opment in the United States and will again lead to large levels of oil imports. The U.S. resource base is capable of precluding such imports, but in the face of deliberate attempts to diminish it, that capability will be largely foregone unless, in the national interest, appropriate support is provided.

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A Visit to Chernobyl

RICHARD WILSON

Details of the accident at the Chernobyl nuclear power plant were given by Soviet experts at a special International Atomic Energy Agency meeting in Vienna, Austria, in August 1986. Several unanswered questions were made much clearer by a visit to the decontaminated and operating power plant at Chernobyl and by discussions with Soviet scientists. The visit gives us insights into the way the Soviets design their technology, the consequences of the accident, and the magnificent way they coped with the disaster. Although there are general conclusions to be drawn for the rest of the world, such as the realization that operators of technological systems can and will deliberately cut out safety systems, the primary specific conclusion is to be grateful that the West did not follow the Soviet route in its development of nuclear power.

IN FEBRUARY 1987, I WAS PRIVILEGED TO VISIT THE V. I. Lenin power plant near Chernobyl in the Ukraine. I carried my own camera and Geiger counter. Immediately after the accident in April 1986, I studied in detail the Russian papers and reports of the accident. I went to the "Post Accident Review Meeting" in Vienna, Austria, in August 1986, where the Soviets described in detail the reactor, the accident, the consequences, and the cleanup in progress at that time (*1*). But at Vienna there were many unanswered questions.

During and before my visit, I also had the opportunity to ask questions of those persons responsible for the following aspects of the accident: advising on the evacuation (Academician L. Ilyin); the prompt medical care (Dr. A. Guskova); the reactor design (Academician Belyaev, Dr. Bulakov, Dr. Kusmin, and Dr. Prazenko of the Kurchatov Institute); the measurement of radioactivity release (Dr. V. F. Demin); the measurements of radioactivity in the environment (Professor Pavlowski of the Institute of Medical Physics); radioactivity in the nearby river (Dr. Khitrov of the Vernatsky Institute of Geophysics and Analytical Chemistry); Dr. Petrosyants, chairman of the State Committee of Atomic Energy; Academician Abagyan, director of the newly formed institute for research into the operation of nuclear power plants; Minister of Atomic Energy, Dr. N. F. Lukonin; Soviet leader Mikhail Gorbachev's adviser, Academician E. P. Velikhov; and many other scientists and individuals. Because of the compartmentalization of Soviet society, no one person could answer all my questions; indeed, there were disagreements about details. By talking to those persons directly responsible, a much clearer picture of the accident, its causes, and the Soviet response to it now emerges.

The Accident

As is well known, at 0123:48 on Saturday, 26 April, unit 4 of the four-reactor complex blew up as the core suffered a prompt critical excursion. The steam pressure as the reactor went to between 100 and 500 times full power (*2*) lifted a 1000-ton cover plate, turned it on its side (*3*), and ripped open the reactor, leaving the hot core exposed to the environment.

In the initial burst, a large amount of radioactive material was released, and more was released over the next 10 days. Dr. Demin estimated (*4*), on the basis of ground deposition and airplane measurements of activity in the plume, that about 3% of the heavy elements of the core were thrown out onto surrounding buildings and the countryside, as were about 13% of the more volatile cesium and 20% of the iodine. Western reports (*5*) suggest that the amount of iodine released was considerably greater than this estimate, probably about 50%. On the basis of the winds measured by satellite and the large initial rise of the radioactive plume, they estimate that much of the radioactivity in the initial burst went high over the countryside of Belorussia to be deposited in Europe, and that the Soviet estimates inadequately account for this. I discussed this issue with Dr. Demin, and although he believes that his estimates are correct within the stated 50% uncertainty, it is clear that the Soviets know less than we do about the initial burst and its composition. In order to deduce the amount released in the initial burst from the

The author is Mallinckrodt Professor of Physics in the Department of Physics, Harvard University, Cambridge, MA 02138.

comparatively small amount of iodine deposited inside the Soviet Union one would need detailed knowledge of the meteorological conditions, and no one has this information. These releases led to radiation exposure of the local populace, evacuation of more than 135,000 people, and an integrated radiation exposure for the world comparable to that from a very large atmospheric bomb blast.

Within hours after the accident, expert medical personnel arrived from Moscow. Boris Sherbina, vice president of the Soviet Union, took charge, emphasizing the priority of the central government. A total of 203 plant workers and firemen developed acute radiation sickness, and 31 died. The account given in Vienna (*1*) of the medical procedures is impressively detailed, and leads many in the West to believe that the Russians have had previous experience with nuclear accidents. Academician Andrei Sakharov believes that this is true (*6*).

The Delayed Evacuation

Many commentators in the Western world were puzzled by the long delay in evacuation of the population from around the plant (*7*). This delay can, however, be understood from the official Soviet evacuation plans (*8*) that follow closely the recommendations of the International Commission on Radiological Protection (ICRP), and the nature of the radioactivity release. The rules state that if the dose to an individual is expected to reach 25 roentgen-equivalent-man (Rem) integrated over time, evacuation should be considered; if the integrated dose is expected to reach 75 Rem, an evacuation plan should be implemented. During the day of 26 April, the radiation levels were only 10 mRem per hour in Pripyat (*9*), not enough to predict that the level required for evacuation would be reached. When, by 2100, the increased radioactivity release accompanying the graphite fire had caused the radiation level to rise to 140 mR per hour on the street nearest to the plant, evacuation was decided upon. It was decided to leave people in their homes overnight, sheltered by the buildings, while transport was assembled. Between 1400 and 1600 the next day they were evacuated. By this time the radiation levels had reached 1000 mR per hour on the nearest street.

Academician Ilyin proudly claims that no one, other than the power plant workers and the firemen, got acute radiation sickness or a larger dose than the standards suggested by the evacuation plans. Those who lived in Pripyat were evacuated on 27 April; they received and will continue to receive an average dose commitment of 3 Rem—less than that allowed for a radiation worker for a year. The 24,000 people living between 3 and 15 km from the plant (but not including the residents of Pripyat) received and will receive an average of 43-Rem radiation dose commitment (*10*), still less than the 75 Rem of the guidelines. The higher figure for these people was due partially to a delayed evacuation and partially to the facts that they lived in wooden houses with less sheltering from the radioactivity and that they lived under the first plume. Persons in Belorussia and the Ukraine, outside the evacuation zone, received and will receive in their lifetimes on average about 1/2 Rem (*11*): the dose increase if one moved from Washington, D.C., to the mile-high city of Denver and lived there for 10 years.

Even Academician Velikhov, who, I was told, climbed up above unit 4 on 26 April to inspect the damage, only got 25 Rem, which he is allowed by occupational standards once in a lifetime for emergency activities.

Effects of the Radiation

The consequences of the accident to the world's health have been detailed elsewhere (*5, 12*). They can be described in various ways (*13*). For example, the 43 Rem received by persons most exposed, adds for each individual a 0.5% probability of dying of cancer. Since 1/6 of all people die of cancer, this is 3% of the natural cancer death rate. Undesirable though this increase is, perspective can be gained by noting that a dose of 43 Rem causes less cancer, heart disease, and genetic defects than a lifetime of cigarette smoking. The integrated effect on the health of the world's population can be described by adding up all the calculated cancers, leading to a prediction of many thousand cancer deaths. But the effect is probably less than that caused by burning fossil fuels for 1 year in the Soviet Union. If, therefore, the average public health is the sole objective, and a Chernobyl accident happens less than once a year, the RBMK reactors in the Soviet Union can be considered less hazardous than coal-fired power plants of similar size.

The Soviets have made such arguments in scientific papers (*14*) and may have persuaded themselves that they had spent enough on safety. It is now obvious, however, that this conclusion was the result of too narrow an application of risk-benefit analysis.

The Soviets, and in particular Dr. Guskova and Dr. Ilyin, are sensitive to the importance of improving our knowledge of the effects of low doses of radiation by studying the health of those most exposed. The internal body concentrations of iodine and cesium have been measured in tens of thousands of people. These measurements can provide information to us not only about the integrated internal dose, but can give an indication of exposure and a check on Pavlowski's estimates of external dose. The internal dose estimates are, on average, ten times less than predicted at Vienna (*15*). The people have been divided into six cohorts, grouped by dose commitment, and help has been requested from some of the world's leading epidemiologists (*16*). It is unclear, however, whether a 3% increase in cancer will be observable except for nonfatal thyroid tumors and possibly leukemia.

Controlling the Accident

The first attempt to control the reactor after the accident was made by local personnel before the Moscow experts, including physicists Legasov and Velikhov, arrived. Their attempt to flood the damaged reactor failed because water passed through passages between the different reactors, threatening the integrity of the adjacent units (this is a small but important design flaw). Later that day, it was realized that the graphite in the reactor was burning, and radioactivity releases were increasing. Then, on 27 April and succeeding days, 5000 metric tons of material was dropped by helicopter. This smothered the fire, but the heat of the radioactivity still kept the core hot and continued to evaporate fission products. Not until liquid nitrogen was introduced into passages below the core, as suggested by Velikhov, did the core cool and the releases stop (*17*).

Reactor Restart

By 6 May the danger was over, but the Soviets faced several huge tasks: to clean up the rest of the power station so that it could operate again; to retrain or replace the staff so the operation would be safe; to decontaminate the countryside so Soviet citizens could return to their homes; and to make enough changes in the design and operation of the RBMK reactors so they can be operated without undue risk to the Soviet people. The purpose of my visit to the power plant, and my questions of the Soviet scientists, was to see how well these tasks have been accomplished. I believe that the Soviets have been remarkably successful.

The first step was to enclose the damaged unit 4 in a sarcophagus to prevent any further release. This was finished in October. Massive new foundations were built by burrowing below the reactor (*18*), and heat exchangers were installed to allow the decay heat to be removed. Almost no radioactivity now escapes: 10 μCi per day of ruthenium, down from 1000 μCi per day in October, and the 100 million curies in early May. After unit 4 was enclosed, decontamination of the other units could be effective. Units 1 and 2 were restarted in October and November, respectively, and when I visited on 23 February 1987, both were in full operation, producing 2000 MW of electricity. Unit 3 was being decontaminated and expected to operate again no later than July; no work was being done on units 5 and 6, which were under construction at the time of the accident. I was told that construction on unit 5 was expected to start again soon, with operation planned for the end of 1989, but a more recent press report says that this has either been indefinitely delayed or canceled. The rapidity of the restart of the contaminated units 1 and 2 may be contrasted with the 6-year delay in restarting the undamaged and uncontaminated Three Mile Island unit 1.

Decontamination of the Environment

The principal long-term problem caused by nuclear reactor accidents is the contamination of the environment with radioactive cesium-137. Cesium is so volatile that a large amount escaped from the reactor. It has a radioactive half-life of 30 years. One unanticipated problem with reclamation during the hot days of summer was the blowing of the radioactive dust from a contaminated area to an uncontaminated one. Disturbing the soil by plowing may therefore be a bad idea. Nonetheless, the decontamination of the area around Chernobyl has proceeded better than the Soviets expected.

As I was driven to Chernobyl from Kiev in February 1987, radiation was not evident until we reached the outskirts of the district center of Chernobyl, where I measured 0.05 mR/hour, down from 1 mR/hour on 29 May 1986 (*19*). I measured 0.4 mR/hour near the village of Lelev (down from 10 mR/hour on 29 May) with a high spot of 0.7 mR/hour just north of the village, and 0.4 mR/hour in the power station parking lot just to the east of the turbine hall. The road from Kiev has been damaged by trucks, but it has not been scraped or resurfaced—only washed with chemicals. Also, until we were within 1 km of the plant, there was little sign of scraping or ploughing the terrain on the side of the road. Inside the plant, I measured much lower levels of radiation—typically 0.06 mR/hour or less—in offices, the turbine room, and the control room. This amount leads to a modest dose for a worker of 0.1 Rem in a year, compared to a maximum dose of 5 Rem allowed for a radiation worker.

From the north side of the plant the road runs west to a junction with the Chernobyl-Pripyat road by the railroad bridge just south of Pripyat. This area was under the first radioactive plume. I was not taken along this road; the reason given was that snow was not yet cleared. However, I was told that the road surface has been scraped both there and in the town of Pripyat, and that the topsoil has been removed and replaced by clean soil on either side of the road. The apartment houses in Pripyat and elsewhere are quite clean; very little radioactivity got inside, but radioactivity remains on the tar roofs. Since Chernobyl had −8°C weather during my visit, the workers were waiting until spring to remove the contaminated tar.

In August 1986 Professor Pavlowski made cautiously pessimistic estimates of the external radiation doses and the way that they would fall with time (*20*). The doses are falling faster than he then estimated, presumably because the cesium-137 is being absorbed into the soil. The integrated dose estimates for a person at a fixed location are therefore smaller than those he previously estimated by factors of 1.5 to 2.0.

The Dnieper River is a source of drinking water for Kiev and for communities along its 200 miles southward to the Black Sea. Its purity was a source of concern since the day of the accident. Dr. Khitrov, who went with me to Chernobyl, took charge of measuring the radioactivity in early May 1986, and showed me his data. He and his associates installed a detector in the Pripyat River 8 km downstream of the power plant. On 2 May, the level of radioactivity in the Dnieper River was 7×10^{-8} Ci/liter (*21*), and 2×10^{-7} Ci/liter on its tributary, the Pripyat River. By 14 to 20 May 1986 the levels at the Kiev hydro station on the Dnieper had fallen to 1 to 5×10^{-9} Ci/liter, about the drinking water standard. As of February 1987, they were between 1 and 2×10^{-11} Ci/liter in the Pripyat River, 1/400 of the drinking water standard. This is about the natural level of radioactivity of potassium-40 in the oceans. Dr. Khitrov believes that most of the cesium-137 remains in the sediment. As the thaw brings the spring runoff to the river, he will check again to determine whether turbulence increases the activity. The radioactivity is further diluted in the reservoir for Kiev and is insignificant. During the summer of 1986, artesian wells were dug to provide a supply for Kiev, but they were not necessary and have not been used.

Resettlement

People can now work in almost all of the houses, even those in Pripyat, and not receive a dose higher than that in the power station, which is lower than that permitted for radiation workers. After the roofs are cleaned in the spring, it is expected that people can return and spend longer periods of time living in the houses without exceeding the 0.5 Rem tolerance for the general public. Many of the evacuees have better housing than before but most, and in particular the elderly, want to go "home" as soon as possible. However, the Ukrainian authorities and their Soviet advisers are being cautious about resettlement. Fourteen villages in Belorussia have already been resettled, and the evacuation zone of 35 km is expected to shrink soon to 20 km in the south to the River Ouge, just south of the town of Chernobyl.

Further decisions about resettlement have not yet been made. Many of the families live on small farms. It would not be possible to stop them from growing food, and it is important that they be able to eat what they grow. At the Vienna meeting, Academician Ilyin and Professor Pavlowski presented a deliberately pessimistic figure of 210 million person-Rem for the integrated internal lifetime dose to the people of Belorussia and the Ukraine (*22*). Western specialists thought that this estimate was at least ten times too large, based on measurements of intake of the cesium from bomb tests (*23*). Although he recognizes this, Professor Pavlowski prefers to wait until measurements of the new agricultural growth in spring 1987 are made before making any recommendations.

Distinction must be made between small, peasant farming (such as the farming of my host, Dr. Ratislaw Beloded of the Ukrainian Academy of Sciences, on his dacha in the area) and the large collective farms. Some restrictions on the types of crops that farmers are allowed to plant may be necessary, and the enforcement of these restrictions may only be possible on collective farms.

Causes of the Accident

After an accident it is obviously important to find the causes, including contributory causes, so that it will not be repeated, but it is also important not to assign scapegoats. At Vienna, Academician Legasov attributed the cause to "operator error" and problems of the "man-machine interface" (*1*). Most of those present at the meeting were dissatisfied with this reason and felt that the plant managers were being shielded. At a fall meeting of the U.S.S.R. Academy of Sciences, he said, "I did not lie at Vienna, but I did not tell the whole truth" (*24*). We are left to speculate what he did not say. My personal view is that the main cause was a bad reactor design. Although many Soviet scientists agree with this privately, it is hard for them to admit it publicly because the Soviet Union is committed to operate the 15 existing RBMK reactors and others now under construction, since there are few alternatives. They do not want to unduly frighten the Soviet public. Therefore, in interviews for Soviet radio, TV, and press I was careful not to criticize the design excessively, and merely stated that "I am impressed with the speed with which you installed the improvements and am also glad that you are now proceeding with the new, safer design of the VVER 1000 reactors" (which are similar to the U.S. pressurized water reactors).

The Design Errors

The RBMK reactors are unique in the world. They have an instability that is particularly dangerous at low power. As the water is boiled in the reactor and replaced by steam, there is less neutron absorption and the reactivity increases. Power then increases, more water boils, and so on in a positive feedback. At high power (greater than 20% of design) this "positive void coefficient" is compensated by a negative temperature coefficient as the neutron absorption lines broaden as a result of the Doppler effect and increase capture. The positive feedback can also be controlled by control rod movement. But these compensating mechanisms can only work if the time constant of the reactor is long enough—of the order of a second. This is the case for small changes in the reactor. Of the neutrons from fission, 99% are released in less than a nanosecond and slow down in 100 microseconds. But 0.5 to 1% come from radioactive decay and are released 10 milliseconds to 20 seconds after fission. Therefore, if rapid changes in reactivity are limited to 1%, the time constant of the reactor will be of the order of seconds—long enough to allow control of the reactor.

Enrico Fermi once said that "without delayed neutrons we could not have a nuclear power program." Every reactor designer in the West ensures that under no circumstances can rapid reactivity increases exceed this 1%. The designers at the Kurchatov Institute violated this fundamental rule. The change in reactivity on boiling the water in all 1670 channels was twice this amount, or three times in the unfavorable circumstance of the accident on the morning of 26 April. At 0123:42 the operators noticed that the time constant was less than a second. The reactor had gone prompt critical and could only be stopped by disassembling and homogenizing itself (*25*).

This design flaw was unnecessary. At the Hanford N reactor, less graphite is used so that the neutrons are not completely slowed down and the water in the channels is necessary to complete the slowing down process. For the N reactor the "void coefficient" is negative and the reactor is stable (*26*). I asked Soviet designers and scientists the reason for the RBMK design. The only answer I ever received was that there is a small gain in economic efficiency. I note that Professor Alexandrov, president of the Soviet Academy of Sciences, publicly declared, just after the Three Mile Island accident, that "this accident can only happen in a capitalistic society where they put profits ahead of safety" (*27*).

When I lectured in the Soviet Union a week later, I reminded my audiences that this was obviously a political statement, but that there was a danger that professional safety personnel would believe it. My belief is that the Soviets fell into this trap to which their political system makes them especially vulnerable. In any case, Professor Alexandrov, who was also director of the Kurchatov Institute, has resigned as president of the Soviet Academy of Sciences, and the Chernobyl accident is generally considered to be the principal reason.

This situation is reminiscent of the attitude in the United States before the accident at Three Mile Island. Many industry leaders believed that no accident could happen, in spite of the calculations and repeated statements of the safety experts.

The design error most discussed in the West is the absence of a containment system. Whereas strong structures would prevent other parts of the plant being damaged in the event of a large steam pipe failure, there is a little protection for the crucial radioactive core itself. If one coolant breaks, the steam is directed downward to a suppression pool. There is no planning for the simultaneous break of several tubes. I asked every designer I met whether the Soviet reactors could tolerate the breaking of two or three pipes. The invariable answer was that the plants were only designed to handle the failure of a single tube. This bizarre inversion of priorities may have occurred because they added U.S. technology (suppression pools) where it was easy; adding a real containment or pressure suppression for the simultaneous failure of several tubes might double the cost.

Management Errors

The instability problems of the RBMK design are so bad, and so apparently unnecessary, that most Western designers did not believe them as they perused the Russian reports before April 1986. But the Russian designers knew of these problems.

They specified a set of operating rules to be rigidly followed. But they forgot that rules that are not understood are often not complied with, and they seem to have made no attempt to educate the plant operators. Six important safety devices were deliberately disconnected on the night of 25 April. The reactor was deliberately and improperly run below 20% power. These incidents would not have occurred if the operators had understood the elementary reactor physics.

Minister Lukonin told me that at the critical times of start-up and shutdown new rules now demand that a senior person be present "whose main duty is to see that the rules are obeyed." But he went on to say that "this by itself would not have prevented the accident at Chernobyl, because it was the deputy chief engineer who was most responsible for breaking the rules." Now, rules in force at Soviet reactors may only be changed in writing, with date and signatures recorded, instead of orally, as was done on 25 April. Operators are told to obey the rules, and to refuse an order to disobey them. Nuclear power stations have now been put into a separate Ministry of Atomic Energy and separated from the Ministry of Electricity, and a new Center for Research into Operation has been started under Academician Abagyan.

The new director of the V. I. Lenin power plant at Chernobyl, Chief Engineer Komarov, was trained at Tomsk Polytechnic Institute. He told me that all the top management of this power station are new, and that the older management have been assigned to duties outside the nuclear power industry. The Soviet press have reported that criminal prosecution is imminent.

These were important admissions of management errors, as distinct from operator errors, but the criminal prosecution suggests a lingering obsession with assigning blame.

Palliatives

It is now almost impossible to completely fix these design errors. However, small but important palliative design changes were announced at Vienna (*1*) and have already been installed in all RBMK reactors. These alterations reduce the total change of reactivity by voiding to less than the fraction of delayed neutrons. The modifications would have prevented the specific accident that occurred at Chernobyl, but are not complete enough to make the many orders of magnitude improvement that is desirable. Changes include increasing the number of control rods in the critical region of the reactor (installed in all reactors by October 1986) and increasing the enrichment of fuel to 2.4% (slowly as fuel is changed). Another contributing cause of the accident was the extraordinarily slow shutdown system—also a design fault. Already stops, or limit switches, have been installed to prevent complete removal of the control rods, and thereby to advance shutdown by 3 seconds. A new shutdown system ten times faster has been tested and will be installed in all RBMK reactors by the end of 1987. The rapidity with which these changes have been made is impressive.

It is clear that light water reactors with containments are much safer than the RBMKs, even with the new improvements (*28*). Although more expensive, and perhaps not justified on a narrow cost-effectiveness criterion, the Soviets have now learned, as we have known for a long time, not to apply risk analysis so narrowly, and they are now willing to pay the extra cost. However, Soviet scientists have freely acknowledged that they were unable to make strong reactor vessels and containment vessels until recently. There have been many delays in the Atommash plant near Leningrad (*29*). However, they now can make pressure vessels, and all new reactor starts will be pressurized water reactors with containments.

Many scientists at Vienna asked whether the Soviets had done a full Probabilistic Risk Assessment (PRA) for any reactors. Although some were told that PRAs exist for the new VVER 1000s, no one in the West has seen one, and the first is likely to be one being conducted for a VVER in Finland by U.S. experts.

International Cooperation

Accidents in the modern technological age have many contributory causes. The RBMK reactor at Chernobyl has one atrocious design feature, and several that made it inferior to Western designs; there were management and operator errors. We obviously want to avoid all of these problems in the future and minimize their interactions.

The Soviets also want to collaborate with the West on safer designs. It is worth noting that Academician Andrei Sakharov, at the "Forum on a Nuclear Free World," held in Moscow, 14 to 16 February, made a plea to those in the West who are opposing nuclear power stations. He noted, as he has before (*30*), that the world will need nuclear energy and called upon the "antinukes" to spend their energies on making reactors safer instead of opposing them.

General Secretary Mikhail Gorbachev has called for greater international cooperation on reactor safety and has proposed that this be done through the International Atomic Energy Agency. However, safety demands openness and cooperation in personal as well as institutional ways.

It is clearly in the interest of the Soviet Union that U.S. reactors are run safely, and in the interest of the United States that the Soviet reactors are run safely. The friendliness, openness, and unfailing courtesy that I met on my visit suggest to me that we may be able to work together toward this goal. If we cannot, I do not see how we can work together on issues where our self-interest is less evident, and the future of the world will be bleak.

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11. This number assumes the small reduction in external dose estimates made recently by Professor Pavlowski, which is discussed in the text, and the smaller internal dose estimates the Western experts believe. See (*12*) and (*22*).
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15. Annex 7, p. 50, in (*1*).
16. Sir Richard Doll and Sir E. E. Pochin were among those mentioned.
17. Table 4.13, in (*1*).
18. E. P. Velikhov, testimony before the Labor and Human Resources Committee, U.S. Senate, January 1987.
19. Figure 5.4, in (*1*). The caption of this figure does not give the date, but both the text and information from private communications set the date at 29 May 1986.
20. Figure 7.2.2, in (*1*).
21. Table 5.7 and section 5.5, in (*1*).
22. Annex 7, p. 65, in (*1*).
23. See, for example, page 7.13, in (*5*).
24. Confidential communication from an auditor.
25. According to (*1*), 30% of the core would have to become homogeneous. It did.
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