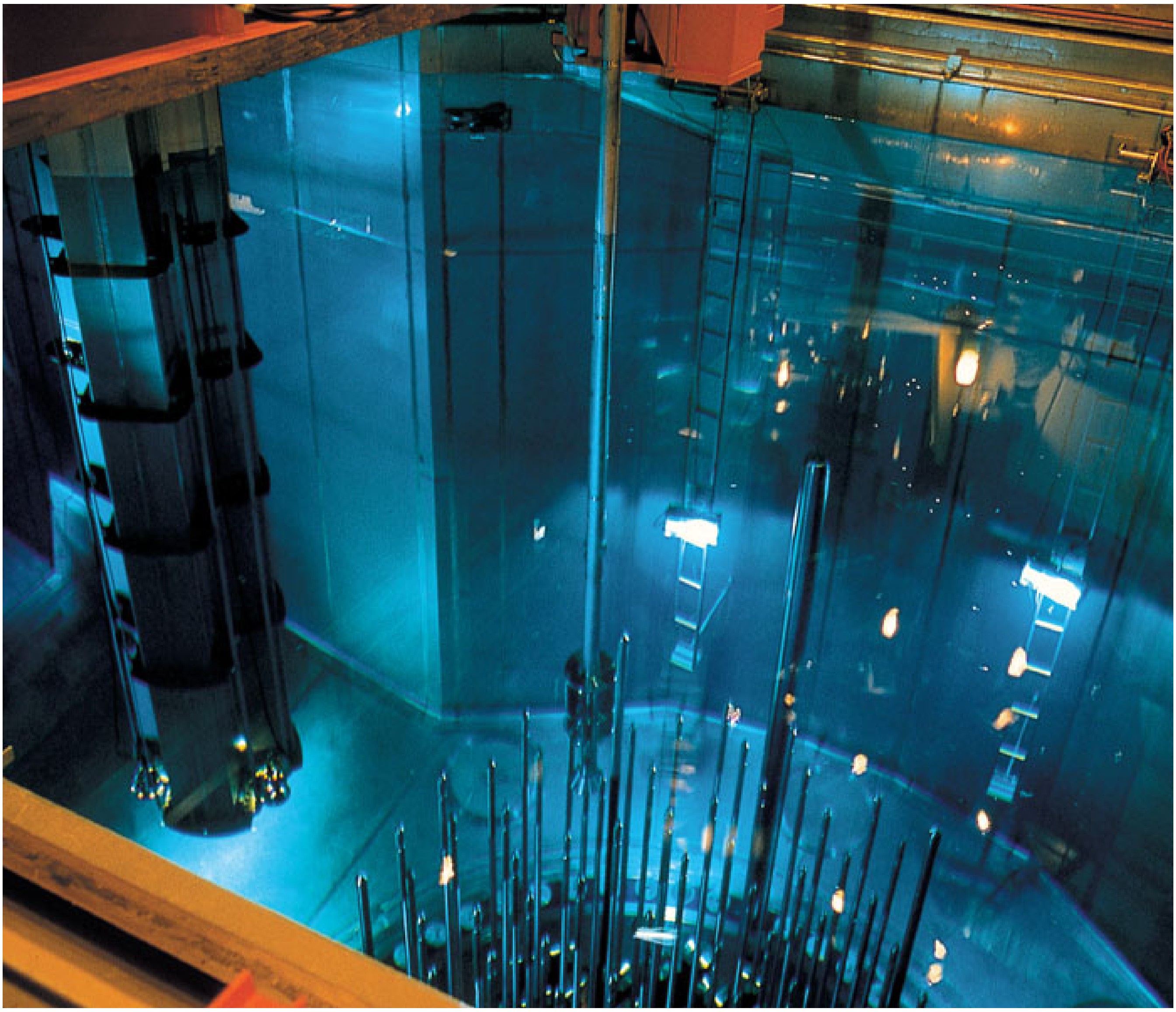
II. NUCLEAR PHYSICS AND REACTOR SAFETY

controlled reactions

Nuclear reactor safety is built upon in-depth knowledge of the phenomena encountered under normal, incident and accident conditions. Those relating to nuclear physics and neutronics are of particular importance and are involved in the three main types of malfunction that might occur: excessive power level, difficulty with residual power removal, and criticality accidents. In the event of uncontrolled divergence or a criticality accident, which can occur not only in a reactor but also in any other facility handling sufficient quantities of radioactive materials, physical feedback effects fortunately tend to check the unwanted process intrinsically. Residual power in a reactor after shutdown is an unavoidable phenomenon as it is linked to the radioactive decay of the products contained in the irradiated fuel. Nonetheless, increasingly precise assessment of its quantity has made it possible to optimize its removal.



C. Pauquet/Framatome

Screwing into place the control rod drive shafts in reactor n° 1 of the EDF Civaux plant.

NUCLEAR REACTIONS AND FEEDBACK EFFECTS

As databases are refined, the safety margins of reactors and other nuclear facilities can be defined with an increasing degree of realism. This is particularly true for the feedback effects that are triggered by nuclear reactions and that tend to check uncontrolled increases in power. It is also true for the consideration of reactor residual power or heat which must removed under all circumstances.

A. Tsiaras/Cosmos

Entrance to reactor n° 2 building at the Three Mile Island plant in Pennsylvania. Partial fusion of the reactor core in 1979 highlighted the problem posed by residual power removal.

Questions relating directly to nuclear physics and neutronics are a vital part of nuclear facility safety assessment in normal, incident and accident situations. For the sake of easier reading, this issue of *Clefs CEA* only looks at these particular questions, but the reader should not lose sight of the fact that under real conditions many other phenomena involving thermohydraulics, thermomechanics, physical chemistry, and so on would also come into play.

The main hazards relating to nuclear physics

The main potential hazard presented by a nuclear reactor is the release of **radioactive** products that could occur if the series of **barriers** put up between the reactor and the environment were to break down (see box D, D

The three barriers – an illustration of the "defense in depth" concept

The safety of nuclear power plants, particularly in France, is based on the "defense in depth" concept, in which many levels of protection, including a series of barriers, are set up to minimize the probability of an accident having any impact outside the plant. This concept is based on the premise that each safety device must be considered *a priori* as vulnerable and must therefore be backed up by another device.

In pressurized water reactors (PWR) such as those operated by EDF, application of this defense-in-depth concept entails putting up a series of tough, leakproof barriers between the potentially hazardous products created by fission and the outside world. The public and environment can be protected against the effects of a nuclear accident by simply ensuring that these radioactive products remain perfectly contained.

There are three such barriers in a PWR (see box E, **The main components of a PWR**). The first is the metal cladding around the fuel, the second is the containment of the cooling system (of which the reactor vessel containing the fuel is a vital part), while the third is the concrete containment, which has been doubled in the most recent reactors.

The third barrier is completely missing from Russian RBMK reactors, such as those installed at the Chernobyl plant. It was because of this shortcoming that radionuclides were released into the environment following the accident in reactor n° 4 on April 26, 1986.

The three barriers – an illustration of the "defense in depth" concept). Basically, this hazard arises from the release of energy, essentially due to nuclear reactions, **fission** on the one hand, and the radioactive decay of elements contained in the fuel on the other. An incident or accident occurs when this energy release is no longer controlled, either because the power exceeds the intended level and can be dissipated, or because a failure has occurred in the normal and emergency power extraction systems.

The fission hazard

With fission, there is the risk of a **chain reaction** being initiated or unexpectedly amplified. The situation varies according to whether we are dealing with a reactor or other type of nuclear facility. In the case of a reactor operating under normal conditions, a stabilized chain reaction is sustained. An accident may arise from an unplanned, excessive extension of this chain reaction ("uncontrolled **divergence**"): this is referred to as a **reactivity** accident. In other types of nuclear facility, care must be taken to avoid any form of chain reaction. Nonetheless, it is not possible to rule out the occurrence of a chain reaction caused by a combination of human error and "favorable" configuration in terms of neutron balance. In facilities handling nuclear materials, this is known as the **criticality** hazard.

Both aspects are considered in detail in this second part as regards reactivity accidents and in the third part from the criticality angle. It would seem that in both cases, a feedback effect takes place, rapidly and effectively preventing any uncontrolled "**power excursion**".

The radioactive hazard

The radioactive hazard is of concern mainly inside the reactor when the chain reaction is stopped. Under nominal operating conditions, the power generated by the radioactive decay of the elements contained in the fuel is low compared to that induced directly by fission, accounting for only a small proportion (a few per cent) of the total rated power of a reactor. It is this power alone that remains, however, when the chain reaction is stopped. Stopping the chain reaction is achieved quite simply by dropping neutron-absorbing **control rods** into the core. On the contrary, the radioactive decay of elements contained in the fuel cannot be stopped. Energy is released as radioactive decay continues. This is a long drawn-out process and though the released energy level decreases over time, it does so relatively slowly. The energy must therefore be removed to avoid any risk of serious damage due to overheating.

Nuclear accidents and calculation codes

By design, a nuclear accident, especially inside a **reactor**, is extremely hypothetical. It can only result from a sequence of many physical phenomena. It is therefore necessary to identify the basic phenomena liable to contribute to such a scenario, then to study and model them. In addition, studies must be carried out to see how they interfere with each other and assess the impact of each one on the others. For example, **thermohydraulics** and **neutronics** would be much more closely coupled in an accident situation than under normal conditions. Thermal-hydraulic phenomena are affected by heat sources, in this case, by the number of **fissions** induced by neutrons, whereas **neutron balance** and the spatial distribution of fissions are highly sensitive to the temperature and density of materials, in other words to thermal and hydraulic transfers.

In practice, specialists compute the progress of an improbable accident using a "system" **calculation code** program capable of acknowledging these coupling factors, and using "modules" that process basic phenomena and run the necessary iterative routines to take account of any feedback effects that might occur.

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