reactor could be stopped only by manual shut-down with all the delay involved.

The sixth error — disconnection of the emergency core cooling system — did not have any effect on accident initiation but the emergency cooling could have mitigated the consequences.

As a result of these errors, when the experiment began at 1:23:00 on 26 April, the reactor was uncontrollable and began a rapid power excursion. At 1:23:30, the power began to rise above the 200 MW operating level. At 1:23:50, the power had passed 320 MW and the period for power doubling was a second or so. At this point, the operators pressed the button AZ-5 to scram (shut down) the reactor. But it was too late. Before the control rods could reach the active zone, the power had gone over the 3,000 MW design power; by 1:23:48, water flow had stopped as the check valve closed; but, by 1:23:49, flow had restarted, presumably because the channels had ruptured. It appears that the control rods stopped before going completely in.

Both halves of the core had the same problems. It is therefore probable that most of the 1,640 fuel channels ruptured within a few seconds — and the reactor can stand the pressure increase of only a few channels rupturing at a time. Inevitably the ejected pieces of the core went through the roof, including both pieces of graphite moderator and pieces of uranium fuel, although whether there was an explosion in the technical sense of the existence of a shock wave is debatable. It should be noted that this is one location, and direction, where there is no containment and ejection of fuel elements like missiles is inevitable.

Why were the operators unaware of the danger? One can only speculate. The idea that one must have several rods partially in the reactor already to achieve a rapid shut-down is not immediately obvious and, to some people, including me, is counter-intuitive; one might think that the more rods that are out, ready to go in, the better. But the problem is the rate of insertion. Be this as it may, it is clear that the operators did not understand the reasons for the rules. One most important procedural requirement was also violated and had probably been violated before. Any experiment is supposed to be checked in detail with the director or the chief engineer of the station; but these staff considered the experiment to be merely an electrotechnical exercise, forgetting that all procedures in a reactor are interconnected.

I suggest that these errors are much more likely to happen in a compartmentalized society, as they have in the Soviet Union, than in the open society of the West. In the United States, a violation of these rules would surely be leaked to the *Washington Post* within a day or two, and the perpetrators brought to account. For this reason, we must especially welcome the Soviet openness at the IAEA meeting. Let us hope it continues, not only between Soviet and US reactor designers but between designers and operators in the Soviet Union itself.

Detailed analysis of accidents, including human error, is common in the United States, particularly since Three Mile Island. The procedure is called "probabilistic risk analysis". It is vital that the Soviets use this procedure to the full to ensure that there are no other problems with these reators that they have not taken into account. Dr Legasov said that "the fact that we have started later than many specialists in thinking about such matters is a fault on our part". Of course the Soviets are taking strong disciplinary and procedural steps to ensure that such a litany of human errors never again occurs. But in addition, several steps have been taken to make the equipment less liable to errors —even premediated ones.

As an interim measure, all RMBK reactors are being modified with limit switches so that the control and shut-down rods cannot be brought to a region where it takes several seconds for them to be effective. The rule that 30 rods must be partially in the core at all times is being modified to demand that 60 be in at all times. This not only makes shut-down faster but reduces the void coefficient. These changes are being made now to RMBK reactors and half are at present shut down for this purpose.

In a year or two, the fuel, which is now enriched to 2 per cent in uranium-235, will be replaced by fuel with 2.4 per cent enrichment. This will further reduce the void coefficient and enhance stability. In the longer term, the Soviets are thinking about faster methods of shut-down such as gas or liquid injection of poisons.

The Canadians, who have experience with positive void coefficients, have offered in the design of shut-down systems with proper interlocks and key boxes to discourage unauthorized violations of regulations as much as possible. These should include simple prominent displays of computed excess reactivity and automatic shut-down if excess reactivity is too small.

There are no direct parallels between the RMBK reactors and light-water moderated reactors (LWRs). LWRs tend to shut down naturally, by boiling of the moderator, and although the Anticipated Transient Without Scram (ATWS) is serious for a boiling water reactor (BWR), there are still some hours for recovery rather than the 10 seconds in the RMBK. Even if six deliberate successive operator errors happen in the West, the hardware would make that less important. I therefore believe that the light-water reactors in the United States are safer than the RMBK 1000 reactors, even after the latter have been improved.

But immediate replacement of the RMBK reactors seems impossible — except perhaps by a return to coal-fired power plants. We must remember that the London air pollution incident of December 1952 caused 4,000 deaths in the first two weeks — which is much more than the 31 deaths and the 4,000 "projected" cancer deaths from Chernobyl — and it has been suggested that air pollution still causes thousands of premature deaths a year. So a simple comparison of risks is likely to suggest to a Soviet decision-maker that the RMBK reactors should continue to operate.

As General Secretary Gorbachev himself has noted, an accident in the Soviet Union affects the rest of the world. The Soviets have asked for help in understanding what steps to take and implicitly ask approval of steps already proposed. While these steps are excellent and deserve support, it was clear that the specialists at Vienna are reserving judgement on the safety of the RMBKs until it is clear that the Soviets are prepared to accept the detailed international scrutiny, both formal and informal, that occurs in the West. This must include exchanges of information and personnel including visits to the Soviet power plants. The compartmentalization of Soviet society must not be allowed to prevent developments such as these, and the outlook is promising. If we do not learn from our mistakes, we shall be condemned to repeat them.

Richard Wilson is Professor of Physics at Harvard University. The American Physical Society report on reactor safety was published in Reviews of Modern Physics *earlier this year.*

Reactor improvements

There is too much at stake for the Soviet Union to consider seriously abandoning its RMBK reactors. Quite apart from past investments in them, the need for power in the populous western regions of the Soviet Union could not otherwise be satisfied. Energy transport already accounts for 40 per cent of rail traffic in the Soviet Union, according to chief delegate Legasov. But the following improvements are to be adopted by 1987.

- **The control rods will be fitted with new stops preventing the last 1.2 m of their present travel.**
- **Partly in compensation but also to give the reactor type a greater reserve of reactivity, the enrichment of the fuel will be increased from 2.0 to 2.4 per cent.**
- **Consideration is also being given to schemes for flooding the reactors with neutron-absorbing liquids or gases for rapid shut down in emergency.**
- **More instruments will be installed in the reactors.** □