WEEKEND BOX

PRIME MINISTER

CHERNOBYL

You might be interested to look over this piece in last week's New Scientist about the design characteristics of the RBMK 1,000 reactor. It was written too early to be informed by the second crisis and I cannot vouch for its accuracy. But two pretty clear claims emerge from it:

i) that the accident involved less than 10 per cent of the core, and the melt-down temperature was not reached anywhere in the core - in other words it could have been much worse; and

ii) that the Soviet design combines a number of features (found only separately or in different combinations elsewhere, including in the UK) in such a way as to render the reactor inherently unstable and liable in the event of failure to lurch, through mutually reinforcing chemical and nuclear reactions, rapidly towards catastrophe.

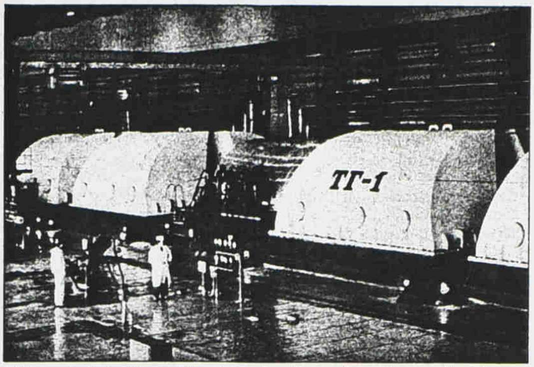
MEA

MARK ADDISON
14 May 1986

BM2AMP

Chernobyl: sorting fact from fiction

Tom Wilkie and Roger Milne



Chernobyl's turbines: the old technology where the accident began

THREE senior officials of the International Atomic Energy Agency (IAEA) are now in Moscow. When they return to Vienna tomorrow, the West should get the first detailed information about events at the stricken Chernobyl nuclear power station.

The full picture may take longer to emerge, however. As an IAEA spokesman pointed out this week, it took the US nearly six months to piece together a detailed sequence of events for the Three Mile Island accident in 1979. The IAEA's team comprises its Swedish-born director general Hans Blix, his Russian deputy director general Leonid Konstantinov, and the agency's American director of nuclear safety Morris Rosen.

The IAEA operates an incident reporting system under which nuclear reactor operators file accounts of any mishaps or incidents at their reactors. The USSR has not yet done so for the Chernobyl reactor, but this is not an abuse of the system. The Agency only expects countries to submit reports after they have themselves analysed what went wrong.

Until the USSR analyses the course of events at Chernobyl and releases details, the various accident scenarios that have been published in the Western media remain, for the most part, speculation.

Our detailed knowledge of what went wrong has not changed in any essentials since the evening of Tuesday 29 April. We know that the refuelling hall that surmounts the reactor has been blown off. We know, from the fact that fission products have been detected around the world, that the reactor vessel itself has been breached and is open to the atmosphere. We do not know the size of that breach, nor whether there has been an explosion within the reactor itself.

We know that the graphite moderator caught fire and that part of the core has melted. We do not know how big the fire is, how much of the core it has affected, nor at what temperature it has been burning. The Soviet Ambassador to the UN told the General Assembly on 1 May that there was no chain reaction and that the reactor was shut down.

A detailed analysis of the contents of the radioactive plume that passed over Sweden last week ought to answer some of these questions. According to the Swedish Nuclear Installations Inspectorate, the plume contained volatile fission products such as iodine and caesium. All the radioactive elements emit beta and gamma rays. So far, no alpha activity has been detected in the cloud.

The Safety and Reliability Directorate of the UK Atomic Energy Authority has been analysing the Swedish findings. Mike Hayns, Head of the Nuclear Safety Technology Branch, says that the readings from Scandanavia indicate that a few per cent (between 1 and 10 per cent) of the iodine and caesium in the reactor has been released. The accident could have released these elements if the temperature within the core rose beyond the melting point of the fuel's zirconium alloy cladding and of the structural steel—about 1800° C. (Traces of these materials have been detected in the cloud also.)

Hayns believes that the graphite fire is not discharging radioactive material that will find its way to the rest of Europe. The fire is not pushing radioactive materials high into the atmosphere. (The radioactive "cloud" over Europe originated from the first release of material before the fire). Nor does Hayns think that the fire is causing more damage to the core than the original accident that sent up the plume.

It is significant that we have not seen any alpha-emitting elements in the fall-out, Hayns thinks. These elements, the actinides, are not volatile. If we do not see a few per cent of the core's inventory of actinides present in the plume, then the temperature in the core cannot have exceeded the melting point of the uranium dioxide fuel itself—2800° C. To get a significant release of actinides, the core would have to get very hot indeed, and this would be difficult with the design of reactor.

The picture that seems to be emerging is this. The reactor itself did not explode; only the structural steel and fuel cladding have melted; the uranium dioxide itself has not melted; and less than 10 per cent of the core has been affected.

A clearer idea is also emerging of the technical characteristics of the Soviet RBMK-1000 reactor. It has four main features:

- Direct cycle—water is boiled directly within the core of the reactor and led off to drive the turbine-generator.
- Pressure tubes—the reactor does not have a single large pressure vessel to contain both fuel and coolant. Instead there are more than 1600 separate pressure tubes.
- Ordinary (light) water is used as coolant.
- Graphite is used as moderator.

None of these features individually is unique to the Soviet design, but the combination is found nowhere else, apart from some military reactors in the US. It is becoming clear that these characteristics have forced Soviet designers to make several unhappy compromises in scaling up the design to 1000-megawatts (MW) from the original prototypes that generated only some 5 MW. Two problems could have caused the disaster.

In the RBMK reactor, water is allowed to boil in the pressure tubes, producing 5400 tonnes of steam per hour at a temperature of 284° C and a pressure of 70 Kg/cm^2. But the steam is actually a "wet" mixture of steam and water which has to be dried before it can go to the turbine. (Otherwise, droplets of water would damage the turbine blades).

Because there are more than 1600 pressure tubes, the steam and water mixture from each one has to be collected before being taken to the turbine. This is done in four huge steam drums (which also act as dryers). These vessels contain steam under pressure, and each has more than 400 welds and joints where the pressure tubes feed in their steam. This presents a formidable problem of quality control: each weld must be carefully inspected to ensure that no cracks or weaknesses are present. Were the steam drum to explode under the pressure of the steam within it, the force of the explosion would be enough to destroy the ▶

The Soviet drive to nuclear power

THE accident at Chernobyl came just as the Soviet Union was at the height of an extraordinarily ambitious programme of "production line" manufacture of nuclear power stations that outstrips anything ever attempted in the West.

The Soviet Union has ample supplies of fossil fuel, and a large potential for hydroelectric power, so it was initially relatively slow in expanding nuclear power. But it has pushed through a large programme in the past 10 years, and intended even greater expansion. In 1979, the USSR's nuclear plant capacity of 4500 Megawatts (MW) was generating 2 per cent if its total electricity. By 1985, the operating nuclear capacity had increased six times to 28 000 MW. The USSR expects to add another 41 000 MW during the course of the next five-year plan, 1986-1990.

The main fuel for the USSR's power stations is coal. But the major coal deposits lie in Siberia or beyond the Urals, and almost 40 per cent of the country's rail transport is taken up in shipping coal from east to west.

The USSR has also explored some unconventional electricity sources, including geothermal production in Kamchatka, a tidal power station on the Barents Sea, and a solar station in the Crimea. The cost of nuclear electricity is said to be 75 per cent of the cost of conventional thermal power.

The Soviet nuclear programme is based on two types of reactor, the RBMK pressure-tube, water-cooled and graphite-moderated reactor of the kind involved in the Chernobyl accident; and the VVER—a Soviet version of the pressurised-water reactor.

The RBMK, a purely Soviet development, uses low-enriched uranium fuel. Each channel, or pressure-tube, can be fuelled individually while the reactor is running on full power. Such a design lends itself to the production of plutonium for the military. This characteristic of the RBMK might explain why this reactor has not been built in any of the other countries of the Eastern bloc. The modular design of the RBMK also allows larger units to be built up. The standard model is now a 1000-MW reactor.

The next stage in the USSR's development of this reactor was a move up to a 1500-MW unit, using two 750-MW turbines. The first units of this size were built at Ignalina in Lithuania. Ignalina-1 started operation in 1984, and Ignalina-2 is nearing completion. A second, four-unit RBMK-1500 station is planned for Kostroma on the Volga. Even larger units may be built. Design work is said to be in hand for a RBMK-2400.

An advantage with the RBMK design is that the units can be built without the need for special manufacturing facilities for heavy pressure components. This requirement has proved a bottleneck for the VVER programme. There are also no limitations on the size of components to be transported, which has had an influence on PWR design. There is, however, no reactor containment.

The main future expansion of nuclear power within the USSR and its allies will come from the Soviet design of PWR, the VVER stations. The first stage of development was the 210-MW unit-1 built at Novovoronezh, which started operation in 1964. A 440-MW station became the first standardised design. It was adopted in both the USSR and the other countries. The USSR exported the reactor to Finland (Loviisa-1 and -2).

The next stage of the VVER development was to increase output to 1000 MW. The VVER-1000 units have a form of containment. All components of the primary system and the reactor hall are enclosed in a sealed space within a reinforced concrete containment vessel with a diameter of 45 metres. There are now 41 of these VVER-1000 units in operation, under construction or planned on 13 sites in the USSR. Of these, five are in operation, the remainder are coming into operation at the rate of about one unit every three months. With the construction of multiple units on one site, a production line of building has been adopted which enables each unit to be completed in some 60 months.

There have been problems, however. For example, the purpose-built Atommash factory makes pressure-vessels and components for the primary circuit. The factory, which is situated at Volgodonsk in the Ukraine, has experienced severe problems. It should have been producing eight vessels a year in 1980, but only managed to deliver its fourth vessel by August 1985. So, contrary to original plans, the manufacture of vessels has continued at the older Izhorski works in Leningrad.

The latest 1000-MW turbines for the VVER-1000 units are manufactured at the S. M. Kirov plant at Kharkov. Designs of even larger machines in the 1800-2000-MW range are now being developed for production in the 1990s.

Some 20 per cent of the USSR's consumption of fossil fuel goes on the production of hot water for "district heating", so there is a strong incentive to turn nuclear stations into a source of heat for such schemes. The larger VVER-100 units are used for generating both heat and power, and units are under construction at Odessa, Minsk, and Kharkov, each with two, VVER-1000 units. These units will supply electricity and heat for up to one and a half million people.

Heat-only reactors, producing temperatures of around 150° C, have also been developed, based on the VVER design. These could meet the heat requirements of a city of 400 000 people. The first two units are under construction at Voronezh and Gorki. The Gorki station is only two kilometres from the city boundary. Obviously, an accident at a nuclear district heating plant, so close to a large city, could be devastating.

The Soviet Union has devoted a considerable effort to the fast-breeder reactor. After experience gained on early experimental and demonstration reactors, the USSR started construction of a powerplant, BN-350. It started up in 1973 at Shevchenko on the Caspian Sea. The next, BN-600 started operation in 1980 at Beloyarsk in the Urals and reached full power a year later. There are now plans for the design and construction of larger 800 and 1600 MW stations.

The USSR maintains a strict control over the whole nuclear industry in t
Eastern bloc. It supplies all the fresh fuel for the VVER units, the only reactor type built outside the USSR itself, and requires that the spent fuel is returned to Russia for reprocessing or storage. Irradiated fuel is transported by rail in standardised containers.

Geoffrey Greenhalgh

AP

Oleg Kovalevitsh in Finland last month. Kovalevitsh is responsible for safety at the Soviet Union's power plants

▸ refuelling hall above the reactor. Such an explosion would immediately mean a catastrophic loss of coolant that the reactors emergency-core cooling systems would have to deal with.

There is a second problem about the direct cycle design, also potentially disastrous. It is not unknown for turbines to fail—sometimes explosively, shedding blades which themselves possess high kinetic energy. Were this to happen, the reactor's control systems would have to shut it down and find a way of removing the heat still being generated within the core. The Finnish engineers who worked on the only Soviet reactor to be built outside the Eastern bloc—Loviisa—found that they had to regrind all the valves and seals in the system. If a valve stuck in the wrong position when the turbine tripped, that too could precipitate a serious loss-of-coolant accident.

This possibility is similar to what happened at Three Mile Island. There, the turbine tripped and a system designed to feed water into the heat exchangers failed to operate. Fortunately, Three Mile Island had an indirect cycle, so this was not immediately serious. However, another valve within the primary circuit opened—as it was designed to do—to relieve pressure within the reactor. It stuck open. It was only at this stage that the reactor experienced a loss of coolant.

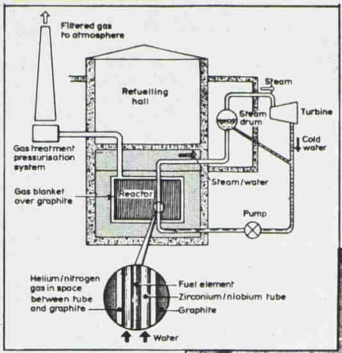
The combination of graphite as moderator and water as coolant is also unhappy, for two reasons: one chemical, the second nuclear. In the core of the reactor, the graphite is subject to a heavy flux of neutrons which heats it up to a temperature of around 7000° C. In fact, nearly five per cent of the power output of the reactor comes from the heat generated within the graphite in this way. There are special graphite rings or collars which keep the moderator in thermal contact with the pressure tubes, so that the moderator can give up some of its heat to the water.

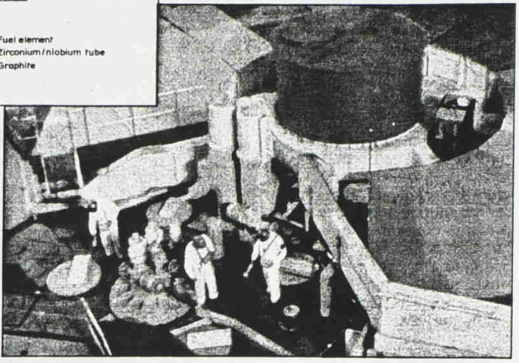
In Britain's Magnox reactors, the graphite runs at about half the temperature of the RBMK-1000, and the Advanced Gas-cooled Reactors operate at around 400° C. In the British design, the graphite is kept cool because the carbon dioxide gas that is used to cool the fuel is first made to percolate throught the graphite. The carbon dioxide also plays a role in providing a chemically inert atmosphere for the graphite.

In the Soviet design, water cannot be used to cool the graphite nor to keep it inert. So in addition to the complicated cooling system of more than 1600 pressure tubes provided for the fuel elements, there is a separate system designed solely to keep the graphite in an inert atmosphere and to prevent it overheating. This is achieved by blanketing the graphite in a mixture of helium and nitrogen gas.

The gas mixture occupies the gap between the zirconium-niobium alloy presssure tubes and the graphite surface of the channel through the moderator. By altering the relative concentrations of helium and nitrogen in the mixture, Soviet engineers can change the heat-transfer characteristics of the gas and so control the rate at which heat is conducted from the graphite to the pressure tubes and so to the coolant water.

The graphite is run very hot in the Soviet reactor—certainly above its ignition temperature in air. So the safety of the reactor depends not only on the integrity of the fuel cooling system, but also on the assured ability of this gas system to exclude air from the graphite.





Part of the cooling system for the Chernobyl reactor. The cylindrical shape is the pump

Popperfoto

The close proximity of high-temperature graphite and steam under pressure also poses a chemical risk. There is a well-known "water gas" reaction:

$$H_2O + C = CO + H_2.$$

If a pressure tube were to rupture, hot steam would play over the graphite. The water gas reaction proceeds at temperatures of about 1000° C, only 250° C above the running temperature of the graphite.

It is possible that the overpressure induced by the production of water gas in the above reaction could rupture the secondary (helium-nitrogen) pressure circuit. This would let in air and, at these temperatures, the gas would ignite instantly on contact with oxygen. However, it is extremely unlikely that enough air could get into the reactor itself quickly enough to allow an explosion. If the water gas seeped into the refuelling hall surmounting the reactor, it could ignite in the large quantitities of oxygen present there.

But the water gas reaction is highly endothermic—it takes in heat. Where could the heat have come from to progress this reaction? The answer to this question stems from nuclear physics and again the key is the close proximity of water and graphite. Ordinary water absorbs neutrons (that's why, in the pressurised water reactor, which uses water both as coolant and moderator, the fuel has to be enriched).

If the Chernobyl reactor did suffer a loss of coolant—as seems almost certain—then, as the water turned to steam, two independent processes came into play. Steam is much less efficient than water at cooling the fuel elements so they would start to overheat. but steam is less dense than water and so absorbs fewer neutrons. The result of this second effect would be a sudden pulse of neutrons, causing the chain reaction to accelerate suddenly and a sudden local overheating in the core.

Soviet engineers have already experienced problems with swings in reactivity in the RBMK reactors. Writing in the journal *Atomnaya Energiya* in June 1984, E. V. Kulikov noted that "the stability in the power distribution decreases as the fuel burns up," and that new systems had to be added into the design to cope with the problem. One system provides "local automatic control" of the power in individual regions of the reactor. The second system "provides for emergency reductions in power when there are impermissible local power rises in spite of the action of the local automatic control system".

The RBMK-1000 reactor is clearly extremely complicated—perhaps too complicated. Many of the likely "initiating events" of the accident at Chernobyl would only be serious because of the conjunction of features of the design. Because Britain's reactors are gas-cooled, they cannot suffer a loss-of-coolant accident. The worst that can happen is a depressurisation of the primary circuit. In that eventuality, according to the head of the nuclear operations support group at the Central Electricity Generating Board, there are already tanks containing tonnes of carbon dioxide on site, permanently piped into the reactors, so that it would be comparatively easy for the station's operators to bleed gas into the reactor to keep its coolant above atmospheric pressure and so exclude any air.

In any case, under normal conditions, the graphite in Magnox reactors runs at a temperature below the ignition point in air. Nor are there fears about the consequences of water getting on to the graphite. This has already happened many times. Boiler tubes have leaked, allowing water into the primary circuit without triggering any adverse chemical reactions. The most celebrated instance was in the 1970s when several thousand tonnes of seawater flooded into the core of the Hunterston AGR in Scotland. Once again, apart from corrosion, nothing untoward occurred. ☐