DOCKET NUMBER
PETITION RULE PRM 51-44 (1)
(51 FR 31341)

Washington
State University

Nuclear Radiation Center, Pullman, Washington 99164-1300 / 509-335-8641

DOCKETED USNRC

'86 SEP 22 P3:45

September 19, 1986

OFFICE OF SECRETARY
DOCKETING & SERVICE
BRANCH

Secretary
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Re: Docket PRM-50-44

Gentlemen:

I strongly oppose the proposed amendments to 10 CFR Pact 50 made by the Committee to bridge the gap in their petition of July 7, 1986. The recent conference held in Vienna, Austria on August 25 to 29 on the Chernobyl accident clearly indicates that the cause of the accident was due to "a prompt critical reactivity excursion and a steam explosion" not by a "graphite fire" (see attached article from the September 11, 1986 issue of Nuclear News). The main contributing factors were human error and the failure to follow prudent safety precautions and written operation procedures, not the presence of graphite in the reactor.

The proposed amendment would serve no useful purpose in decreasing the likelihood or mitigating the effects of a Chernobyl type accident. The Chernobyl accident in effect substantiates the NRC's position that a graphite fire caused by the Wigner effect in a small research reactor is a "non-credible" event. The imposition of unnecessary regulations and requirements upon research reactors will really decrease overall safety rather than increase safety. A diversion of effort on the part of the staff of a research reactor from managing the day to day operations of the facility and bona fide safety considerations to "non-credible" events lessens the attention given to "credible" events and increases the likelihood of human error precipitated events.

Notwithstanding, there are lessons to be learned from the Chernobyl accident, and changes in the NRC regulations in certain areas may well be advisable. The proposal by the Committee to bridge the gap, however, was obviously made prematurely before all the facts were revealed and consequently did not address the real problem but only a perceived problem.

Sincerely,

W. E. Wilson

W.E. Wilson
Associate Director

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add: John Philips, 4000 MNBB

Acknowledged by card SEP 26 1986

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nuclear news®
Special Report—Sept. 11, 1986

Helicopter inspecting the damaged plant (photo: *Soviet Life*)

Chernobyl: The Soviet report

From August 25 to 29, the International Atomic Energy Agency held a unique conference in its headquarters city of Vienna, Austria. The meeting was devoted entirely to the April accident at the Chernobyl-4 power reactor in the Soviet Union, and featured the presentation by Soviet officials of a large volume of information—surprisingly large, in the view of some attendees. NN European Editor Simon Rippon was present for the conference, and he covered both the Soviet revelations and the analyses of them by outside observers.

Why the experiment?

The Chernobyl-4 accident took place because of a variety of poorly conceived actions and procedures related to an experiment. This was one of many candid assertions made in a remarkable five-hour presentation on August 26 by Valery Aleksevich Legasov, head of the Soviet delegation to the conference. The Soviet disclosures may not have included enough technical detail or procedural justification to satisfy every conference attendee, but by Soviet standards the Legasov address was unusually informative and self-critical.

The experiment was intended to demonstrate that, in the event of turbogenerator disconnection along with loss of offsite power, the inertia of the turbine rotor could contribute to auxiliary electricity supplies during those vital seconds before the startup of standby diesel generators. This technique has been used in a number of countries to provide power to feedwater pumps and emergency core-cooling systems (ECCSs), and to relieve some of the wear and tear that a very rapid startup imposes on diesels.

It came as a surprise to some Western experts that the Soviets seemed also to be trying to supply the main circulation pumps from the rundown of the turbogenerator. The flywheels on these pumps are already designed to provide a longer coastdown until natural circulation can be established. The initial misunderstanding may have come from a mention of the connection of four of the main circulation pumps to the test generator and the other four to the grid. This connection, it seems, was used to maintain the reactor at power with cooling from four pumps during the turbogenerator rundown, thus allowing the test to be repeated quickly, if necessary, through the opening up and shutting off of the steam valves once again. The four pumps connected to the test turbogenerator would have been disconnected from that supply in the normal way when the steam valves were first shut off, leaving only the feedwater pumps drawing energy from the running-down turbine.

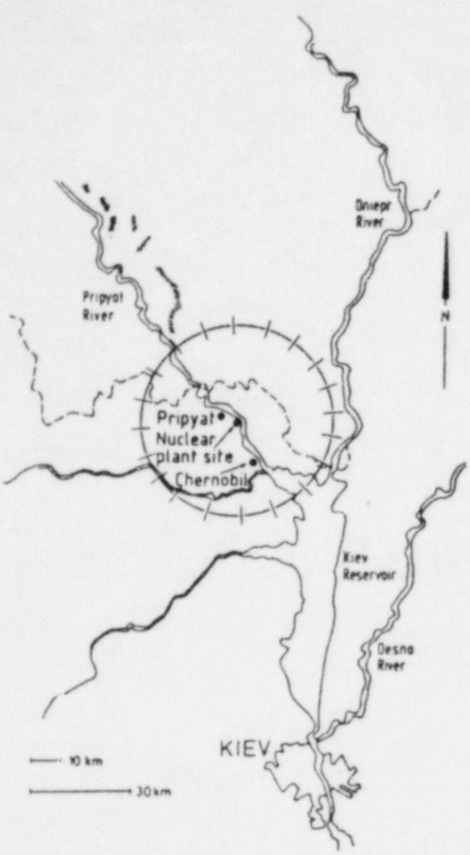
The meeting was also told that there had, in fact, been earlier tests of this kind at Chernobyl-4, in 1982 and 1984. In these tests the regulation of the field coils of the generator had allowed the voltage to fall off much more rapidly than the inertial energy of the turbine rotor. The latest test was intended to see if this could be overcome with a new voltage regulation system.

The human errors started here. Although there had been plenty of discussion of the justification of the experimental program in general, the specific test program is said by the official Soviet report—released a few days before the start of the conference (*NN*, Sept. 1986, p. 23)—to have been improperly prepared:

"The quality of the program was poor and the section on the safety measures was drafted in a purely formal way. (The safety section said merely that all switching operations carried out during the experiments were to have the permission of the plant shift foreman, that in the event of an emergency the staff were to act in accordance with plant instructions and that before the experiments were started the officer in charge—an electrical engineer, incidentally, who was not a specialist in reactor plants—would advise the security officer on duty accordingly.)"

The program made essentially no provision for additional safety measures, though it called for the deactivation of the ECCS, so that it would not trip in as the circulation pumps ran down. The procedures also placed extra demands on the auxiliary power supplies.

In reply to press questioning in Vienna, a representative of the Soviet delegation said that it was personnel of a



Map from Soviet report to IAEA

"commercial electro-technical" organization, Domtechenergo, that had asked for the tests on Chernobyl-4. Domtechenergo had, presumably, been responsible for the development of the new voltage regulation system that was being tested in the experiment.

The sequence of events

The detailed sequence of events leading up to the accident at Chernobyl-4 was presented by Legasov on the first afternoon of the accident review meeting in Vienna. He followed the written description fairly closely, but added one or two significant asides and comments. He noted, for example, that there would have been pressure on the operators to complete the tests as they shut down on this occasion, because the next planned maintenance period would be more than a year away. He also said that, in hindsight, it can be seen that technical means could easily have been used to prevent the operators from overriding safety protection systems and otherwise violating procedure. Failure to provide adequate protection for such human error represented "a tremendous psychological mistake" on the part of the designers of the RBMK reactor.

The run up to the accident started at 1 a.m. on April 25, with the reduction of reactor power over the next five minutes from 100 percent (3200 MWt) to half that much. Then the unwanted turbogenerator was shut down. The plant systems that had been connected to this turbogenerator, including four of the main circulation pumps and two feedwater pumps, were switched to the grid busbars of the turbogenerator that was still on line.

At 2 p.m., the ECCS was isolated to prevent it from kicking in automatically. The start of the test, however, was then postponed at the request of the local electricity dispatcher. As a result, the plant was maintained in the unauthorized state with no ECCS for the next nine hours, although this particular violation did not in actuality play any important part in what followed. Still, the delay may have aggravated operator impatience over the test, and contributed to the "mindset" that led plant personnel to ignore procedures and block safety systems in their effort to get the plant to the proper power level for the test.

At 11:10 p.m., the load demand was lifted, and preparation for the test resumed with power reduced to the required level, 700–1000 MWt. The automatic control system that operates on groups of control rods in 12 zones of the core, to stabilize power density distribution, was switched off, in keeping with a low-power operation requirement. At higher power levels, these zonal rods also regulate the average power automatically. When the local controllers are switched off, automatic controllers working on a signal of the average power of the whole core come into play, but it appears that the operators did not synchronize this automatic system quickly enough to the required power setpoint. There was an overshoot in the power reduction, and the level fell below 30 MWt.

By 1 a.m. on April 26, the operators were able to stabilize the power back at 200 MWt, but this was as high as they could get it due to the xenon poison buildup that had started during the excursion to lower power and was still continuing. To drag the reactor up to 200 MWt, the operators had pulled far too many of the manual control rods out of the reactor, and the neutron flux distribution in the core was such that the reactivity worth of those rods that would be effective in the first few centimetres of travel back into the core was limited to the equivalent of six to eight fully inserted rods.

According to the rules, this operating margin of reactivity should not be allowed to go below 30 rod equivalents without special authorization from the chief engineer of the power station. Legasov said that if the margin ever falls below 15 rod equivalents, "nobody in the whole world—not even the Prime Minister—can authorize continued operation of the reactor." But the operators were so intent on getting the reactor up to an acceptable power level for the test—another attitude attributed to the mindset—that they ignored the touchy state of the reactor.

Thus, the operators at Chernobyl-4 decided to press on, and at 1:03 and 1:07 a.m., they started the sixth and seventh main circulation pumps in immediate preparation for the tests. Since the reactor power, and consequently the hydraulic resistance of the core and the recirculation circuit, were substantially lower than planned, the full eight pumps produced a massive coolant flow through the reactor, 56 000 to 58 000 m^3/hr. At some individual pumps, the flow was up to 8000 m^3/hr, compared with a normal operating level of 7000 m^3/hr. This was another violation, because of the danger that pump breakdown and vibration could be caused by cavitation at the pumps. But the most serious consequence of the increased flow was the creation of coolant conditions very close to saturation, with the possibility that a small temperature increase could cause extensive flashing to steam. The steam pressure and the water level in the steam separation drums had also dropped below emergency levels—but, as part of the continuing attempt to keep the reactor running long enough for the test to be started, the operators also blocked the resulting signals of the low levels to the emergency protection system.

At 1:19 a.m., the feedwater supply was increased—to as much as four times its initial value—in an attempt to restore the water level in the steam separation drums. This reduced both the reactor coolant inlet temperature and fuel channel steam production, with consequent negative reactivity effects. Within 30 seconds the automatic control rods had fully withdrawn in response to the negative reactivity, and the operators attempted to withdraw the manual rods as well. But the operators again overcompensated, and the automatic rods began to move back in.

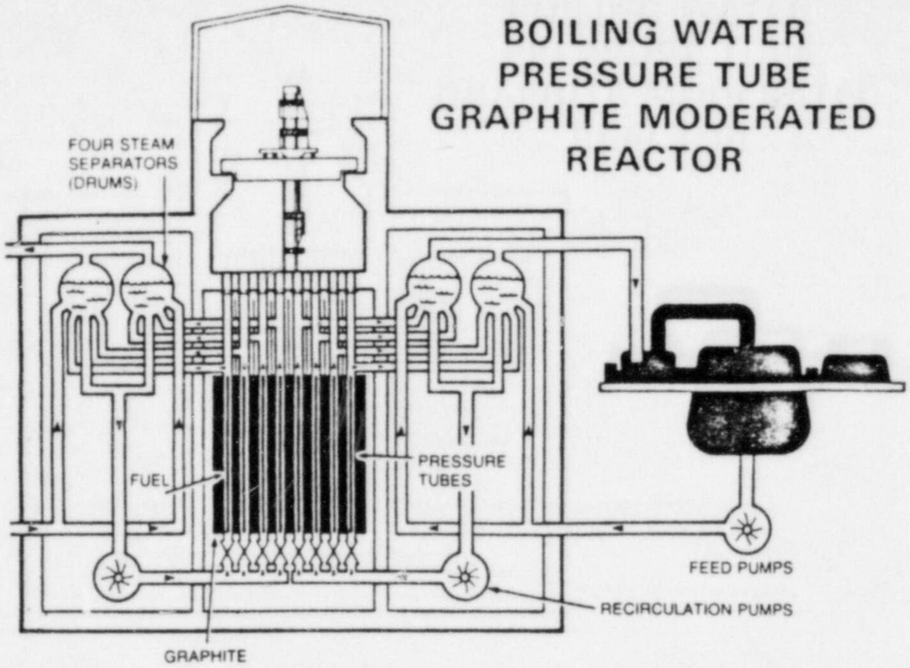
Soviet delegation leader Legasov (photo: AP Wide World Photos)

At 1:22 a.m., the reactor parameters were approximately stable, and the decision was made to start the actual turbine test. But in case they wanted to repeat the test again quickly, the operators blocked the emergency protection signals from the turbine stop valve, which they were about to close, so that it would not trip the reactor. Also, just before they shut off the steam to the turbine, they sharply reduced the feedwater flow back to the initial level required for the test conditions. This boosted the coolant inlet temperature, creating a transient situation that could not be addressed because safety systems were cut off.

At 1:22:30 a.m., the operators obtained a printout from the fast reactivity evaluation program, giving them the position of all the rods and showing that the operating reactivity margin had fallen to a level that required immediate shutdown of the reactor. But they delayed long enough to start the test. There was clearly a failure to appreciate the basic reactor physics of the system, which had rendered the control rods relatively worthless. The neutron flux distribution in the core had been pulled into such a distorted shape that the majority of the rods would have to go well into the core before they would encounter sufficient neutron flux for their absorption to be effective.

At 1:23:04 a.m., the turbine stop valve was closed. With the isolation of the turbine, four of the primary circulation pumps started to run down—another transient situation for which the automatic responses had been cut off.

Shortly after the beginning of the test, the reactor power began to rise sharply. The bulk of the coolant was very close to the saturation point at which it would flash to steam, because the operators had earlier run an excessive level of coolant flow with all eight pumps on during low-power reactor operation. The RBMK reactor, with its positive void coefficient, responds to any such formation of steam with an increase in reactivity and power, and further increases in temperature and steam production—producing a runaway condition.



Schematic diagram of the RBMK-1000, a heterogeneous water-graphite channel-type reactor (source: Soviet report to IAEA)

At 1:23:40 a.m., the scram button—which would drive all control rods into the core—was pushed. Legasov told the Vienna meeting that there seemed to be some ambiguity about the motivation for this action, as unearthed during subsequent questioning by investigators of the fatally ill shift foreman, who had given the order—he may have been belatedly responding to the printout of reactivity margin; he could have been responding to the sharp rise in reactor power; or he may simply have believed that the test had now run long enough to allow him to shut down the reactor.

After a few seconds a number of shocks were felt in the control room, and the operator saw that the control rods had not reached their lower stops. He therefore deactivated the rods to let them fall by gravity.

At about 1:24 a.m., observers outside the plant reported two explosions, one after the other; burning lumps of material and sparks shot into the air above the reactor and some fell onto the roof of the turbine hall and started a fire.

In his presentation of Table I, which delineates the operator violations, at the Vienna meeting, Legasov said that if any one of the first five violations had not been committed, the accident would not have happened.

Inside the reactor

The mechanism of the accident, particularly in the last few seconds before the explosion that literally blew the top off the reactor, was the subject of intense interest for one of the working groups at the meeting. By the end of the week, the consensus of international experts was that the accident mechanism as described in the Soviet report—a prompt critical reactivity excursion and a steam explosion—was a wholly plausible explanation for what happened. There is still a need for more detailed understanding of the mechanism, and some doubts linger on the cause of a second explosion that was reported to have taken place three or four seconds after the first.

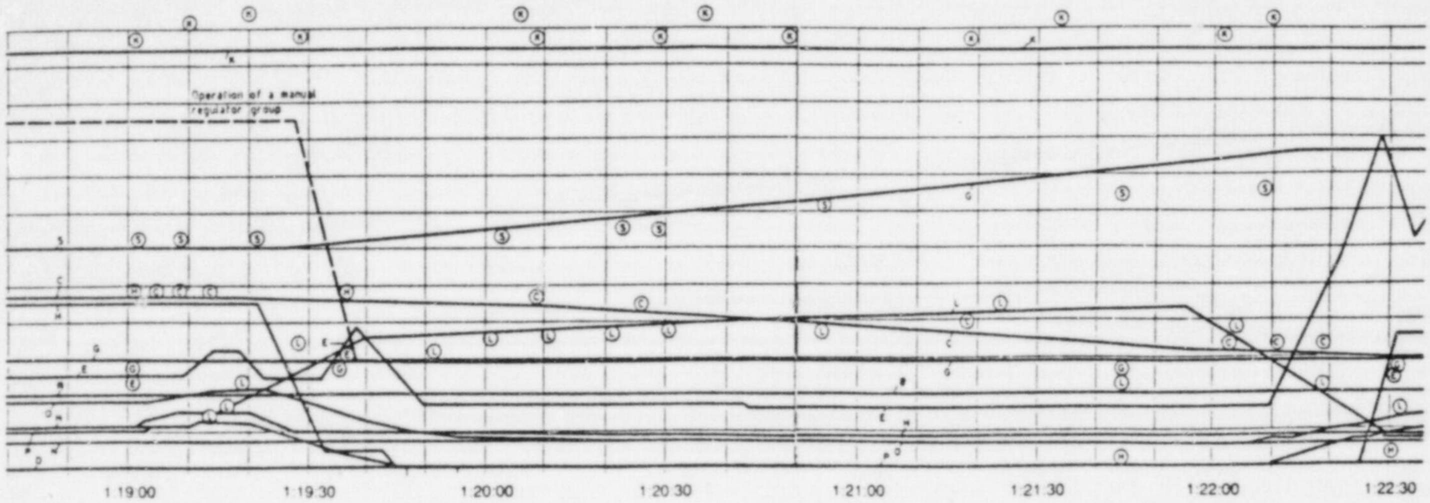
The Soviet analysis is based mainly on computer modeling of the reactor conditions starting from 1:19 a.m., some four minutes before the accident (see chart, next page). This was the point at which the operators started to introduce a significant perturbation on the reactor system by increasing the feedwater flow to restore the water level in the steam separator drums. The data-logging sys-

TABLE I
THE MOST DANGEROUS VIOLATIONS OF OPERATING PROCEDURES AT CHERNOBYL-4*

Violation	Motivation	Consequence
1 Reducing operational reactivity margin below permissible limit	Attempt to overcome xenon poisoning	Emergency protection system was ineffective
2 Power level below that specified in test program	Error in switching off local auto-control	Reactor difficult to control
3 All circulating pumps on with some exceeding authorized discharge	Meeting test requirements	Coolant temperature close to saturation
4 Blocking shutdown signal from both turbogenerators	To be able to repeat tests if necessary	Loss of automatic shutdown possibility
5 Blocking water level and steam pressure trips from drum-separator	To perform test despite unstable reactor	Protection system based on heat parameters lost
6 Switching off emergency core cooling system	To avoid spurious triggering of ECCS	Loss of possibility to reduce scale of accident

*From the Soviet Union summary of its report to the IAEA.

Modeling of the Chernobyl accident



Notes: Vertical lines on chart represent 10-second intervals from 1:19:00 to 1:23:30. At that point, the vertical lines begin representing one-second intervals. At 1:23:43, the neutron power curve switches from A to D, with a change in the vertical scale (see legend).

Parameter	Scale (Min.)	Scale (Max.)
A Neutron power, low range (%)	0	120
B Reactivity, sum (%)	−1	+5
C Steam drum pressure (bar)	54	90
D Neutron power, high range (%)	0	480
E Auto-rod, group 1 (fraction in)	0	1.2
G Auto-rod, group 2 (fraction in)	0	1.2
H Auto-rod, group 3 (fraction in)	0	1.2

Parameter	Scale (Min.)	Scale (Max.)
K Main circulation flow (m^3/h)	2	8
L Feedwater flow (kg/s)	0	600
M Steam flow (kg/s)	0	600
N Fuel temperature (°C)	200	2000
O Mass steam quality (%)	0	6
P Volumetric steam quality (void fraction)	0	1.2
S Steam drum water level (mm)	−1200	0

tem had also recorded the position of all three sets of automatic control rods at this time, providing a good reference point for the modeled curves.

Actual measurements from the data-logging system, and information gleaned from the questioning of operators, are indicated on the chart (with corresponding letters in circles) with the curves obtained from the computer model, and they all seem to tie in fairly well. Unfortunately, there were relatively few reactor measurements from the data-logger because much of its capacity had been switched to record information relevant to the turbine rundown test.

As the feedwater flow was increased (curve L, 1:19 to 1:22), the water level in the steam separator drums was restored (curve S), and the steam pressure decreased (curve C). As the colder water from the drums reached the reactor core, the steam generation in the fuel channels probably decreased, and the steam quality went down (curves O and P). Responding to the negative reactivity that this would have introduced, the automatic control rods withdrew (curves E, G, and H move down, indicating less absorber in the core). It is believed that the operators, in their attempt to maintain the power at 200 MWt, attempted to "help" the automatic rods with manual rods (dotted curve, 1:19:30) and further reduced the reactivity margin.

As the feedwater flow was cut back at 1:22, a minute before the start of the actual turbine rundown test, the steam quality in the fuel channels increased again, and the automatic rods started to reinsert (curves E and H) and managed to compensate for the resulting reactivity transient.

A detailed printout of power density distribution and rod positions at 1:22:30 has provided a picture of the neutronic state of the reactor core at this point in time. It indicates that in the radial-azimuthal direction, the neutron flux for all practical purposes showed a smooth convex shape, but that in the vertical direction, the curves showed a double hump, with a greater release of energy in the upper part of the core. This neutron distribution is consistent with a burned-out core, practically all rods withdrawn, volumetric steam quality in the upper part of the core much greater than lower down, and greater xenon poisoning in the central region than in the periphery. The reactor would have been in an unusual and impermissible state, with the excess reactivity worth equivalent to only six to eight rods.

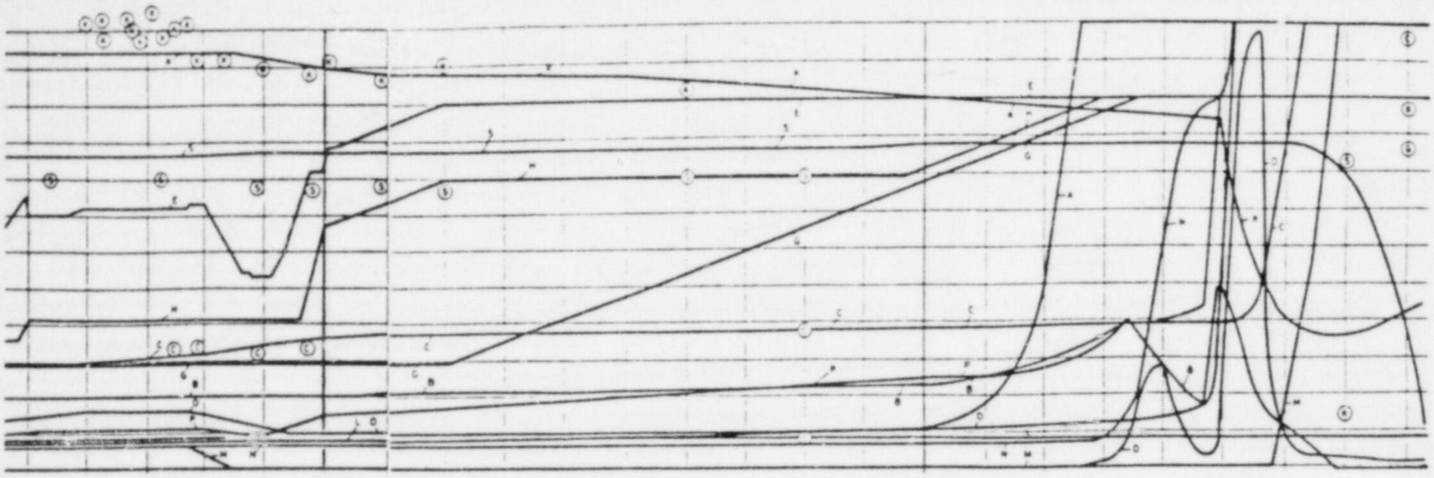
But at 1:23, the reactor parameters would have appeared to be closer to stable than they had been for some time. At 1:23:04, the turbine stop valve was closed for the start of the test. A reduction in total coolant flow occurred (curve K, 1:23:12) as the four main circulation pumps that had been connected to the test turbogenerator started to run down. This, together with the earlier reduction of feedwater flow, would have allowed increased steam production in the fuel channels (curve P) despite competition from increasing steam pressure in the drums (curve K). The condition of the reactor was such that a small increase in power increased the volumetric steam quality much more than it would at normal power, and resulted in a large positive reactivity insertion.

After 1:23:31, the volumetric steam quality (curve P), reactivity (curve B), and neutron power (curve A) all began to increase. At 1:23:40, the scram button was pressed, but the automatic rods were already inserted, and the reactor power was on the brink of taking off. (On the chart, the neutron power curve switches from A to D at 1:23:43, with a change in the vertical scale.)

The prompt critical excursion took the power first to around 530 MWt at 1:23:40, and only the Doppler effect of the fuel heating up to an estimated 3000 °C pulled it back down briefly. The continuing reduction of water flow through the fuel channels during the power excursion led to intensive steam production, the destruction of the fuel, a rapid surge of coolant boiling (with the particles of destroyed fuel entering the boiling water), a rapid and destructive increase of pressure in the fuel channels, and finally the explosion that destroyed the reactor.

A second power excursion at 1:23:45, to more than 1000 MWt, is represented

Modeling of the Chernobyl accident



in the computer modeling by redistribution of the disintegrating fuel in the boiling water and graphite moderator.

At precisely the moment of fuel disruption, which was simulated in the model when the power density in the fuel exceeded 1260 J/g, there was an abrupt fall of the coolant flow (curve K) as check valves on the main circulation pumps closed in response to the increased pressure in the core. This loss of flow was also recorded by the data-logging system. The flow from the pumps would have been partially restored after the rupture of the fuel channels, but the water was now directed into a mass of damaged zirconium and hot graphite. The ensuing reaction would have produced large amounts of hydrogen and carbon monoxide, which—upon contact with air above the reactor—could have caused the second explosion.

RBMK modifications

One of the most sensitive issues for both Soviet and Western experts was the extent to which design features had contributed to the accident. The Soviets, while stressing the overabundance of human errors, were relatively frank about the few identifiable design weaknesses—if only to assert that forthcoming modifications are sufficient to allow continued operation of other RBMKs. Experts from other countries sought to substantiate the claims that many of them had made prior to the meeting, to the effect that such an accident could not happen in their reactors because of fundamental design differences from the RBMK.

One of the design flaws specifically referred to by Legasov in his opening remarks was the lack of automatic systems to prevent the operators' violations. He compared the situation to that of an aircraft designer considering it unnecessary to provide automatic locks to stop a pilot from testing the doors during flight, because nobody could imagine that a pilot would be stupid enough to try. He suggested that the Soviet Union had recognized somewhat later than other countries the need to protect against this kind of human fallibility.

On the specific question of the most serious violation—the operation of the reactor far below the authorized limit for reactivity margin—Legasov said that an automatic system to prevent this had been considered at the early design stage. But at that time such a system, which would rely on a fairly complex calculation of the power distribution in the core and the reactivity worth of all the reactor control rods, was not considered to be sufficiently reliable to incorporate as an automatic shutdown system.

Since the triggering event of the Chernobyl accident was a prompt critical reactivity excursion, a great deal of the criticism of the design centers on the subject of reactor physics—although if one listens to many of the experts trying to explain the situation, one can sympathize somewhat with the operators accused of having an inadequate understanding of their reactor. The positive void coefficient of the light-water coolant in the fuel channels is clearly the most significant characteristic of this reactor, though in itself this does not make the reactor impossible to control as long as there is an adequate number of effective control rods. The large size of the reactor, with low-enrichment fuel and highly efficient graphite moderator, also tends to lead to a system that is subject to local power instabilities. These can be controlled, subject to a system of automatic regulation coupled to good instrumentation. But at low power, the instabilities are more apparent, and the instrumentation is less effective.

To understand why the withdrawal of too many rods can be a dangerous situation in the RBMK—even though the situation appears to be a relatively safe one because more rods are available to be dropped in—one must consider the role of lost neutrons in the chain reaction balance equation. The description of the RBMK reactor as one with a high neutron efficiency means that the losses of neutrons by leakage from the very large core, and by absorption in the various materials within the core, are relatively small. Under these circumstances, the light-water coolant becomes one of the more significant absorbers in the core, and any reduction caused by boiling will have a significant positive effect on the neutron multiplication. If, on the other hand, a great many control rods are still partially inserted, the removal of some water becomes less significant.

Among the immediate measures being taken on other RBMK reactors is a lock on the rod drive mechanism that ensures at least 1.2 m of insertion into the core. Also, the authorized minimum operating margin of reactivity has been increased from 30 rod equivalents to 80. This means that in their first second of insertion, the available rods must have a reactivity effect—sometimes referred to as reactivity bite—equivalent to the full insertion of 80 rods.

Modifications proposed for the slightly longer term include the installation of more control rods and the provision of a diverse rapid shutdown system that would use some form of fluid injection. The absence of a diverse shutdown system is the RBMK aspect that was perhaps the most criticized by specialists from other countries, particularly those from Canada, who pointed out that they learned the lessons about the need for such a system after the criticality accident at the NRX research reactor at Chalk River back in the 1950s.

Another change designed to help overcome the positive void coefficient is the introduction of fuel with an enrichment of 2.5 percent instead of 2 percent. It was stated that this change-over will begin next year, but will take some time to be fully effective, since fuel is changed on-load over a period of years. Higher enrichment fuel has been developed for the larger design of RBMK, which gets an output of 1500 MWe from a reactor of the same size as the 1000-MWe units at Chernobyl. The apparent contradiction of improving the situation by putting more fissile material into the core is, according to one knowledgeable reactor physicist, also related to a greater proportion of non-water atoms capturing neutrons in the critical balance equation.

Another RBMK feature that has come in for criticism from abroad is the high temperature of the graphite moderator during normal operation—but it is not yet certain that this contributed significantly to the severity of the Chernobyl accident. At a temperature of 700–750 °C, the graphite represents a significant source of heat in an RBMK reactor, compared to other graphite-moderated and heavy-water reactors, where the moderator acts as a large heat sink. During the low-power operation of the Chernobyl-4 reactor just prior to the accident, it is also likely that the nitrogen-helium gas mixture, which is used for partial cooling of the graphite, would have been changed to pure nitrogen, which has poorer heat removal properties. This would have placed additional reliance on the coolant in the fuel channels to remove heat from the graphite, and may have weakened the transition joints between the zirconium alloy and stainless steel at the tops of the fuel channels, in the area where they were ruptured by the initial steam explosion.

On the vexing question of containment, the Soviets asserted that much of the plant, in the strong-box compartments that formed the containment for the design basis loss-of-coolant accident, appeared (in the available video pictures) to be still intact. With a design pressure of 4.5 atmospheres (0.45 MPa), these compartments are capable of providing a high degree of protection of the primary circuit components and pipe work. To prevent radionuclide escape into the area above the reactor, the design relies on the huge volume of the building that houses the fueling machine and spent-fuel storage pool to provide pressure reduction and containment. It goes without saying that the steam explosion in the Chernobyl-4 reactor was beyond the design basis accident. The Soviet specialists maintain, however, that there was, and still is, no practical possibility of providing an all-embracing pressure containment building of the light-water reactor type over the top of this very large reactor. Instead, the Soviets try to ensure that an accident beyond the design basis cannot occur.

Asked at press briefings if an LWR containment could withstand a similar steam explosion, the first response of Western specialists was that there was no possible mechanism in their reactors for a prompt critical reaction that could produce fuel-coolant interaction similar to that which appears to have taken place at Chernobyl-4. The only scenarios for possible steam explosions involve core meltdown and melt-through, with a significant time delay and thus much less severe release consequences if a steam explosion were to occur. But on the question of whether an explosion of comparable energy to that at Chernobyl-4 would breach their containments, the general view was that it might cause cracking and some openings, but would not completely destroy the structure, which would still have some effectiveness in reducing radioactive releases.

Inevitably, there was much talk in Vienna of the need to "improve the man-machine interface." The Soviet specialists seemed to acknowledge that they have lagged behind the West in this area. They also accepted the need for improved training and retraining of operators, with greater use of simulators. But, scoring a rather perverse point, they noted that the excellent routine performance of their plants to date was one of the reasons why the operators at Chernobyl were ill-equipped to deal with an abnormal condition. The fact that the Chernobyl-4 unit had been the top-ranked reactor in the performance figures of Soviet plants was also cited as a possible cause of complacency on the part of the operators.

Accident consequences

The damage to Chernobyl-4 was shown in a screening of the video pictures taken mainly from helicopters on the second day after the explosions. These included two brief glimpses of the red glow of the core seen through the debris above the reactor. There has obviously been some editing of these pictures, since the IAEA visitors to Chernobyl in May were apparently shown much longer shots of the glowing core. But the remaining video, and Soviet descriptions of the damage, were enough for the working group on accident damage to determine that the whole of the top plate of the reactor had been lifted off by the explosion and deposited at an angle to one side of the reactor. In the process, all of the fuel and control rod channels—roughly 2000 in total—had been ripped open.

The working group agreed that the power excursion and steam explosion could have produced the necessary energy. The energy release calculated by the French delegation was on the order of 200 MJ, generating a pressure of some tens of atmospheres under the top plate. Rough calculations also indicated that it would only have taken about two atmospheres to lift the plate.

For some observers, the severing of the fuel channels pointed up a weakness in the RBMK design. With the graphite hotter than 700 °C during normal operation, and dependent on the coolant channels for heat removal, the Zircaloy pressure tubes could easily be subjected to a temperature at which they would rupture readily, especially in the region of the transition joint to stainless steel just above the reactor.

The fire on the roof of the turbine hall was the most immediate cause for concern for firefighters. The hot lubricating oil in the turbines and the hydrogen coolant for the generators were vulnerable, giving rise to fear that the fire could spread to the adjacent Chernobyl-3 unit and even to Units 1 and 2, which share the same long turbine hall. The fires above the reactor were dealt with mainly

Spraying water on streets in towns and villages near Chernobyl (photo: *Soviet Life*) with fire extinguishers and installed fire hydrants. All of these fires were extinguished by 5 a.m. on the morning of April 26. Only then was the adjoining Chernobyl-3 reactor shut down. This revelation came as a surprise to some delegates; so did the Soviets' statement that the other two units were not shut down until the following day. The Soviets said that this was an indication of how the damage had been confined to the one unit.

The video of the damaged reactor included some shots of components in the equipment vaults around the reactor, and indicated that, at the lower levels, much of this equipment had survived almost intact. On one side of the reactor, the cells containing four of the main circulation pumps were intact; on the other side, away from the added partial support of the turbine building wall, the other four circulation pumps were visible standing out of the rubble.

It is estimated that about 3.5 percent of the fuel material was ejected from the core, and that some 10 percent of the graphite was ejected or ignited. Much of the fuel (0.3–0.5 percent) was deposited as heavy particulate matter, some tens of microns in size, around the site. A further 1.5–2 percent was distributed over a 20-km zone, while 1–1.5 percent was distributed as small particulates, down to micron size, over the rest of the 30-km evacuation zone.

The initial large release from the reactor fortunately missed the nearby town of Pripyat, but caused considerable contamination of the forested areas through which evacuation routes had to be planned. This was the reason given by Legasov for the apparent delay in evacuation, which had drawn some criticism from outside observers. Once safe evacuation routes were established, said Legasov, the evacuation was carried out with what was termed remarkable efficiency, in 2.5 hours with a fleet of 1000 buses.

TABLE II
ESTIMATED RELEASE OF RADIONUCLIDES FROM THE CHERNOBYL ACCIDENT*

Nuclide	Released activity (MCi) by May 6	Released (percentage) by May 6
Xe-133	45	up to 100
Kr-85m	—	up to 100
Kr-85	0.9	up to 100
I-131	7.3	20
Te-132	1.3	15
Cs-134	0.5	10
Cs-137	1	13
Mo-99	3	2.3
Zr-95	3.8	3.2
Ru-103	3.2	2.9
Ru-106	1.6	2.9
Ba-140	4.3	5.6
Ce-141	2.8	2.3
Ce-144	2.4	2.8
Pu-238	0.8E-3	3.0
Pu-239	0.7E-3	3.0
Pu-240	1E-3	3.0
Pu-241	0.14	3.0
Pu-242	2E-6	3.0
Cm-242	2.1E-2	3.0
Sr-89	2.2	4.0
Sr-90	0.22	4.0
Np-239	1.2	3.2

*Estimated error ±50%

The pattern of radioactive release (see Table II), calculated on May 6 with allowance for decay of short-lived material, obviously started very high on the first day (amounting to 12 MCi), then fell to 2 MCi on days four and five, and then rose rather alarmingly to 7 and 8 MCi on days eight and nine before falling off sharply. The increase on days eight and nine was attributed to a rise of temperature in the core as various materials were dropped on top of the damaged reactor to seal it off. The release fell off again as some nitrogen gas cooling of the core was established and as the sealing became effective.

Cover-up operation

Reports of helicopters dropping a variety of materials onto the burning reactor sounded like a fairly desperate effort to cover it with anything at hand. The Soviets maintained in Vienna, however, that it was a rather more carefully thought-out operation.

Immediately after the accident, attempts were made to get some cooling water into the damaged core via the emergency auxiliary feedwater pumps, but this proved unsuccessful. Considered next were covering of the open reactor vault or allowing the fire to burn itself out. The former was adopted for the fairly obvious reason of trying to limit radioactive releases, but it raised the problem of fuel heatup and the remote possibility of some fuel melting into masses that might go re-critical.

The first thing dropped on the core was some 40 tons of boron carbide, to reduce the possibility of re-criticality. This was followed by 800 tons of dolomite (limestone), to absorb heat as it decomposed and also to release carbon dioxide to help extinguish the graphite fire. Next there came 2400 tons of lead, also to absorb heat as it melted but additionally to run down through the core, if possible. It was also hoped that the lead would build up some shielding against gamma radiation, not the least for the benefit of the helicopter pilots. The covering was completed with large quantities of sand and clay, both to smother the graphite fire and to filter escaping fission products.

The covering did indeed heat up the fuel and increase releases of radioactivity until it was possible to establish cooling by pumping nitrogen gas—from a compressor station on the site—into the space below the reactor vault. By May 6, the temperature was stabilized, and the release of radioactivity fell to a low level.

Spraying buildings with decontaminant (photo: *Soviet Life*)

With a loading of something like 5000 tons from the covering on top of the reactor, and with the possibility of continuing high temperatures, there was real concern for the supporting structures of the reactor. The Soviets stated that it was this fear, rather than the speculation about the danger of core melting, that led to an urgent decision to construct a large slab of concrete below the reactor. This has a heat exchanger on top of it and is described in the Soviet report as an "artificial heat-removal horizon." Because of the high radiation doses still prevailing around the reactor, the concrete was pumped in through tunnels dug to the basement of the reactor.

The next stage will be to build some sort of entombment around the whole of the damaged reactor. Work is already under way on the construction of walls, particularly between Unit 3 and the damaged reactor, and the long-range plan calls for all of the debris to be roofed over. The Soviets have not finished the detailed design of the entombment, and seemed eager in Vienna to get views from other countries, especially on the relative merits of a natural circulation open cycle cooling scheme versus some form of closed cycle cooling.

Radiation effects

As of late August, 31 people had died as a result of the Chernobyl-4 accident. All of these were operating personnel, firefighters, and emergency workers who had dealt with the immediate consequences of the accident. Apart from two people killed at once, one from steam burns and one from falling debris, all the deaths have occurred among the 203 people hospitalized with acute radiation sickness (others were hospitalized with less severe symptoms). Medical specialists from other countries praised the speed with which expert medical teams reached the site and the efficiency with which the severe cases were selected.

Biodosimetry on the 203 severe cases has revealed that they all received doses in excess of 1 Gy (100 rads), with 35 receiving more than 4 Gy and a few exposed to extreme doses of 12–16 Gy. All the deaths thus far have been among those who received more than 4 Gy.

A mass of invaluable information has been provided by the Soviet doctors on the treatment of the victims, which, again, was judged by other experts to have been excellent. There was praise for the good conventional medicine applied to the majority of the victims, as opposed to the much-publicized bone marrow transplants, which were applicable only for cases within a small band of radiation dose and which were largely unsuccessful.

Nobody beyond the bounds of the Chernobyl site is reported to have suffered any symptoms of direct radiation sickness. The majority of the 135 000 people in the 30-km evacuation zone, including the 45 000 from the town of Pripyat, received external radiation doses of less than 25 rem from the radioactive cloud. A few people living in villages situated in the most contaminated areas may have received between 30 and 40 rem. These external doses are estimated to account for a collective dose of 1.6 million person-rems. Taking account of the projected spontaneous cancer deaths for this population over the next 70 years—14 000 cases—the Soviet report suggests 2 percent as an upper limit of additional cases as a result of the accident.

A radiation checkpoint at the edge of the 30-km evacuation zone (photo: Sovfoto)

Building up the banks of the Pripyat river to prevent contamination (photo: *Soviet Life*)

The Soviets said that a highly efficient operation employing youth volunteers ensured the widespread distribution and use of potassium iodide tablets in the town of Pripyat and some surrounding areas. This has provided the first large-scale test of this technique for blocking iodine doses to the thyroid. The first reported indications are that the technique has proved effective and that there have been no undesirable side effects. Measurements indicate that the majority of the people in this area would have received a thyroid dose of less than 30 rads. In the period after the accident, a large number of the population from the evacuated zone and beyond, including almost 100 000 children, were checked for radioiodine in their thyroids. The measurements were reported to have shown levels significantly below those that could cause any health effects.

Outside the 30-km evacuation zone direct radiation measurements of several times natural background of 0.008–0.012 mR/hr were recorded, and in Kiev, levels peaked at 1 mR/hr before falling off slowly. The averaging of the radiation measurements for the whole of the population of the European part of the Soviet Union outside the 30-km evacuation zone gives values of individual doses of external radiation that do not exceed 1.5 rem for 1986, nor 50 rems for the next 50 years. The Soviet report therefore concluded that there is no health danger to this population as a result of the external radiation from the Chernobyl cloud.

The question of doses from the fallout of radioactive material, both external gamma radiation from the ground and internal doses from consumption of contaminated food, is much more complicated. The Soviet report has attempted to produce highly conservative figures using maximized assumptions at all stages to obtain a quick assessment of whether any special medical provisions need to be made for the regions of the Ukraine and Byelorussia, where some 10 percent of the activity released from Chernobyl is estimated to have fallen out. For the external radiation from this fallout, the upper limits of the collective doses are put at 8.6 million person-rems for 1986 and 29 million person-rems for a period of 50 years.

On the still more difficult question of estimating the internal doses from consumption of food contaminated with cesium, a figure of 210 million person-rems for the next 70 years has been produced—but discussion in the working party at Vienna concluded that, in their attempt to produce the most pessimistic estimate, the Soviets may have overestimated by a factor of 10. Some support for this view came from whole-body measurements that have already been carried out on about 1000 people from the region. Of these, 97 percent showed levels that were 10 times lower than the expectation based on the pessimistic assumption of cesium ingestion. The Soviet report stated that on the basis of its maximized figures, the cancer mortality rates in the Ukraine and Byelorussia may be increased by no more than than 0.05 percent as a result of the external radiation, and less than 0.4 percent as a result of the internal radiation.

This report was prepared principally by European Editor Simon Rippon, with contributions from E. Michael Blake, Jon Payne, and others on the NUCLEAR NEWS *staff.*