioactive gas were released within the building, the gas would be sucked through filters to remove the radioactivity before being vented to the outside. However, the building at Chernobyl was not designed to withstand much overpressure.

Events Leading to the Chernobyl Accident

The electricity generated by a nuclear power plant is not relied on to provide the electricity needed to run the plant. The power generated by the plant is sent off-site to main distribution stations, and lines from other power stations return electric power to the site to run the essential elements of the plant. Many systems within a nuclear power plant require off-site electricity, for example, instrumentation, many of the control systems, and some of the pumps. Other pumps are run by steam generated by the plant. Because of the positive void coefficient in the RBMK, the emergency feed water pumps must be kept running to circulate water through the system.

A major potential problem with nuclear power plants is "station blackout," when all off-site (and some on-site) power is accidentally lost. To generate the electricity necessary to safely shut down the plant, U.S. plants are required to have emergency batteries for instantaneous response and diesel generators with a run-up time of 10 seconds from cold-start to full power. Soviet plants also have diesel generators. Although the Soviets have said their diesel response time is 15 seconds, the report released in Vienna indicates a need for other sources of power for at least 45 seconds (*6*). For a source of power during a station blackout the Soviets depend on the energy stored in the turbines. The electricity generated in the plant comes from steam that turns huge turbines; each RBMK plant has two turbines, and each one generates 500 MW. When the turbines are turned off, the rotors do not stop immediately. Indeed, a large amount of kinetic energy is built up in the rotating machinery during operation. While the turbines coast down, this energy can be used to generate electricity to run emergency systems until the diesel generators are able to take over. The Soviets describe the particular accident for which this use of turbine power was designed as "the design basis accident" (*6*, part II, annex 2, p. 132; *8*).

At Chernobyl, a test was planned to demonstrate the feasibility of this procedure; the test had been performed at other plants. When the test was run previously at Chernobyl reactor unit 4, the voltage available from the generator had been insufficient. The new test was performed to check a modification that had been made to increase the voltage.

Figure 2 shows the thermal power of the plant as a function of time (*9*). Descriptions of events depicted at points A through K in Fig. 2 follow. The plant had been running at 3200 MW (A) and was scheduled to be shut down for maintenance. The vertical dashed line separates 25 and 26 April 1986. On 25 April at 0100, the operators started lowering the power for shutdown (B). At 1300, the operators disconnected turbine no. 7 (C) because, as part of the test, steam was to be turned off to turbine no. 8, in order to simulate the loss of off-site power. The plant was then at half power. At 1400, with the plant operating at 1600 MW, the load dispatcher asked the operators to hold the power steady (D); apparently, the power was needed in the grid. At this point, the operators disconnected the emergency core cooling system. This was appropriate under the test procedure, but it was a violation of the operating rules for this plant. However, the disconnection apparently had no bearing on the accident. Its significance is that it was the first of several deliberate "violations of instructions and operating rules committed by the staff of the unit" (*6*, part I, p. 23). The test procedures had been developed by a station electrical engineer, and the operators thought it was an electrical test. They did not conceive it as a nuclear test.

At 2310 on 25 April, the operators apparently were given permission to bring the plant off the grid, and they again started reducing power (E). The test was planned to be run between 700 and 1000 MW thermal. At 0028 on 26 April, the operators switched off the local automatic controls, putting the plant on a global control system (F). However, the global, or average-power, control system is primarily used as a backup to the local control system. The local system is more accurate and smooths out the effects of perturbations. Local control is required to be used during transitions from one operating regime to another (*6*). Furthermore, once the power started to go down, xenon began to build up in the fuel rods (*10*). (Xenon is a poison that captures neutrons.) The power and the controls were then mismatched, and the xenon poisoning was making it harder to generate additional neutrons (the reactivity was dropping). The operators inserted control rods in order to continue shutting the plant down. Because of the mismatch and the excessive poisoning, the power dropped faster than desired or anticipated. The plant power went down to only 30 MW thermal, 1/100 of the normal operating power (G). The operators recognized this drastic undershoot, far below the test minimum of 700 MW thermal (*11*). Therefore, they started pulling out control rods, in order to increase the power. At this next point (H), they finally managed to get the plant to start back up. They got it up to about 200 MW thermal and stabilized it (I). Almost all of the automatic rods were now pulled out—pulled out beyond their limits—and in this system it takes about 20 seconds for the rods to be fully reinserted.

Six out of eight pumps were running, and the operators were having difficulty getting a stable flow of water. Because of this difficulty, at 0119, an operator manually blocked the system that normally would react to instabilities in the water-steam separator by tripping the reactor and shutting everything down.

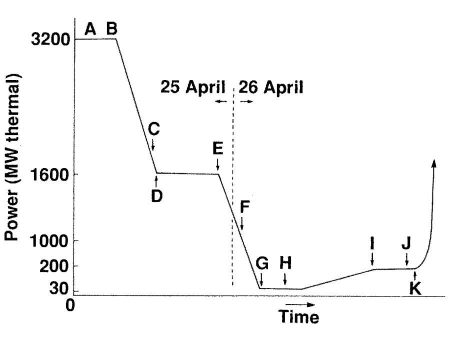

Fig. 2. Schematic diagram showing thermal power changes the day before the accident and the rapid change as the accident developed. Letters refer to events explained in the text. B to F covers approximately 24 hours; F to K, 1 hour.

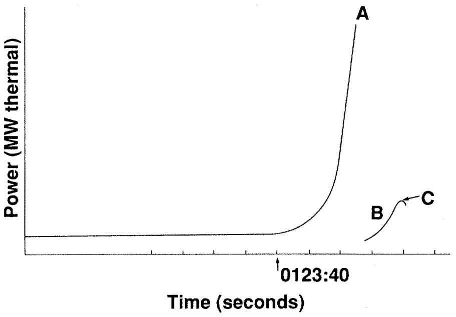

Fig. 3. An expanded diagram of the final section of Fig. 2. The vertical axis has two scales. Power goes from 200 to 3800 MW thermal for the curve marked A, and from 3800 to 120 times normal for the curve marked B–C.

To ensure reactor control, the test is to be run with four pumps stopped and four running. The four tripped pumps are to be replaced by the automatic feedwater pumps to be run off electricity generated by the turbine as it coasts down. So that four pumps could be tripped while four remained running, the operator then started up the other two pumps, so that eight pumps were running. This act was also a violation of the operating rules, because, with eight pumps running, vibrations are set up in the hydraulic system. At this flow there also is the danger of cavitation in the pumps, that is, not enough water flow for the pumps to operate properly, causing the pumps to begin pumping pockets of air. (The Soviets did not report whether cavitation occurred at Chernobyl.) With eight pumps running, there was a very high flow of water, but very little steam was being generated since the reactor was at low power.

The operators at this point recognized that because of the instabilities in this reactor and the way xenon poisoning builds up, once the reactor is shut down, they would have to wait a long time before starting it up again. Therefore, they did not want this shutdown to occur, because if the test were not done correctly, the operators would want to do it over again immediately. However, when the turbine generator goes off, the reactor will trip automatically. Therefore, an operator also manually disconnected that automatic trip safety system.

The reactor had four times the normal flow rate of water. Because of the enormous amount of water being pumped, the reactor inlets were subcooled: the water coming in was much cooler than it normally would be, and almost no steam was being generated. This cooler, steam-free water was a poison. At this point, the reduction in steam caused the remaining automatic rods to withdraw. The Soviets believe the operator also raised some manually operated control rods (*6*).

Before the operator tripped the generator to start the test, he reduced the pumps to three-quarters of the normal flow rate (J). That reduction would show up at the input of the core after the transit time between the point where the feedwater comes into the system and the point where it enters the core, which is about 30 seconds. About 30 seconds after the operator cut the flow, he tripped the generator to start the test (K).

The flow rate dropped, and the inlet temperature started to rise. Boiling began; the rods were all out. All of the trip circuits were blocked or off. At this stage the plant was very sensitive to the void factor: it takes about 0.8 second for an exponential growth. The last section of the curve of Fig. 2 shows what happened to the power.

The Soviets have run a simulation model, which they believe approximately describes what happened. Figure 3 with points A through C shows the model results for the power as a function of time [data from (*6*, part I, figure 4, p. 53)]. The rise started at about 0123:40. Within 2.5 seconds the power level was at 3800 MW thermal (A)—about 20% above the normal operating level. The vertical scale on the figure now changes (B). In another 1.5 seconds, the power is at 120 times normal (C).

Exactly what happened during those final few minutes is not certain, but one thing is clear: the number of control rods in the core was far fewer than required. Regulations required a minimum of 30 rods in the core. In Vienna the Soviets stressed that not even Gorbachev himself could bring the rod number down to less than 15. But, apparently, at the time of the accident only six to eight rods were inserted.

Because the fissioning was now occurring unabated, a great amount of heat was generated within each of the fuel pellets. The U.S. Nuclear Regulatory Commission (NRC) has calculated that about 260 cal/g are required to melt the fuel and about 700 cal/g are needed to vaporize it (*9*). The Soviets calculated that if the thermal power that was being generated was deposited uniformly in all the fuel it would have led to 300 to 350 cal/g.

This heat production in the fuel elements occurred over too short a time for thermal transfer. Enormous pressures would build up inside the fuel rods and fracture the fuel rods, probably those in the lower third of the reactor. This energy would interact with the water there and generate pressure in the tens of kilograms per square centimeter. Some investigators have described this as a classical steam explosion (*2*). The NRC staff are not yet sure and the Soviet Union is not yet confident that the Soviet model provides the exact details of what happened. In any event, the consensus is that there was no time for heat transfer to occur, so enormous pressure built up in the vertical pressure pipes. This pressure was channeled vertically, lifted the slab, took off the roof, and blew the fuel out.

Some investigators think that a reported second explosion was a hydrogen explosion, although a few experts in Vienna believe it might have been an additional fuel excursion. The initial fires were started by the burning debris that was spewed out at this time. The core graphite also caught on fire, and the raging fire acted as a chimney to loft the fuel and fission products quite high.

Release

The reactor contained about 3000 MCi (million curies) at the time of the accident (*6,* figure 4.4, annex 4, p. 17; *12*). At Vienna, the Soviets presented their estimates of the amount of radioactive material that was released. This is the "source term," the description used in accident calculations for the radioactivity released. The Soviets calculated that about 10% or 250 tons, of the graphite burned, and about 3 to 4% of the fuel was expelled from the core. The total radioactivity release was estimated to be about 50 MCi of noble gases, primarily xenon, and about 50 MCi of other radionuclides. The isotope with the largest release in terms of curies was iodine-131.

Figure 4 shows the calculations presented by the Soviets in Vienna for the number of curies released per day (*13*). The maximum release occurred on the first day. Releases decreased for the next 4 days, and the release was proportional to the initial inventory of fuel, implying a transport of fuel products. During this time the Soviets dropped 40 tons of boron carbide on the top of the reactor to stop the reaction. They also dropped about 800 tons of dolomite, in the hope that carbon dioxide would put out the graphite fire, and about 2400 tons of lead, primarily to act as a heat absorber. The lead would later serve as a radioactivity shield for the top of the reactor. About 800 tons of clay and sand were dropped as well. The core was then insulated, and there was no natural circulation. Decay heat caused the core temperature to increase, and the amount of radioactivity released also increased. The rise in radionuclide release from days 6 through 9 involved particularly volatile species. This rise provides an explanation for some reports that perhaps a second accident had occurred, because radionuclide measurements outside the Soviet Union suddenly increased. The very sharp decrease on day 10 probably occurred because the graphite fires were going out and the core was being cooled by a combination of liquid nitrogen, which was introduced to cool the core, and carbon dioxide, which was reduced when the dolomite smothered the graphite.

After the Accident

Three fire-fighting teams went to the site immediately, and by 0230 on 26 April they had confined the fires to the roofs of the surrounding buildings. The principal objective of the fire fighters was to prevent the fire from spreading to reactor unit 3. They used primarily water to extinguish the fires, which were mainly on the surface. These external fires, but not the graphite fire, were put out by 0500. The U.S. delegation at Vienna was uniform in its praise for the description of the fire fighting performed by the Soviet response teams.

The other reactors operating at the site were not immediately shut down. Reactor units 1 and 2, not directly connected to the damaged reactor, were not shut down until 24 and 25 hours, respectively, after the accident. Reactor unit 3, which is connected to reactor unit 4, was not shut down until 0500 on 26 April, about 3½ hours after the accident (*6*). The Soviets gave no reason for continuing to operate this reactor, which shares some systems, including ventilation, with the damaged reactor. The personnel in reactor unit 3 might have been evacuated at the time of the accident, and the Soviets then may have been unable to get into this reactor to shut it down until after the fires were under control.

Comparison Between TMI and Chernobyl

There are several similarities in the accidents at TMI and at Chernobyl. In both cases the accident occurred in the early morning, about 0400 at TMI, and a little after 0100 in the Ukraine. These are typically slow periods on shifts.

Also, both reactors are very sensitive. In the Chernobyl accident, the operators had a short time, minutes or perhaps seconds, to respond. At TMI, a useful response could have been taken over several hours. The positive void coefficient makes the Chernobyl-type reactor extremely sensitive to perturbations in the system. The

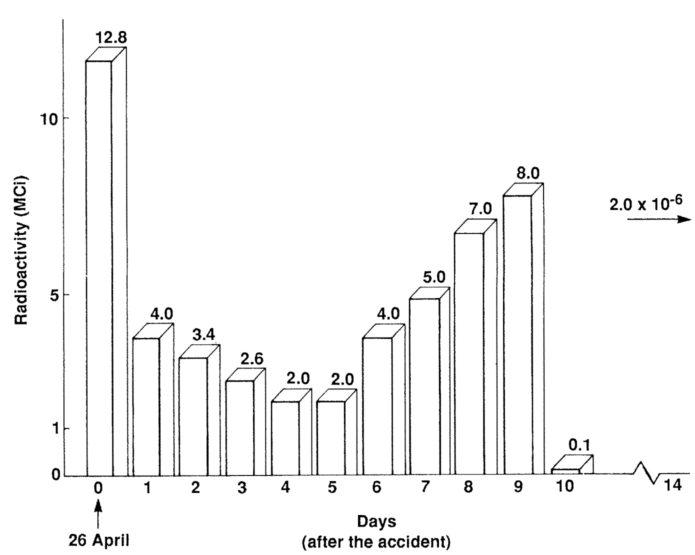

Fig. 4. Calculated daily release of radioactivity from the day of the accident until the quenching was successfully completed.

Babcock & Wilcox reactor at TMI has a once-through cooling system, with a small volume of water compared to other U.S. reactors. This design is well known within the U.S. nuclear reactor industry as being more responsive to perturbations than other U.S. reactors.

The more serious similarities stem from general complacency. In both their report and in conversations at Vienna, the Soviets stressed that one of the problems at the Chernobyl plant was that the operators had become complacent. This plant had a very high capacity factor and had run so well that the operators began to be too relaxed—they slipped into the dangerous attitude that an accident could never happen. A U.S. observer in Vienna said the Soviets were still incredulous that the accident could have happened.

I do not know the relative complacency of the TMI operators. However, a feeling had pervaded the whole U.S. industry—utilities, vendors, regulators, and even much of the government oversight committees—that a major accident could not happen in the United States. So, to that extent, complacency was an essential element in both cases.

The Chernobyl operators did not pay attention to warnings from various sensors. At TMI, a power-operated relief valve (PORV) had stuck-open, allowing steam, and therefore water, to escape. The TMI operators did not believe the temperature readings that indicated steam was exiting.

Another common element is that the operators took a series of steps that were deliberate and that defeated the safety systems. The Chernobyl operators turned off a number of safety systems to prevent the plant from shutting down automatically. They overrode instructions by pulling out many more control rods than allowed and by pulling them far beyond the point to which the rods should have been pulled out. At TMI, high-pressure injection pumps came on automatically because of the drop in pressure in the inside of the reactor, which was caused by the water that was being lost through the stuck-open valve. The operators overrode the safety system, reduced the pump flow, and finally turned the pumps off. After more than 2 hours into the accident, a newly arrived crew member recognized the relief valve was stuck open, and shut it. Another hour passed before the high-pressure injection pumps were turned on, which then re-covered the core.

The operators at Chernobyl had no simulator training for the accident sequence that occurred. Similarly, TMI operators had never trained for the sequence of the stuck-open PORV, and instructions on how to handle such an event were not written in their emergency procedures.

The chief of the Soviet delegation at Vienna, Valery Legasov, said (*14*, p. 36) that the "accident had dramatized the need for greater training for nuclear power workers, especially through the use of computerized simulations of possible accidents. . . . [F]or those on duty at Chernobyl for the 24 hours leading up to the accident, [their] specialized training had included no computer simulations that could have helped them cope with the crisis." As a result, the Soviet Politburo has announced that computer simulation will be introduced in the training of reactor operators (*14*).

Both TMI and Chernobyl accident reviews found weaknesses in the approval of operating procedures. Legasov said that the plant's chief engineer and resident representative of the atomic safety committee were not consulted in the test design (*15*), and the Soviet report stressed that the test procedures were not reviewed by safety personnel.

The TMI accident reviews led to a requirement for plant safety committees to ensure that operating procedures are reviewed, particularly when a new procedure is going to be included. Such committees were not standard before the TMI accident.

Another common feature was that the operators did not understand their plant (*6*, part I, p. 23): "[T]he [Soviet] staff was insufficiently familiar with the special features of the technological processes in a nuclear reactor and also they had lost any feeling for the hazards involved." Similarly, the TMI reviews stressed that most of those involved in the TMI accident did not understand the plant engineering (*16*).

Thus the reviews of the two accidents pointed out that mechanical systems were defeated by operators who did not understand what they were doing and took actions that deliberately overrode safety systems. In both cases, the plants were particularly sensitive to such an override. However, in the TMI accident, a significantly longer period of time went by in which knowledgeable operators could have corrected the actions. In the Soviet case, because of the extraordinary sensitivity of the system, once the initiating events began to take place there was little time to prevent the accident. However, during the coast-down time, particularly after the plant reached 30 MW, there was an opportunity to continue the plant to shutdown. The Soviets had a requirement that this type of test not be run below 700 MW because of the sensitivity of the RBMK design. Disregarding that requirement was one of several violations of procedures that the Soviets have reported.

The TMI reviews led to significant changes in the way U.S. plants are operated. These changes included requiring simulators for plants and simulator training, including accident sequences; increased training for operators and upgrading the quality of operators; and safety review committees. Overall, great emphasis was placed on personnel issues, one reason being that much of the hardware was already in place. There also were additional hardware requirements, which were quite expensive in some cases.

Effects of Chernobyl on IAEA and the Soviet Union

The impact of Chernobyl was worldwide. Three major impacts, which are still unfolding, were on the IAEA, the Soviet Union, and the United States.

The IAEA. The IAEA has been in existence for more than 25 years. However, at least for the last 15 years, only two activities of the agency have received much attention. The first is the nonproliferation regime in which the IAEA is an essential player. The IAEA runs the safeguards inspection system for the world. The second is technical assistance, in which the agency provides equipment and offers technical advice for a wide variety of nuclear-related efforts, including power reactors and research reactors and on the use of radioactivity for diagnostic techniques and for sterilization of foodstuffs.

Although nuclear safety fits under the general umbrella of IAEA interests (*17*, p. 2), "[t]he safety function of the Agency has received less attention from its members than the promotion and safeguards functions. At present only about 7% of the Agency's budget is earmarked for nuclear safety activities. . . . [A] possible reason is that international inspections to monitor compliance with mandatory nuclear safety standards for design and operation of nuclear power plants would infringe much more on national sovereignty than inspections to simply account for nuclear materials."

Having learned from the TMI accident, in 1981 the United States proposed a convention to the IAEA to require member nations to report immediately on nuclear accidents that could send radiation across national borders. At that time many European nations, including France and the Soviet Union, opposed the idea. Attitudes have changed significantly, and the United States and the Soviet Union, along with other members, recently have agreed to a convention that requires such notification (*18*).

In 1982, the IAEA started to offer reviews of operating safety at nuclear power plants, by using operational safety review teams (OSARTs). This effort has suddenly received attention. West Germany has asked for three OSART visits, and the United States and Britain have both said they will invite a team to visit (*19*).

This interest will move the IAEA into an essential area of nuclear power, nuclear safety. It also will restore some international prominence to the agency and should, therefore, assist in its nonproliferation role. However, the agency will now face the difficulty that it had already been facing with respect to safeguards: getting enough competent inspectors. If the demand for safety inspections is large, hiring enough competent people to perform inspections will be difficult, particularly in the highly politicized environment in which the IAEA operates and with the reluctance in the past of IAEA members to increase funding for the agency. The result might be to transfer safeguards inspectors over to work as safety inspectors, which would be detrimental. Different knowledge is required for these positions, and this transfer would take away from the nonproliferation efforts of the agency.

Finally, the IAEA asked its International Nuclear Safety Advisory Group to recommend what actions the agency should take in response to the Chernobyl accident. This group has recommended an extensive expansion of the agency's activities in nuclear safety (*2*). The agency should be cautious in exploiting the new international interest in the IAEA. It is easy to overcommit an agency. The long-term gains to the world nuclear community and to the IAEA will be greater if the IAEA carefully considers reactions before taking action.

The Soviet Union. The Soviet Union ranks second in number of nuclear plants to the United States and third to the United States and France in total nuclear capacity; they have plans for more nuclear plants to provide both heat and power (*20*). Although the Soviet Union possesses large fossil fuel reserves, it relies heavily on these to obtain hard currency: in 1985, 60% of Soviet foreign income came from oil exports. Furthermore, the largest percentage of the Soviet Union's fossil fuel deposits are in the Asian part of the country, but the European part accounts for 80% of the fuel consumption. As a result, transporting fuel from eastern to western regions makes up about 40% of the country's combined cargo turnover (*20*).

Some aspects of the Chernobyl accident and its aftermath indicate a different approach to the international community on the part of the Soviet Union. The candor of the Soviets at Vienna was remarkable. For the Soviet Union to ask the West for assistance is unique in the post–World War II period. For the Soviets to admit in an international meeting that there was a weakness in their design, or in their appreciation of the problems with that design, is also unique.

The Soviet reports hinted that they were learning many of the lessons the United States learned after TMI: the necessity for using simulators, particularly simulators focused on accident sequences; the necessity for better training of operators, even to the extent of having accredited training; and the necessity to have procedures checked by a safety committee before tests are performed. The Soviets may not have paid much attention to the TMI reviews for a variety of reasons. Reports indicate that much damage at Chernobyl could have been avoided had the Soviets paid attention to these U.S. reviews (*21*).

Effects on the Soviet Union are hard to estimate. It is difficult for us in the West to see into the Soviet government or the Soviet system to understand what changes may be taking place. Some people have been expelled from the Communist party, and some senior officials have been replaced by others not associated with the past nuclear power program. These steps indicate that the Soviet government is taking the accident seriously and attempting to correct weaknesses.

However, the Soviets have yet to submit any data to the operating plant data system which was started in 1980 by IAEA. A list of actions were generated from the Vienna meeting, focusing to a large extent on international collaboration with the Soviets. If successful, this level of international collaboration will also be remarkable.

Effects of Chernobyl on the United States

Chernobyl can be expected to affect at least four groups in the United States: the Nuclear Regulatory Commission (NRC), the Department of Energy, the nuclear industry, and the public.

NRC. The effect of Chernobyl on the NRC is uncertain. Reacting to the extremely harsh criticism after the TMI accident, the NRC assembled a long list of items in an action plan. In most cases, these actions were to be taken by the nuclear plant vendors or the utilities. In many cases, the requirement was to introduce new equipment. The industry and its supporters in Congress objected strongly. The long list of actions was made under great pressure and was not thought through carefully enough. As a result, the NRC now is going to react cautiously to what has been learned from the Chernobyl accident. Certainly they will reexamine so-called "criticality accidents"; these were thought to have been "designed out" of reactors. However, Chernobyl showed that such accidents are still possible.

The NRC also may rethink its research program. For example, the NRC has proposed the elimination of all research on radiation effects on people and the reduction of research on human factors.

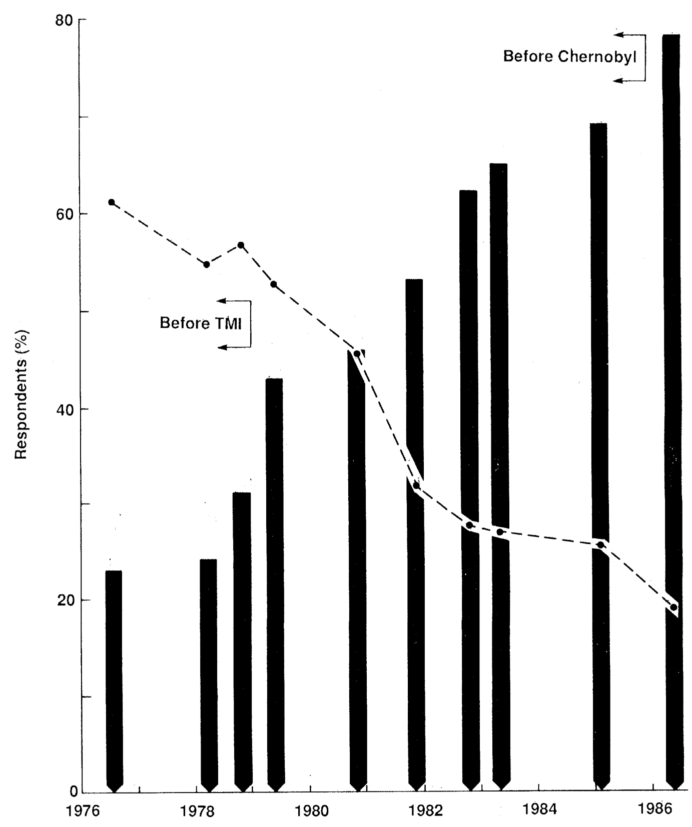

Fig. 5. Presentation of polling results in response to the question: "In general, do you favor or oppose building more nuclear power plants in the United States?" The dashed line shows the percentage of the public in favor, and the bars show the percentage opposed.

The NRC has done little research on how to manage accidents, although that may more properly be an area for the Federal Emergency Management Agency to handle.

Department of Energy. The NRC has been precluded from doing safety reviews of Department of Energy (DOE) reactors, although DOE does informally submit its military reactors for NRC review. The General Accounting Office criticized DOE safety review procedures (*22*). In addition DOE asked the National Academy of Sciences to review the DOE reactors and requested a group of outside experts to recommend actions with respect to the Hanford graphite-core N-reactor. Since receipt of the N-reactor recommendations, DOE has shut down the reactor for 6 months to make several safety improvements (*23*). As a result of these reviews and of the congressional oversight hearings that will probably follow, the NRC will most likely be required to review the DOE reactors. Congress will be able to legislate this requirement, particularly if the NRC reviews are exempted from the Administrative Procedures Act, which would exclude intervention by outside groups.

Industry. U.S. vendors have stopped designing reactors for the domestic market. Westinghouse and General Electric have joint ventures with Japan to design advanced LWRs for sale in Japan. Obviously, these companies would hope to sell in the United States also. On the basis of the expected increased use of electricity and problems with burning fossil fuel, nuclear vendors have been hopeful of finding new orders within the United States. However, that is not going to happen for at least 5 to 10 years. Transfer of power across utility systems (wheeling), new transmission grids, access to power in Canada, a continued decrease in energy per capita consumption in the United States, and a stagnant economy will lead to a continuation of the moratorium on new nuclear power plants.

In addition, I believe that another effect of the Chernobyl accident will be to eliminate all conventional light water designs for future use in the United States. Efforts to design a safer reactor will be accelerated. I avoid such terms as "inherently safe," that sound like "cannot have an accident." However, there will be much greater interest in designs that have greater simplicity and controllability.

Public. "Nuclear power in the United States has a fatal flaw: it cannot get public acceptance. The system evolving public policy in the United States leads to eventual support for programs which do get public acceptance and for final disavowal of those that cannot" (*24*, p. 84).

Since 1975, a Harris poll has asked, "In general, do you favor or oppose the building of more nuclear power plants in the United States?" After the accident at TMI, the percentage of respondents opposed jumped and then leveled off. This new plateau brought the opponents of nuclear power to more than 40% (*25*). According to a Gallup poll, 73% of Americans polled after the Chernobyl accident said they would oppose construction of nuclear power plants within 5 miles (8 km) of where they live. This is more than 10% higher than a similar poll taken in 1979 (*26*).

Figure 5 shows a summary of responses to several polls from 1976 to 1986 (*27*). Although opposition rose after both TMI and Chernobyl, there has been a steadily increasing disavowal of nuclear power in the United States. A few years ago I concluded (*28*, p. 382): "To recover in the United States, the nuclear industry needs the following: (a) energy demand, that is, a growing economy that in spite of conservation and new technologies still needs more electrical energy; (b) a solution to the waste-management problem, that is, an actual location and repository under construction; (c) no major accidents; and (d) competent management."

Today, the demand for electrical energy grows. However, at present there is no solution to the waste management problem in terms of location of a repository. A major accident has occurred at Chernobyl. In addition, sweeping moves to improve the competence of management are not evident (*29*).

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8. This accident had actually happened in January 1980, when there was a full loss of power at the Kursk nuclear power station (*6*, part II, annex 2, p. 181).
9. H. Denton, T. Speis, B. Sheron, F. Congel, briefing to the U.S. Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards, Washington, DC, 12 September 1986.
10. Xenon is produced in the decay chain from tellurium, one of the direct products of ^{235}U fission:

$$^{135}\mathrm{Te} \xrightarrow{2\ \mathrm{minutes}} {}^{135}\mathrm{I} \xrightarrow{6.7\ \mathrm{hours}} {}^{135}\mathrm{Xe} \xrightarrow{9.2\ \mathrm{hours}} {}^{135}\mathrm{Cs} \xrightarrow{2\times 10^{4}\ \mathrm{years}} {}^{135}\mathrm{Ba}\ (\mathrm{stable})$$

While the reactor is operating, the amount of xenon reaches an equilibrium level, at which the rate of formation by fission product decay is equal to the rate of removal by decay and neutron capture. Once the reactor is shut down, xenon concentration builds up for a few hours and then falls off slowly.
11. This level was set by another feature of the RBMK: although the reactor has a positive void coefficient, the fuel temperature coefficient is negative. These two effects counteract each other. However, the net effect is positive below about 640 MW thermal. Thus, unlike U.S. reactors, the RBMK is a greater hazard at low power (*2*, p.4).
12. However, the INSAG report estimates 1000 MCi (*2*, p. 47).
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19. D. Fishlock, *Energy Daily* **14** (no. 176), 3 (12 September 1986); L. Scheinman, personal communication.
20. Plans have been announced for a nuclear plant to provide heat for the Black Sea port city of Odessa, which has a population of more than 1 million [V. Legasov, L. Feoktistov, I. Kuzmin, *Sov. Life* (February 1986), p. 15].
21. A similar view was expressed by INSAG in referring to the need for a safety display panel: ". . . an analysis of the Chernobyl event might possibly result in verification of the lessons learned from the Three Mile Island accident" (*2*, p. 99).
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27. Polls conducted by ABC and NBC News, Louis Harris, and the *Washington Post*. Data from W. Schneider [*Nat. J.* **18**, 1562 (21 June 1986)].
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30. I acknowledge with gratitude helpful discussions with R. Bernero, J. Hendrie, W. Kerr, H. Kouts, F. Remick, D. Rosenbaum, and T. Speis.