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Reactor Accidents in the Early Days of Nuclear Power

Abstract This chapter covers reactor accidents from the beginning of nuclear power until the 1980s. The accidents at Windscale (Great Britain), Vandellos (Spain), Vinča (Yugoslavia), SL-1 (USA), Santa Susana (USA), K-19 (USSR), Lagoona Beach (USA), Chapelcross (England), Grenoble (France), Lucens (Switzerland), Saint-Laurent-des-Eaux (France), Leningrad (Russia), Bohunice (Slovakia), and Constituyentens (Argentina) are analyzed in detail. Other less spectacular accidents are mentioned. The whole is abundantly illustrated with photos and diagrams.

The history of reactor technology is studded with accidents, like all other major human technologies. Those of the early days of nuclear power shed light more specifically on the engineers' understanding of physical phenomena. Improving reactor safety requires an understanding of past errors.

Windscale, a Fire in the Reactor (England, 1957)

The first major reactor accident occurred in 1957 on the first British military reactor at Windscale (Photo 2.1). Beginning in 1947, the British built a set of two graphite-moderated, air-cooled piles to produce weapons-grade plutonium. Windscale was located in the county of Cumberland, in the northwest of England, on the coast of the Irish Sea. This region was rather poor and sparsely populated, with barely 70 inhabitants per square kilometer at the time. Population therefore welcomed the arrival of an industrial complex that

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Photo 2.1 An ominous-looking photo (cloudy sky? low angle shot?) of the two military reactors at Windscale. One notices the filters placed abnormally at the top of the chimneys

would bring more than 3,000 jobs to the region. The plant was built on the site of one of the British government's weapons factories that manufactured TNT during World War II. The purpose of the Windscale piles was to produce plutonium by burning-up uranium. These two nuclear piles allowed the British to produce some 80 kg of plutonium per year, the equivalent of about ten atomic bombs. This plutonium was used for Operation HURRICANE, the code name for the first British atomic test, carried out off the coast of Australia on 3 October 1952. In addition, next to the piles, there was a separation plant (1951–1964) for separating plutonium from spent fuel (Butex process). An advanced Gas-cooled Reactor AGR (Fig. 2.1), prototype of the British AGR reactor type, was built on the site to replace the accidented reactor. The AGR is a much more modern reactor with a containment vessel for radioactive products that contains the reactor vessel and the steam generator. This reactor, unlike the accidented reactor, produced electricity. This complex is now called Sellafield, extends over 10 km^2, includes a spent fuel processing plant, the four Magnox reactors at Calder Hall, a MOX fuel plant, and employs over 10,000 people.

The choice of air as a heat cooling fluid, rather than water used in the American Hanford piles, is the choice of simplicity: no problems of oxidation

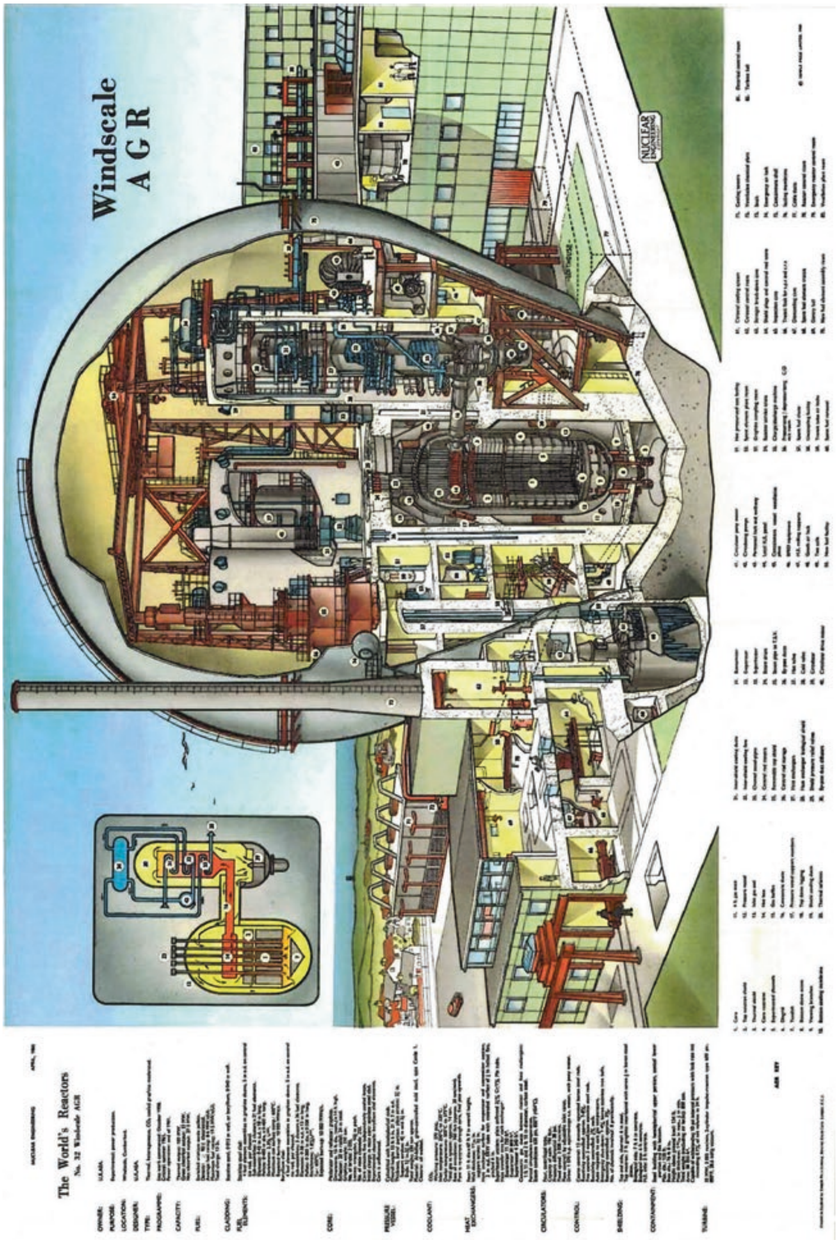


Fig. 2.1 Windscale AGR (1963-1981) cooled with carbon dioxide. Not to be confused with the accidented reactor. (Courtesy NEI)

or neutron effect due to reactor draining. The disadvantage of air is the risk of fire of the graphite, risk exacerbated by the *Wigner effect*. This effect had indeed been predicted by Eugène Wigner as early as 1942 during the work on American military reactors during the war. The ejection of carbon atoms by the neutron shock can take place from a neutron energy of 25 eV.[1] In fact, a fast neutron that thermalizes[2] in carbon atoms can displace them many times, especially during a burn-up[3] at low temperature, which creates vacancies in the lattice. If these ejected atoms do not recombine, which is the case when the burn-up temperature is low (around 115 °C), energy accumulates in the lattice and can reach 2000 J/g. This energy is released spontaneously and dramatically (temperature excursion higher than 1200 °C) when the reactor rises in temperature, because the displaced atoms find their place by increasing the thermal agitation. For graphite, to activate the Wigner Effect, the graphite burn-up temperature must be lower than 115 °C and the integrated fluence, which characterizes the damage of the material following the neutron shocks, must be higher than 0.1 displacement per atom (dpa[4]). Above 170 °C, the Wigner effect "disappears," or at least its harmful effect of heat up by restructuring, because the defects recombine at the same time as they are created. The Wigner effect can eventually generate graphite fires, especially if the air is present. The solution is to voluntarily restructure the graphite by long-term slow thermal annealing.[5] The Wigner Effect becomes really dangerous when the rate of energy release in relation to the temperature in the graphite exceeds its thermal capacity:

$$\frac{dE}{dT_{[\text{calorie/g/°C}]}} > C_p\left(T\right)_{[\text{calorie/g/°C}]}$$

Thermal capacity C_p of a material, which depends on the temperature, characterizes its capacity to store energy. This is called thermal inertia. The rate of release as a function of temperature depends on the dose received by the graphite (it increases with the dose), but also on the temperature (it

[1] The electron-Volt (eV) is the energy acquired by the accelerated charged electron in a potential difference of one Volt. It is a unit of energy more convenient to handle than the *Joule* in the context of particle physics.

[2] A neutron that loses its energy as a result of shocks in matter is said to *thermalize* when it reaches the average energy of the medium in which it evolves.

[3] Burn-up is the accepted term for a material subjected to a neutron flux.

[4] For a neutron fluence of one dpa, each atom of the structure concerned undergoes on average one displacement.

[5] We voluntarily heat the fuel to restructure it.

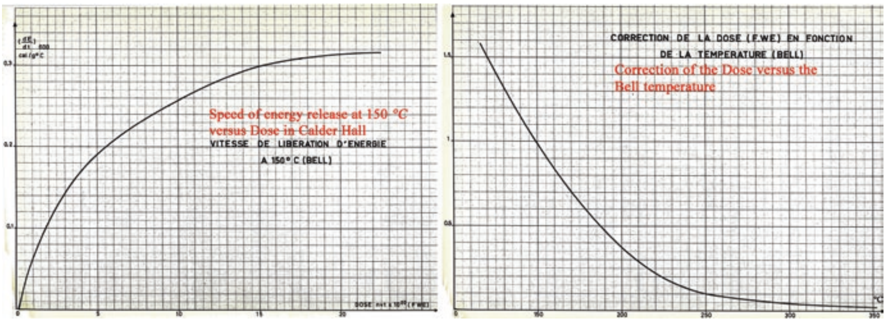


Fig. 2.2 Energy release rate in graphite at 150 °C as a function of the Wigner neutron flux (called dose at the time) and corrective factor of the dose as a function of temperature for neutron spectra encountered in the Calder Hall (Great Britain) or G2 (France) reactors. When graphite in a reactor is hotter than 150 °C, the corrective factor is less than 1. because there is a constant rearrangement of the carbon atoms of the graphite by the "annealing effect." The higher the temperature, the less the Wigner Effect. It is considered that the risk becomes negligible from 300 °C

decreases with temperature) (Fig. 2.2). As the temperature increases, the rate of relaxation decreases because the crystal lattice is constantly rearranged at high temperature. This is called annealing. This temperature annealing technique is sometimes applied to steel that contains cracks and defects caused by neutron impact (i.e., a reactor vessel). This type of annealing should not be confused with melting the steel to fill the cracks. The annealing temperature is in fact much lower than the melting temperature of the material to be restructured, and the annealing must last for long periods (several weeks) to be effective. If the material releases energy faster than it can store it, a limit is reached where the temperature goes out of control, and in the worst-case scenario, we speak of a *Wigner fire*. The first graphite reactors had low operating temperatures (below 200 °C), which justified a Wigner risk analysis (Fig. 2.3).

Nevertheless, at Windscale, the risk of an air-fed fire was judged, hastily at the time, to be negligible compared to the water loss accident. In anticipation of the risk of release of fission products from a possible defective fuel cartridge, filters were installed at the outlet of the 410-foot high stacks (123 m, 14 m in diameter, 50,800 tons of reinforced concrete). These chimneys, highly visible from the surrounding area, were called Cockcroft's follies, after the

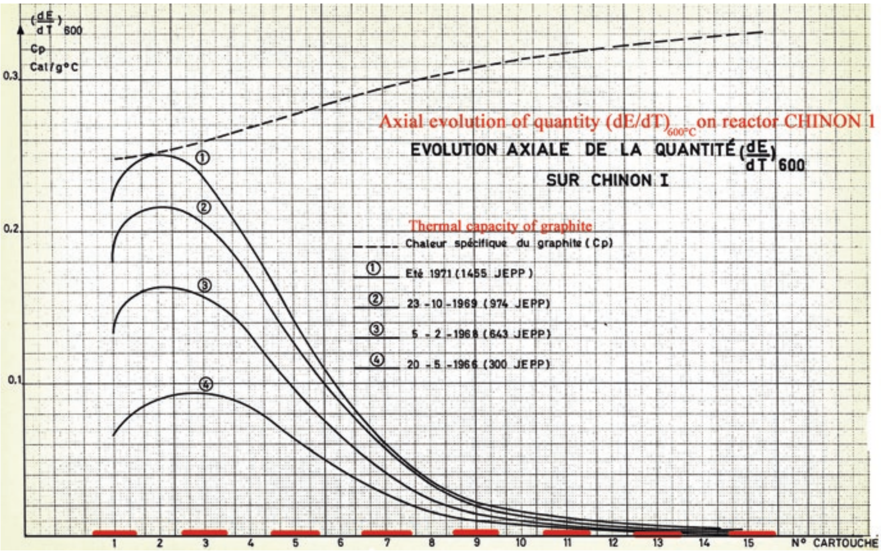


Fig. 2.3 Wigner effect predicted in the reactor of Chinon-A1 (nicknamed "the Bowl"). These predictive calculations at the end of 1969 show that the Wigner risk appears at the level of the first three cartridges (the most burned-up) as early as the summer of 1971. This problem can be treated by annealing at higher temperatures to restructure the graphite

physicist John Cockcroft[6] suggested the introduction of these filters after visiting the Oak Ridge site, which was experiencing problems with the unexpected release of uranium particles.

The filters, made of glass wool, would have been more effective if they had been placed at the base of the stacks, but the system was added after the stacks were built, so they could only be placed at the top. The purpose of these filters

[6] Sir John Douglas Cockcroft (1897–1967). British physicist. Nobel Prize in Physics with Ernest Walton on the transmutation of atomic nuclei by proton acceleration. After studying mathematics at the University of Manchester, he worked at the famous Cavendish laboratory, then became a professor at Cambridge. During the war, he became a member of the Maud Committee on the atomic bomb, then was sent to safety in Canada where he directed the Chalk River laboratories and participated in the Manhattan Project. After the war, he became the director of the British atomic center at Harwell.

Cockcroft and George Gamow at the Cavendish laboratory in 1931.

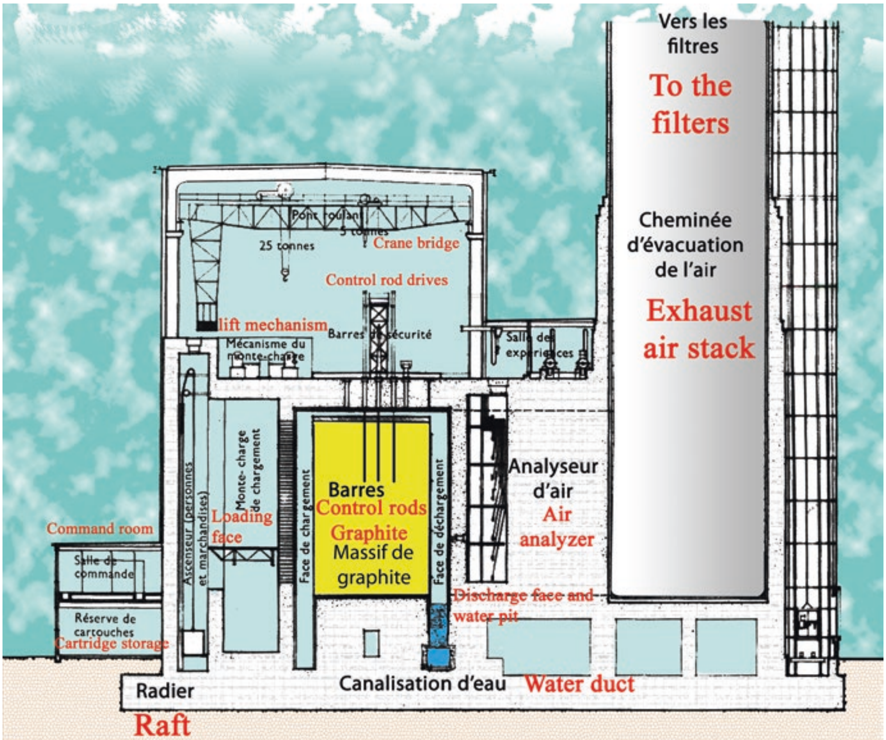


Fig. 2.4 Cross-section of the Windscale reactor building

was to retain solid particles during normal operation of the pile, and not to deal with a massive release in the event of an accident, but they were nevertheless very useful in mitigating the consequences of the accident.

After solving many technical problems, the British diverged the first pile in October 1950. The two piles, each located in a reinforced concrete containment to ensure biological protection against burn-up, are made up of a cylindrical graphite block with a horizontal base weighing 2030 tons, build from 50,000 graphite blocks, the whole being 15 m in diameter and 7.6 m long (Fig. 2.4). Each block is in the form of octagonal logs 25 feet long and 50 feet in equivalent diameter. The graphite assembly is drilled parallel to its axis to form 3440 horizontal channels (Photo 2.2). Inside the latter are natural uranium rods 2.5 cm in diameter, enriched to about 0.7% in uranium 235, the fissile isotope of uranium. The fuel is cladded in aluminum and provided with cooling blades to improve heat exchange (Photo 2.3). Each of the 3440 channels contained 21 "*fuel cartridges*" horizontally (Photo 2.4). There was a total of 72,240 fuel cartridges. The aluminum of the cladding strongly limits the

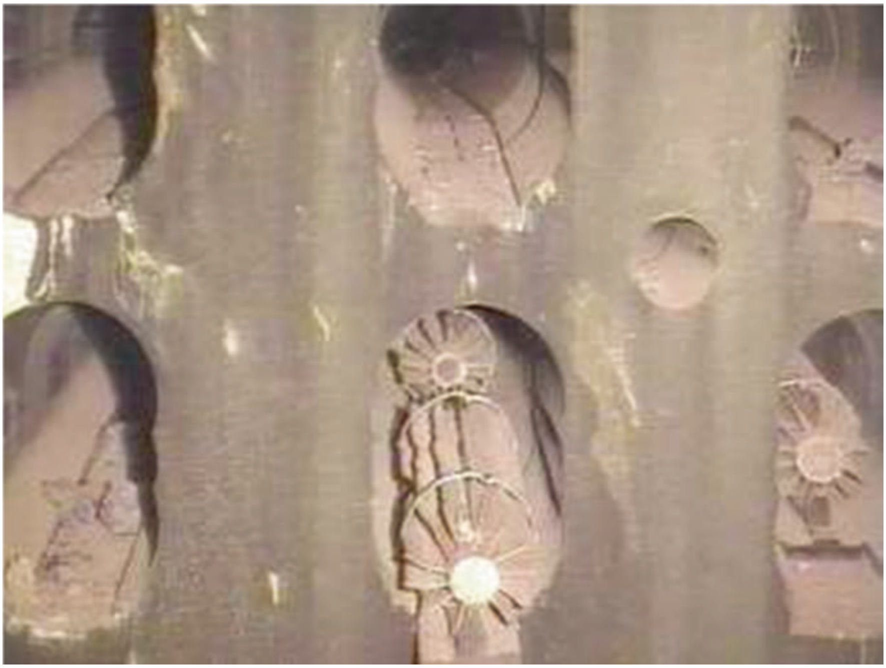


Photo 2.2 Fuel cartridges in the channels in the graphite. The fuel elements were loaded from the front of the piles, then during unloading, they were pushed towards the exit, from the back, where they fell into a compartment full of water. The sole purpose (not electricity production) of this reactor being to produce plutonium 239, the fuel elements were recovered after a short burn-up (so that the plutonium would be as rich as possible in plutonium 239), and then sent to a separation plant located on the Windscale site in order to limit the transport of dangerous materials. Within this plant, they were stored in a large pool to reduce their activity and their temperature because of the residual power

Photo 2.3 Drawing of a fuel cartridge with a uranium rod clad in aluminum and cooled by blades. Heated aluminum ignites easily in air, as does magnesium

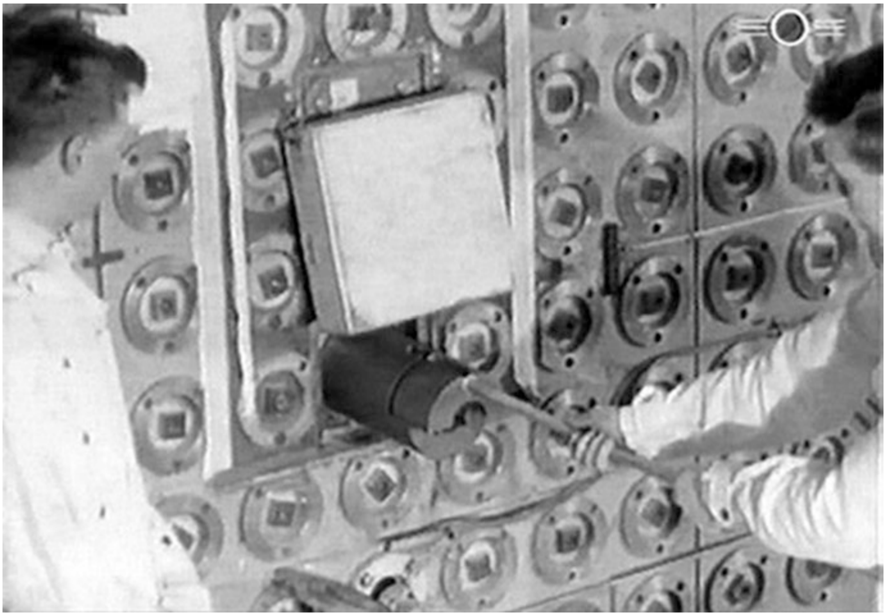


Photo 2.4 Handling in normal situation of a cartridge in front of the loading face of Windscale. The white parallelepiped is probably a biological protection. During the accident, it is with long steel rods that the courageous operators will push the cartridges towards the front face of the reactor. We notice that the operator on the right does not even have gloves, perhaps because the reactor is shutdown at the time of the photo

admissible temperatures due to the relatively low melting point of aluminum (660.3 °C). The load can be carried out continuously, pile in operation, thanks to a platform-hopper which positions the cartridges horizontally in the core by the loading face. The cartridges are loaded by pushing them through a push rod handled by manual operators. When a cartridge is loaded, the last cartridge is ejected from the channel into a recovery compartment filled with cooling water located below the other side of the reactor (Fig. 2.4). The (vertical) columns of graphite are pierced with horizontal fuel channels. The power of the pile is regulated by 12 horizontal control rods inserted on each side (24 rods in total). A set of 16 vertical shutdown control rods could drop vertically by gravity into the core in case of emergency. A group of 8 blowers was used to cool the core with air. A detection system made it possible to alert if a fuel channel released fission products. On October 3, 1952, the British detonated their first atomic bomb using plutonium extracted from Windscale, on an uninhabited atoll off Australia.

The phenomenon of Wigner energy storage was unknown when Windscale started. Lorna Arnold (Arnold 2007) reported that a first incident had occurred in May 1952 in pile n°2, where an unexplained increase in temperature was observed, which could be controlled by increasing the flow of the blowers. An identical phenomenon appeared in the pile n°1, which caused a light fire of lubricating oil of the plant blowers, which had escaped in the core. The understanding of the physical phenomenon made it possible to attempt a voluntary annealing in pile n°2 in January 1953. The operation was successful, and a rapid increase in temperature was observed in the lower part of the pile, after having operated the pile at reduced power for a certain time. From this point on, many voluntary anneals were successfully performed. The annealing procedure became standard and consisted of instrumenting the core with 66 thermocouples to monitor the annealing, which were removed during normal production period. Unfortunately, only one of these thermocouples was continuously readable and allowed to visualize the dynamic behavior of the heat up. In fact, the behavior of the pile was different at each annealing, which was attributed to "pockets" of graphite that had not properly released their Wigner energy, without being noticed by the thermocouples, especially in the areas near the load face where the Wigner energy was maximum because the graphite temperature was lower. This zone, difficult to access for the instrumentation, was not investigated in the end, so that the operator did not have access to the hottest point of the reactor during the annealing process.

On October 10, 1957, at 4:30 p.m., during the ninth annealing of pile n°1 begun on October 7, a fire broke out in the center of the reactor. Following a first low-power nuclear heating (2 MWth i.e., about 1% of the power of the pile), the temperature had risen to a little more than 200 °C, which made it possible to hope that the beginning of the release of Wigner energy would be sufficient to initiate the total annealing of the pile, making it possible to shut down the thermal chain reaction, which was actually done. But the temperatures seemed to stabilize and even decrease, suggesting that the annealing was incomplete and weakening. The reactor was diverged again, allowing the temperature to rise to 330 °C, and then the reactor was shut down again. On October 9, the temperature rose rapidly to over 400 °C. The fan doors were opened to air cool the pile according to official procedure. On October 10, radioactivity was detected in the stack of pile 1, an unusual occurrence since the pile was shut down at this stage of annealing. From noon onwards, the radioactivity increased at the chimney outlet. The temperature continued to rise, so that the staff started the blowers again to cool the reactor, which was like blowing air on a fire! One think then of a failed cartridge and not yet of a fire. It is then decided to open a channel to check in visu the suspect channel. The four visible channels were red hot and so distorted that it could not be possible to eject them! With long steel rods, the operators ejected the surrounding channels to prevent the fire from spreading to the rest of the pile.[7] The temperature of the pile measured now exceeds 1200 °C to the great horror of the physicists present in the control room.

In the end, 120 channels were on fire. Personnel will perform heroically by relentlessly pushing the partially burning fuel cartridges toward the back side of the pile with all available steel rods, protected only by portable respirators and conventional protective suits. On October 11, an attempt was made to inject carbon dioxide from the Calder Hall plant to try to smother the fire, but without any noticeable effect, because the quantities of gas were too small. It should be noted that tests carried out in France afterwards showed that it was very difficult to cool down a graphite fire even with argon. One can imagine that the graphite burns at least during a certain time thanks to the oxygen trapped in the carbon matrix, which degasses. Water was then brought in with the means at hand because no connection was foreseen (in particular, no water was to be present in the reactor building to avoid any criticality risk). Despite the risk of a steam explosion, the personnel sprayed with great apprehension (because of the criticality risk!) the pile on top in the hope of extinguishing the fire, initially with a minimum flow. After an hour of injection and the shutdown of the fans that kept a breathable atmosphere in front of the loading face, the situation improved. The paradox was that the cooling of the pile by air inevitably maintained the fire. For 30 hours, the pile was flooded by pumping water that had become highly radioactive after its passage through the core from the pit below the core to tanks. The situation was deemed to be under control on 12 October, the pile having become cold again. No special measures were taken regarding the population, and the local police were only notified one day after the first detection of radioactivity. Later, the government bought back contaminated milk from local producers at a generous price to avoid any local discontent (Fig. 2.5). two million liters of milk will finally be pierced into the Irish Sea.

The authorities communicated rather evasively on the affair under cover of defense secrecy, and a commission of inquiry was set up in October 1957, the Penney Commission , to draw the first conclusions of the accident. The main conclusion is that it was the second nuclear heating that was too fast and too close from the first, which must have produced ruptures of the cartridges, the

[7] We are still amazed by the "radiation protection" aspects of this operation, as the operators are almost in contact with the spent fuel.

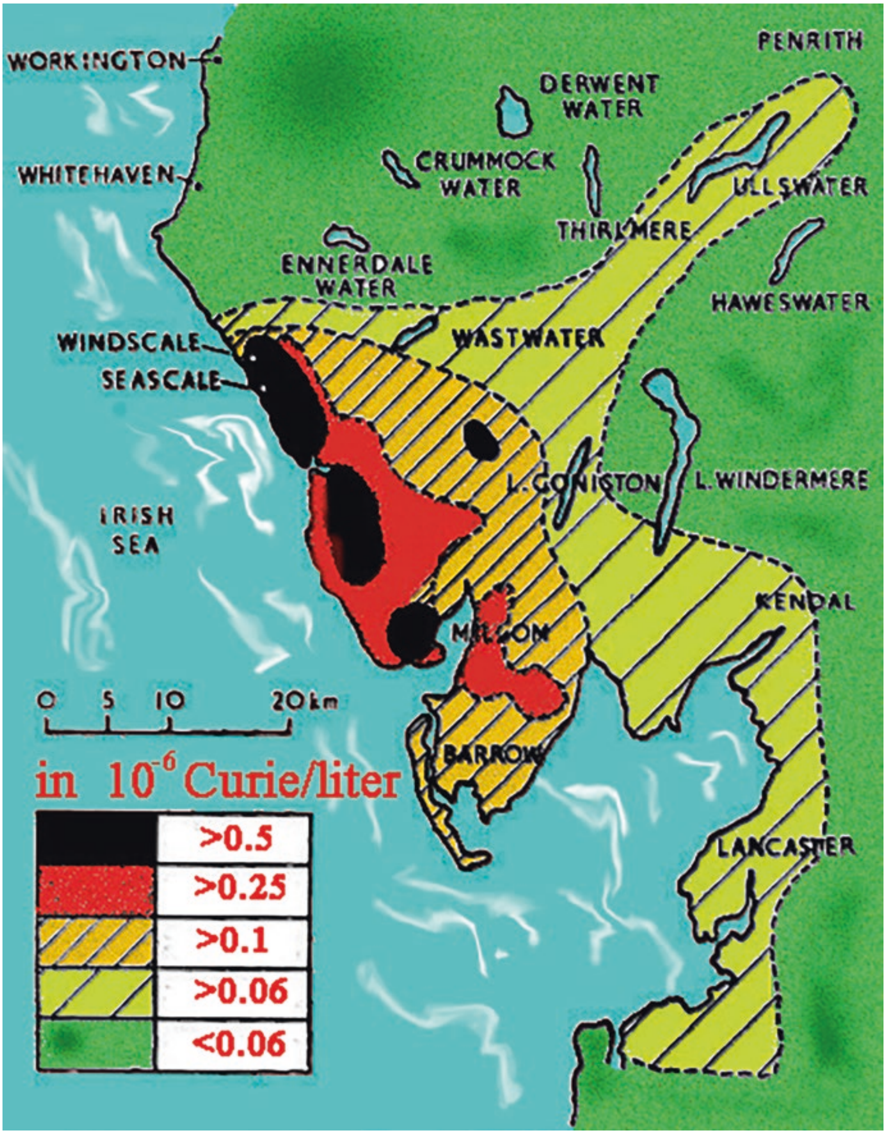


Fig. 2.5 Iodine activity in milk as of October 13, 1957

oxidation of the uranium then adding to the temperature excursion. The possible oxidation of the magnesium in the cartridges containing lithium placed there to make military tritium is another scenario that has been mentioned. The inadequacy of the location of the thermocouples is also widely criticized, as well as the absence of clear written operating procedures for annealing. The absence of what is now called an Internal Emergency Plan (IEP) was also pointed out. To be honest, nothing had been planned! The Penney report, which was very factual, was not made public in the end, under the pretext of defense secrecy. A watered-down version of the Penney Report was finally published in the *White Paper* on the Windscale accident. While the Penney report exonerated the operators, the White Paper seems to point the finger at the failures of individuals, presenting annealing as a routine procedure poorly managed by the operators, and insisting on the absence of risk in the case of the British Magnox reactor type used for energy production (cooled with carbon dioxide). In the end, it is especially the lack of knowledge on the behavior of burn-up graphite, in a context of all-out development of reactors in England, that raises questions. It was not until 1958 that these graphite problems were studied in detail. Reactor 1 was definitively shut down and Reactor 2 was also shut down shortly afterwards, because the cost of upgrading the instrumentation was considered unreasonable in relation to the life expectancy of the reactor. This expectation was reduced by the fact that the analysis of some graphite samples from reactor 2 showed oxidation rates 3,000 times higher than the expected average! As the excursion temperature of oxidation of carbon in the air is of the order of 320 °C (for oxidation in the mass of graphite), and as the release of Wigner energy raises the air temperature to at least 250 °C, this leaves a very small margin of barely 70 °C between the two thresholds for an annealing that does not massively oxidize the graphite. It is this technical observation that will finally sound the death knell for Reactor n°2. The plutonium will then be produced in the more powerful Calder Hall power reactors.

A significant amount of radioactivity was finally released during the accident, estimated today at 740 *TBq*[8] (20,000 *Ci*[9]) of ^{131}I, 22 *TBq* (600 *Ci*) de ^{137}Cs, 3 *TBq* (80 *Ci*) of ^{88}Sr and 330 *GBq* (9 *Ci*) of ^{90}Sr. At noon on October 10, the wind was light with a tendency to blow from the southwest. But at the start of the accident, the winds strengthened as they turned north and then northwest on the morning of October 11, sending easily detectable releases as far south as Yorkshire, largely to the southeast. The main iodine deposition was over Lancashire and Cumberland. By the end of the 11th, the plume reached Belgium, Frankfurt in Germany by the end of October 12, and even Norway on the 15th. France was largely spared because the wind flux was along the northern border with Belgium. The initial plume, oriented from the

[8] 1 Tera Becquerel (TBq) = 10^{12} Bq.

[9] One *Curie* equals 3.7 10^{10} *Becquerels*. 1 *Becquerel* corresponds to one disintegration per *second*. One *Curie* corresponds to the activity of one gram of radium 226 (3.7 10^{10} *Becquerels*), discovered by Marie Curie.

plant towards the southeast and running roughly along the coast, very quickly deposited radioactivity that significantly contaminated the soil over a distance of about 10 kilometers, hence the contamination of cow's milk in this farming region, since no containment measures had been taken. As for the operators, the thyroid dose measurement on 96 persons indicates a maximum dose of 9.5 rads,[10] the second highest being 2.1 rads and an average of 0.4 rad by inhalation of iodine 131. Outside the building, the maximum dose equivalent recorded over 13 weeks was 4.7 rems, well below the 12 rems recommended at the time.

It was not until the 1990s that epidemiological studies were published to try to determine the real impact of the accident. A controversy occurred in the 1980s when a librarian from the University of Newcastle-upon-Tyne, John Urquhart, contested the official figures of the low number of radiation-induced cancers by calculating the dose induced by polonium 210, isotope produced by the burn-up of bismuth 209 for military purposes[11] (polonium is used as an α-emitter to initiate fission in bombs though reaction (α,n) on beryllium). Polonium 210 is extremely radiotoxic, as the case of the poisoning of Alexander Litvinenko proved to the public in 2006 in England.

Vandellos, a Fire of Turbo-Blowers (Spain, 1989)

In terms of fire, we should mention the accident at the Natural Uranium-Graphite-Gas (UNGG) reactor No. 1 in Vandellos near Tarragona, Spain. This 480 MWe reactor is the twin of the French reactor of Saint Laurent de Eaux-A2, since it was built by a Franco-Spanish "joint venture" with HIFRENSA (*HIspano-FRancesa de Energia Nuclear*) in November 1966. It brought together EDF and Catalan producers, of which EDF held 25%. This was an attempt to export French nuclear know-how at the initiative of General de Gaulle and General Franco. Work began in 1968 (Photos 2.5 and 2.6), and the reactor was put into operation in 1972 (Photo 2.7). The reactor being of continuous fuel load, General Franco did not hide his ambitions of a Spanish

[10] The rad is the old unit of dose and corresponds to 0.01 Gray = 0.01 J/kg.

[11] This bismuth irradiation would have been largely hidden because the British government did not want it to be known that the bomb starters were still manufactured at that time by such an obsolete means. The bomb primers were not made like that already at that time by the other countries and the British showed a certain delay in the matter.

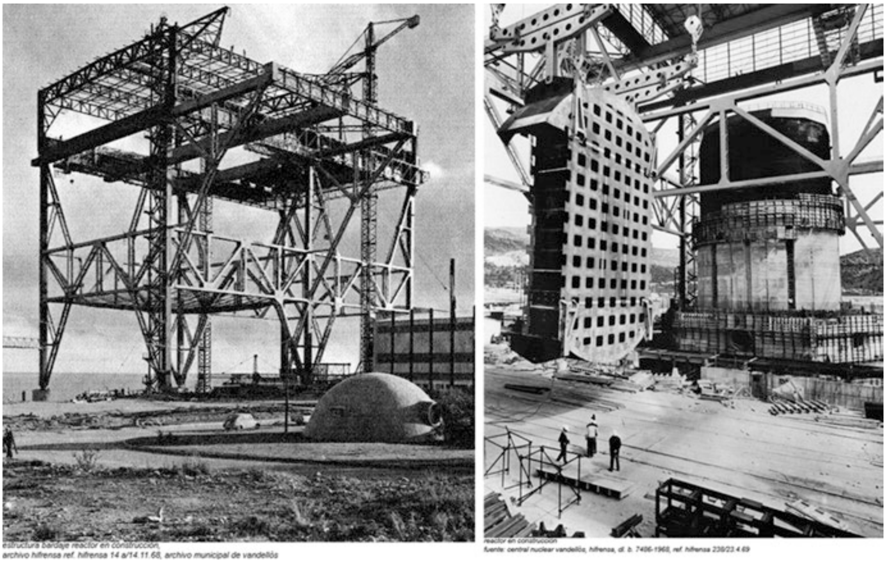
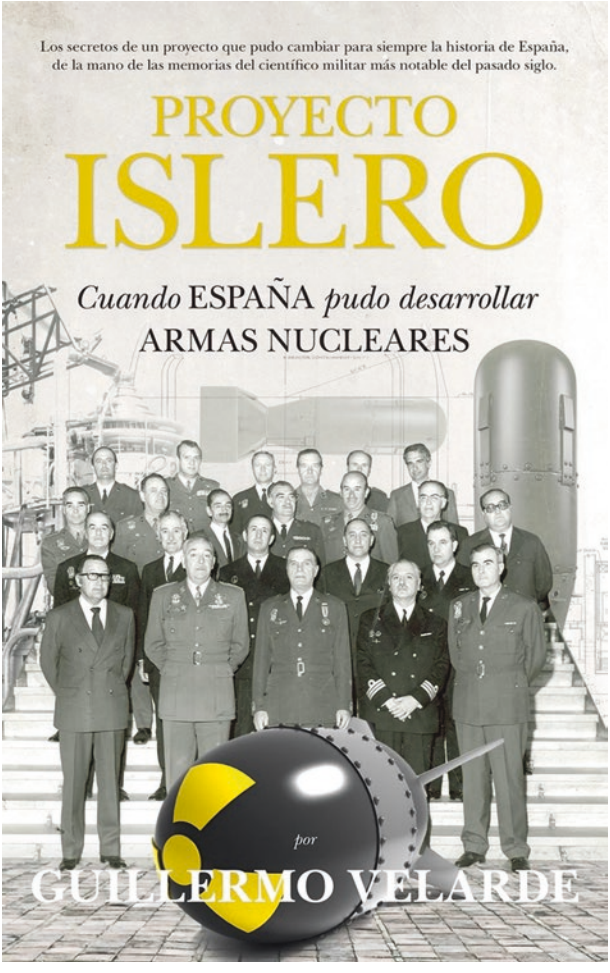


Photo 2.5 Construction work: Siding, pouring the concrete of the caisson and loading face (municipal archives of Vandellos)

Photo 2.6 Assembly of the inner containment and the lower compartments and support of the graphite block (municipal archives of Vandellos)

atomic bomb[12] based on plutonium 239, perhaps with the help of France (it has been said that General de Gaulle would not have been opposed to help (?), De Gaulle was known to be hostile to American domination within NATO).

[12] This is the *Islero* project, which began secretly in 1963 and was led by José María Otero de Navascués, director of the equivalent of the French Atomic Energy Commission (*Junta de Energía Nuclear* or JEN). The project relies on the production of plutonium 239 by Vandellos-1, which Franco intends to keep, on the model of what France did at the end of the 1950s with the G reactors at Marcoule, and on French assistance for a plutonium separation process. The pressure of the Americans, allies of Spain during the Cold War, and who feared scientific dissemination, put an end to this dream of greatness.



The book of Guillermo Velarde well documented on the question.

Photo 2.7 The Vandellos-1 plant in Spain

On the night of October 19, 1989, alarms began to sound in the control room of the Vandellos-1 nuclear plant. The first alarm announced the strong vibration of one of the shafts of the generator turbine. Several alarms went off when suddenly the operators heard explosions. A fire broke out from 9:39 p.m. in the generator in the turbine building. In fact, a shear crack in the shaft of turbine n° 2 led to a clean fracture, destroying 37 of the 92 blades of the turbine, causing rapid decompensation of the turbine. The rapid braking of this 5-tons turbine ignited the lubricating oil of the shaft bearings by friction. The explosion was amplified by the destruction of a hydrogen outlet terminal (cooling of the alternator). The flames spread at high speed, causing severe damage to the reactor cooling systems, and the fire was visible for miles around. This fire spread to the electrical circuits. Two of the four turbo-blowers that circulate the carbon dioxide coolant in the reactor were destroyed. The other two were accidentally drowned by firefighters in an attempt to reduce the fire. Josep Pino, chief of the Amposta fire station called to the rescue, will say "*The technicians fled the affected premises, and we were left alone; some technicians were taking water samples and others were calling France,*[13] *while we were shouting "the reactor is running away, the reactor is running away!"* (quoted by Mr. P. Pons in an article in El Païs). "*Along the way, I heard "if the*

[13] France sold the reactor in the early 1970s.

alternator burns out, does it affect the reactor?" This only made me more worried. When I arrived, the access barrier was up, and people were fleeing in a hurry because at first you have to evacuate those who are not essential. But of course, I did not know it at the time", recalls Fèlix González, head of the emergency region of *Tierras del Ebro*, who was at the time in charge of the *Reus* fire station. Those in charge of the plant immediately called the employees who were on call, such as Carlos Arriola, who worked on the mechanical maintenance of the plant. "*There was a lot of smoke, the priority was to get the water out. I was one of the first to go down the reactor pit. There was almost no lighting, the sound of alarms, drums floating, a meter and a half of water deep*..." he recounts. "*One firefighter kept saying to me, 'But are we safe here?' We were up to our necks in water, and we didn't know if it was contaminated, until I tasted it, and luckily it was salty.*[14]" Most of the plant's staff came to help out with the problems. "*We were the only ones who knew about the plant and could solve the situation.*"

With difficulty, the operators finally managed to cool the reactor with the secondary cooling circuit, to prevent a general flashover of the graphite block, the situation that had occurred at Windscale. The accident will be classified afterwards as 3 on the INES scale and it is considered that only the firemen, who intervened without much preparation, were exposed to ionizing radiation. Repairs proved too costly (Photos 2.8, 2.9 and 2.10), the reactor was finally definitively shut, then progressively dismantled, and a sarcophagus was built around the reactor (Photo 2.11).

A week after the accident, a new failure due to a short circuit in an auxiliary transformer caused a small fire and a plume of smoke that panicked the surrounding population for no reason, causing a spontaneous evacuation.

Vinča, a Serious Criticality Accident (Винча, 1958)

After the Second World War, Eastern countries also embarked on the race to the atom under the impetus of the Russian big brother. However, Yugoslavia was a special case because Marshal Tito did not align himself strictly with the USSR, adopting a more open policy with the West. In 1958, a nuclear program was launched at the Institute of Nuclear Sciences « *Boris Kidrič* » of

[14] Thus, coming from the sea and not from the reactor.

Photo 2.8 Photo taken outside (shadow of the photographer) probably showing a fan motor cowling damaged by the fire (photo J.L. Sellart)

Photo 2.9 Firefighters and technicians after the fire in an unidentified area of the reactor

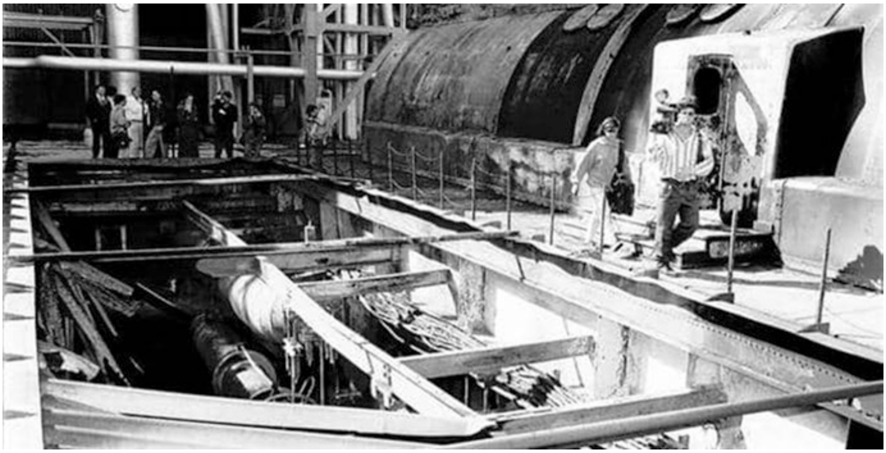


Photo 2.10 Journalists and photographers visit the degraded installation without special protection

Photo 2.11 Hexagonal sarcophagus from Vandellos-1 in 2014

Vinča, 15 km from Belgrade (Институт за нуклеарне науке Винча) and 2 km from the Danube (Photo 2.12). The institute was founded on January 21, 1948, and named after the leader of the Slovenian Liberation Front against the Nazi occupiers during World War II. The institute was placed under the

Photo 2.12 The site in Vinča in 1952. Building 2 is the physics department. Building 4 is the department of physical chemistry, building 5 is biology, building 6 is the particle accelerator V15, building 7 is the library, building 8 is radiobiology

authority of Professor Pavle Savič,[15] specialist in physical chemistry, trained at the Radium Institute in France, then former collaborator of the great Soviet

[15] Pavle Savič (Павле Савић, 1909–1994) is a Serbian physicist and chemist. He graduated in 1932. In 1936, he received a six-month scholarship from the French government to study at the Radium Institute in Paris; instead of 6 months, Savić stayed in France for 4 years. In 1937 and 1938, he worked with Irène and Frédéric Joliot-Curie on research relative to the action of neutrons on heavy elements. Together with the Joliot-Curie couple, Savić was nominated for the Nobel Prize in Physics. Savić returned to Yugoslavia to fight as a partisan against the German occupation. After the war, he was one of the first promoters of the idea to build the Institute of Nuclear Sciences in Vinča. He was the director of the Institute from 1960 to 1961. In 1966, he returned to his position at the University of Belgrade. He was elected president of the Serbian Academy of Sciences and Arts from 1971 to 1981.

Savič in Paris-1937. Serbian stamp in honour of Savič.

physicist Piotr Kapitsa. Although the idea of producing a Yugoslavian atomic bomb was evoked at the beginning, the Institute quickly turned to more peaceful and more affordable applications. A group of reactor physics was constituted in 1955 whose first task was to produce heavy water, an expensive liquid because its production requires much electric energy.

Two nuclear research reactors were built there, the RA and RB reactors, the largest of which, the RA reactor, had a power of 6.5 MWth and was fueled by 80% enriched uranium from the Soviet Union. The RB reactor was what is called a zero-energy reactor, in fact of very low energy, from a few 10 mW to about 50 Watts, to carry out critical experiments first with a natural uranium (metal) assembly moderated[16] by heavy water. Heavy water is a compound whose hydrogen is composed almost entirely of deuterium atoms ^2H while ordinary water is made of ^1H. To indicate deuterium, physicists usually use the symbol D and note the heavy water D_2O, while ordinary (or light) water is noted H_2O. Heavy water is a better neutron moderator than light water because of its near absence of neutron capture. The objective was to measure precisely the height of heavy water in the vessel of the small reactor and the bulge of the neutron flux by the method of measuring the critical buckling.[17] To do this, a 10 mm aluminum vessel (a light metal with a density of 2.7 compared to water) is mounted on a platform more than 4 m away from any surface that could reflect neutrons (this is called a reflector). The vessel can contain 6.36 m^3 of heavy water. The vessel is closed by a 7 cm aluminum cover with two small inspection windows. The presence of reflectors would reduce the critical size of the reactor and thus the mass of fissile material required (this is called the critical mass). The supporting structure (Figs. 2.6 and 2.7, Photo 2.13) is made of aluminum and can support a weight of 15 tons. Two working platforms allow the operators to control the pile. It is placed in the center of a pond 8 × 8 m wide and 1.5 m deep, which serves as a backup receptacle for heavy water in case of an incident.

The reactor (Fig. 2.8) is presented as a lattice of cylindrical fuel rods made of metallic uranium, 2.10 m high, 2.5 cm in diameter, and with a square pitch of the rod positions of 12 cm. The total weight of uranium is 3995 kg. The cladding of the rods is made of 1 mm thick aluminum. The rods are separated

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[16] Moderation represents the capacity to slow down neutrons by successive shocks. The more the neutron is slowed down, the better its capacity to fission uranium, because the probability of fission of heavy nuclei increases when the speed of the neutron decreases.

[17] The method of the critical buckling consists in measuring the radius of curvature of the 3D neutron flux shape in the core. Without going into detail, this radius of curvature is related in critical situation (stable reactor) to the neutron properties of the fissile material of the reactor and to the geometry of the pile in what is called the "*fundamental mode.*"

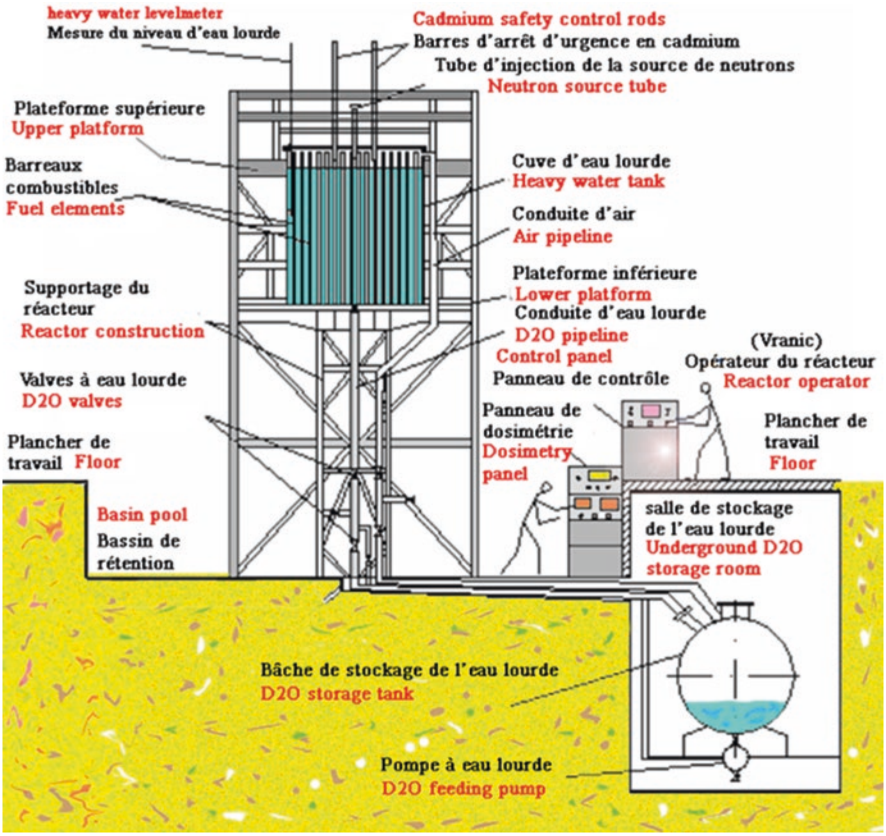


Fig. 2.6 Position of the most affected operators during the Vinča accident in Yugoslavia (15 October 1958), adapted from M. Pesič: *Some examples of accident analyses for RB reactor*, IAEA Technical meeting on Safety Analysis for Research reactors, Vienna, Austia, 5–7 June 2002)

by two grids at the top and bottom of the vessel. The absence of power simplifies the cooling of the reactor (Fig. 2.9).

On October 15, 1958, 6 months after the start-up of the first core, during a criticality experiment on the RB reactor, a bad evaluation of the height of heavy water necessary to make the device critical, led to a power excursion of the heavy water research reactor, following a bad adjustment of the heavy water level. The rate of rise of the heavy water in the vessel was rapid: 2.5 cm/min. With the water level at 175 cm, 3.5 cm below the expected critical level, the operating team was distracted by non-team personnel entering the hall. The crew intended to stabilize the reactor at 177 cm just below the critical level, but the booster pump was allowed to run due to distraction, and the

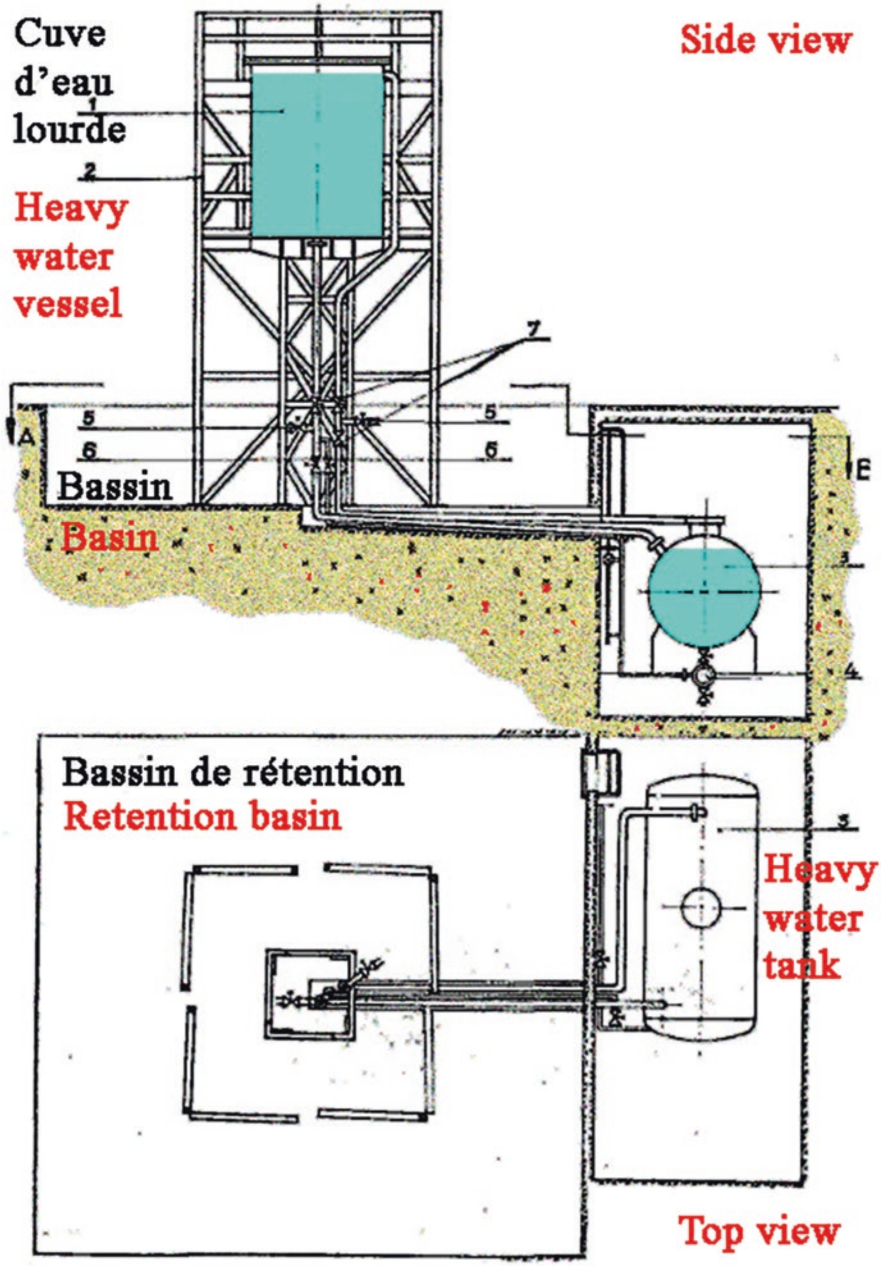


Fig. 2.7 View of the RB installation. 1: Reactor vessel, 2: Supporting structure, 3: Heavy water filling tank, adapted from (D. Popovič, S. Takač, H. Markovič, N. Raisič, Z. Zdravkovič, j. Radanovič: *Zero Energy Reactor « RB »*, Bulletin of the Institute of Nuclear Sciences "*Boris Kidrič*," Vol. 9, N°168, March 1959, Laboratory of Physics)

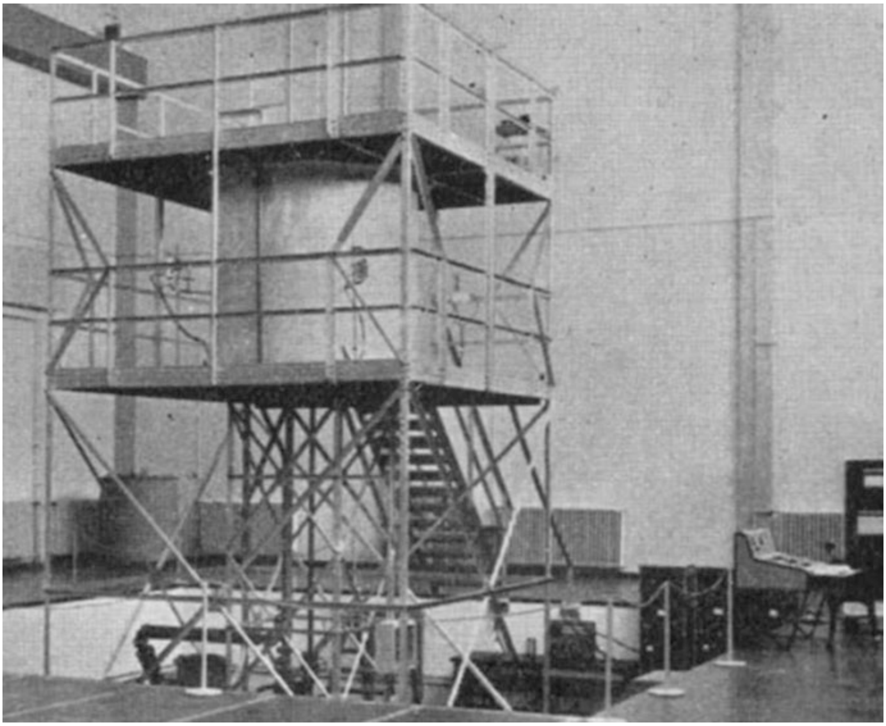


Photo 2.13 Photo of the RB reactor in 1958. One can recognize the vessel placed on its support, itself placed in the pond with white walls in unevenness compared to the service desk. The control consoles are visible on the right of the picture, a few meters away from the building, without any particular biological protection

level continued to rise. The instrumentation used for dosimetry and the alarm systems were disconnected or partially removed, a serious mistake with serious consequences. 84 s after reaching the 175 cm level, the 178.5 cm level was reached, and the pump, still operating, raised the level to 4.5 cm above the critical level! The reactivity and power of the reactor then began to increase. Two BF_3 neutron radiation counters saturated during the power excursion, still without worrying the operators. A third counter, suspected to be out of service, was turned off. Yet another automatic recorder, located 540 m outside the hall and responsible for measuring air activity and possible radioactive deposits, did measure this power and gamma radiation increase for about 10 min. It is estimated that the heavy water level remained too high for 433 s.

The term *criticality* can mislead the reader. Indeed, for the reactor to remain in a stable operating condition, it must be critical, whereas the word in its common meaning rather raises concern. To reach this state, heavy water is slowly raised in the vessel. As long as the water level does not reach a "critical

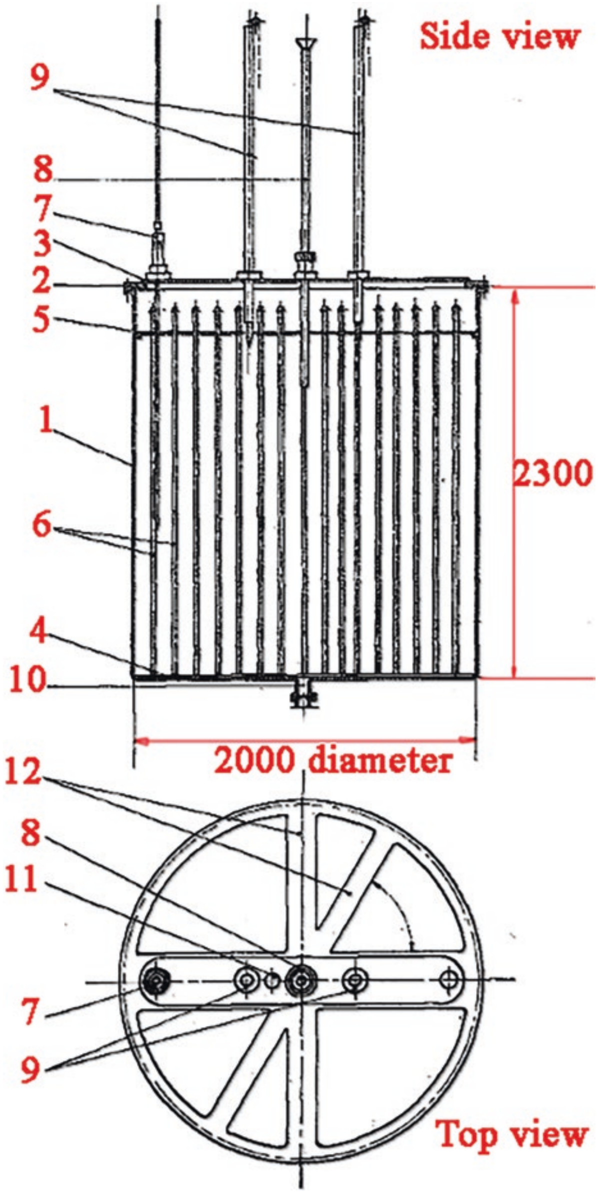


Fig. 2.8 Schematic of the RB reactor. 1: Aluminum reactor vessel (10 mm), 2: Aluminum vessel cover (7 cm), 3: Instrumentation channel cover, 4: Lower fuel rod grid, 5: Upper fuel rod grid, 6: Uranium rods, 7: Heavy water level measurement, 8: System for injecting the 500 *milliCurie* (Radium-Beryllium) neutron source per reaction (α, n), 9: Two neutron safety absorber rods, 10: Bottom of the vessel with the heavy water inlet and outlet, 11: Two sight glasses, 12: Radial ribs as stiffener

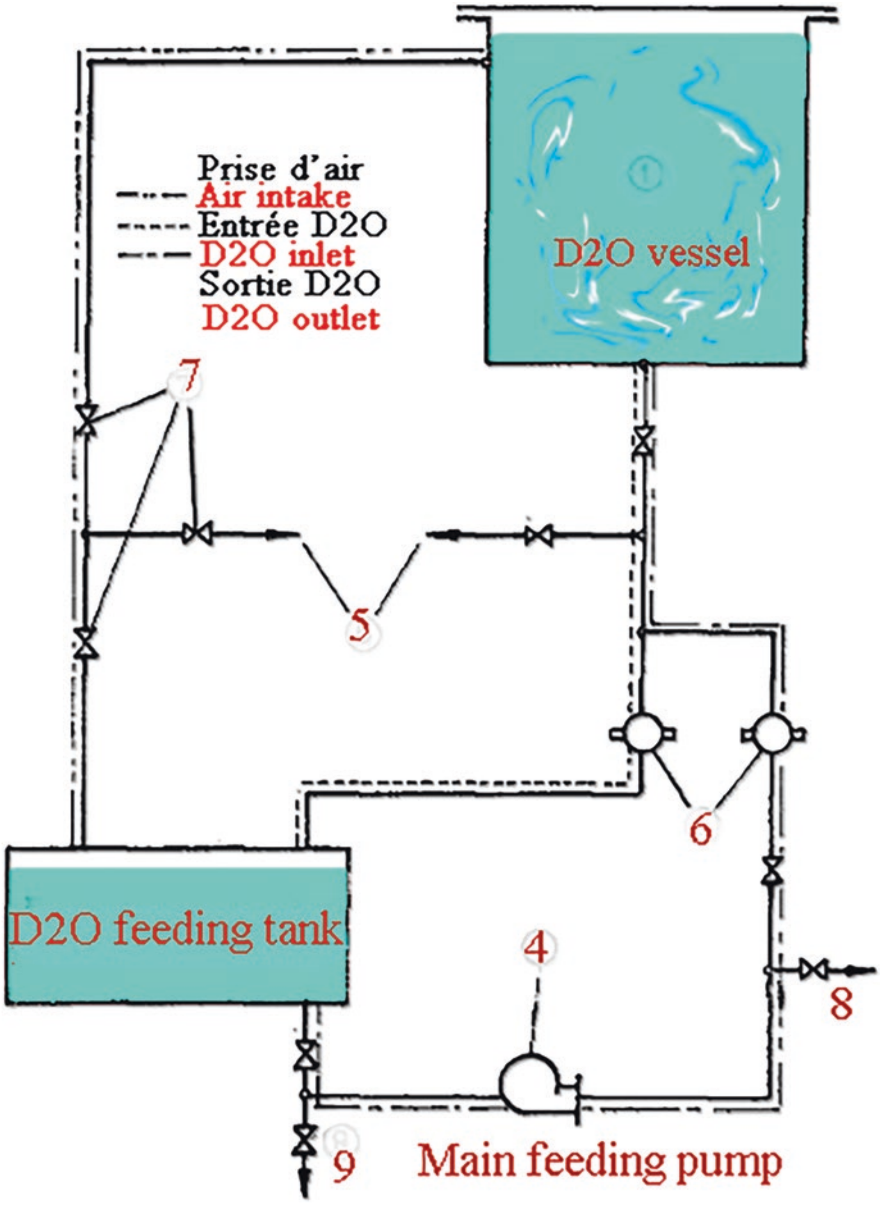


Fig. 2.9 The filling circuit of the RB reactor. This circuit does not even contain a heat exchanger since the pile is not supposed to produce energy. As heavy water is very expensive, it is carefully collected in a tank when the reactor vessel is emptied. The circulation of dry air prevents the heavy water from becoming loaded with moisture, which would lower its deuterium content

level" calculated by clever physics calculations, the reactor is said to be subcritical and cannot maintain a stable level of neutron flux unless an external neutron source is introduced. When the critical level is reached, i.e., 178.5 cm ± 0.1 cm at 22 °C estimated by Yugoslavian physicists, the reactor becomes stable, and the production of neutrons by fission is compensated by the disappearance of these neutrons by absorption and by leakage from the reactor. If the critical level is exceeded, the reactor is said to be over-critical and runs away. Its power increases until the heat up of the fuel causes what reactor physicists call the Doppler effect to appear. This Doppler effect results from a very strong absorption of neutrons by uranium 238 present in the nuclear fuel, when the temperature of the fuel increases. This absorption leads to a very rapid power decrease of the reactor, which will re-diverge when the reactor cools down if the geometric conditions and the chemical compositions of the materials remain unchanged. If the temperature has risen sharply during the power excursion, there is a possible loss of critical geometry by mechanical explosion or by evaporation of the liquid in the reactor. In the case of the Vinča accident, no explosion but a relatively slow power excursion producing a flash of gamma rays and neutron flux. The overflow of the critical water level engaged the reactor in a so-called "over-critical" behavior. This excursion is generally accompanied by a flash of greenish light in the air and by the production of ozone O_3[18], which has a characteristic odor similar to bleach. Ozone is produced in the presence of an intense electric field (e.g., as in transformers), in this case, produced by the charged particles produced by the fissions. This release of ozone was detected olfactory by an operator who operated the reactor shutdown system (insertion of the safety rods), but six people close to the vessel were strongly irradiated. The core itself was not damaged because there was no explosion as such (contrary to what is suggested by the comics strip Figs. 2.10, 2.11, 2.12, 2.13, 2.14 and 2.15).

The subsequent heat up of the heavy water probably caused it to expand, and it is possible that some heavy water was discharged from the vessel through the air line at the top of the vessel, which was placed there to evacuate air when the water level in the closed vessel rose. Since the fuel rods were not degraded, this heavy water should not have been heavily contaminated by radioactive fission products. It must be understood that this type of criticality accident generally lasts only a few tens of milliseconds to a few seconds for

[18] Ozone is an allotropic variety of oxygen, less stable than the oxygen gas O_2. Ozone is detectable by the human sense of smell up to 0.01 ppm (parts per million). Ozone is known to the public through the ozone layer that surrounds the Earth between 13 and 40 km in altitude and which intercepts nearly 97% of ultraviolet rays. The hole in the ozone layer which is constantly growing at the North Pole worries scientists because too many ultraviolet rays cause skin cancers.

Fig. 2.10 The comic strip transcription of the human adventure of the rescue of the Vinča accident in the children's magazine *Okapi* No. 40 of July 1, 1973.The death of Albert Biron

Fig. 2.11 The Yugoslavian team

Fig. 2.12 Due to lack of information, the artists, although talented, describe rather the explosion of a power reactor than a modest experimental reactor. A fireball (!) surrounds the operator Vranic

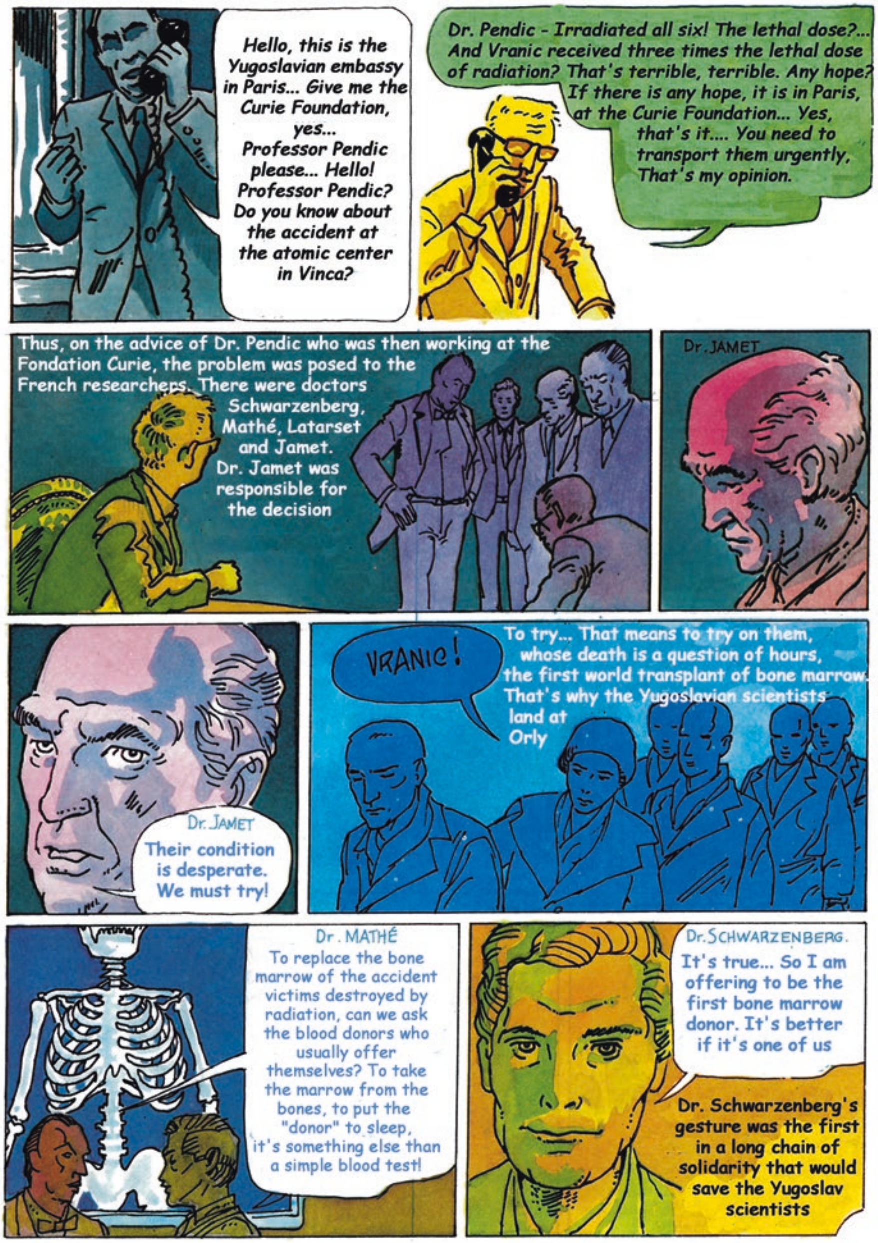


Fig. 2.13 The French medical team

Fig. 2.14 The D Day

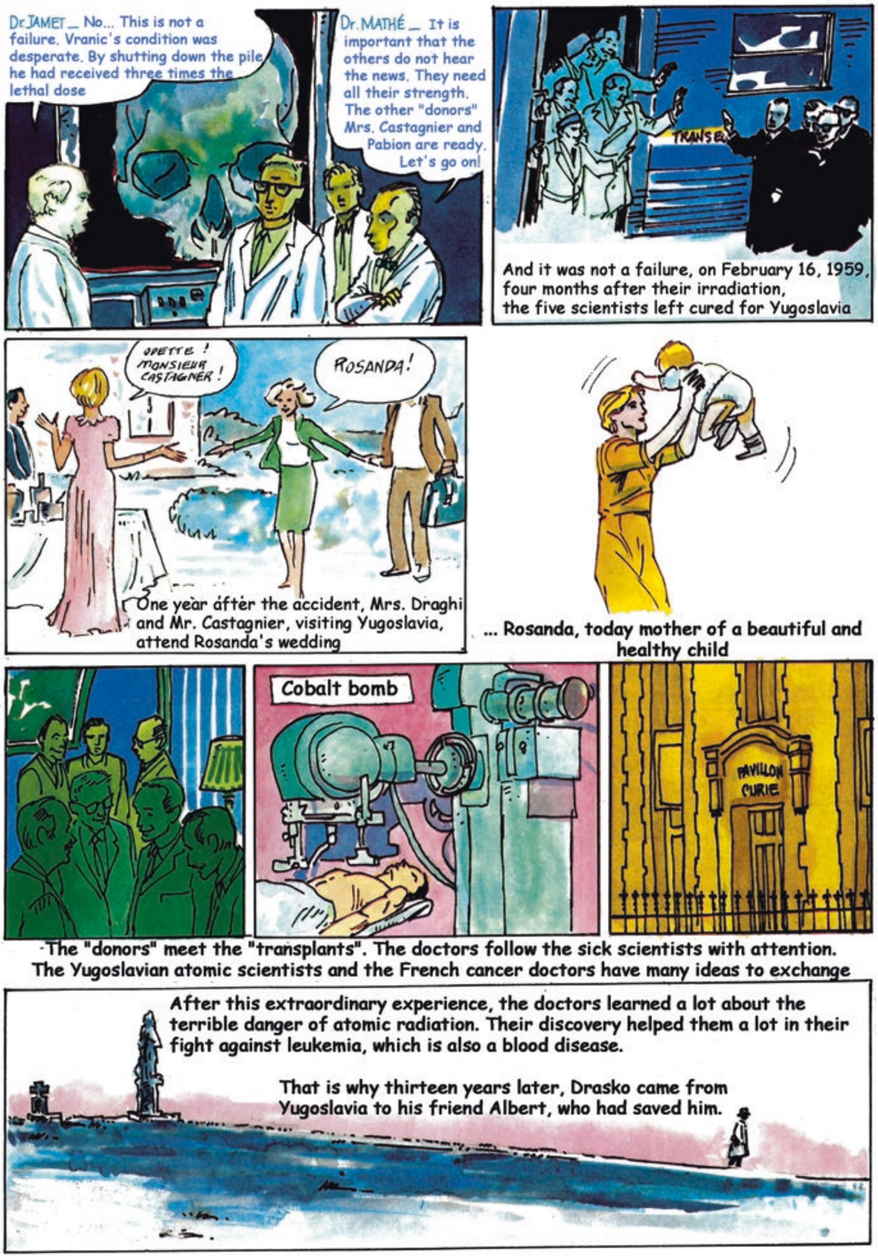


Fig. 2.15 Life wins over Death!

large over-criticality, and that only the fuel has time to heat up. In the present case, the power excursion linked to a weak over-criticality led the reactor into an overpowered state for about 400 s, which must have allowed the heavy water to heat up and expand thermally. The fact that there was a partial rupture of the vessel is not mentioned in the most serious references. The presence of contaminated water sometimes reported must rather refer to the badly managed draining of the air line. Neutron physics confirms that it is the Doppler effect that shuts down the power excursion, the emergency rod drop is only effective to ensure a subcritical geometry at the end of the accident (the power excursion is often faster than the rod drop). In the Vinča accident, recent calculations showed that the excess reactivity for a 4.5 cm heavy water surge was about +0.305 β_{eff}[19], i.e., a relatively moderate overactivity. Physicists know that rapid power excursions occur when the excess reactivity is of the order of or greater than β_{eff}. This means that the power excursion was finally slower and therefore longer than in the very fast accidents that we will describe in the case of the SL-1 reactor. The period of the reactor , i.e., the time for which the power is multiplied by the Neper constant (aka Euler constant) $e = 2.718$, is estimated at 12.3 s, leading to a power of 2.5 Mega Watt thermal with a total energy released during the excursion of 80 MegaJoules (Fig. 2.16), approximately 2.8 10^{18} fissions.

Six physicists and operators were standing near the reactor at the time of the accident: Radojko Maksič, Roksanda Dangubič, Draško Grujič, Živorad Bogojevič, Stjepan Hajdukovič and Života Vranič. Maksič and Vranič activated the shutdown via a control panel located very close to the vessel. It is estimated that Vranič, the closest to the reactor, experienced an irradiation of 433 *rem*[20] (4.33 *Sievert*), and the five other people were irradiated at

[19] The fraction of delayed neutrons β_{eff} expressed in pcm is used as a reference for whether the reactivity ρ is strong or not. When the ratio β_{eff}/ρ is small in front of 1, the overactivity is small, and the power excursion kinetics is relatively slow. This is the case for the Vinča accident, which will last on the order of 400 s. If this ratio approaches or exceeds 1, the kinetics become increasingly violent and the power peak will be much stronger, but the accident time much shorter. For the most violent peaks, the fuel core temperature will exceed the fuel melting temperature and the fuel rod will burst with dreadful consequences, releasing molten fuel into the medium surrounding the rods, heavy water in the case of Vinča (which did not happen because the supercriticality was low), light water in the case of Pressurized Water Reactors, or the pressure tubes containing light water in the case of Chernobyl. Such a release causes a steam explosion and the dissemination of highly radioactive fission products. In the case of Vinča, it was rather a flash of neutrons and photons that irradiated the operators.

[20] the rem or « *röntgen equivalent man* » is an old unit of measurement for equivalent dose. The unit now official since 1979 is the *Sievert* (symbole Sv). 1 rem = 10 milliSv. The rem is still widely used in industry. The equivalent dose takes into account the damage done to human tissues according to the type of particle (dose equivalent) whereas the dose in Gray is a unit of energy (Joule/kg). Above 4 Sv, it is estimated that 50% of those affected will die. Above 10 Sv, death is almost certain.

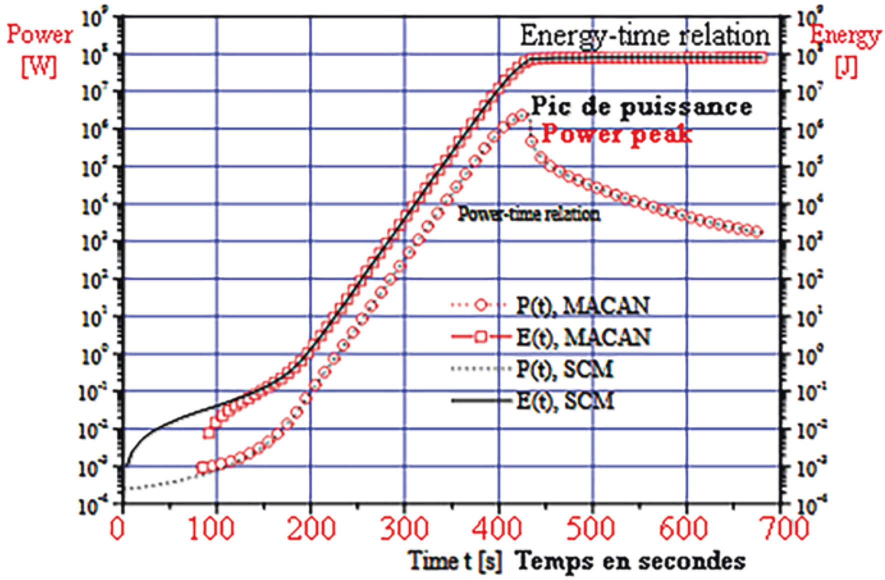


Fig. 2.16 Power excursion calculated by the MACAN and SCM calculation codes in the 1990s. It should be noted that the ordinate scales are logarithmic, i.e., each main scale is ten times the previous one. Paradoxically for the uninitiated, the power excursions are all the more violent as the initial power level is low, but the peak lasts less time because a high power leads to a higher temperature in the fuel, thus a stronger Doppler effect. A stronger Doppler effect will increase the absorption of neutrons and "crush" the power peak more quickly. We note a good match between the two calculation codes. Adapted from M. Pesič: *Some examples of accident analyses for RB reactor*, IAEA Technical meeting on Safety Analysis for Research reactors, Vienna, Austria, 5-7 June 2002)

205 - 320 - 410 - 415 and 422 *rem*. The day after the accident, the six irradiated were transferred to the hospital in Belgrade, but the Serbian doctors were baffled by this atomic disease described in the Japanese survivors of the atomic bombs of Hiroshima and Nagazaki, and on which the known medicines seemed to have no effect. Director Pavle Savič, a former student of Irene and Frédéric Joliot-Curie, called the Curie Institute in Paris for help. Savič learnt from professor B. Pendic of the Curie Foundation in Paris that the oncology

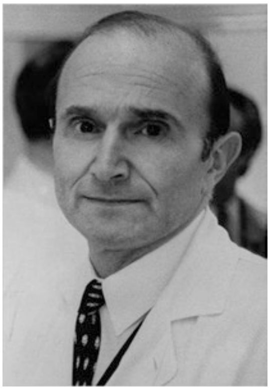


Photo 2.14 The Professor Georges Mathé

professor Georges Mathé[21] (Photo 2.14) experimented with a bone marrow transplant technique with his team. The French immediately agreed to treat the Serbian irradiated patients who were transferred to France as a matter of

[21] Georges Mathé (1922–2010) is a French oncologist. He was awarded a doctorate in medicine in 1950 (gold medal from the Paris Hospitals) and participated in the development of exanguino-transfusion, the first extra-renal purification procedure in 1948. He was introduced to immunology with Baruj Benacerraf in Bernard Halpern's laboratory in 1950, then to oncology with Joseph Burchenal at the Memorial Sloan-Kettering Cancer Center in New York in 1951. In 1953, he was appointed Chief of Clinic at the Faculty of Medicine in Paris, with Professor Paul Chevallier in Hematology at the Broussais Hospital. In 1954, he became assistant physician at the Paris hospitals, Deputy Director of the Research Center for Leukemia and Blood Diseases directed by Professor Jean Bernard at the Saint-Louis Hospital. The same year, he was appointed Associate Professor of Oncology at the University of Paris. In 1961, he became head of the hematology department at the Gustave-Roussy Institute in Villejuif, before founding the Institute of Cancerology and Immunogenetics (INSERM-CNRS). In 1963, he cured his first leukemia with a bone marrow transplant preceded by a irradiation. In the 1970s and 1980s, Georges Mathé participated in the development of poly-chemotherapy, cooperating in the development of several important molecules. When the AIDS epidemic appeared, he became interested in it as an immunotherapist and hematologist. In 1989, he designed a quintuple therapy that limited the side effects. He died on October 15, 2010, the anniversary of Vinča's accident, in the department he had created, at the Paul-Brousse Hospital in Villejuif. His research work resulted in the publication of more than 1000 articles and numerous books (adapted from Wikipédia and the Inserm website https://presse.inserm.fr/deces-du-professeur-georges-mathe/14728/).

Georges Mathé is honored worldwide as a pioneer in cancer research. On the left of the poster, the daughter of G. Mathé.

urgency on October 16, 1958 (Figs. 2.10, 2.11, 2.12, 2.13, 2.14 and 2.15). Mathé looked for donors in the Paris area to try to save their lives. It is important to understand that the technique was totally experimental and has never been applied to humans. The risk for both donors and recipients was significant.

Despite this, five Frenchmen agreed to donate their bone marrow for this last chance operation: the doctor and future professor Léon Schwartzenberg (member of the team of professor Mathé), Marcel Pabion, Albert Biron, Raymond Castanier and Odette Draghi, to whom we pay tribute here. The latter, although herself a mother of 4 children and informed of the risks of the operation, nevertheless insisted on helping by giving her marrow to Roksanda Dangubič. The operations took place from November 11 to 16, 1958. All the transplanted will survive, except the young Zivota Vranič (Photo 2.15), the most affected, who will die shortly after his transplant. Roksanda Dangubič will get married in the presence of Odette Draghi, and she will give birth to a perfectly healthy child. In the winter of 1972, Draško Grujič will come to the bedside of Albert Biron, who was very ill and who had given him his bone marrow, during the 3 weeks before his death. These bone marrow transplants gave great hope in the treatment of cancers, in particular leukemia. Professor Mathé kept all his life close links with Serbia by going regularly and free of charge to give treatments at the hospital of Belgrade (Photo 2.16).

Photo 2.15 Zivota Vranič was the young operator (24 years old at the time of the accident) who did not survive despite the bone marrow transplant given by Raymond Castanier. Vranič did not flee at the alert but helped bring the reactor back to subcritical, which ultimately cost him his life

Photo 2.16 Professor Mathé (left) in 2007 with Radojko Maksič at the opening of the cancer unit named after him at the "*Bežanijska kosa*" clinical center in Belgrade

Beginning in 1962, the RB reactor was modified several times, in particular by the introduction of uranium metal enriched to 2% and uranium oxide enriched to 80%. In January 1961, a French team from the CEA specialized in instrumentation (Jacky Weil, J. Furet…) contributed to an international IAEA dosimetry experiment by being in charge of monitoring and safety. Weil was the technician who had spotted the divergence criticality in Zoé, the first French reactor, on the millimeter paper of the neutron flux level recorder in 1948. The work of the French showed that the weight of the two cadmium control rod i.e.,−1300 pcm of reactivity, was still modest compared to the 1200 pcm of over-reactivity that could be reached in the event of total untimely filling of the vessel. This is why it was decided to add a third safety rod, making it possible to raise the anti-reactivity of the three rods to −2500 pcm. This additional rod will act as a water level control rod, its position being directly linked to the water level by a contact point. The control rod has been deliberately slowed down to a speed of 4 pcm/s to avoid any problem of untimely withdrawal (Fig. 2.17). The control room, which had

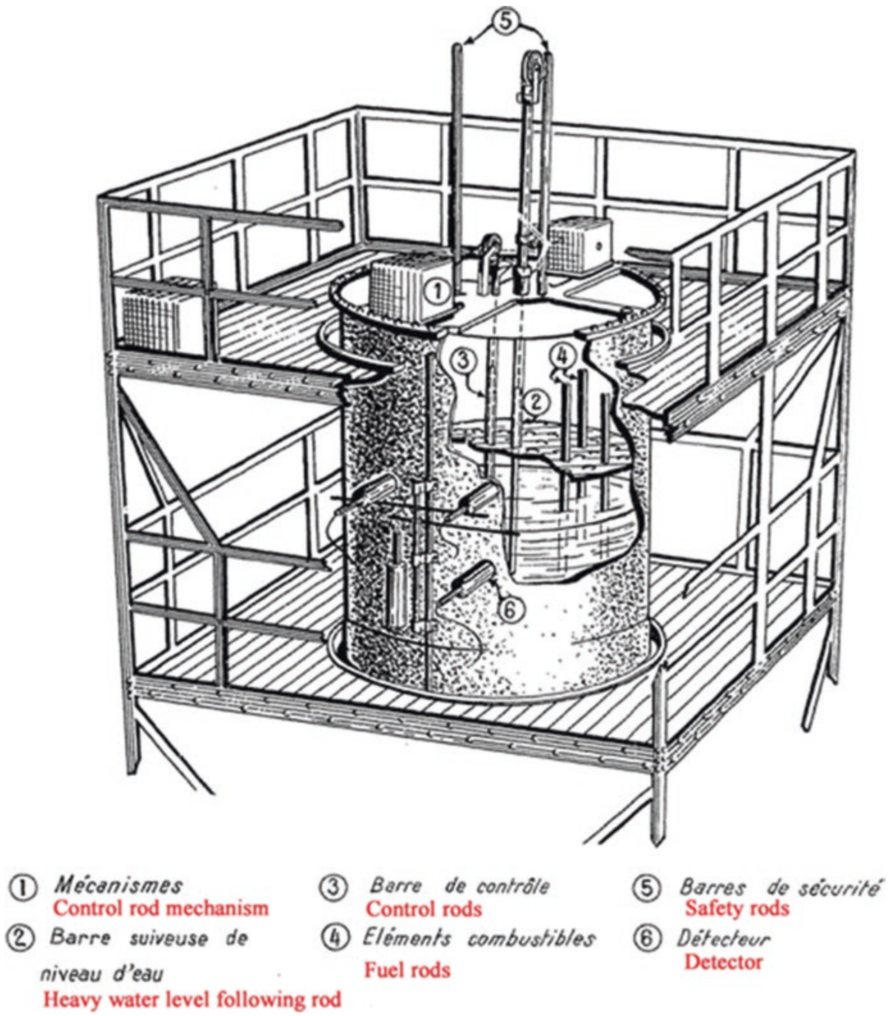


Fig. 2.17 Detail of the Vinča vessel after the French modifications

been moved 7 m from the reactor without a direct view of it after the accident, had its protection against radiation reinforced. The French reinforced this protection against radiation by bringing from Saclay protective concrete bricks and strips of cadmium, a powerful neutron absorber, and by building a baffle of concrete bricks in front of the entrance to the control room (Photo 2.17).

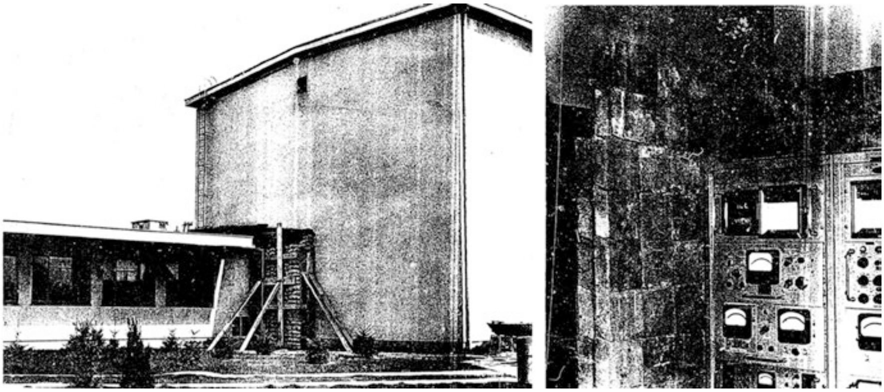


Photo 2.17 Improvement of the biological protection of the entrance door of the reactor building (left) and of the control room (right) protected by bricks of absorbing material (1961). These old photos, unfortunately of poor quality, give an idea of the improvements made in 1961 by the French in the field of radiation protection. A first in the collaboration between East and West in the middle of the cold war!

Zoé, a Near Criticality Accident (France, Circa 1948)

The Vinča accident is strangely reminiscent of a little-known incident that occurred around the end of 1948/beginning of 1949 on the first French reactor: Zoé . The Pile Zoé (Photos 2.18, 2.19 and 2.20) consists of an aluminum vessel containing heavy water D_2O (the moderator, 5 tons) and uranium oxide rods (1950 kg), surrounded by a 90 cm thick graphite reflector, all placed in a hollow concrete block used for the radiation protection of personnel (Photo 2.21). The primary pump, which circulates heavy water for cooling the Pile, is external to the reactor block, the logic being to have easy access for maintenance. There is a strong similarity to the Vinča device except for the strong concrete biological shield surrounding the vessel and the graphite reflector that saves fissile mass. Zoe diverged by going critical on December 15, 1948, at 12:12 pm. A nice Christmas present for the team (Photo 2.22) led by its creators Frédéric Joliot-Curie and Lew Kowarski .

The listing of the detector (Photo 2.23), which traces this feat, signed by Jacky Weil , who will later go to Vinča in 1961, is pictured in the museum that became the Zoé building on the CEA site in Fontenay aux Roses (France).

In all fairness, there was no accident in Zoe, but the similarity of the near accident, which we will describe, with what happened in Vinča is striking. The filling of the vessel in Zoé is done by a small booster pump, which is shown on Fig. 2.18 (number 11). In order to protect against the risk of untimely

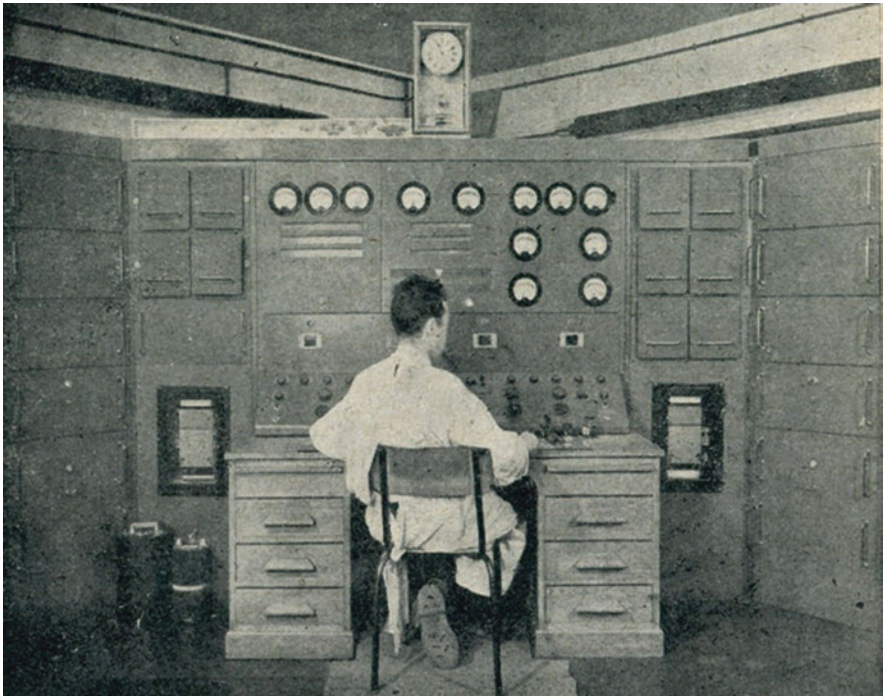


Photo 2.18 The control room of Zoé in 1948. Note the "head up" unrecorded measurement dials on the vertical panel above. Two scrolling graph paper recorders are placed on the sides of the cabinet, hardly visible to the operator (CEA photo)

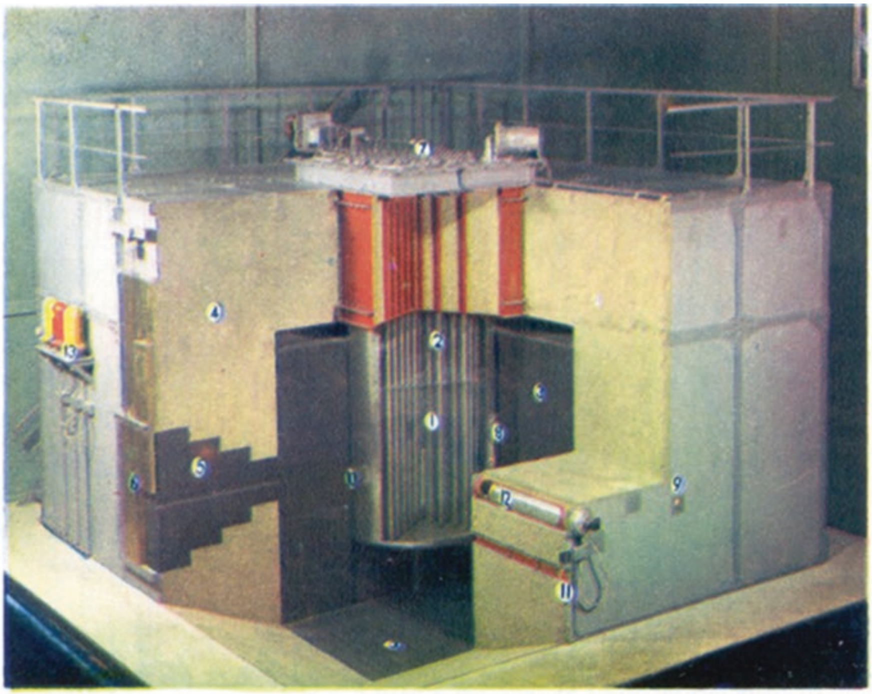
criticality, its operation is automatically limited in time by a protection that shuts down the pump after a programmed time (of the order of one minute). At the end of this time, the protection triggers the power supply to the pump, which shuts down. But this pump having a small flow, it appeared that it was extremely fastidious for the operators to constantly reset the pump during a complete filling of the vessel, the volume of the vessel being very important. The low flow rate of the pump was of course intended by the designer for safety reasons, but the impatient nature of humans being what it is, it did not take long for an excited operator to remove the time protection and let the pump run continuously. The reader who has followed my comments on Vinča will of course have understood what happened next. The critical level of heavy water was almost reached because of the forgotten disconnection of the booster pump protection or because the operator reacted too late to the pump shutdown. Fortunately, the uncertainties of the calculations of the time, all

Photo 2.19 The same control room of Zoé (France) renovated at the end of the 60s. Many “head-up” recorders were installed. We can see the “Human Factors” progress brought to the control console. ZOE’s core shutdown on April 6, 1976 at 11:51 a.m. after 28 years of good and loyal service, and above all without accident! (CEA photo)

done by hand with the poor knowledge of the properties of fissile materials at the time, led to an underestimation of the real critical level, introducing a happy conservatism into this type of situation. Following this near miss, the safety of the pile was of course improved by physically preventing the booster pump from operating without its protection.

Zoé has rendered invaluable services in the acquisition of knowledge in reactor physics, in the irradiation of materials of all kinds, in the production of radioactive isotopes useful to industry and medicine (Photo 2.24). Nowadays, Zoé has become a museum that can be visited during open days or by contacting the CEA in Fontenay aux Roses (Photo 2.25). Some memories recall the importance of this reactor in the history of French nuclear power (Photo 2.26).

In both the Zoe and Vinča situations, human error is glaring: distraction in the case of Vinča, whose operators were unfortunately punished in their flesh;



1. Eau lourde. - 2. Barres d'oxyde d'uranium. – 3. Réflecteur en graphite. – 4. Protection en béton. – 5. Colonne diffusante. – 6. Protection de la colonne diffusante constituée par une porte en laiton cadmié. – 7. Commande des barres de sécurité. – 8. Plaques de réglage. – 9. Ouverture des canaux. – 10. Canal d'irradiation constitué par des briques mobiles de graphite. – 11. Canal d'irradiation (blocs de béton mobiles). – 12. Chambres d'ionisation pour les mesures de puissance. – Trois chambres d'ionisation.

Photo 2.20 Description of the pile Zoé (France, 1948) by a partially sectioned model. 1—Heavy water, 2—Uranium oxide fuel rods, 3—Graphite reflector, 4—Radiation protection in concrete, 5—Neutron diffusing column, 6—Protection of the column made of a cadium-platted brass door, 7—Safety absorbent rods mechanism, 8—Adjustment plates, 9—Opening of the channels, 10—Irradiation channel made of mobile graphite bricks, 11—Irradiation channel (made of concrete mobile blocks, 12—Ionization chamber for power measurements (3 chambers)

illicit (and irresponsible!) behavior in the case of Zoe that fortunately did not lead to an over-critical situation. If Man is not perfect, constraining procedures and well thought-out devices must force him to excellence, because any loophole could be borrowed. Let the one who has never crossed the street outside the limits cast the first stone! Moreover, it should be noted that hierarchical punishment is absurd, insofar as it would lead to hiding one's mistakes, making up one's behavior, looking the other way when a problem is detected…

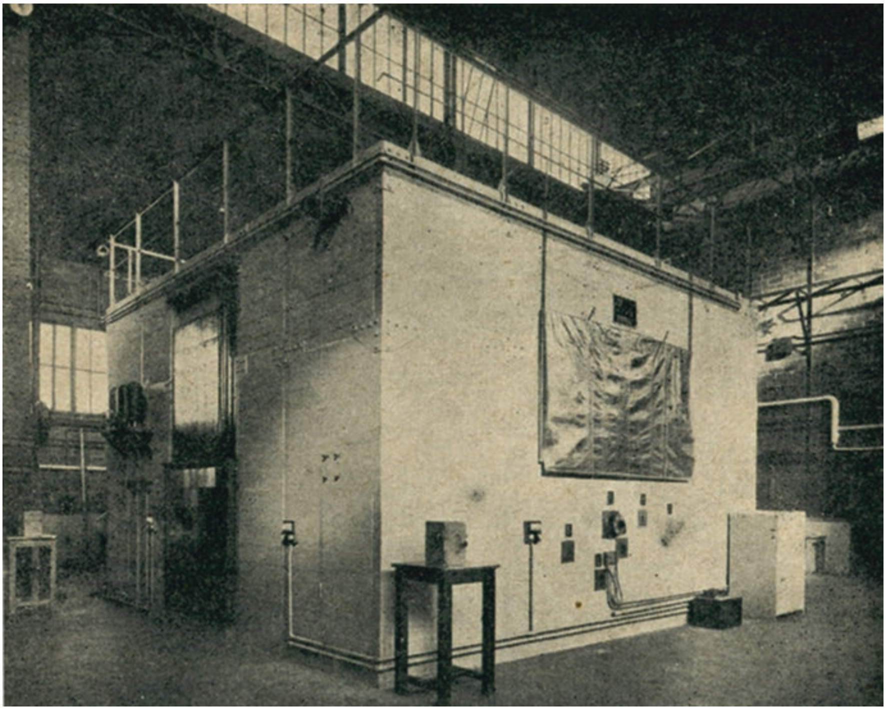


Photo 2.21 The Zoé pile inside its hall. The vessel is trapped in the concrete block seen in the photo. Nothing to do with the lack of biological protection of the Vinča assembly (photo CEA)

Santa Susana, a Partial Blockage of the Flow in the Core (California, 1959)

At the end of the 1950s, the US effort in nuclear technology became considerable. Numerous types of experimental reactors were developed. Some improbable concepts were tried. This is the case of the thermalized graphite reactor and cooled by liquid sodium ! Today, sodium is rarely considered except for cooling fast neutron reactors, so the Santa Susana Field reactor, also called *Sodium Reactor Experiment* (SRE), presents rather the disadvantages of the two reactor types, fast and thermalized, than their respective advantages. In any case, in these times of greed for knowledge, this reactor was implemented at the *Santa Susana Field Laboratory*, a complex of industrial research and development facilities located about 11 km northwest of Canoga Park (California, USA) and 48 km northwest of Los Angeles (Photo 2.27).

Photo 2.22 The team of designers and operators of Zoé, the first French atomic pile. Seated from left to right: A. Ertaud (head of the pile physics department), B. Goldschmidt (head of the industrial chemistry department), M. Surdin (head of the electrical construction department), L. Kowarski (technical director), F. Joliot (High Commissioner for Atomic Energy), E. Le Meur (head of the mechanical construction department), J. Guéron (head of the department of general chemistry), S. Stohr (director of the Châtillon center), R. Echard (attaché to the cabinet of the high commissioner). Standing the technicians and engineers: MM Foglia, de Laboulaye, Martin, Beaugé, Pottier, Weill, Berthelot, Rogozinsky, Valladas (photo CEA)

The reactor diverged on April 25, 1957, and produced a thermal power of 20 MWth for an electrical power of 5.8 MWe. The reactor vessel is a cylinder 180 cm in diameter by 180 cm high. The graphite is placed in the vessel in hexagonal claddings coated with a thin layer of zirconium. The sodium circulates at ambient pressure through an external main loop and is circulated by a main electromagnetic pump. This loop can evacuate a power of 20,000 kW. It is therefore a loop reactor concept, in contrast to the *Superphénix* type pool reactors. The primary sodium exchanges its heat with a secondary sodium circuit which heats water through steam generators. This secondary circuit acts as a barrier to the radioactivity of primary sodium (Fig. 2.19).

Because of all these intermediaries, the efficiency of the installation is therefore low (about 29%). A second, so-called auxiliary loop, redundant to the main loop but less powerful (1000 kW), allows the residual power to be evacuated to a small, separate secondary circuit that transfers its heat to a

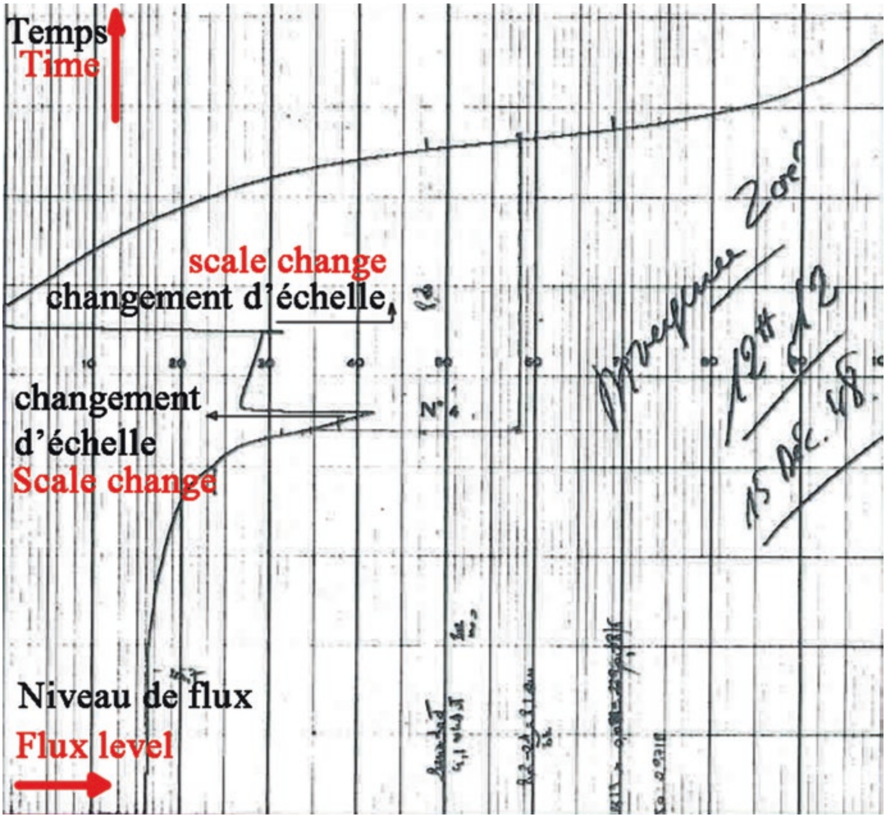


Photo 2.23 The listing of the historical divergence of Zoé on December 15, 1948, 12 h12, signed by the operator Jacky Weil. As the neutron steam flux increases strongly during the divergence, the scale of the counter has been changed so that the signal remains on the graph paper. The scale changes cause a sudden apparent decrease of the signal while the measured neutron flux level increases continuously from the bottom of the image to the top. The comments about the calibration and scale changes were added by me

forced-air heat exchanger. This circuit is only used when the reactor is shutdown. An inert nitrogen atmosphere overlaps the sodium in the vessel to avoid any risk of ignition on contact with air. The inlet temperature of the primary circuit is 260 °C, and the outlet temperature is 516 °C. In the context of the time, the reactor does not have a thick concrete Reactor Building, but a conventional building (Photo 2.28).

The fuel assemblies are suspended from cables inserted from the vessel cover. The reactor core contains 43 assemblies, consisting of 7 fuel rods (Fig. 2.20). These are cladded in stainless steel, measuring about 180 cm in height and containing low-enriched uranium (2.77%). A seal of NaK, an

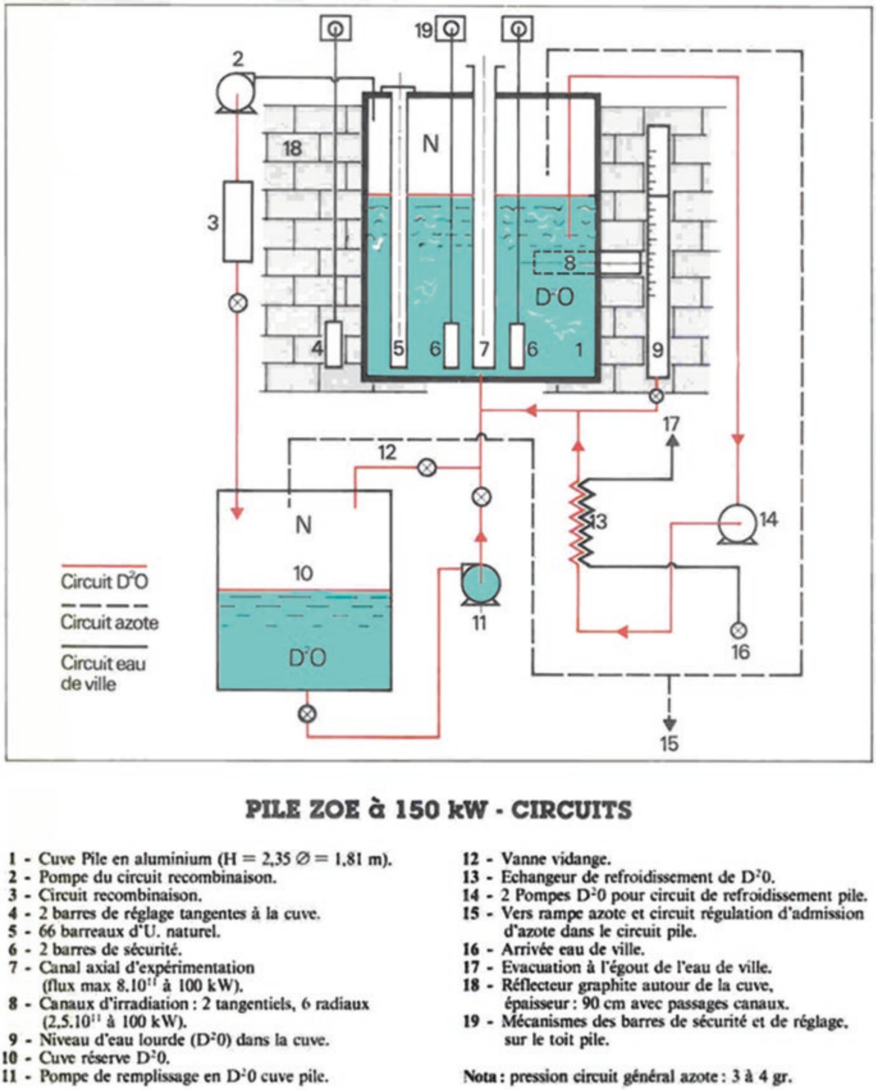


Fig. 2.18 Schematic of the heavy water systems of Zoé. As the power of the pile is much more consequent of that of Vinča (150 kW instead of 50 W), we will note the presence of an exchanger and a real circulation of the heavy water in the vessel via pump 14. The pump 11 is a booster pump for filling the vessel. 1—Reactor vessel in aluminum, 2—Recombination circuit pump, 3—Recombination circuit, 4—2 control rods tangential to the vessel, 5—66 fuel rods in natural uranium, 6—2 safety rods, 7—Axial channel for experimentation (neutron flux 8 10^{11} n/cm^2/s at 100 kW), 8—Irradiation channels (2 tangential, 6 radial, neutron flux 2.5 10^{11} n/cm2/s at 100 kW), 9—Heavy water level in the vessel, 10—Heavy water tank, 11—Main feeding pump for vessel filling, 12—Discharge valve, 13—Heavy water cooling heat exchanger, 14—2 heavy water pumps of the cooling circuit, 15—to the nitrogen circuit, 16—Light water for cooling inlet, 17—Cooling light water discharge, 18—Graphite reflector surrounding the vessel 90 cm thick with crossing channels, 19—Safety and control rods mechanism on the roof of the pile

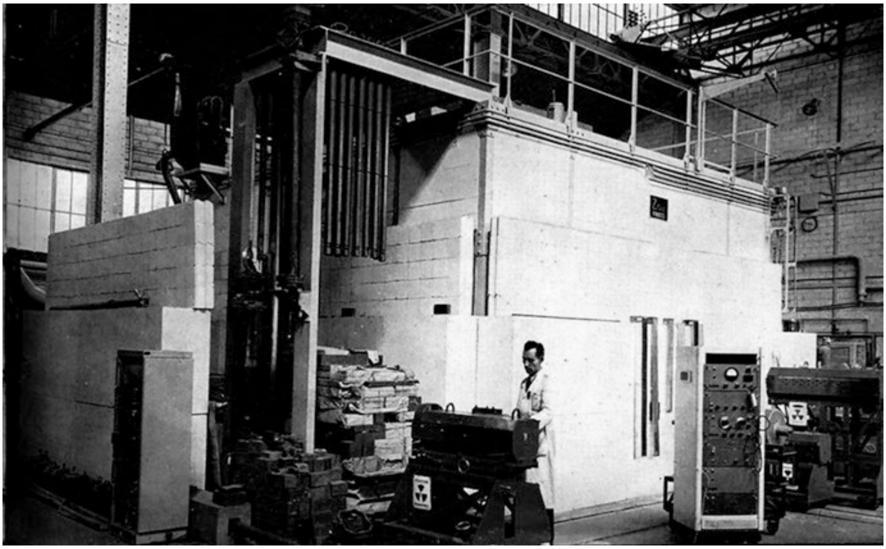


Photo 2.24 A photo from the early 1950s (before 1956) of the Zoe hall. Additional layers of protective bricks were added after the power was increased from 5 kW to 150 kW. Steel rods that support the fuels hang from a gantry in the foreground. One of the fans is also visible, which cools the reflector when the pile is in operation. The device for loading and unloading the samples, which are loaded into the dedicated irradiation channels, moves on a rail (photo CEA)

Photo 2.25 The Hall of Zoé has now become a museum. A plate, updated regularly and screwed on the external wall of the pile, indicates the contact dose, which has become extremely low and without danger for the visitor (photo CEA)

Photo 2.26 An amusing souvenir from Zoé: a portion of heavy water caught in a block of Plexiglas. It remains to be seen whether this heavy water has really been subjected to neutron radiation, in which case beware of tritium! One can doubt it

alloy of sodium and potassium that is liquid at room temperature[22] whose 22%(Na)-78%(K) eutectic only vaporizes at 785 °C, provides the thermal bond between the fuel and its steel cladding, an innovation that takes into account the thermal creep of the metal fuel and its significant thermal expansion while maintaining a good heat exchange.

On July 13, 1959, a blockage of some sodium channels led to the partial melting of 13 fuel assemblies. The cooling channels were blocked by products of decomposition at high temperature of the oil, tetralin[23], used to cool the seal of the primary circuit pump (Fig. 2.21). In fact, the vertical axis of the pump rotates inside of a bearing. This bearing is isolated by a technological trick. A frozen sodium film seals the pump body. This is done by cooling the bearing from the outside with liquid tetralin, a special oil that does not react with sodium, to ensure that the sodium in the film solidifies approximately in the middle of the vertical bearing. This oil seeped through the seal of the primary pumps into the primary circuit. It decomposed at about 426 °C into hydrogen, naphthalene, and carbon which, by aggregating, clogged some very narrow cooling channels in the core. When the temperature rose due to the lack of cooling, the uranium and iron in the cladding steel produced a low melting point eutectic (725 °C), which facilitated the degradation of the core.

Curiously enough, and probably because of a lack of instrumentation, the operators did not realize that the fuel had melted until the end of the test cycle on July 26, during dismantling. Eyewitnesses reported a certain amateurism

[22] This eutectic has a melting point of −12 °C. It has a density and viscosity close to water, but its heat capacity is lower than water and its thermal conductivity is higher. It should also be noted that this eutectic is corrosive with cadmium, antimony, lead, tin, magnesium and even silicone. The only metals with which it is satisfied are chromium, nickel, or steels…

[23] Tetralin (tetra-hydro-naphthalin $C_{10}H_{12}$) is a hydrocarbon obtained by catalytic hydrogenation of naphthalene. It is an excellent heat transfer agent that has little affinity with sodium (absence of oxygen).

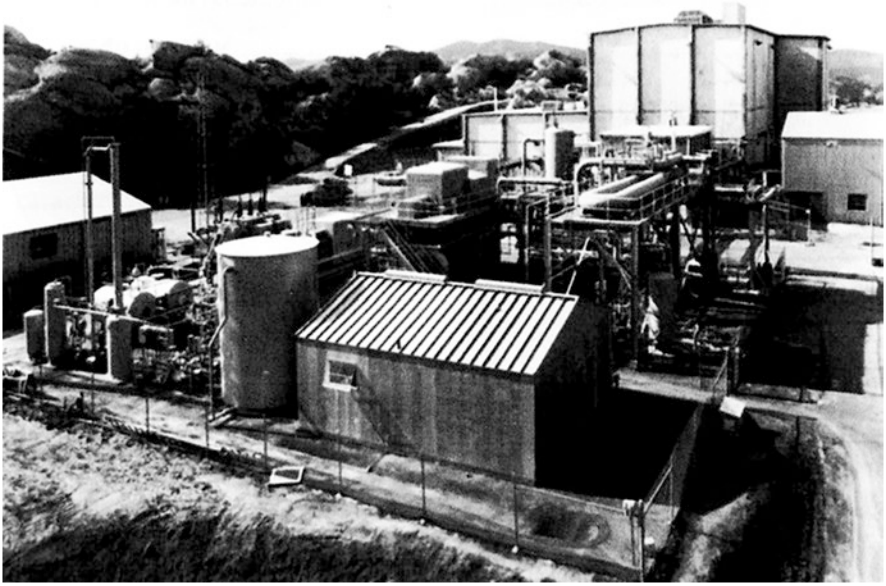


Photo 2.27 The site of Santa Susana in the 60s

in the fuel management of the reactor (several attempts to restart the damaged core during cycle 14 after the accident, despite the strong temperature variations, sealing radioactive gas leaks with adhesive tape!) We can imagine today that their radioactivity detection system was ineffective or in any case, largely insufficient, insofar as the released radioactivity is estimated at about fifty curies. After 14 months of repair, the reactor restarted in September 1960 and operated without problem until 1964. The tetralin was replaced by kerosene, water being of course prohibited because of the risk of sodium-water interaction. The reactor was finally dismantled between 1976 and 1981.

Such an extraordinary reactor would certainly have deserved abundant and reliable instrumentation. This accident perfectly illustrates the risks of loss of cooling caused by a closed channel plugging, a situation that can be encountered in fast neutron reactors whose technology is similar. Instantaneous total blockage (BTI) of a hexagonal tube of a fast neutron reactor is a design accident that must be checked to ensure that it does not lead to a propagation of the melting to the six neighboring tubes.[24] The hexagonal tube is a casing that

[24] Detecting a BTI is difficult, especially if not all channels are instrumented. It is necessary to be able to guarantee the shutdown control rod drop if the meltdown spreads to the neighboring channels. In fast neutron reactors, the assemblies are closed (hexagonal tube) to be able to regulate their flow, and thus their power, which makes it possible to have zones of the core with variable flow rates, and thus to regulate the power shape.

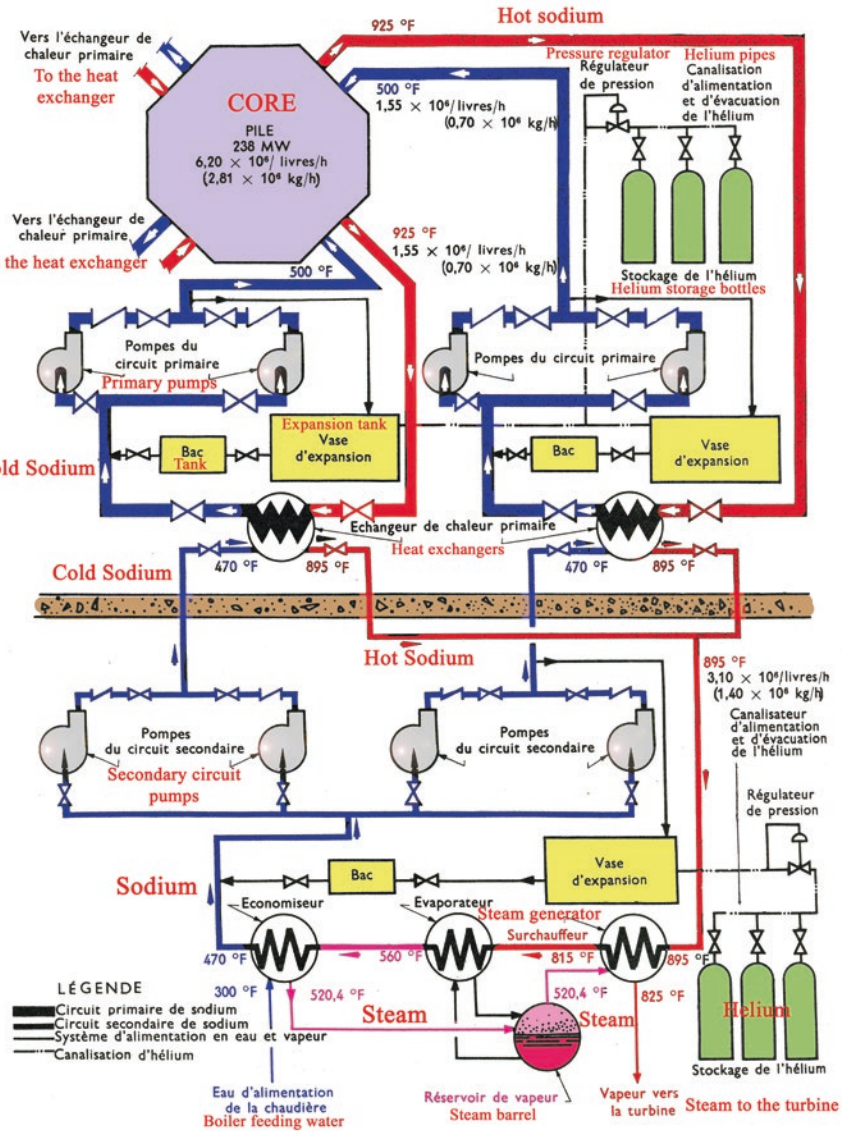


Fig. 2.19 Circuits of the SRE reactor of Santa Susana

makes the assembly sodium-tight with respect to its neighbors (no lateral flow of sodium). An accident of this type happened on October 5, 1966, in the fast neutron reactor Enrico-Fermi-1. A migrating body, namely a zircaloy plate, partially blocked two sodium cooling channels, causing the partial melting of

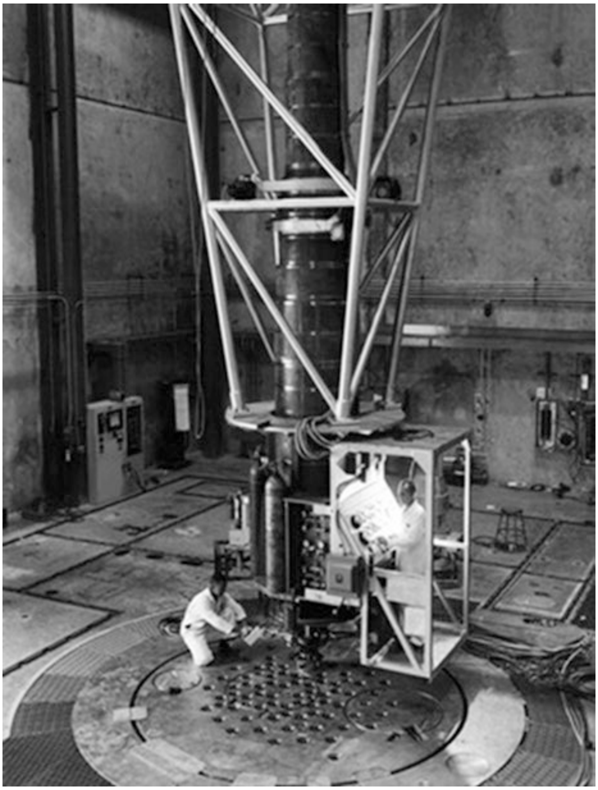


Photo 2.28 Operators handle the fuel loading machine for the assemblies above the Santa Susana reactor vessel cover. The plugged housings of the assemblies can be seen. The small size of the radial dimension of the core can be seen in relation to the height of a man. It can also be seen that the reactor building is only a conventional building made of superimposed cast concrete slabs

the two assemblies. This plate came from a set of six triangular plates welded in the shape of a lemon press at the entrance to the lower plenum and intended to separate the corium in the event of a core meltdown and its relocation in the cold manifold. The purpose of such a partitioning of the corium was to limit the risk of recriticality of the corium at the vessel bottom. This accident led to improvement on the design of the assembly feeder vents, which must consider the risk of clogging. Following this accident, the reactor was shut down for 4 years until 1970, only to be restarted for two more years of operation. The risk of clogging is much less acute in pressurized water reactors where the geometry of the assemblies remains open (there is no casing surrounding the fuel rods).

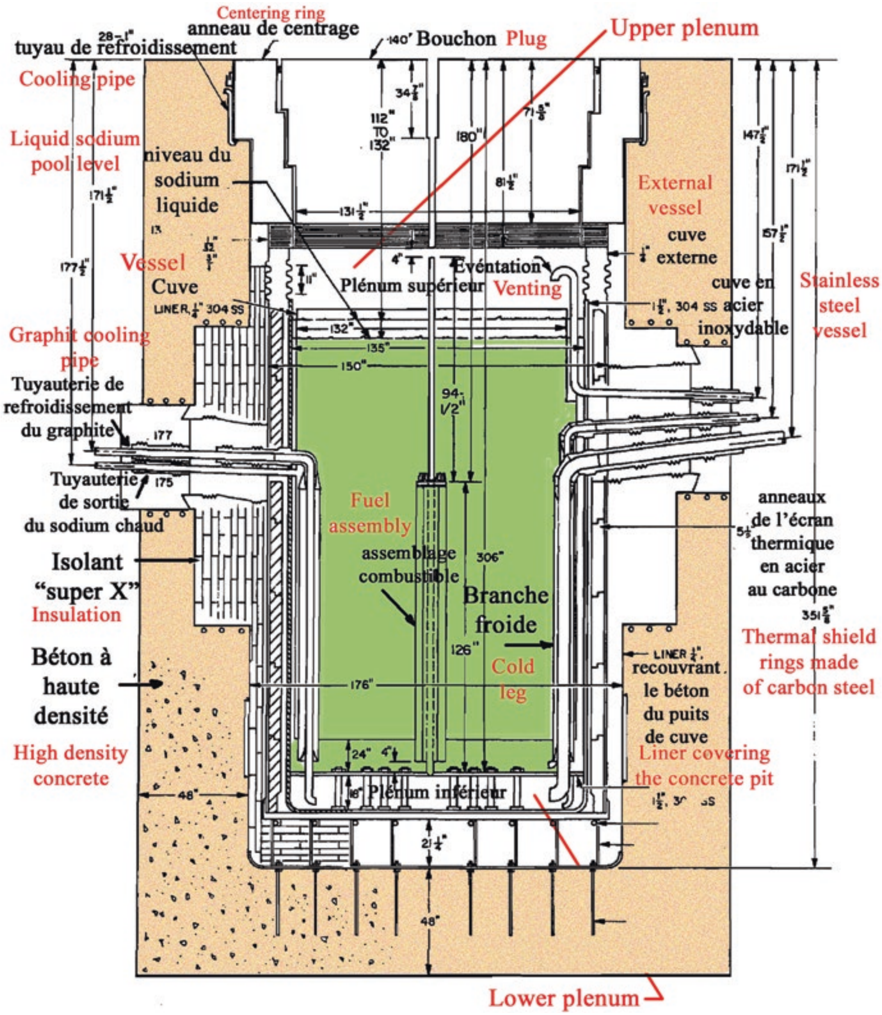


Fig. 2.20 Geometry in vertical section of the Santa Susana reactor (California, USA)

For the record around the Santa Susana case, five members of the cast of the hit family TV series "*Little House on the Prairie*" (205 episodes from 1974 to 1983) unfortunately developed cancer, four of whom, including star actor Michael Landon (1936-1991) who plays the role of the benevolent family father and main actor of the series, died of the consequences of the disease (pancreatic cancer for Landon). For a long time, the origin of these illnesses was attributed to the set, which would have been contaminated (without any proof by measurement) by radioactive fallout from the Santa Susana reactor

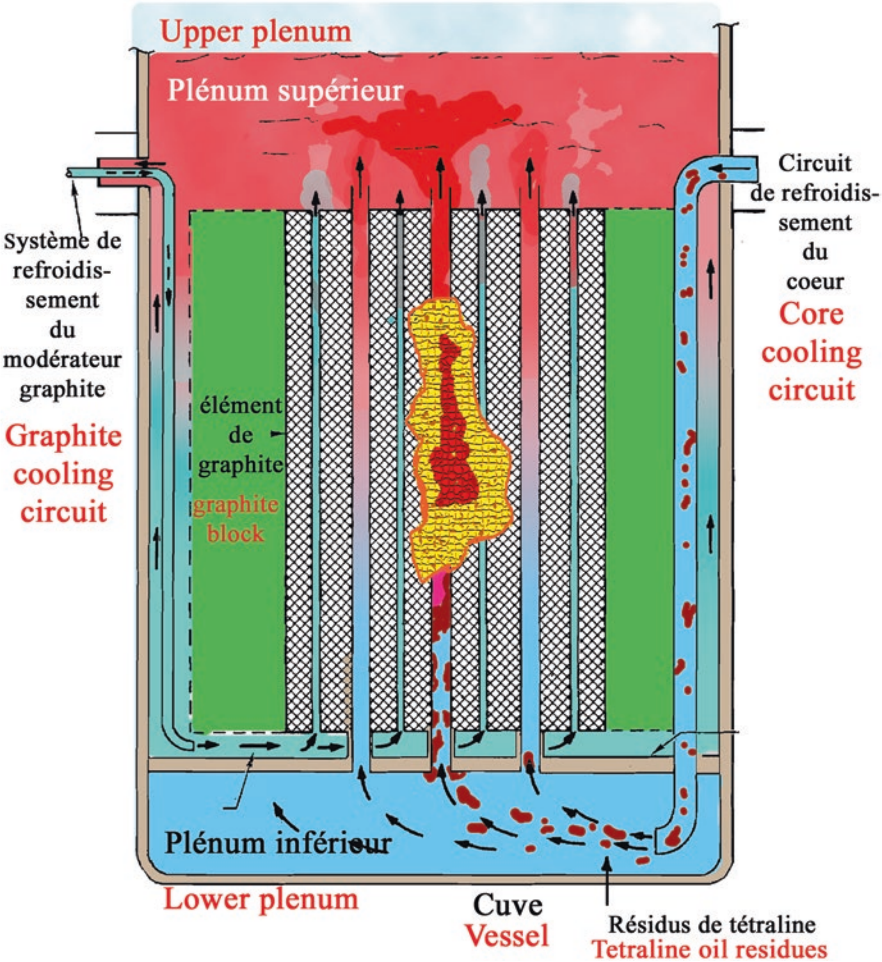


Fig. 2.21 Accident at Santa-Susana Field (California, USA, July 13, 1959). The clogging of a cooling channel due to coagulated residues of oil used for cooling and isolation of the pumps and seeping into the primary circuit, caused the melting of about 30% of the reactor core (13 fuel elements out of 43). Curiously enough, the accident was not discovered until the end of the test cycle on July 26, 1959, despite a significant release of radioactive fission gas. The radioactive releases were estimated to be about 300 times the dose released during the TMI-2 accident

meltdown in 1959. The interior sets were located at Paramount Studios in Los Angeles, but the exteriors were shot at the *Big Sky Movie Ranch*, northwest of Los Angeles. The filming location was just north of Simi Valley, while the reactor is just south. However, despite the obvious proximity of the sites (Photo 2.29), these facts can easily be explained by the risk of cancer deaths in the United States (215 per 100,000 inhabitants in 1991). It should be

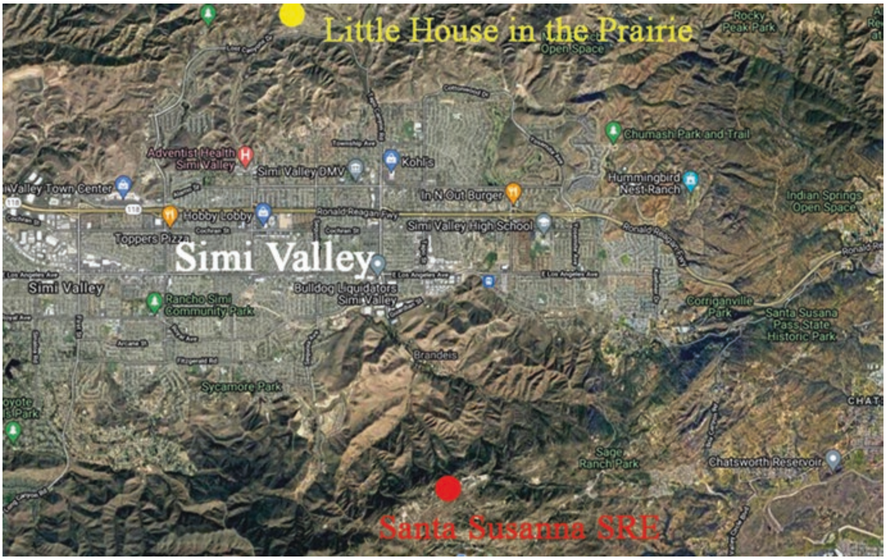


Photo 2.29 Location of the filming sites of "Little House on the Prairie" and the Santa Susana reactor (adapted from a Google map). This proximity, although real, does not stand up to a factual statistical analysis of cancer risk in the population of the region

noted that no increased risk has appeared in the population of Simi Valley, which is located between the two sites, and that the radioactive releases have been very small. The controversy therefore seems to be hardly supported by scientific facts, and it is very likely that it is a sad coincidence. Michael Landon readily admitted that he had been a heavy smoker in his life and that he enjoyed alcohol outside of the play set.

Idaho Falls, a Control Rod Ejection (USA, 1961)

The accident of the *Stationary Low-Power Plant n° 1* test reactor, (SL-1) in the Idaho Falls site (Figs. 2.22 and 2.23, Photo 2.30), on January 3, 1961, was the deadliest nuclear accident on American soil. The SL-1 is an experimental boiling water reactor built by Argonne National Laboratory on order of the American army, with the objective of providing energy and heat for a possible arctic installation. The reactor is a direct cycle reactor, without secondary circuit to save space, producing steam by natural circulation, with a net power of 3 MWthermal, for an electrical production of 200 kWe.

Construction of the reactor began in 1957. The site is integrated into the National Reactor Testing Station in a desert part of Idaho, where in 1954, a

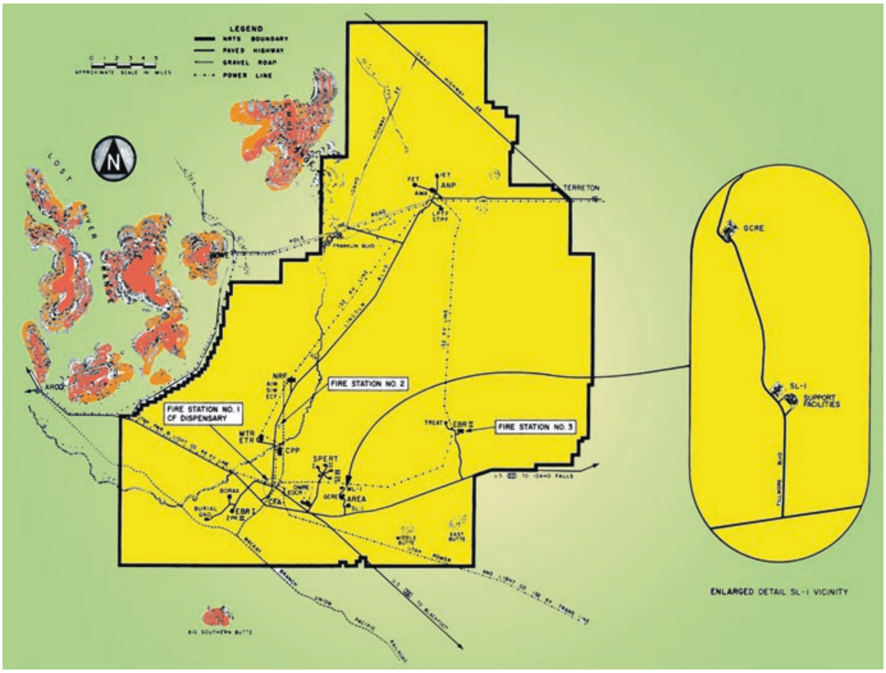


Fig. 2.22 Location of the SL-1 reactor (Idaho Falls), adapted from (Tardiff 1962 (*[Tardiff, 1962]*: A.N. Tardiff: *Some aspects of the WTR and SL-1 accidents*, Reactor safety and hazards evaluation techniques, proceedings of the symposium, Vienna, 14-18 May 1962, IAEA STI/PUB/57, pp. 43–88 (1962)))

power excursion was deliberately induced on the BORAX reactor for experimental purposes. From February 1959 on, the reactor will carry out its task of training military personnel and providing feedback on operational experience. The reactor was built on support "posts" to simulate its planned construction in a permafrost region. The lower part of the reactor is filled with gravel, also readily available in these latitudes, which serves as biological protection around the reactor vessel. The core (Figs. 2.24 and 2.25), very compact, is approximately 90 cm square, containing 40 fuel assemblies (Fig. 2.26) with 5 cruciform control blades (Fig. 2.27). The blades are made of cadmium. The assembly contains 14 kg of highly enriched uranium. The core is designed to last without reloading for at least 4 years (refueling in the arctic zone being inherently difficult). For nearly two years, the reactor operated without any particular problem. On December 23, 1960, the core was shut down for routine maintenance.

The maintenance of the neutron flux detectors began during the night of January 3, 1961. This operation requires unhooking the control rod clusters

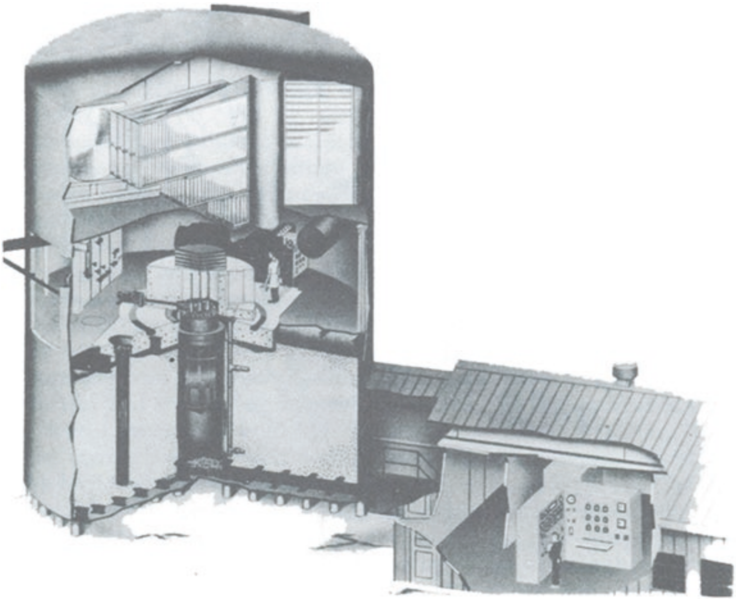


Fig. 2.23 SL-1 reactor building: the lower part of the reactor building is filled with gravel

that are in the way of access to the detector housings. The three operators[25] on watch are preparing to lower the water level to its normal level, to put the plugs back in and to reconnect the control rod clusters mechanisms (Fig. 2.28).

At 9 h01 p.m., the procedure indicates to manually raise a few centimeters the control rod cluster to hang it up on its gripper, which was undoubtedly carried out by one of the operators (Richard Legg). It is thought that this raising was too sudden, causing a power excursion. In four milliseconds, the power of the reactor reached 20 GW (Fig. 2.29) and the violent steam explosion that followed expelled the control rods. The reactor vessel itself "jumped" in its housing by a vertical movement, dragging gravel! (Photo 2.31). The first

[25] John Byrnes (25 years old), Richard McKinley (22 years old) and Richard Legg (25 years old) were very young Army or Navy personnel in training on SL-1. As soon as the emergency services arrived, the level of radioactivity was such that they could not immediately enter the building. It was not until 10:30 a.m. that the rescue team discovered two mutilated bodies, one dead, the other still alive but particularly contaminated, and which was to die during its transport to the hospital. A macabre detail, it took several days to extract the third man, the shift supervisor Richard Legg, who was literally crucified like a butterfly on the ceiling of the reactor hall, directly above the reactor, by an ejected control rod (Fig. 2.23). His recovery was extremely delicate, with the help of a protective net, in part because of the fear that his fall into the gutted reactor could cause material displacement and a criticality feedback. The record of McKinley, who was buried at Arlington Military Cemetery in a lead casket and placed in concrete containment, states that his body is contaminated with long-lived isotopes and that his body cannot be moved without the explicit approval of the Atomic Energy Commission.

Photo 2.30 The SL-1 building

phase of the accident analysis was to determine whether the reactor had experienced a neutron excursion. In fact, the Hurst gold foil dosimeter located at the entrance to the control room level measured a thermal-neutron fluence of about 2 10^8 neutron/cm^2 (reaction $^{197}_{79}Au + ^{1}_{0}n \rightarrow ^{198}_{79}Au$). The analysis of the brass lighter of one of the men indicated a neutron fluence of 9.3 10^9 neutron/cm^2. This analysis was confirmed by the measurement of activity after dissolution of the gold ring of the shift supervisor. The degradation of the core was confirmed by the presence on the crew's clothing of uranium and fission products, confirmation evident by the photos taken under difficult conditions in an extremely dosing environment (authorized time of 30 s!) during the initial phase of the search for the missing third man. The blast, because of the lateral biological protections, was channeled upwards above the reactor, just where the operators were. Radioactivity was measured between 5 and 10 Gray/hour[26] near the top of the reactor.

[26] 1 Gray = 1 Joule/kg = 100 Rad. The gray is the official unit of energy deposit since 1986.

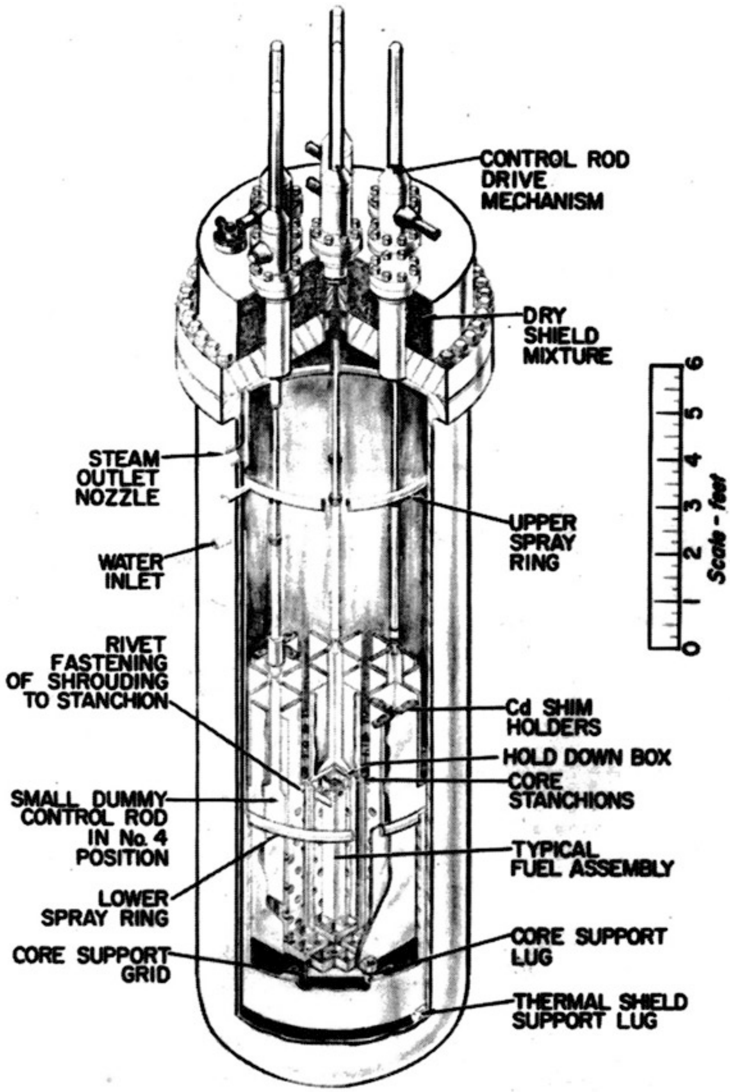


Fig. 2.24 The vessel and core of SL-1, according to (*[Tardiff, 1962]*: A.N. Tardiff: *Some aspects of the WTR and SL-1 accidents*, Reactor safety and hazards evaluation techniques, proceedings of the symposium, Vienna, 14-18 May 1962, IAEA STI/PUB/57, pp. 43–88 (1962))

The inspection of the reactor will be done by a shielded camera which showed that 4 of the control rods remained in place, and that only the central rod was violently ejected. The progressive dismantling of the reactor, first by extruding the vessel with its core still inside, showed that the central part of

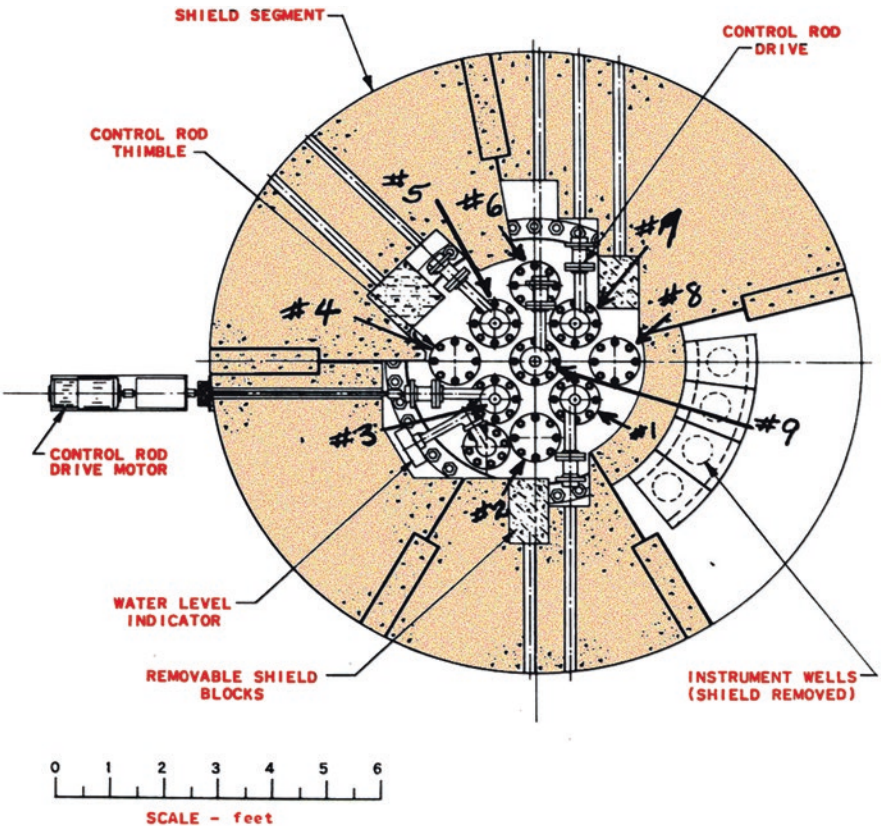


Fig. 2.25 Top view of the SL-1 core: you can see the horizontal views to the cluster control motors and the 5 control rod clusters

the reactor had melted and that 20% of the core was totally destroyed (Photos 2.32 and 2.33).

What were the causes of the accident? The desire to have a small core for easy transport led to a reduction in the number of assemblies and control rods. As a result, the plant's control rod cross was found to carry a very high anti-reactivity weight (Fig. 2.30). Moreover, a careful analysis showed that it was sometimes necessary to help the introduction of the rods mechanically, friction preventing a rod from going to the bottom thrust. In fact, personnel were accustomed to random difficulties due to friction blocking the free movement of rods. The usual procedure was to lift the rod only 4 inches to reconnect it, but there was no thrust to actually limit this lift. Based on the last critical rod position measurement, there should have been 12 inches of margin to criticality, but visual evidence showing scratches tends to prove that

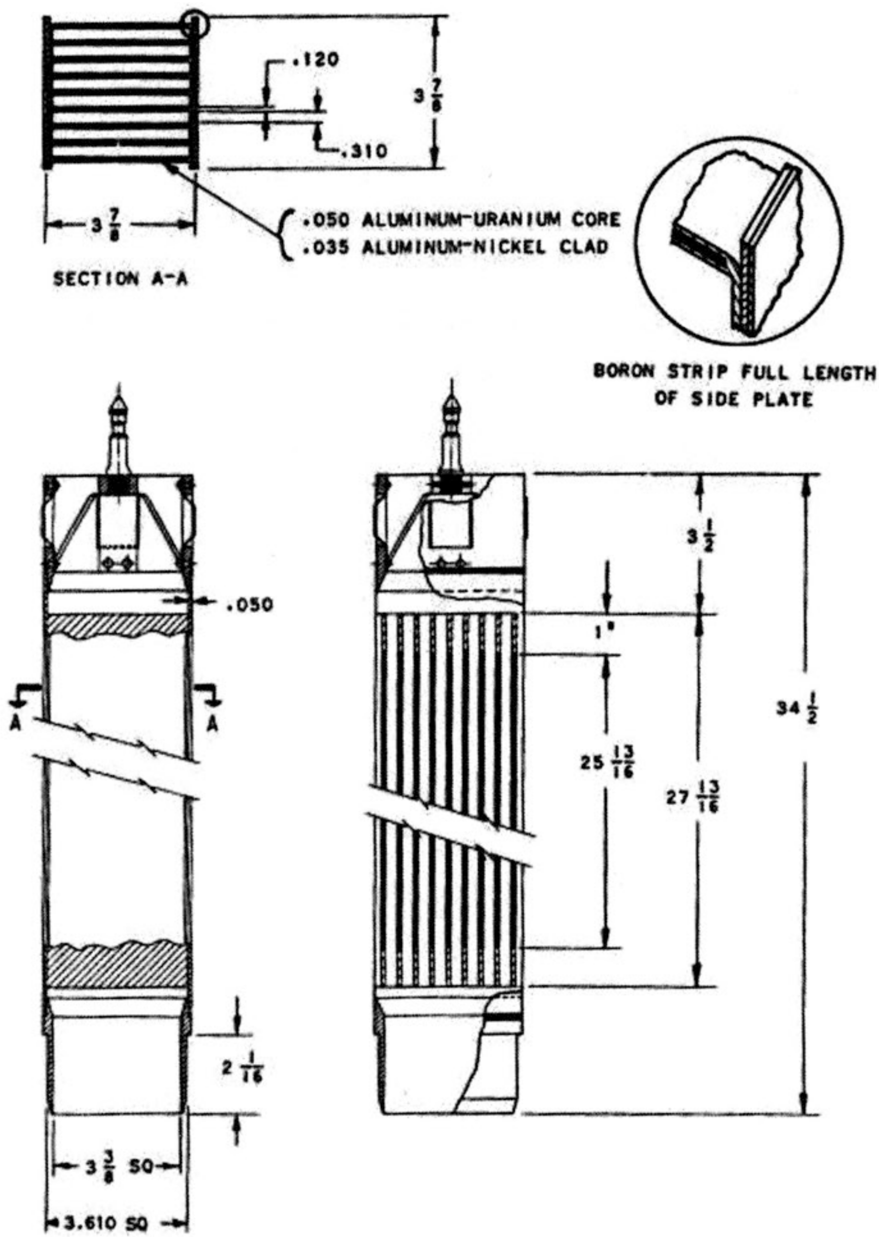


Fig. 2.26 SL-1 fuel assembly using plate-shape fuel

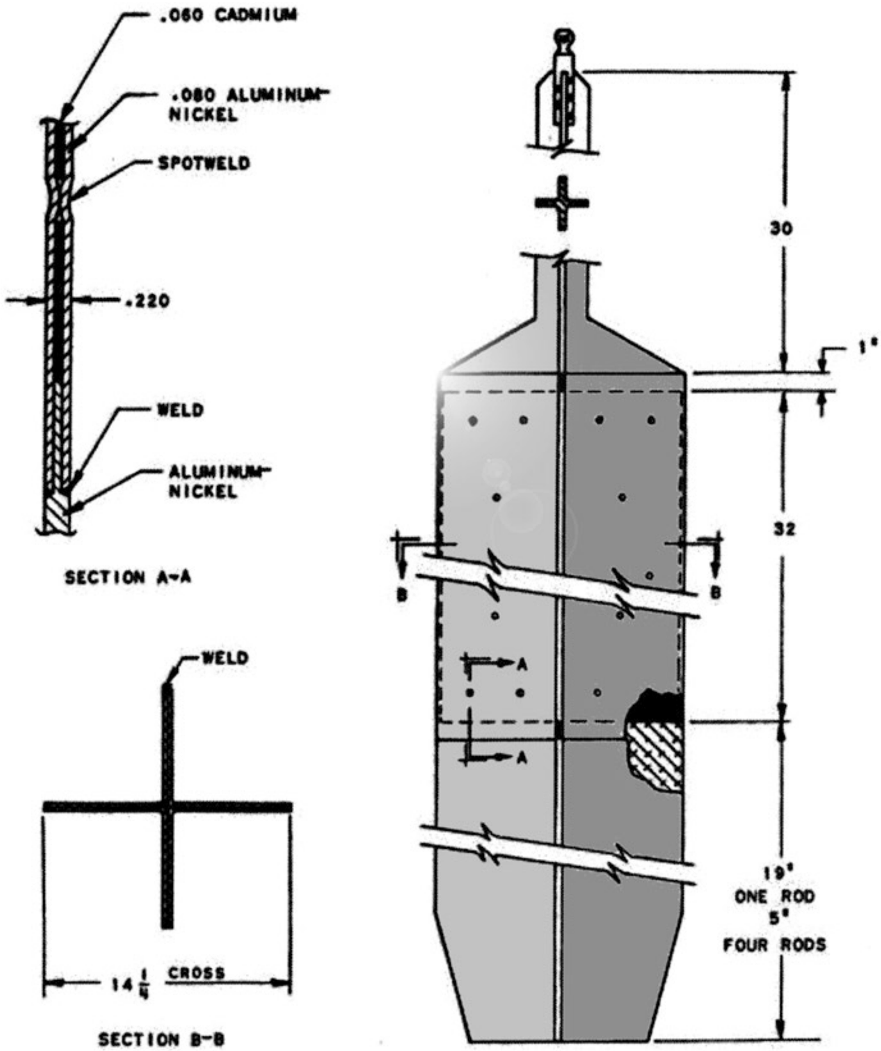


Fig. 2.27 SL-1 Control cross

the operator raised the rod at least 16 inches. It is conceivable that the operator forced the rod out of its socket and, unaware of the danger, pulled it back too far, carried away by his own inertia? In fact, the ejected rod did pierce his stomach, as if he had bent over for the vertical pull, as a classical position to pull up a heavy weight.

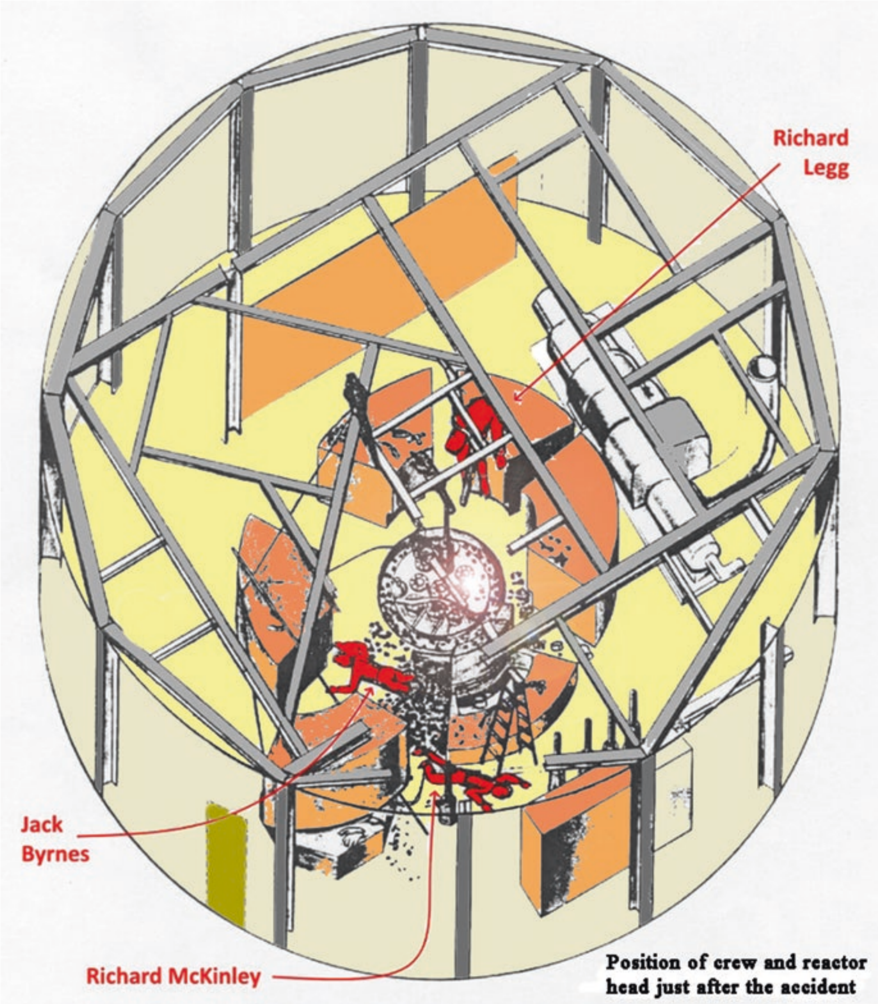


Fig. 2.28 Location of the three bodies of the crew in the reactor building. Only one was still living but died in the ambulance while transport to the hospital. The body was so radioactive that he was left in the ambulance waiting for a leaded coffin. Richard Legg was pinned under the roof of the building where he was found several hours after emergency, causing a false rumor that he was at the origin of the accident

In any case, when the explosion occurred, the reactor was destroyed by a pressure wave estimated to peak at 10,000 psi[27] with great uncertainty, i.e., about 700 bars, and a massive water hammer propelling the water at about 50 m/s, which jammed the central rod cross with a shrinkage of about 20

[27] 1 pound per square inch = 6894 Pascals.

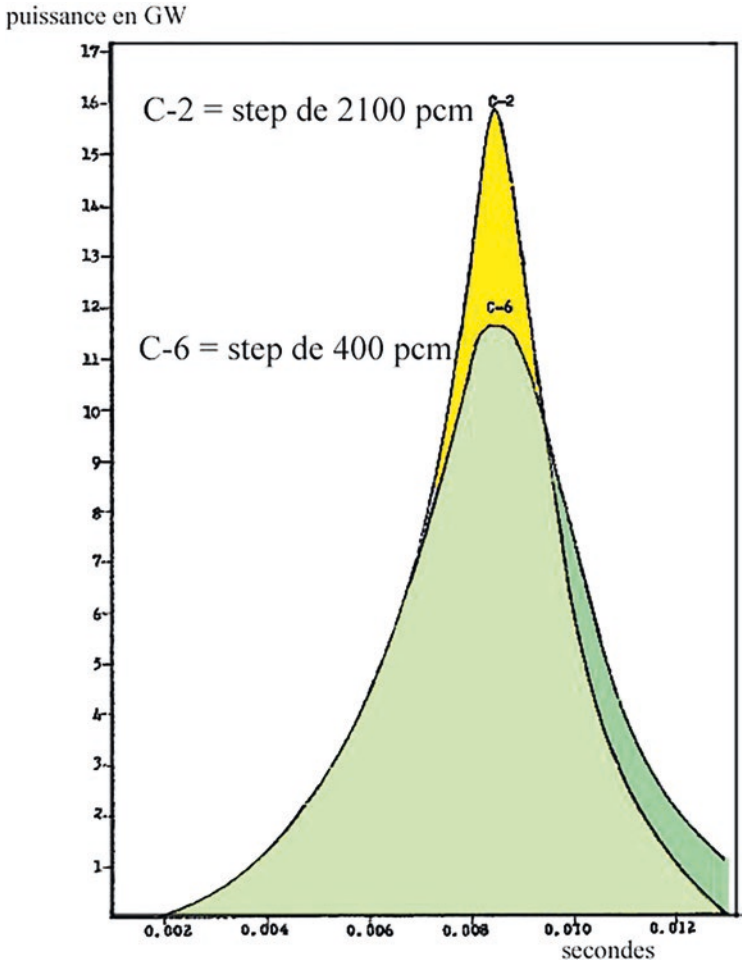


Fig. 2.29 Simulation of SL-1 response to a reactivity step reconstructing the accident (power in GigaWatt)

inches and completely twisted the substantial bolts of the vessel cover (Photo 2.34).

The steam explosion was powerful enough to lift the vessel more than 10 feet. Curiously, the vessel then fell back into its housing in roughly its original position, but pieces of the thermal shield littered the floor. The nuclear energy released by the power excursion caused by a reactivity of 2400 pcm is estimated at between 80 and 270 MJ over less than 10 ms, making it completely impossible for the operators to react. It is the dispersion of materials (loss of critical geometry) and the effect of neutron feedbacks by the

Photo 2.31 Upper part of the SL-1 reactor: one recognizes the gravel of biological protection, initially around the vessel, strewn on the ground (INEL)

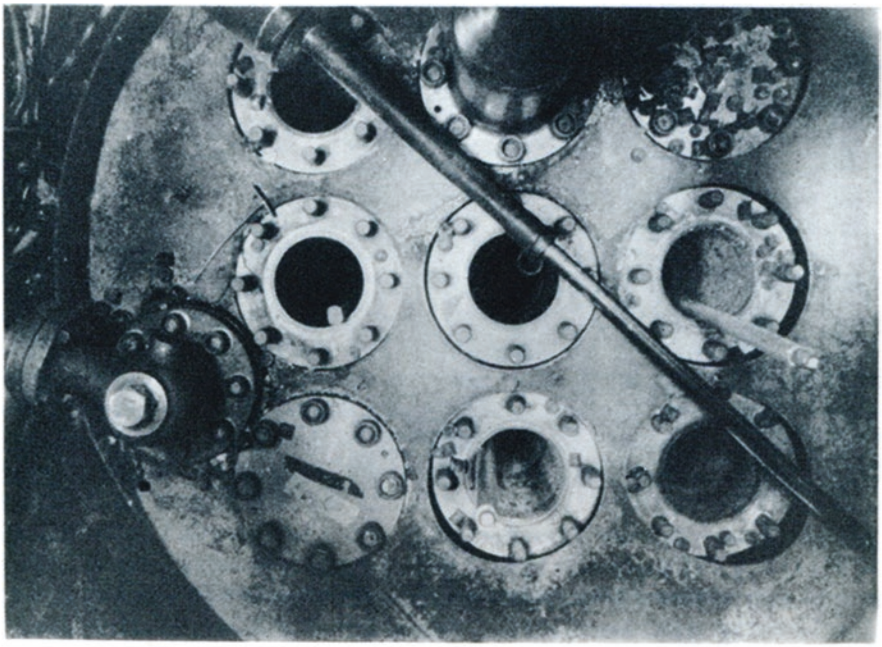


Photo 2.32 Top view of the vessel cover after the accident

Photo 2.33 View of the core during disassembly (1962, INEL)

appearance of void fraction (the average void coefficient was −0.1 pcm/cm^3) which definitely stopped the accident.

What lessons can be drawn from this dramatic accident? The fact that the partial withdrawal of a single rod (see Fig. 2.31 for the mechanism) can inject reactivity greater than the fraction of delayed neutrons in the core ($\beta_{eff} \approx 700$ *pcm*) is a most serious design error, which goes against the Single Failure Criterion (SFC)), an absolute dogma of modern safety. The current evaluation criterion of the Shutdown Margin where all rods dropped except the most anti-reactive one, also called the *single rod criterion*, follows directly from the SFC because of the blocked rod penalty. On the other hand, the possibility of using a boric acid injection system in the core water could be engaged manually at the operator's discretion. If a more realistic assessment of the *Reactor Shutdown Margin* had been established at that time, it could have been increased by this easy and safe means of poisoning the core. It should be noted that the operational procedures were not very formalized by documents and that a large part of the initiative was left to the operators. On the other

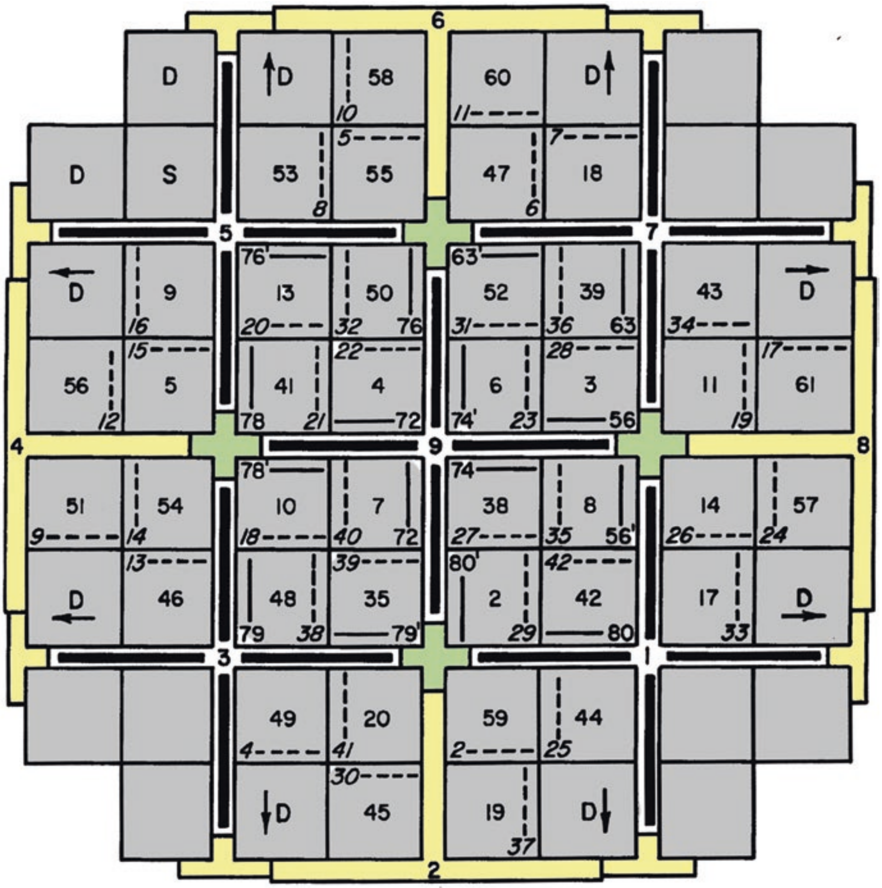


Fig. 2.30 Fuel loading pattern of the SL-1 core. It is easy to see that each control blades will weigh by its size, compared to the size of the core, an important anti-reactivity weight

hand, the weakness in the number of staff in the shift team (a shift supervisor, an experienced operator, and a junior trainee) was based on the need of the military to evaluate what was the critical size of a maintenance team, always in this idea of arctic operations.

Manual dummy rod extraction reconstructions were conducted a posteriori to assess whether a human could extract a rod quickly. They clearly showed that it was possible to extract 23 or 24 inches, i.e., the whole height of the rod, in a time short enough for the reactor period to reach 5.3 ms and to engage the reactor in an exponential power progression by an excess of 1800 pcm of reactivity. If these tests strongly confirm the hypothesis of an unfortunate displacement of the rod, the mystery remains as to the cause of this

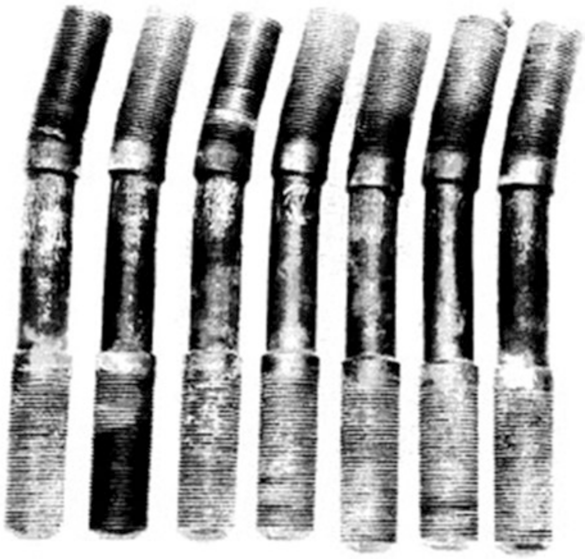


Photo 2.34 An impressive photo of the twisted SL-1 vessel-cover bolts after the water hammer (INEL)

withdrawal: error of judgement? ... One even evoked a suicide attempt, not very credible in the context.[28] The hypothesis of an exaggerated movement to counteract friction finally remains the most credible of the hypotheses. The concept of the SL-1 reactor was finally abandoned by the American army, which had other preoccupations as US army was sinking in the Vietnam war. The only positive point is that this steam explosion showed that a reactor, by losing its geometry, cannot behave like an atomic bomb, where everything is done to contain the explosion at its very last point. The vessel and its highly radioactive core were extracted from the reactor pit with a mobile crane for repository (Photo 2.35). Nothing much remains on the site of this accident except diffuse radioactivity disseminated through the building openings (Photo 2.36).

[28] When asked afterwards by the scientists about their knowledge of the fact that the removal of the plant rod could cause a prompt-critical accident, they were told somewhat cheekily: *"Of course! We had discussed what we would do if Russians showed up at our radar station... We would have blown it up!"*, Anecdote reported in Susan Stacy's Proving the principle (Stacy 2000).

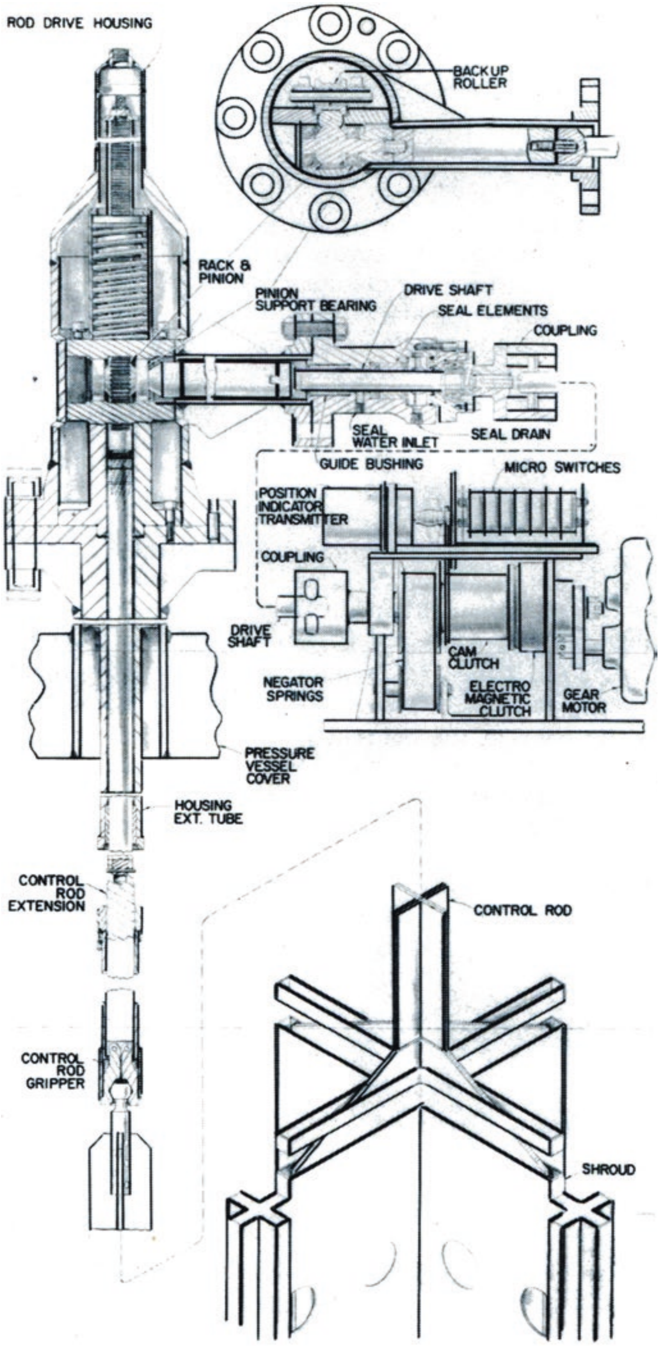


Fig. 2.31 SL-1 reactor control rod cluster mechanism

Photo 2.35 Extraction of the vessel through the reactor dome with a mobile crane. A trailer truck carries a transport cask for the vessel

Photo 2.36 The fence of the SL-1 site and a warning stone with clear depiction

Barentz Sea, the Submarine K-19 Suffers a Loss of Primary Coolant Accident (USSR, 1961)

On July 3, 1961, incredibly the same day of the SL-1 accident described just before, the Soviet submarine K-19 (Photo 2.37) was diving during the Polyarni Krug exercise in the Barents Sea when a leak appeared in the primary circuit (LOCA or Lost Of Coolant Accident) of the starboard reactor. The K-19, 114 m long, has two VM-A pressurized water reactors of 70 MW powering two turbines that propel it at 26 knots in diving. The submarine was launched on 8 April 1959. The accident happened on the first day of its service at sea. The K-19 is a nuclear-powered ballistic missile submarine of the "*Hotel*" class in the NATO breviary. It carries R-13 ballistic missiles, which can only be fired from the surface, unlike the American submarines of the time, which could fire under the water, thus in a much stealthier way.

The incident immediately raised fears of a reactor meltdown because of the residual power. The relative pressure of water in the reactor fell to zero and caused a shutdown of the primary circuit (cavitation?). A separate accident deactivated the long-range radio system, so the submarine could not warn Moscow of the damage. Although the control rods were lowered automatically by scram, the temperature of the reactor continued to rise uncontrollably, reaching 800 °C. No emergency water supply system having been foreseen

Photo 2.37 The K-19 on the surface (left) and a modern model of the submarine. The submarine was nicknamed the "*widow maker*" or "*Hiroshima*" by the sailors. Numerous accidents occurred during the construction of the ship, causing a dozen deaths even before she was commissioned (fire, asphyxiation, crushing..)

at the time of the design of the reactor (exclusion of a large LOCA break at the design!), the commander Nikolaï Zateïev ordered his sailors to fabricate a new cooling system by diverting some of the fresh water stored on board through the ventilation system, thus cooling the reactor. A team of welders took turns in the partially submerged and heavily contaminated boiler compartment to line a new water supply train while being exposed to high radiation. The primary circuit failure resulted in a large release of contaminated and highly irradiating effluent, which spread throughout the building through the ventilation system. Thanks to the courage of the crewmen, the improvised system allowed the reactor to be cooled. A conventional diesel submarine, the Soviet S-270, managed to pick up a distress signal and reached the K-19 to help.

It was said that the cause of the rupture was due to a pressure test of the primary circuit at the reception of the primary circuit. During this test, the pressure was increased to 400 bars (i.e., twice the permissible design pressure of the primary circuit) because of the omission of an operational pressure measurement system. The incident was hidden or glossed over so as not to hinder the progress of the project or for fear of possible sanctions. In any case, no measurements, even non-destructive ones (X-rays), were taken to verify the conformity of the primary circuit and the real effect of this overpressure. The Russian government will later declare to have found evidence of a defective welding (?), which is difficult to doubt from the survivors' account. The real question is to know if this failure was structural at the origin (what were the radiography control procedures at that time in the USSR?), or if this failure was induced by the overpressure of the primary circuit test. The accident of July third caused at least eight deaths by severe irradiation in the following two weeks and about 15 in the two years following. The submarine, however

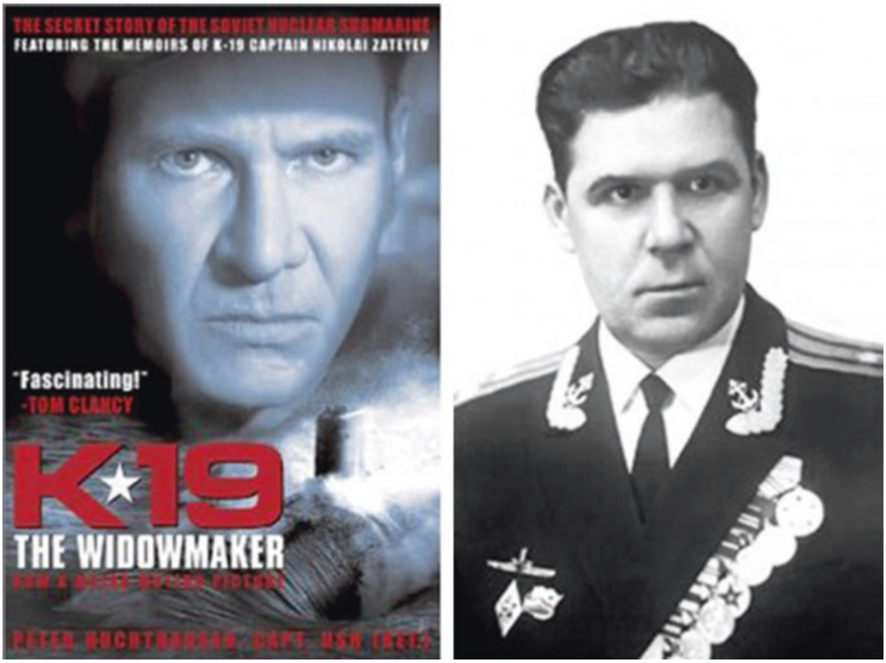


Photo 2.38 The poster of the film from the events and the real Nikolai Vladimirovich Zateyev (Николай_Владимирович_Затеев). Harrison Ford has the good part in the film. The real origin of this case remains darker

nicknamed "Hiroshima," was later rehabilitated, and the reactor compartment was cut out and replaced by a new one during operations which lasted two years. The irradiated compartment was simply drowned in the Kara Sea. Dose reconstructions give figures that are chilling: 54 Sieverts for Lieutenant Boris Kochilov, commander of the group of welders and in the front line (he will die "only" on July 10, 1961, despite this appalling dose that should have killed him before), and doses higher than 10 Sv, the lethal dose, for many sailors who died also in July 1961 despite bone marrow transplants whose technique was initiated by Professor Mathé on the irradiated scientists of Vinča in 1958. The K-19 was deleted from the soviet naval fleet lists on April 19, 1990. The American film K-19 by Kathryn Bigelow (2002) with Harrison Ford and Liam Neeson (Photo 2.38) relates these dramatic events by giving the good role to the commander of the ship.

Fermi-1, Fuel Melting in a Sodium Cooled Reactor (1966, Michigan, USA)

The Fermi 1 reactor, located in Michigan, underwent a partial core meltdown on 1966, October 5. This reactor was a prototype breeder reactor, launched in the 1960s while France was developing its own fast neutron reactor known as *Rapsodie*. Fermi-1 was the world's first commercial fast neutron reactor, followed two other experimental reactors of the same type built in USA, EBR-I and EBR-II (Photos 2.39 and 2.40).

The site also houses a 1170 MWe Fermi-2 boiling water reactor (Photo 2.41). In 2016, NRC renewed the operating license of Fermi-2 for an additional 20 years through March 2045. In July 2019, NRC ordered an inspection assessing the potential of degraded paint inside a portion of the reactor possibly to impede safety systems. The inspection aimed to assess if the degraded paint inside a portion of the reactor containment at the plant could

Photo 2.39 Fermi-1 plant in the sixties

Photo 2.40 Fermi-1 pant in the seventies. New buildings appear

affect certain safety systems in accident conditions. The move followed the US NRC's recent engineering inspection, which reported a deprivation in the paint inside the torus, a donut-shaped component of the reactor containment located below the reactor vessel (Fig. 2.32). The torus, which is filled with water, is designed to absorb energy from the reactor or supply water to safety systems during an accident. According to the regulator, the torus' loose paint chips could potentially impede the water flow to safety-related equipment at the time of an accident (adapted from Kondapuram Rani from NS Energy).

Unlike thermal neutron reactors, which must slow down the neutrons by collision on a moderator atom in order to favor fissions (water in the case of PWRs, graphite in the case of French UNGGs or Soviet RBMKs), fast neutron reactors do not use a moderator. Indeed, while a thermal reactor uses the fissile property of Uranium 235, fast neutron reactor will rather target the fertile property of Uranium 238. This isotope being non-fissile to thermal neutron, the aim of fast breeder reactors is to keep the neutron spectrum as fast as possible to benefit from the fission of "even" isotopes such as ^{238}U or ^{240}Pu, called fertile isotopes. Thus, in a reactor containing fertile as well as fissile material, the ratio between the consumed and the fertile nuclei converted

Photo 2.41 The Fermi-2 air coolers. The Fermi 2 reactor is a 1170 MWe boiling water reactor (BWR), commissioned in 1985, initially for 40 years (2025) and built by General Electric which is owned by DTE Energy and operated by its subsidiary Detroit Edison

into fissile material is called the conversion factor. For example, if for every ten U-235 nuclei, eight ^{238}U nuclei are converted into ^{239}Pu, the conversion factor is 0.8. In a thermal reactor, by definition, the conversion factor is less than 1 as thermal reactor mainly consume initial fissile nuclei. In a CANDU (thermal) reactor, the conversion factor is about 0.8. In all types of reactor, a neutron capture by ^{238}U induces rapidly a production of ^{239}Pu through the equation:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np \rightarrow ^{239}_{94}Pu$$

The half-life of ^{239}U is 23 min as the half-life of ^{239}Np is 2.3 days. Since ^{239}Pu is a fissile isotope under thermal and fast neutron, ^{238}U is therefore a large source for future fission of ^{239}Pu in the fuel. It is also possible to design a reactor with a conversion factor greater than 1. This is called a breeder reactor, i.e., a reactor that produces more fissile material than it consumes, because the harden neutron spectrum favors conversion. The extra-plutonium produced

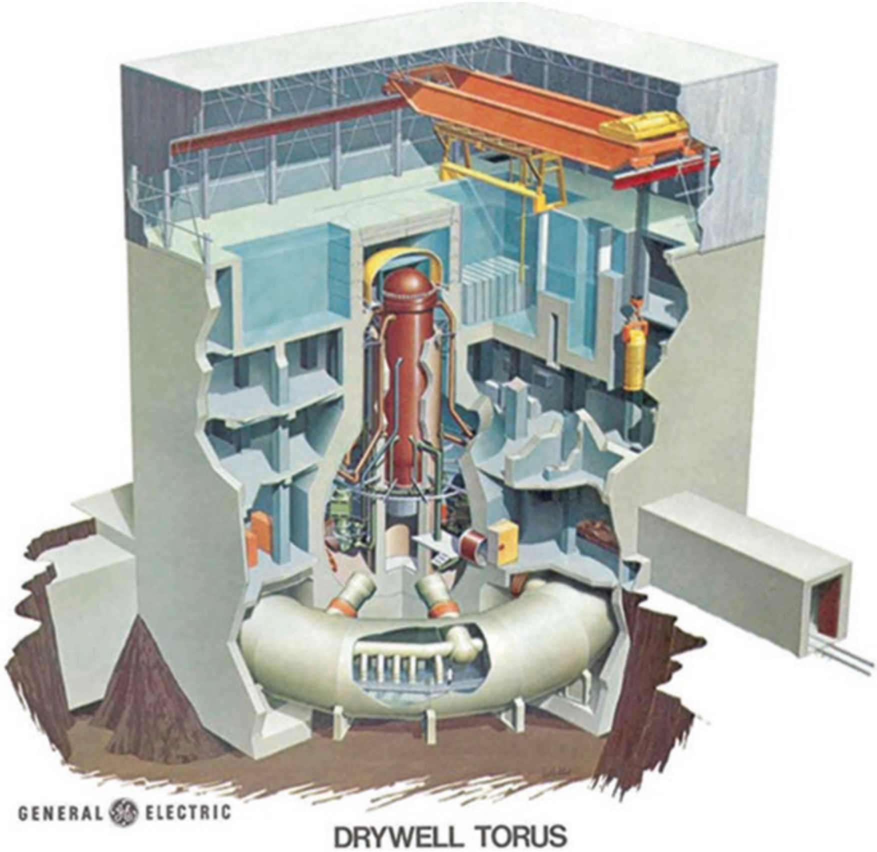


Fig. 2.32 The Fermi-2 Containment building showing the drywell torus on which the defective paint was found

in breeders can efficiently fuel thermal reactors or even other breeders. It is necessary to understand that breeders should not moderate the neutrons like PWRs to avoid thermalization of neutrons, thus it is necessary to avoid water as coolant. Hence the use of sodium or lead-bismuth as coolant. The liquids are bad moderators as their constitutive isotopes are much heavier than hydrogen.

Historically, the first nuclear reactor to produce electricity was a fast neutron reactor. On December 20, 1951, in Idaho, the National Reactor Testing Station (NRTS) commissioned the Experimental Breeder Reactor-1 (EBR-1), which produced enough electricity to power four 25 W bulb-shape light. The first real power reactors based on the principle of breeder principle were the British Dounreay Fast Reactor at Caithness in the north of Scotland, the EBR-2 in Idaho and the "*Detroit Edison Fermi 1*" reactor near Detroit in Michigan, named after Enrico Fermi. One of the fundamental difficulties of

FBRs is that 400 times more neutrons are needed than a thermal neutron reactor to produce fission. A greater density of neutrons is then required. As we said previously, it is essential that these neutrons should be slowed down as little as possible. The core of an FBR must therefore contain no moderator and a minimum of other structural materials to avoid parasitic captures.

Nevertheless, the use of sodium has its drawbacks. As every chemist knows, sodium reacts strongly with water. Therefore, even if sodium is not under pressure, the open surfaces in a Liquid Metal Fast Breeder Reactor (LMFBR) are covered by an inert gas such as argon. Unlike gases or water, sodium is opaque, which makes remote inspection of the reactor particularly difficult. Of course, sodium must not be brought below its melting point, i.e., 97.5 °C once in the circuit, otherwise, it will solidify. Moreover, even if sodium does not easily absorb fast neutrons, when this capture takes place, sodium 23 self-activates in sodium 24, which is an intense gamma radiation emitter. Its half-life is only 15 h, but it has a high activity. Therefore, the sodium primary circuit must be completely surrounded by the biological barrier of the core. Practically, this requires a second sodium circuit with a heat exchanger inside the biological barrier. This secondary sodium circuit, protected against neutrons, carries the heat from the primary circuit through the barrier to the second heat exchanger, where steam is generated. The steam generators, in which the sodium and water are only separated by thin tube walls must be manufactured according to very strict standards. The steam generators are among the most troublesome features of LMFBRs.

Prototype breeder reactors, such as Fermi-1, use oxides as fuel because of the high melting point. The fuel is not only made of uranium oxide, but a mixture of uranium and plutonium oxides. The uranium is not enriched. The low thermal conductivity of the mixture of oxides requires the fabrication of individual small-diameter stainless steel cladding (less than 6 mm in diameter). The core is enclosed in an open tank of liquid sodium (hot plenum), itself inside a larger tank of molten sodium (cold plenum). The sodium passes through the fuel elements and then flows through an intermediate heat exchanger, where it transfers its heat to the secondary circuit, containing non-radioactive sodium. Three intricate circuits are required. The first sodium circuit is completely inside the vessel and cools the active core. The secondary sodium circuit transports the heat outside the biological barrier, where a third water circuit produces steam via steam generators in order to run the turbine. The second circuit avoids sending water directly in the vessel in order to eliminate any risk of massive sodium fire. No pipes or other penetrations enter the primary circuit below the sodium level, thus avoiding reasonably the risk of loss of primary coolant.

The Fermi 1 reactor (Photos 2.42 and 2.43) was the first commercial LMFB (liquid metal cooled breeder) reactor, the only one and the last one built in the

Photo 2.42 A rather threatening image from the Fermi-1 presentation brochure from 1970, where we see that public communication is in its infancy

Photo 2.43 Aerial plant view (from the brochure)

United States. Fermi-1 followed the experimental breeder reactors EBR-I and EBR-II. Note that EBR-1 experienced a severe core meltdown in November 1955 (see Chap. 1). The Fermi I reactor was a prototype fast reactor designed with a power of 430 MWth or 94 MWe, but the first core A was limited to 200 MWth or 69 MWe. The nuclear plant was located on the western shore of Lake Erie, at Laguna Beach in Monroe County (State of Michigan), halfway between the city of Detroit and the city of Toledo (Ohio). Construction of Fermi-1 began on January 8, 1956, achieved criticality in 1963, produced its first MWe in December 1965. Fermi-1 was connected to the grid on May 8, 1966. Its design was the work of two subsidiaries of the consortium Atomic Power Development Associates (APDA), Dow Chemical and Detroit Edison. The latter was the operator. Fermi-1 was built by Power Reactor Developments Company (PRDC).

FBRs include two different designs. For both designs, two heat exchangers are used in order to isolate the primary sodium from the rest of the installation. In the pool design, an intermediate sodium–sodium heat exchanger is drowned under sodium inside the vessel, so that the primary sodium never leaves the core vessel (Fig. 2.33). On the other hand, in the loop-design reactor, the primary hot sodium flows out of the vessel to feed the intermediate heat exchanger (IHX) and the IHX is out of the vessel (Fig. 2.34). Pool-design is universally considered safer than loop-design as no active sodium leaves the vessel, but pool-design requires immerged electromagnetic pumps to push the primary sodium in the active core.

Fermi-1 (Fig. 2.35) was of the loop-design, i.e., the intermediate heat exchanger is located outside the primary circuit. The core is located inside the reactor building as well as the Intermediate Heat Exchanger for evident radioprotection purpose (Figs. 2.36 and 2.37). The reactor building has an easy-recognizable hemispherical dome. The vessel is hidden by a top roof that can be lifted with the polar crane, allowing the transfer cask car to approach for refueling. The car moves on rail to reach the rotating plug closing the vessel and protecting operators from sodium vapor. Steam generators stand right in the auxiliaries building next to the reactor building and provide steam to the turbine located in the turbine hall. The technology of electromagnetic pumps was not mature at that time, hence a loop-design. The primary circuit was filled with sodium in December 1960. The reactor reached criticality for the first time in August 1963. The reactor operated at very low power during the first years of operation. Once the authorization to operate at high power was received, the power tests began immediately in December 1965.

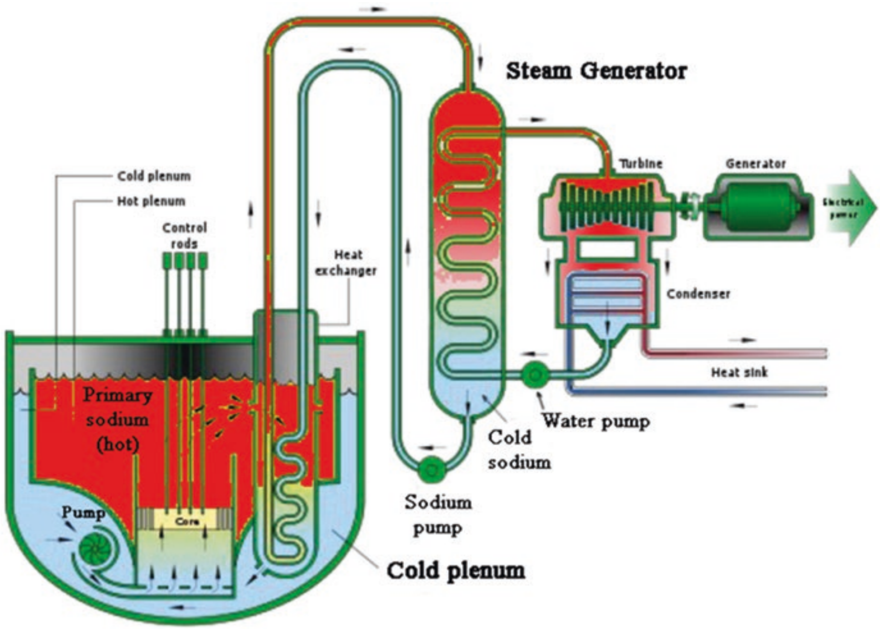


Fig. 2.33 Pool-type FBR. The primary sodium is highly radioactive but stays in the vessel, transferring its heat to the secondary non-radioactive sodium through an immerged intermediate heat exchanger. Doing that way requires that electromagnetic primary pumps lay inside the vessel. The secondary sodium heats water in the steam generator. The steam runs the turbine

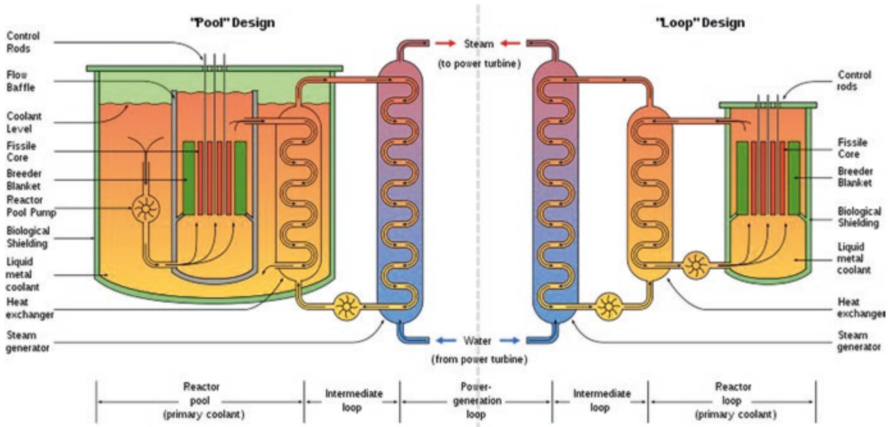


Fig. 2.34 Pool-design FBR (left) compared to loop-design FBR (right). The Intermediate Heat Exchanger (IHX) is located inside the vessel in the pool-design and outside the vessel in the loop-design. Primary pumps of the loop-design are classical volumetric pumps

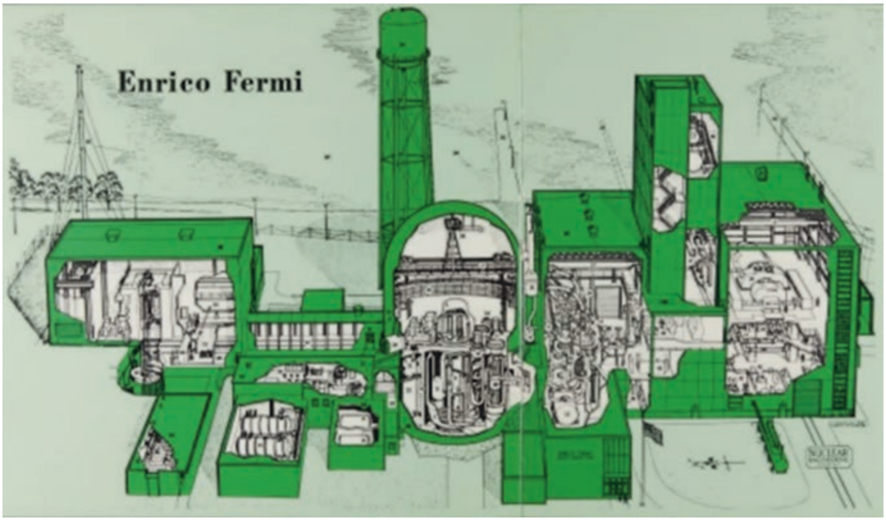


Fig. 2.35 General plan of Fermi-1 (from the brochure)

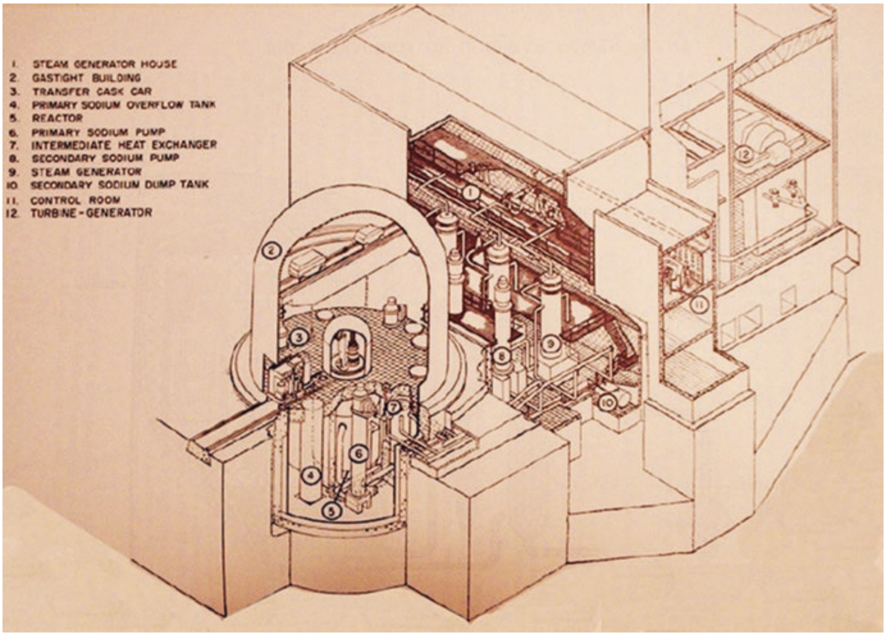


Fig. 2.36 Period plan of the reactor building and the nuclear auxiliaries

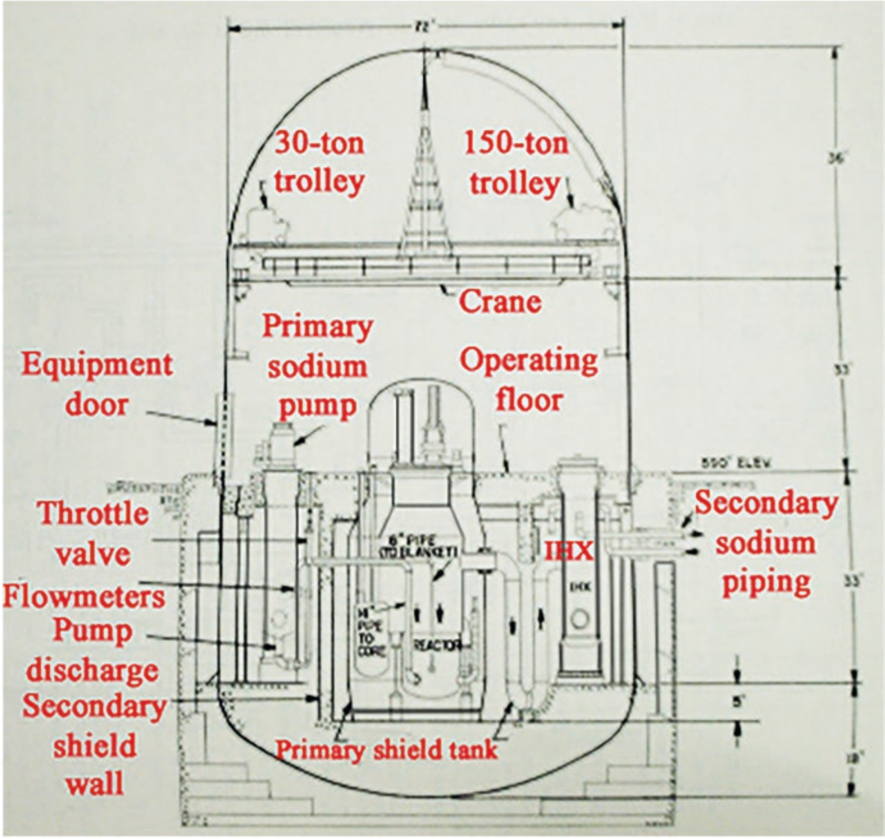


Fig. 2.37 Axial cut of the Fermi-1 reactor building from an old plan. The size of the primary pumps is impressive, almost as high as the vessel (adapted from an old blueprint)

The active core is placed in a stainless-steel vessel (Figs. 2.38 and 2.39, Photo 2.44) sealed atop by a rotating shield plug (Photo 2.45). The rotation of the plug allows to reach any position in the core for refueling purpose. The core is surrounded by cylindrical blankets of depleted uranium (99.7% in ^{238}U) acting as a reflector, but the main interest of this blanket is to allow breeding as all neutron captures in the blanket produce ^{239}Pu. The external diameter of the blanket is 80 inches (203 cm) and 70 inches high (177.8 cm). The active core has a diameter of 31 inches (78 cm) and 31 inches high.

The sodium enters the "*cold plenum*," crosses the core from bottom (288 °C) to top (427 °C) under 8.27 bars before ending up in the "*hot plenum*." The sodium then exits the vessel to feed the intermediate heat exchanger. The average temperature of the coolant inside the core was about 310 °C. Before the

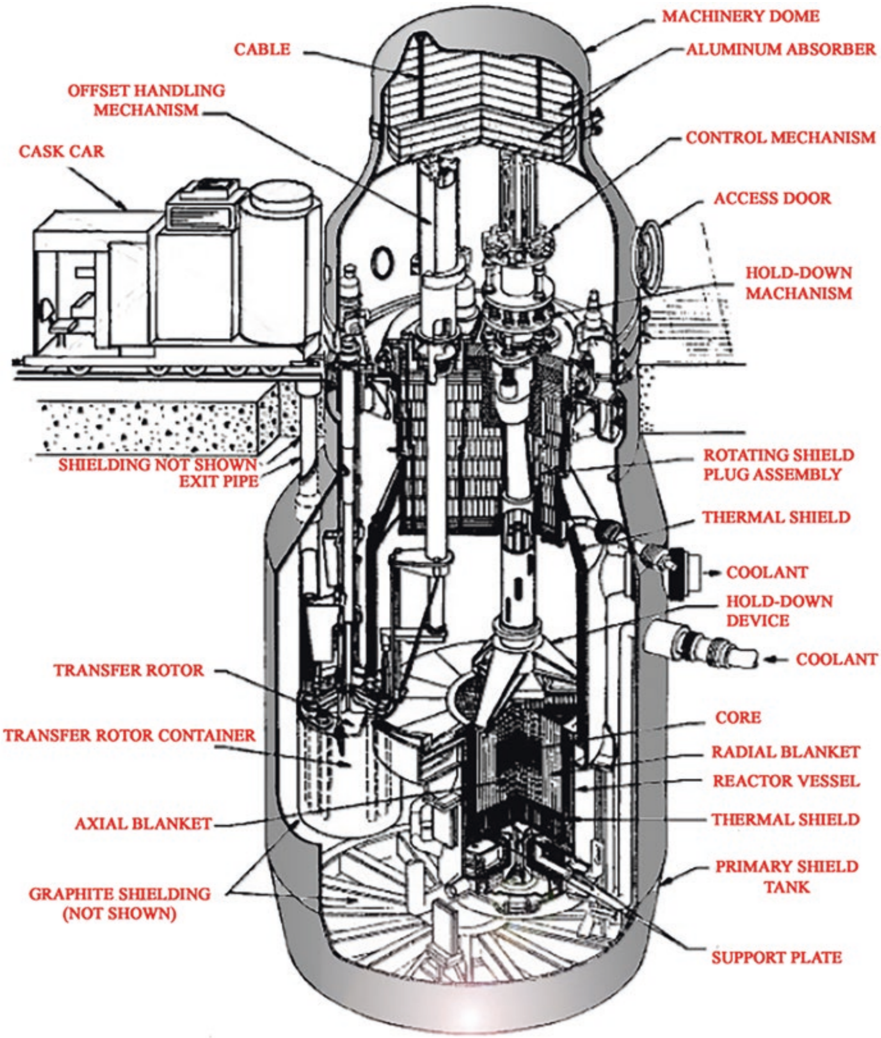


Fig. 2.38 Cut view of the Fermi-1 vessel

incident, the core used an uranium metal fuel surrounded by a zirconium cladding. The core contained 105 assemblies in total. One can also see the different protections surrounding the core, in particular the thermal barrier and the different fertile blankets in depleted uranium (Fig. 2.40). The fuel elements were 4 mm in external diameter, 79 cm high, and were arranged in a square lattice of 2.646 inches (Fig. 2.41).

Fermi-1 was subject to a partial meltdown of the core during its power up on October 5, 1966. A few weeks before the incident, abnormally high

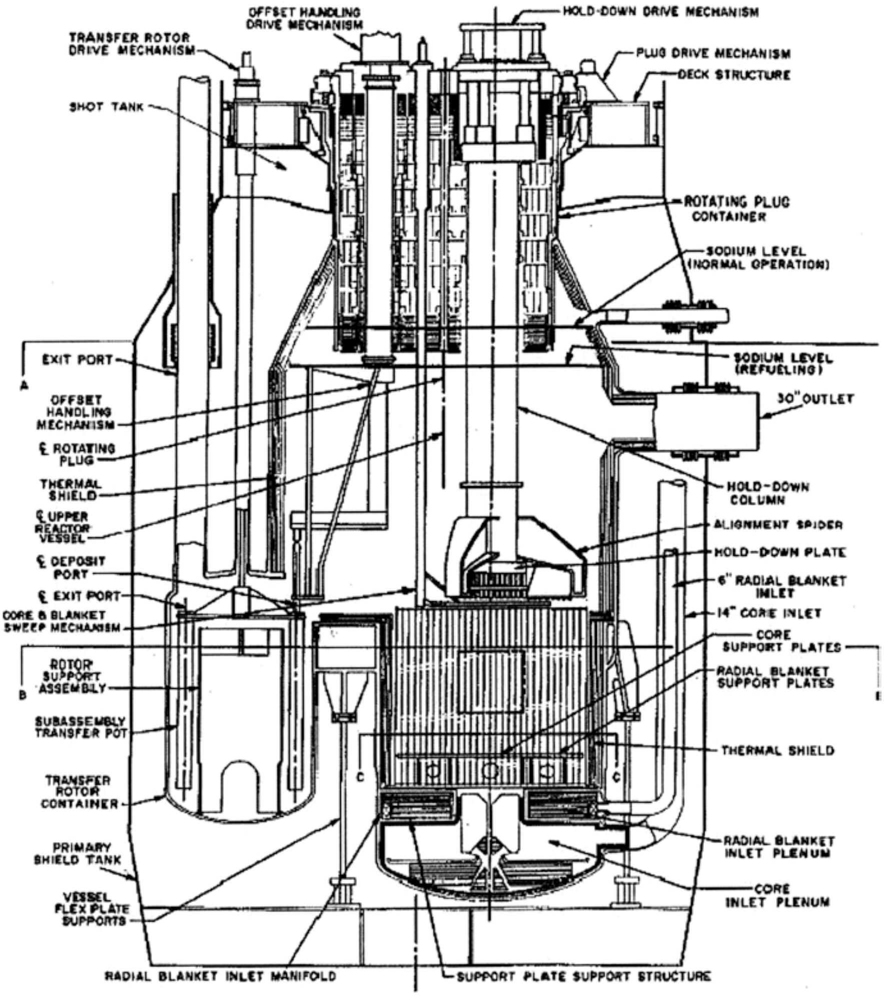


Fig. 2.39 Complete view of the Fermi-1 vessel, including the subassembly intermediate storage barrel on the left of the core. This ingenious device allows a direct transfer from the barrel to the core without lifting the core rotating plug. This technic was also used on the *Superphenix* French FBR (1200 MWe) but could not be longer used as the barrel rapidly appeared to leak. The French barrel was made of carbon steel instead of stainless steel due to economic reasons

temperatures at the level of assemblies were observed by the thermocouples located at the outlet of the coolant. In June, these temperatures were 20 to 25% above normal, then in August from 40 to 47% above normal. The operations were then carried out at low power. In addition, another thermocouple placed above one of the assemblies indicated an abnormally low temperature

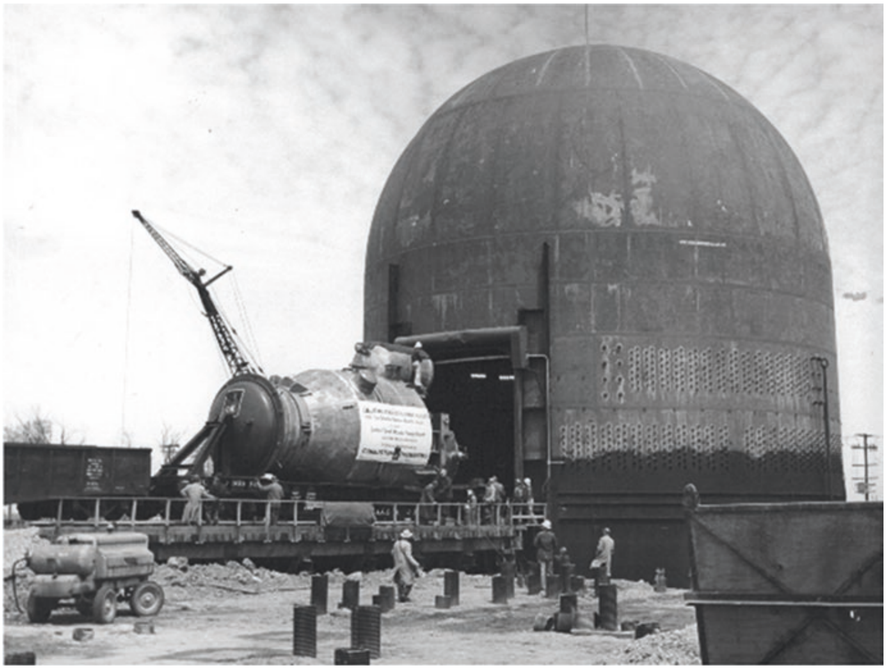


Photo 2.44 Entrance of the vessel in the Fermi-1 containment through the hatch. Surrounding buildings are still to raise

of the coolant compared to normal conditions. The reading of the thermocouples seemed suspicious. To verify the validity of the measure, the reactor was shut down, and the assemblies indicating abnormally high temperatures were reinstalled under different thermocouples, using the intermediate storage barrel. This was done to determine if the anomaly was due to thermocouples or the fuel assemblies themselves. It was then observed that the location of the abnormally high-temperature data varied at each start-up but was not correlated with the movements of the fuel assemblies. The reactor operated without incident at a power of 100 MWth. Then on October 5, 1966, the power was lowered at 67 MWth, then again at 20 MWth at 3 a.m. The operator then observed a control signal indicating an erratic neutron population. The problem had already occurred sometime earlier and was thought to be an electrical fluctuation in the control system. The reactor was placed under manual control, and when the fluctuations disappeared, the control system was returned to automatic control. At 3:05 a.m., the power was restored to 27 MWth, the error signals were again observed. It was noticed later that the control rods were pulled out further than the normal location. Two of the assemblies showed temperatures of 370 °C. This was much higher

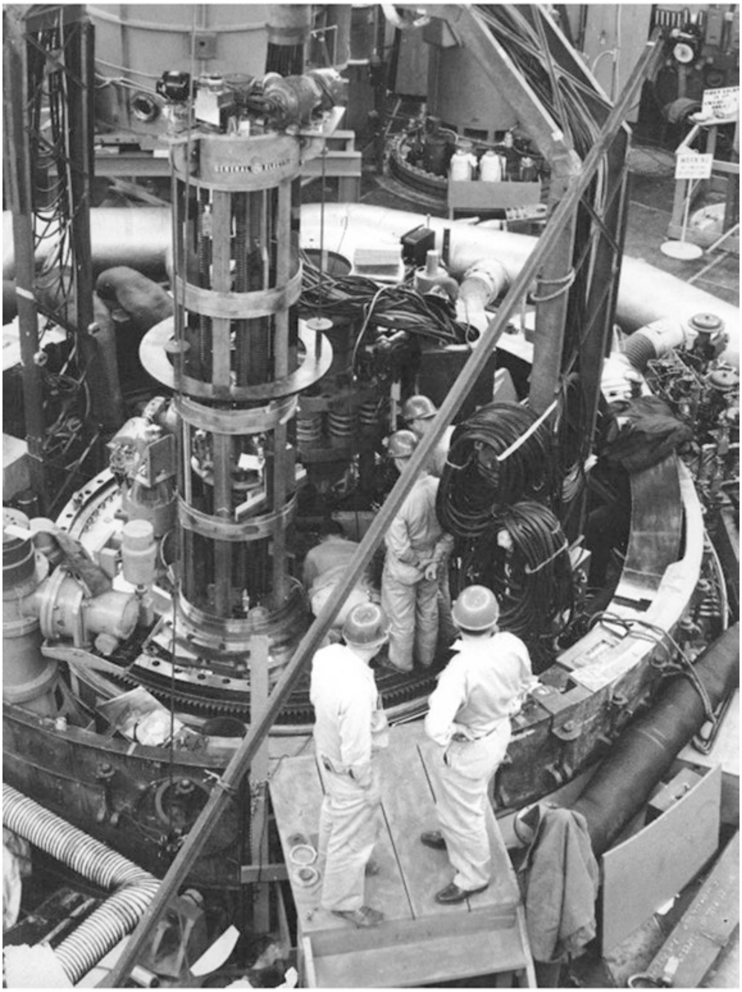


Photo 2.45 Top view of the vessel cover and the rotating plug

than the ordinary range of coolant temperature around 315 °C. At 3:09 a.m., the alarms in the upper part of the building began to sound indicating a damage of the fuel and a release of radioactive fission products. These alarms were triggered by ionizing radiation. The building was immediately isolated. A radiation emergency plan was declared. The power increase of the reactor was stopped at 31 MWth, followed by a power reduction. At 3:20 a.m., the reactor power was reduced to 26 MWth and it was manually shutdown. Over a one-year period, many assemblies were moved in order to perform examinations. The cause of the incident was considered "*relatively trivial*." The

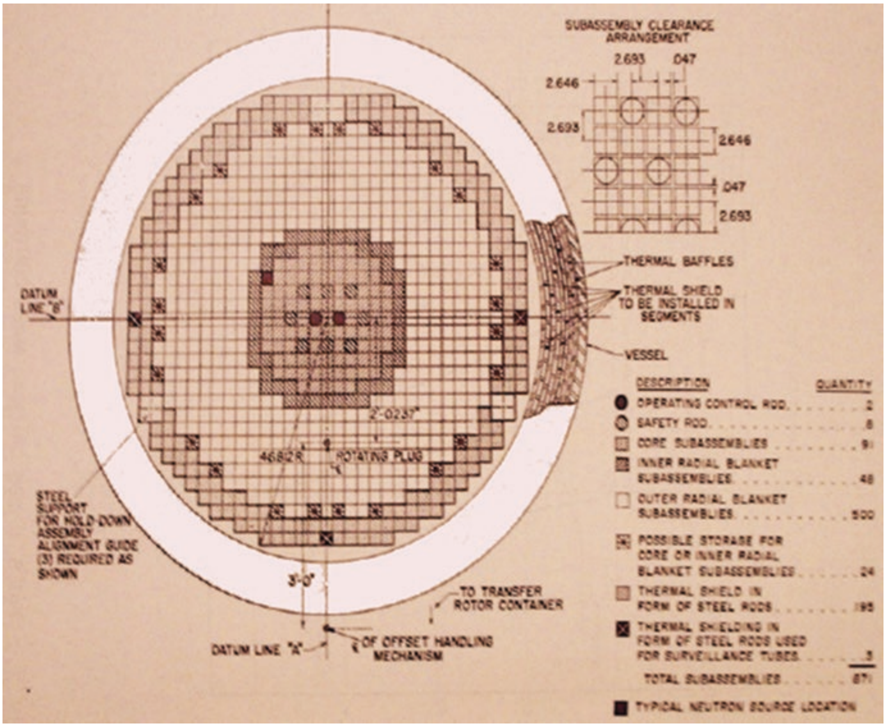


Fig. 2.40 Map of the core

examinations revealed that the partial meltdown occurred in two adjacent fuel assemblies. A third (possibly fourth) assembly was deformed but without internal damage. On September 11, 1967, a piece of debris defined as a "*foreign body*" was found stuck to the inlet plenum. The investigation showed later that this debris was a zirconium plate of the "*melt down section liner*" located originally in the vessel bottom of the reactor. In fact, at the bottom of the core, six zircaloy plates were welded to the inlet of the plenum to solve the problem of re-criticality in the event of core meltdown. This recommendation was made by the Advisory Committee on Reactor Safeguard, the safety authority, in 1959, in order to "divide" the mass of the falling molten core by spreading on a conical corium-flow divider, and to ensure the subcriticality of the resulting corium fragments. Two of its six plates broke off, became loose and one caused a blockage of the coolant flow at the inlet of the assemblies. The zircaloy plate was carried by the coolant and moved between different positions until it partially or completely obstructed the inlet channels of the various assemblies during the shutdown and restart phases of the reactor. The coolant flow would have been limited, through the assemblies concerned, to

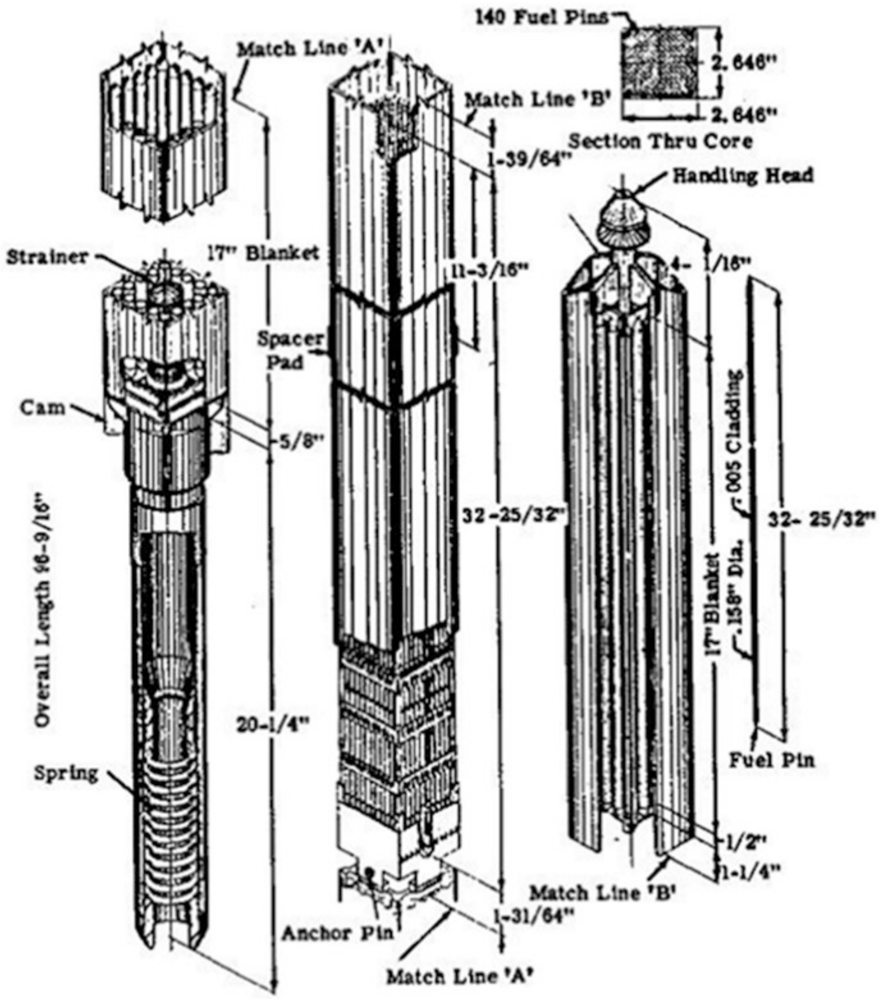


Fig. 2.41 Fermi-1 fuel bundle and control blades

between 3% to 30%. Figures 2.42 and 2.43 show in detail the zone between the vessel bottom and the fuel core. Figure 2.44 shows where were found the loose plates (top view).

On January 30 and 31, 1968, the Joint Committee on Atomic Energy led a congress to shed light on the partial meltdown of the core. On February 2, PRDC formally notified that the foreign body that had blocked the neutron flux was from one of the six triangular-shaped pieces of metal installed at the bottom of the vessel, in this case the zirconium plates. To repair the damage inside the core, it was not necessary to use a tool specially designed to operate

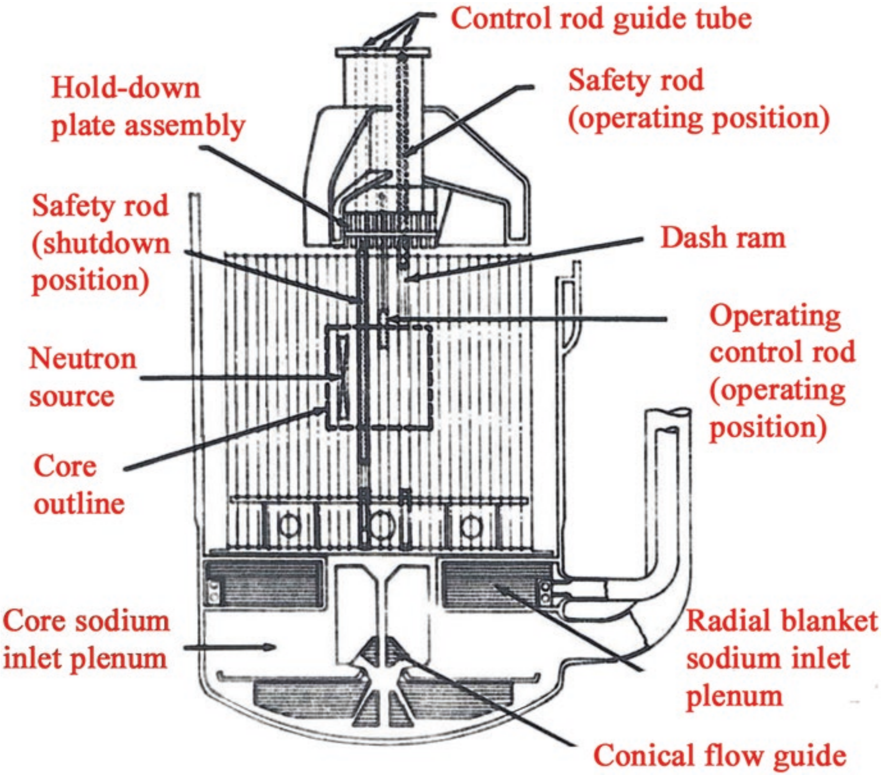


Fig. 2.42 Simplified sketch of the vessel internals

in highly irradiating environment. The metal fuel core was then removed and replaced by a uranium oxide core. On December 16, 1968, the last of the six zirconium plates was removed from the entrance of the plenum. On February 10, 1970, PRDC was authorized to restart the reactor. The reactor then restarted on July 18, 1970, four years after the incident. Its restart, initially planned for May, was delayed until July, due to a sodium fire. Its operation ceased in 1972. There were no injuries, and no radioactivity was released into the environment. The safety system revealed an activity of 10,000 Curies due to fission products released inside the coolant. Fortunately, the damage did not spread to adjacent assemblies, and the accident did not reach the worst-case scenarios. The incident put in light the problems associated with the coolant blockage. The zircaloy plates that were found were not intended to be included in the original design of the reactor, and plates were unfortunately chosen for budgetary reasons.

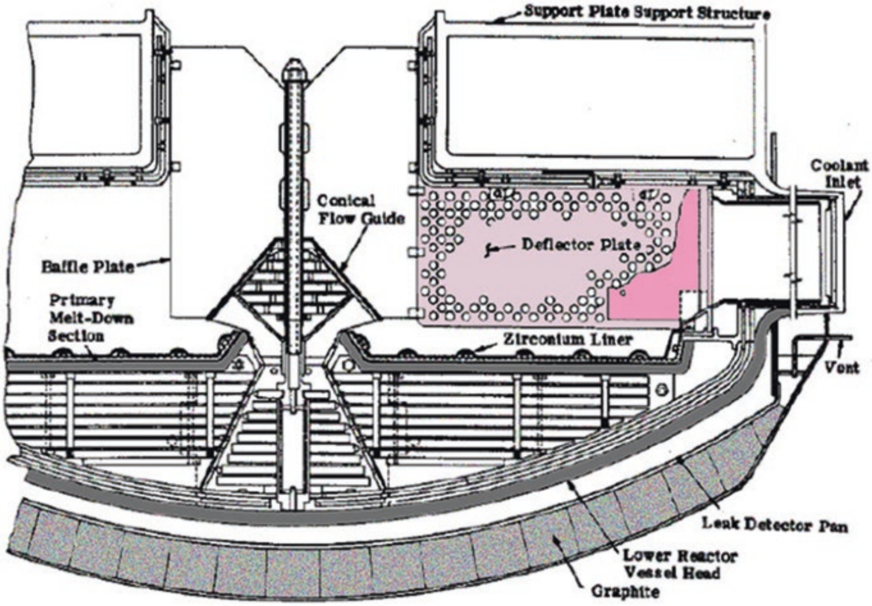


Fig. 2.43 Vessel lower internals

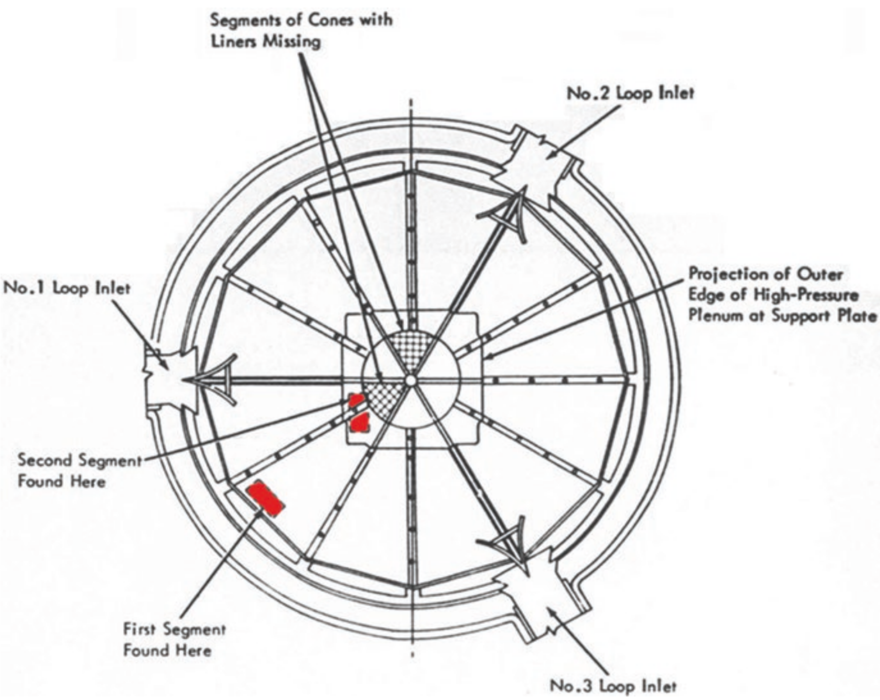


Fig. 2.44 Location of the loose fragments of the corium-divider cone liners spread in the lower plenum

Since the Fermi-1 incident, the fuel assembly inlet nozzles, at the level of the tubes, include multiple by-pass passages for the coolant that make impossible the total blockage by external debris. Research and testing of internal and external blockages have been undertaken to quantify and understand the damage caused by such mechanisms. The scenario of internal or external blockage of an assembly has been taken into account in reactor design. Their design must follow different recommendations at the level of:

1. The design of the assemblies: provide several coolant orifices inside the assemblies.
2. Inlet plenum design: ensure coolant flow distribution and the feeding of the assemblies.
3. Instrumentation design: detection by multiple thermocouples, delayed neutron detectors, gas "beacon" detector.
4. The design of the fuel handling equipment (technology of spent fuel concrete casks).

In addition, other lessons were learned, notably concerning the parts of the reactors likely to be damaged by vibrations. They must be carefully designed and monitored to prevent possible release of debris. In some countries, the scenario of fuel assembly jamming was adopted as a "design basis accident" for fast neutron reactors.

This partial meltdown of the core, even if it led to the shutdown of the Fermi-1 reactor for nearly 4 years, did not prevent the reactor from returning to service in 1972. Fermi-1 was decommissioned in 1975, once plans for a new facility were proposed. However, this project was abandoned in the 1980s by the American authorities, who preferred to develop the treatment of spent fuel. This incident nevertheless allowed the reactor type to benefit from important feedback concerning blockage issue. Thus, many improvements of the reactor design have been proposed, in order to avoid a single piece of debris blocking the flow of coolant. LMFBRs technology is still considered in the GEN-IV program for future reactors.

The obvious conclusion is that the technology of laterally closed fuel tubes, which is widely used in fast neutron reactors, is a design weakness that has led to numerous accidents of partial or total plugging of one or more assemblies. This problem is also recurrent in the case of concepts with separate cooling channels like CANDUs or RBMKs. In the case of FBRs, these housings impose the desired rigidity of closely spaced rod bundles and allow the liquid metal flow in each channel to be adjusted for better flattening of the power sheet. The idea of introducing cooling feedthroughs into the hexagonal tubes of the power FBRs is being considered, but this will likely result in a loss of stiffness and even the risk of vibration induced by fluid jets. In nuclear technology, one must be wary of jumping to conclusions and making risky arrangements. The message given in the American Nuclear Society about Fermi-1 ("*New age for Nuclear Power*," Photo 2.48) was rather obscured by the partial meltdown of the reactor core.

The episode at Fermi 1 in Frenchtown Township was the subject of the 1975 anti-nuclear book (Photos 2.46 and 2.47), "*We Almost Lost Detroit,*" written by John Fuller, and the inspiration for a song of the same name by the late Gil Scott Heron. The song was more recently covered by the Detroit indie band JR JR that still regularly plays the tune before audiences around the world (source https://eu.freep.com/story/news/ local/michigan/) (Photo 2.48).

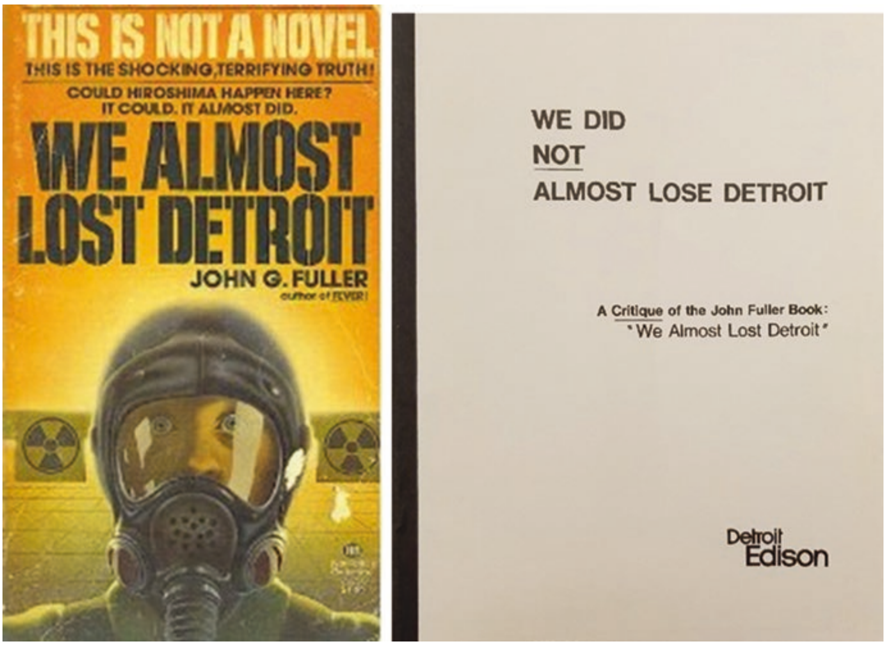


Photo 2.46 The provocative "*non-novel*" book "*We almost lost Detroit*" written by John Fuller, and the provocative answer from Detroit Edison "*We did not almost lose Detroit*". Believe it or not? Judge by yourself. At least, left cover is much more commercial!

NUCLEAR DISASTERS FROM DETROIT EDISON

By Alan Lenhoff and Jan Prezzato

DETROIT—The death toll is nearing 133,000 as millions of southeastern Michigan residents try to escape the poisonous radioactive shroud that hangs over the region. Relief to the panic-stricken millions has become a futile effort as scores of people clog every exit out of the area. Michigan, which is now under martial law, has become the center of the World's attention and concern.

The catastrophic events of the past few days were set off when the metal fast-breeder reactor of the $120 million Enrico Fermi Nuclear Power Station No. 1, in Lagoona Beach, near Monroe, suffered a meltdown of its nuclear core, which sent jets of radioactive particles into the atmosphere, threatening life for hundreds of miles around.

The almost apocalyptic event was blamed on the subassemblies which house the radioactive fuel. They were thrown out of their core due to a piece of metal which mysteriously appeared in the reactor's housing.

A Class I alert was first made known through the State Police, who initiated Civil Defense measures. Warnings have been sent to outlying areas as the cloud of death, trapped by unseasonably warm weather, moves east over Lake Erie . . .

It almost happened, as John G. Fuller so vividly portrays it in his recent book, *We Almost Lost Detroit*. Life

continued on page 4

Nuclear Disasters From Detroit Edison

We Almost Lost Detroit

The power of Idaho Falls' SL-1 plant was only a fraction of the power of the Fermi plant. If the Fermi plant had an accident similar to the one that occurred at SL-1 in 1961, chances are you wouldn't be reading this review.

Photo 2.47 Alan Lenhoff and Jan Prezzato talk about "*death toll*" in the Ann Arbor Sun, June 17, 1976. The text, also introducing the accident of SL-1 in Idaho, is a strong support to Fuller's book. The photomontage shows a radioactive death cloud spreading over the city of Detroit. Real facts are rather short

Chapelcross, a Carbon Dioxide Flow Blockage and Magnesium Cladding Melting (1967, Great Britain)

Great Britain chose very early on to develop a national reactor type based on the choice of the first plutonium reactor at Windscale for the military program. This reactor type was named Magnox (for Magnesium Non-OXidizing). This type of reactor uses natural uranium metal, moderated by graphite and cooled with CO_2 carbon dioxide. Construction was spread out from 1953 to 1971, the first being the Calder Hall reactor, which was inaugurated in 1956 by Queen Elizabeth II (Photo 2.49), and the last one was the Wylfa plant. Since the end of 2015, they are all out of service because they have been replaced by an evolution of the concept: the AGR (Advanced Gas-cooled Reactor). They used this famous "*stainless magnesium*," which was a magnesium-aluminum alloy used to clad the fuel in this type of reactor. The uranium must not be in direct contact with the carbon dioxide that cools it to limit contamination by radioactive fission products.

Chapelcross is a site near Annan in the province of Dumfries and Galloway in southwest Scotland (Fig. 2.45), with 4 Magnoxes of 48 MWe each (182 MWth, thus a modest efficiency of 23%), which began construction in 1955

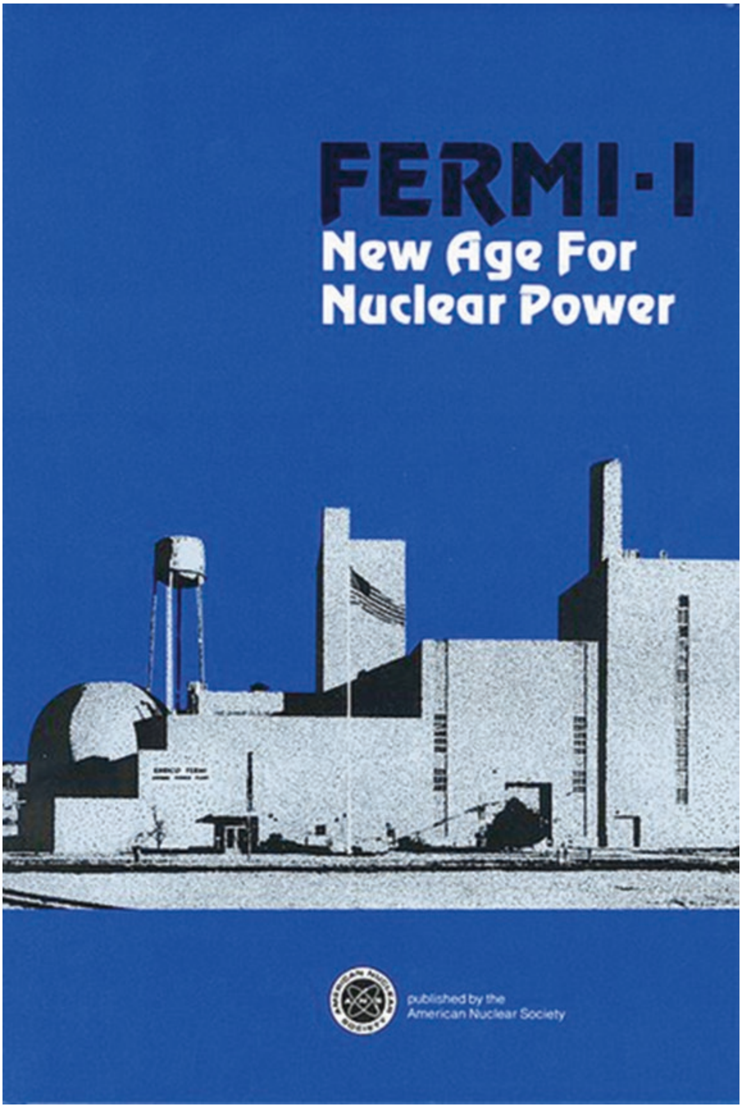


Photo 2.48 A much more scientific text about Fermi-1 from the American Nuclear Society, unfortunately, obscured by the partial meltdown event of 1966

and was coupled to the electric grid in 1959. Chapelcross is the sister reactor of Calder Hall (Photo 2.50). Note that the fuel at Chapelcross is slightly different from that at Calder Hall (more on this later). Another difference from Calder Hall is that Chapelcross has its own cooling pool for spent fuel, which is necessitated by its distance from Windscale. The core consists of 1696 channels in a 203 mm pitch lattice for loading fuel rods. The active core has a diameter of 9.45 m and a height of 6.4 m. 112 channels allow the insertion of

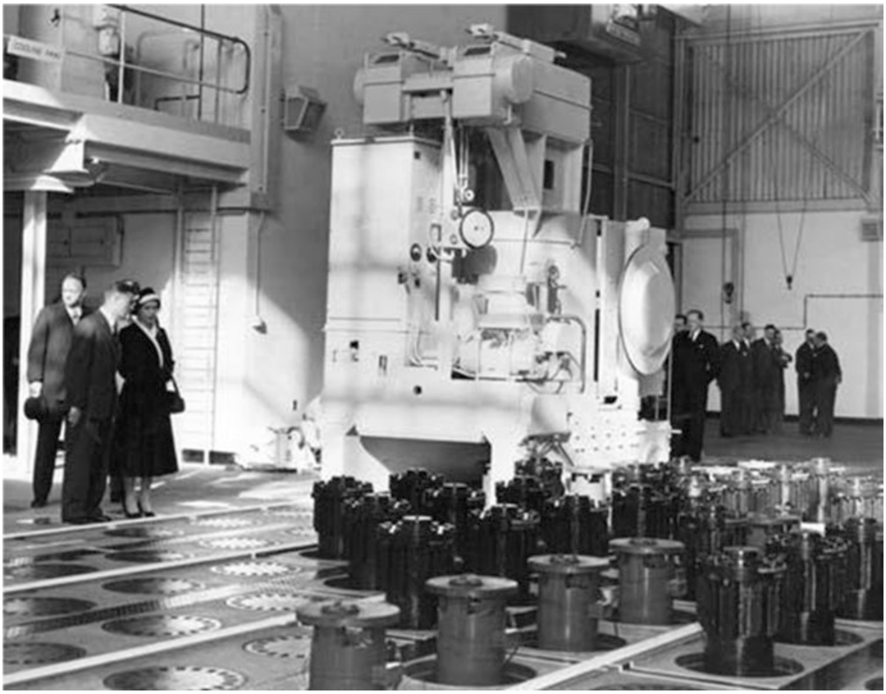


Photo 2.49 Queen Elizabeth II inaugurated the Calder Hall reactor on October 17, 1956. This view shows the fuel loading machine (in white in the background), which runs on rails. A sealed part of the machine is connected to the primary circuit by means of conduits. The circular fuel caps and the asperities in counter-relief that allow unscrewing, are clearly visible on the ground

Photo 2.50 The four reactors of Chapelcross are particularly standardized except for a color inversion of the SGs siding (photo NDA)

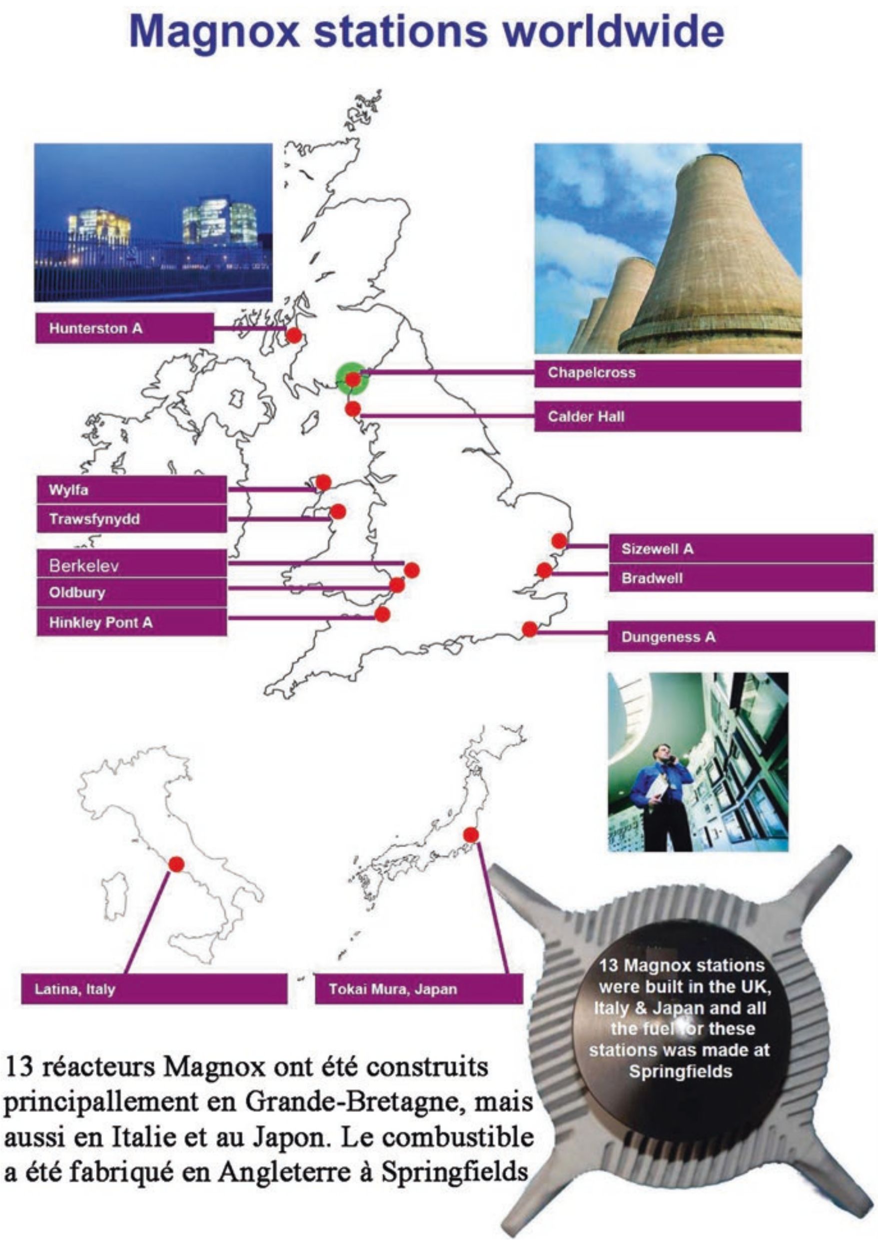


Fig. 2.45 Implementation of the Magnox reactor type in the world. Chapel Cross, the site of the 1967 accident, is located in Scotland (green dot on the map)

control rods. The core is cooled by a carbon dioxide CO_2 at a pressure of 7 bars that enters at 140 °C and exits heated to 336 °C with a flow rate of 891 kg/s. The fuel is in the form of natural uranium metal in the form of six 1016 mm cast rods, each clad with Magnox-C, a magnesium alloy. The six rods are embedded in an assembly. The total mass of metallic uranium is 120 tons. The vessel containing the fuel and the graphite moderator blocks is made of steel (Low-term A-kill mild steel) with a cylindrical shape closed by two domes (internal diameter 11.28 m, external 21.3 m, thickness of the dome plates 51 mm). The vessel itself is contained in a concrete compartment (called a caisson or leak tight housing) (Fig. 2.46). The caisson is contained in a conventional building with windows (Fig. 2.47). Four centrifugal fans (total 5.4 MWe) move the coolant CO_2 (Fig. 2.48) through 4 primary loops (Fig. 2.49). Four steam generators act as heat exchangers CO_2/H_2O and produce 180 tons/hour of steam at 310 °C under 14 bars (Fig. 2.50). This steam turns a turbine and two alternators of 23 MWe each at 3,000 rpm.

The reactor was loaded via a fuel loading machine that runs on rails placed in a lattice on the loading face (Fig. 2.51). The machine moves and positions itself in front of a pressure tube. The mast containing the fuel assembly to be loaded is connected to the "tulip-shape socket" which closes the pressure tube and unscrews the cylindrical socket-shaped plug, which seals the primary circuit. In doing so, carbon dioxide from the primary circuit enters the sealed mast, and a new fuel can be lowered without any gas leak, or an existing fuel can be removed. The aim of this machine is to avoid the spread of radioactive gases on the service desk. The operations are automated as much as possible to avoid human presence and radiation protection risks.

The fuel rods of an assembly are in the form of a uranium metal "rod" entirely cladded with a magnesium alloy. The cladding alloy has a complex shape with cooling blades to improve heat exchange with the carbon dioxide that flows past the outer face of the cladding (Fig. 2.52).

On May 11, 1967, a fuel element in a channel of Reactor 2, which was loaded with fuel elements being evaluated for the future AGR commercial reactor program, suffered a partial carbon dioxide flow blockage, attributed to the presence of graphite debris. Due to the burn-up and high temperature, the graphite that makes up the core of the reactor was deformed until a portion broke off. As it fell, the graphite debris became blocked in a loading channel, partially obstructing it and greatly disturbing the flow of CO_2. With the cooling impaired, the fuel elements in the channel rapidly rose in temperature, until the cladding failed, and fission products escaped, contaminating the core. In practice, the fuel overheated and the Magnox cladding, made of a magnesium-aluminum alloy, failed, leading to a deposit of contamination

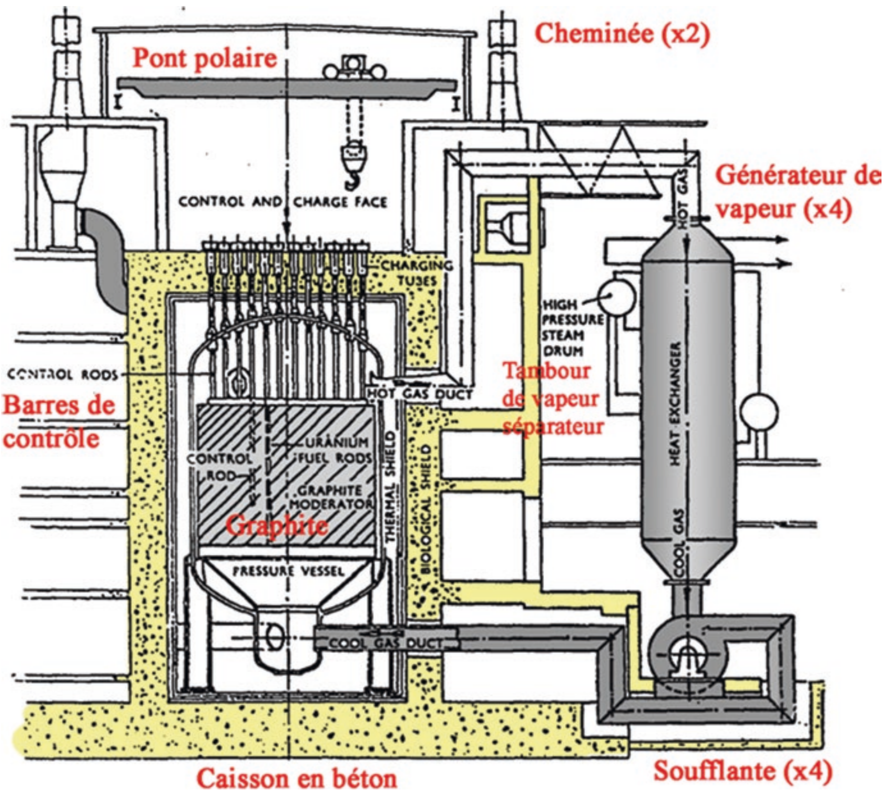


Fig. 2.46 Axial section of the reactor (Calder Hall and Chapelcross). We notice that the steam generators (imposing!) are located outside the building. They are surrounded by a siding in grating, which allows a visual inspection but has no real function of external protection

in part of the core. It should be noted that the use of magnesium cladding limits the temperature of the carbon dioxide to 360 °C because the melting points of magnesium (650 °C) and aluminum (660 °C) are relatively low. The triggering of a radioactivity alarm in the carbon dioxide caused the shutdown of the reactor. After depressurizing the reactor's primary circuit (initially to 7 bars), cameras were inserted into the offending fuel channel, which revealed a blockage caused by the melting of a Magnox cladding. As the gas could not circulate in the channel, the magnesium ignited, starting a fire in the reactor. Due to the deformation of the fuel, the personnel could not adopt the usual method of clearing the channel with the top unloading machine, which

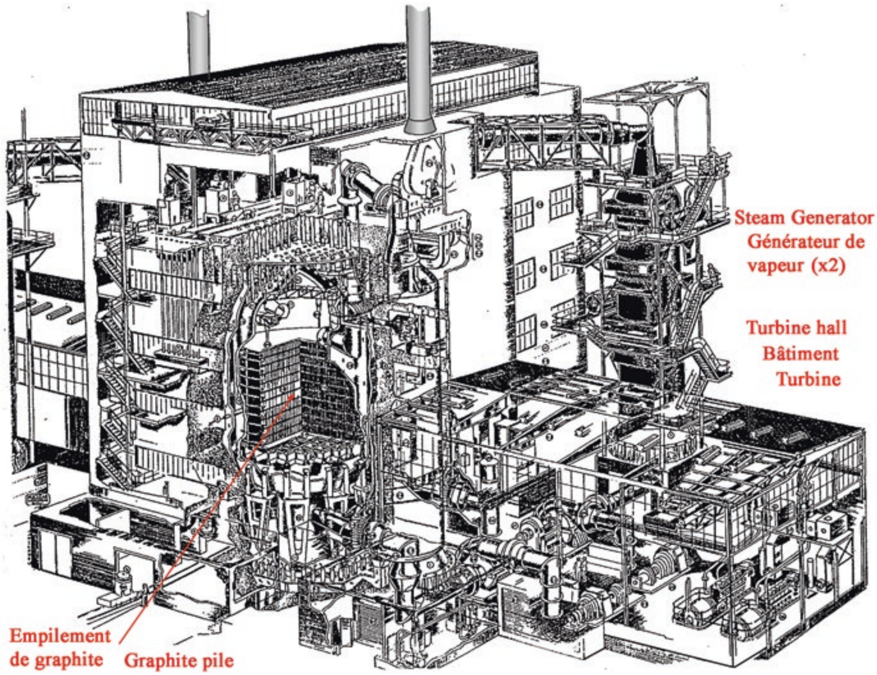


Fig. 2.47 General plan of the Calder Hall and Chapelcross reactors

required the development of a special technique. After the accident was stopped, volunteers had to enter the concrete caisson and steel vessel to install a containment tray under the failed fuel elements to ensure that no graphite and/or cladding fragments fell further down into the reactor. Senior staff members, Dr. J.H. Martin, Director of Health, Physics and Safety, Mr. David MacDougall, the Assistant Superintendent and Mr. L Clark volunteered to enter the reactor to perform the operation (Photo 2.51). This maneuver had been carefully rehearsed and closely timed on a realistic model before being attempted. A special isolation hatch was built around a duct leading to a cooling air access, where Dr. Martin and Mr. MacDougall entered dressed in PVC suits. Their only link to the outside was an air hose, a radio communication cord, and a nylon lifeline attached to their waists. There were no windows in the caisson, and it was like a black pitch with no lighting, an extremely stressful situation. Upon exiting, the men commented: "*The suits were cumbersome,*

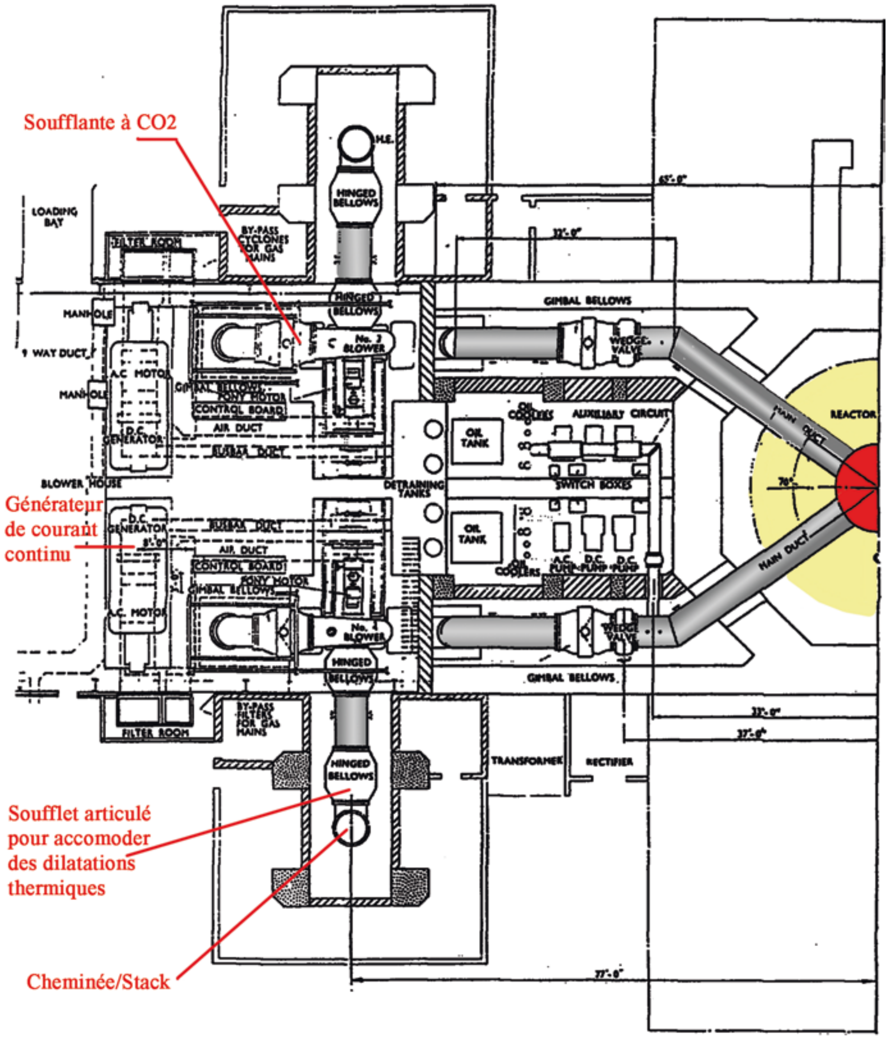


Fig. 2.48 Diagram of a half-circuit for the circulation of carbon dioxide. The same half-circuit is found symmetrically on the other side of the reactor

and we were sweating a lot... we never thought about the danger... we felt a bit like men on the Moon". Mr. Clark was the sentry at the entrance to the duct, while Dr. Martin went in to take final radioactivity measurements, and Mr. MacDougall made sure the recovery bin was in place. (adapted from Sarah Harper's article https://www.coldwarscotland.co.uk/chapelcross-almost-chernobyl-chapelcross-fire-1967).

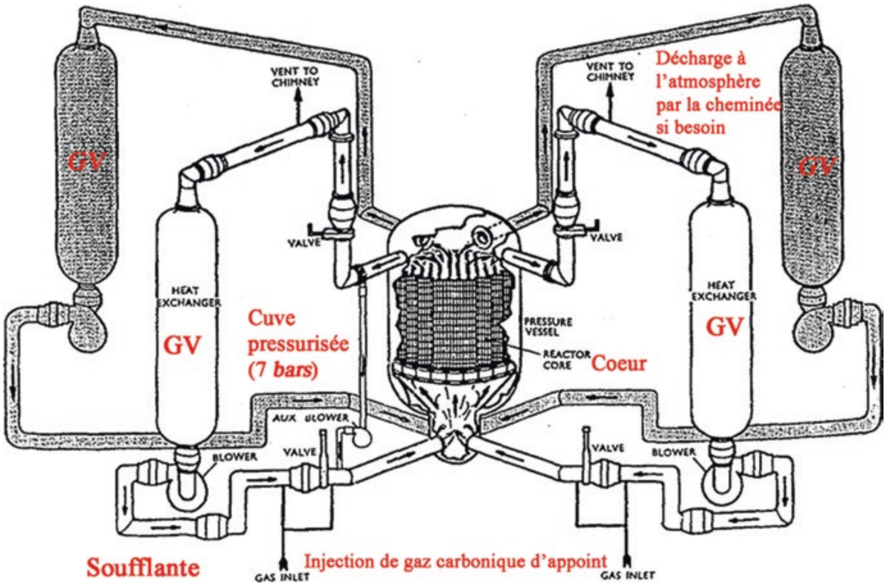


Fig. 2.49 Diagram of a 4-loop Chapelcross primary circuit

The deformation of graphite under temperature and irradiation is a known phenomenon, as well as the release of energy (Wigner effect) when the graphite is irradiated at too low temperature (see the importance of the Wigner effect in the Windscale accident described above). After the release of Wigner energy in the Windscale No. 1 pile in 1952 and after the severe Windscale fire in October 1957, the UKAEA Energy Commission recommended that graphite temperatures in the C.E.G.B. power reactors be increased to a level that would prevent the accumulation of stored Wigner energy over the lifespan of the reactors. This recommendation resulted in the inclusion of removable graphite sleeves in the fuel channels of the Chapelcross No. 2, 3, and 4 reactors. The inclusion of sleeves creates a thermal gradient that increases the temperature of the graphite in the core of the moderator blocks, particularly in the lower part of the core. The graphite sleeve completely surrounded the rod and its cladding without being in contact with the cladding to allow cooling carbon dioxide to pass through. The temperature increase, due to the insulation of the fuel channels from the cooling gas, comes from the gamma and neutron heat up. In this way, the graphite moderator is intrinsically self-healing (permanent thermal annealing) with respect to the Wigner Effect. However, it should be noted that the graphite and gas temperatures are higher in this situation, compared to a more open geometry. The choice of magnesium as cladding material may seem curious when one knows the risks of

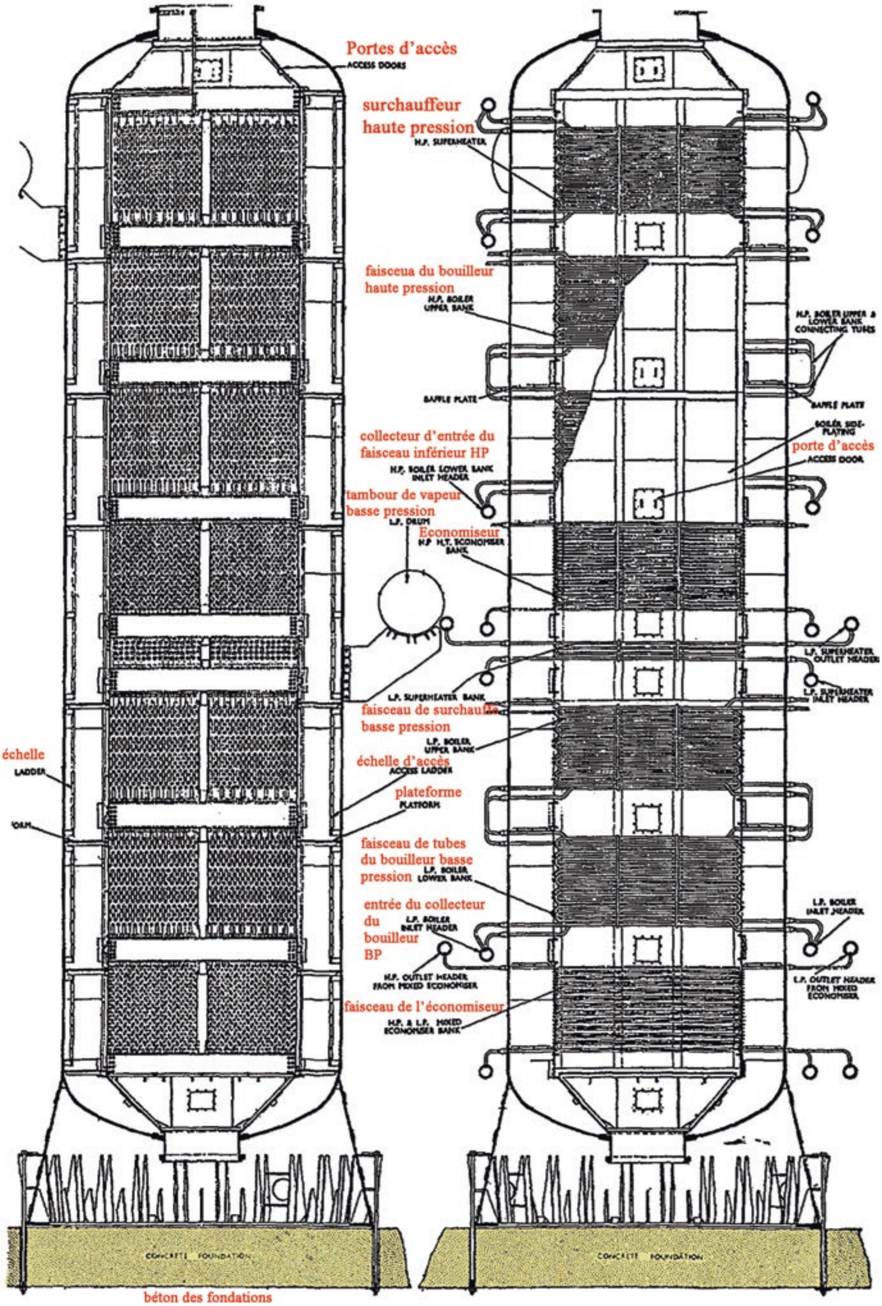
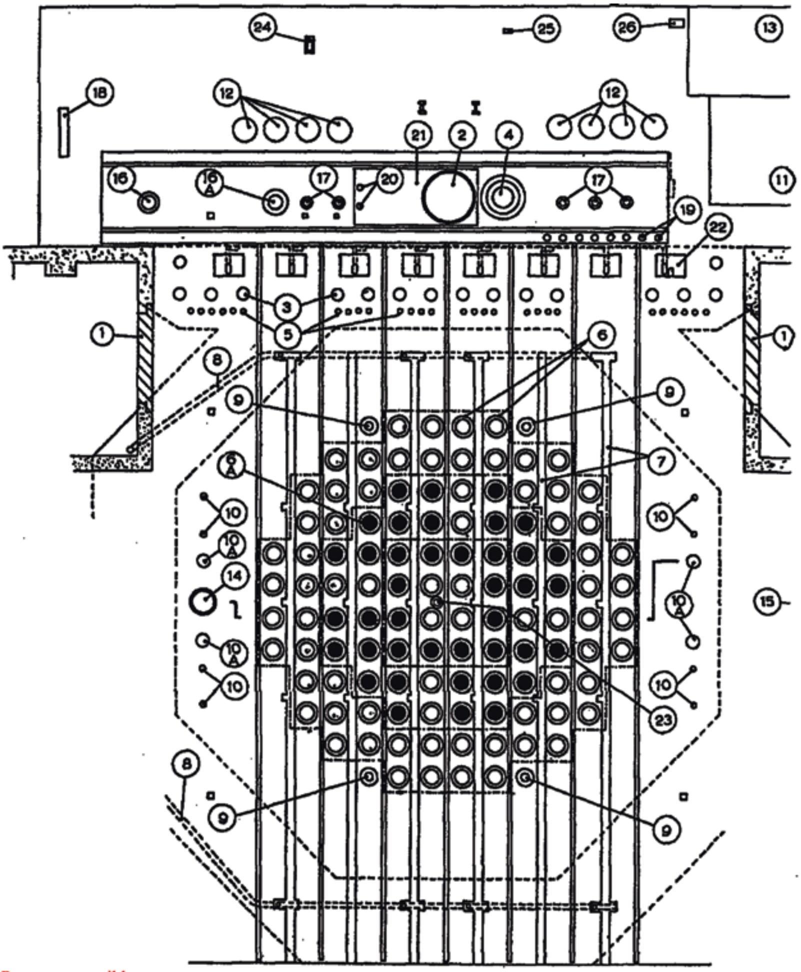


Fig. 2.50 Axial section of a Chapelcross steam generator



1 Panneau amovible
2 Puits de décharge
3 Trous de stockage
4 Verrin hydraulique
5 Trous de stockage des barres de contrôle rebuttées
6 Tube de force
6a tube de barre de contrôle
7 Tranchées de service
8 Systèem de purge de la machine de chargement
9 Trous pour des tests de contamination
10 Trou d'inspection par caméra
11 Puits du treuil
12 Stockage intermédiaire de la charge à évacuer
13 Escalier

1. Removable panel
2. Discharge well
3. Mortuary holes
4. Hydraulic cylinder
5. C.R. mortuary
6. Charge tubes
6a. C.R. positions
7. Service trenches
8. Machine purge system
9. Contamination test holes
10. Remote viewing holes
11. Hoist well
12. Charge chute stowage
13. Stairway
14. Access hole
15. Removable panel
16. C.R. test hole
17. Grab access holes
18. Ancillary CO_2 feed
19. C.R. stowage
20. Door hydraulics
21. Cross traverse
22. Charge machine contacts
23. P.V. probe
24. Oil pipes
25. Hoist footing
26. Cable slots

14 Trou d'accès
15 Panneau amovible
16 Trou pour tester les barres de contrôle
17 Trou d'accès pour saisie
18 Alimentation auxilliaire en CO2
19 Stockage des barres de contrôle
20 Système hydraulqiue des portes
22 Contacts de la machine de chargment
23 Sonde PV
24 Conduites d'huile
25 Pied du treuil
26 fentes pour les câbles

Fig. 2.51 View of the loading face. The loading face is located above the reactor. On this face moves the fuel loading machine that can load and unload the reactor while it is running. This so-called "continuous" loading makes this type of reactor particularly interesting to produce weapons-grade plutonium, insofar as it is possible to unload spent fuel with an isotopic percentage of plutonium 239 greater than 95%. The more the fuel is irradiated, the more the plutonium will contain even isotopes of plutonium 240 and 242) that are detrimental to the optimal functioning of a nuclear weapon

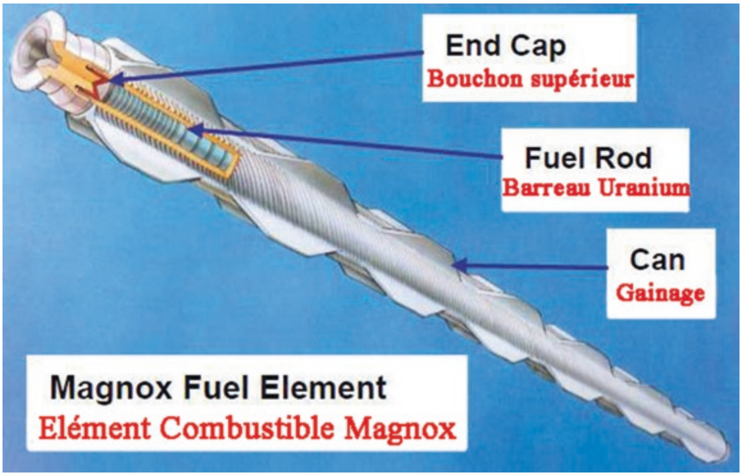


Fig. 2.52 A Magnox fuel element. These fuels have evolved constantly and significantly over the course of Magnox reactors, and it is safe to say that no two reactors in this reactor type will have the same fuels. The external blades are designed to increase the exchange surface, as well as the surface threading, in order to improve heat exchange

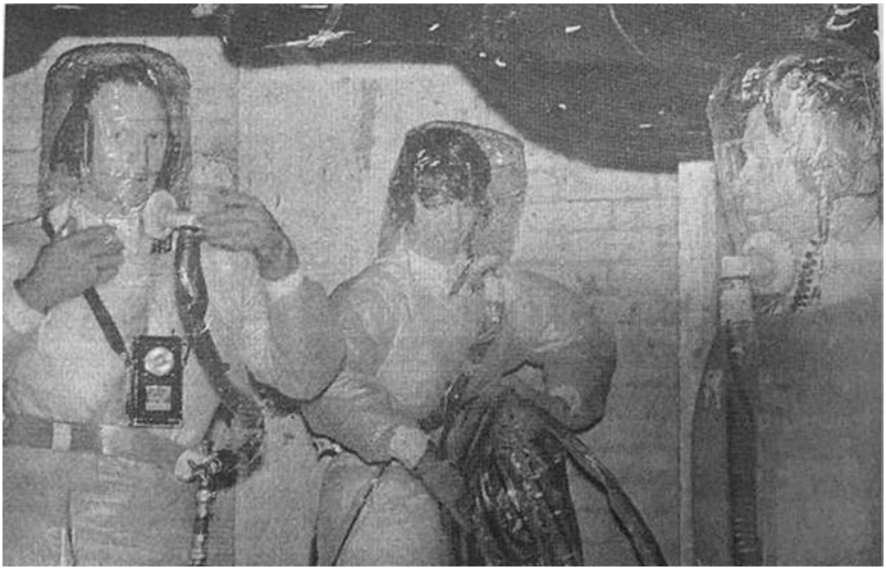


Photo 2.51 Three volunteer managers: From left to right: J.H. Martin, David MacDougall, and L. Clark are about to enter the carbon dioxide depressurized caisson at Chapelcross-2. They are equipped with an externally ventilated (non-self-contained) "*Mururoa*" (Mururoa is a French island in the pacific where atomic bombs were tested underground in real conditions. Hence the name of the special suits used by the personnel) type suit (photo *The Annadale Observer*)

oxidation in the presence of water steam and even in pure carbon dioxide, but its neutron capture cross-section for thermalized neutrons (or slow neutrons) is very low. Magnesium, which is lighter than aluminum, is easily spun into tube form, has a good weldability, and does not produce low melting point eutectics on contact with uranium metal. It is also abundant and rather inexpensive. However, the significant coarsening of the magnesium grain on heating is detrimental to the mechanical strength of the fuel elements. It is therefore necessary to consider the addition of other metals to refine the grain, such as zirconium, zinc or, as in this case, aluminum. Its low melting point (650 °C) does not allow the heating of the CO_2 at more than 400 °C in nominal conditions (leaving some margin for incidental situations). But the particularly closed geometry of the fuel element in its graphite channel reinforces the risk of obstruction of the channel in case of channel degradation and debris formation. Unfortunately, magnesium oxidizes in the presence of water steam (see the Lucens accident below), and oxidizes even in the presence of pure CO_2 according to the chemical reactions, driven by the Gibbs free energies ΔG:

$$CO_2 + Mg => MgO + CO \quad \Delta G = -74\,000 \text{ calories}$$

$$CO + Mg => MgO + C \quad \Delta G = -86\,000 \text{ calories}$$

$$CO_2 + 2Mg => 2MgO + C \quad \Delta G = -160\,000 \text{ calories}$$

$$CO + Mg0 => CO_3Mg \quad \Delta G = -800 \text{ calories}$$

And considering traces of air (oxygen + nitrogen) in the CO_2:

$$O_2 + 2Mg => 2MgO \quad \Delta G = -254\,000 \text{ calories}$$

$$N_2 + 3Mg => Mg_3N_2 \quad \Delta G = -77\,700 \text{ calories}$$

It appears that all these reactions are possible under atmospheric pressure from 400 °C to 500 °C except the production of carbonate CO_3Mg, which dissociates upon 420 °C. These reactions are even favored by the pressurization (7 bars) of carbon dioxide. Let us note also that the radiolysis carbon dioxide produces free oxygen, which is very corrosive. In air, magnesium is very flammable. A pure magnesium ribbon will catch fire with a simple match. In powder form, it becomes explosive by increasing the contact surface. The flame produced is strong white and very incandescent. Hence its use in the flashes of the early days of photography, causing many accidents. For these same properties, it is used today in the manufacture of some pyrotechnic materials. Magnesium produces, during what can be called a “fire,” a significant amount of heat which is communicated to the surrounding structures and self-sustaining the fire. Magnesium, like aluminum, has a strong reducer character and therefore oxidizes easily, releasing a lot of heat. It is a good fuel in the air. Magnesium is such a good reducer that it can burn in the CO_2, which is usually not a good oxidizer. This reaction produces white powdery magnesia MgO and black solid carbon. Thus, the accident scenario is refined. The loss of geometry of the channel, partially or totally blocked by carbon debris of the graphite channel deformed in temperature, led to a strong temperature increase of the carbon dioxide. This temperature excursion led to an accelerated oxidation of the magnesium-aluminum cladding, which “burned” and melted, releasing radioactive fission products into the primary circuit.

The reactor was restarted in 1969 after successful two-year cleanup operations, and it was the last reactor of its type to cease operation in February 2004.

Siloé, Melting of Fuel Plates (Grenoble, France, 1967)

Siloé was a French nuclear research reactor, of the pile pool light water type with an open core (but covered with water) and a thermal power of 15 MWth at start-up. Built from August 1961 by Indatom on the scientific polygon of Grenoble on the site of the CEA near the city (Photo 2.52), The reactor diverged on March 18, 1963, at 11:15 p.m., one year after the first Grenoble reactor, Mélusine, and eight years before the high-flux reactor (RHF) at the nearby *Institut Laue-Langevin*. A model of Siloé was tested in April 1962 in the Mélusine reactor. The core is composed of plates made of an alloy of uranium metal and aluminum highly enriched to more than 90% in ^{235}U. The core is reflected by beryllium plates. The building housing the reactor-pool consists of a vertical cylindrical concrete body 25 m high and 27 m in diameter. The two floors of this hall are equipped with experimental areas. A hot cell for treating the fuel completes the equipment. The primary function of Siloé was the doping of silicon crystals and the production of medical radioisotopes by neutron irradiation. In 1968, the power was increased to 30 MWth, then to 35 MWth in 1974, and even to 40 MWth in order to carry out tests on materials requiring large neutron fluxes. The core of Siloé is submerged by a large quantity of water which acts as a biological protection against radiation, so that one can operate freely on the reactor service desk during operation (Photos 2.53 and 2.54).

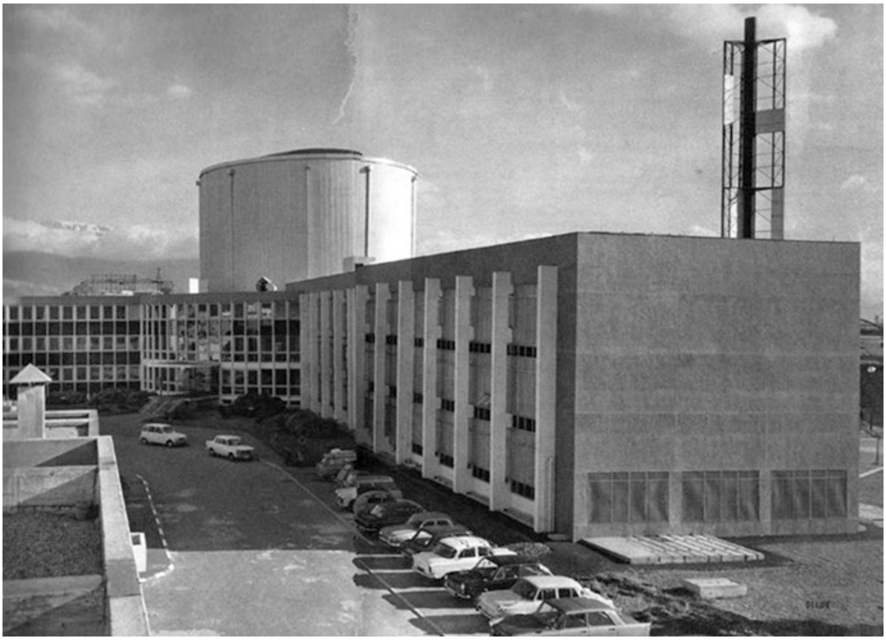


Photo 2.52 Siloé building inside the CEA site. The reactor is located in the white cylindrical building

The civil engineering of the SILOE reactor pool had two compartments: a compartment called the "*main pool*," with a volume of 213 m^3, containing the reactor core at the bottom, and a compartment called the "*working pool*," with a larger volume of 322 m^3, arranged in a horseshoe shape around the main pool (Fig. 2.53). This pool was used for storage of experimental devices and safe interventions (out of neutron flux) on them. The faces of the pools in contact with the water are tiled in the manner of a real pool, except that the tiles are joined with Araldite glue, which is more waterproof than conventional joints. Nevertheless, this tiling was to pose recurrent sealing problems from 1965 to 1970, until a leak at the foot of the "*stool*" supporting the core was visually detected by air bubbles (Fig. 2.55). A stainless steel plate joined by a synthetic foam was then affixed. The degradation of this foam under irradiation necessitated replacement with a rubber gasket held in place by lead. The problem was only permanently solved in 1972, and the leakage was estimated at 1500 m^3 of tritiated water, which must have polluted the groundwater table. To finish with the leaks, a hole of 5 mm in diameter was detected in 1986 in a corner at the bottom of the pool, which had to be repaired. The press echoed these leaks, which caused a stir in the population. Beginning in

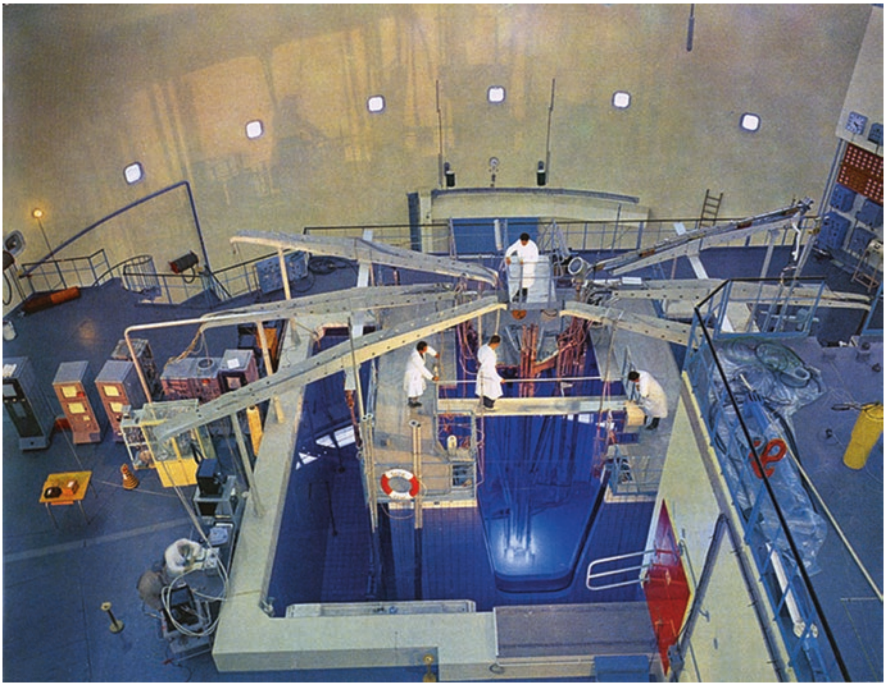


Photo 2.53 The Siloé core during operation. One can see the intense bluish Cerenkov-Mallet radiation that characterizes the core in operation. The operators can handle the core on the bridge (photo *Association des Retraités de l'Institut Laue-Langevin*)

1987, the CEA undertook important work to bring the pile up to standard: a stainless steel casing 3 mm thick was installed on the walls of the main pool, a vessel known as the "BORAX vessel" 7 mm thick, the vessel itself is placed on a stainless steel plate 20 mm thick mounted on shock-absorbing para-seismic pads. The aim of these modifications is to guarantee the strength and tightness of the reactor pool in the event of an explosive accident or earthquake.

A neutron equipment was added later to perform experiments using neutrons (neutron diffraction in powders and crystals, polarized neutron diffraction...). Siloé was thus equipped with neutron exit channels that do not look directly at the core, but at the beryllium reflector which adjoined one of the four sides of the core. These channels are like trenches that promote the leakage of neutrons to the detectors. At the beginning, there were only two radial channels and two devices (DN1 and DN3). After the closure of Mélusine (1988), a tangential channel was added that looked at the beryllium wall through the plant.

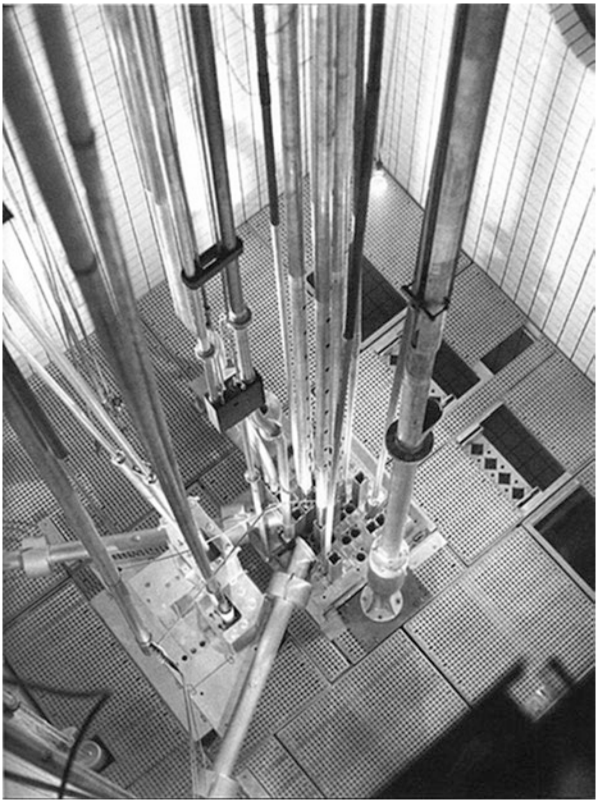


Photo 2.54 The core of Siloé (photo CEA)

On November 7, 1967, during a power increase to 42.3 MWth carried out as part of authorized tests in preparation for an increase in the nominal power of the reactor to 30 MWth, a partial fusion of six fuel plates belonging to a fuel element occurred. This test aimed to characterize the phenomenon known as "flow redistribution." When the power of 42.3 MWth was reached, a sudden decrease in power without any pilot action of about 7 MWth in one second was observed, followed by a slower decrease until it stabilized, 20 s later, at 20 MWth. The reactor was manually shutdown 26 s later, by dropping the two-reactor safety elements. A rapid increase in radiation dose rates was then observed (detected by a submerged dose rate measurement chamber, up to 1000 rad/h (10 Gray/h), and on another measurement chamber, located above the pool water, up to a value of 220 rad/h (2.2 Gray/h). This detection led to the evacuation of the reactor building and annex buildings, and the use of iodine traps in the emergency ventilation system. These high values indicate a loss of fuel tightness and the release of radioactive fission products.

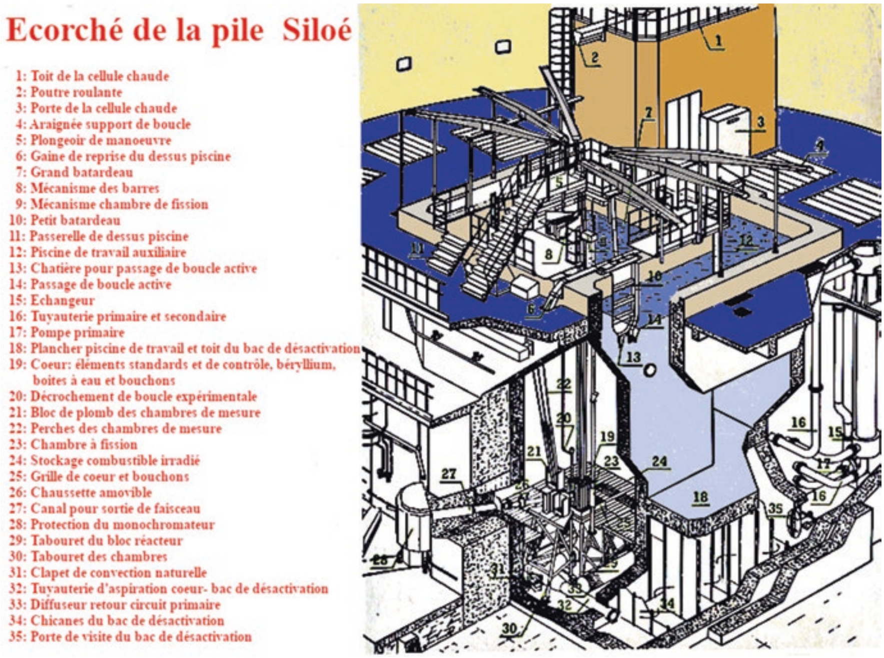


Fig. 2.53 Sketch of the Siloé pile. 1- Roof of the hot cell, 2- Rolling beam, 3- Hot cell door, 4- Loop support spider, 5- Maneuvering plunger, 6- Pool top recovery duct, 7- Large cofferdam, 8- Control rod mechanism, 9- Fission chamber mechanism, 10- Small cofferdam, 11- Pool top walkway, 12- Auxiliary work pool, 13- Cat flap for active loop passage, 14- Active loop passage, 15- Heat exchanger, 16- primary and secondary duct, 17- Primary pump, 18- Working floor and roof of the deactivation tank, 19- Core: standard fuel and control, beryllium, water boxes and plug, 20- Disconnection of the experimental loop, 21- Lead block of the measuring chambers, 22- Measuring chamber poles, 23- Fission chamber, 24- Spent fuel storage, 25- Core grid and plug, 26- Movable sock, 27- Channel for beam output, 28- Monochromator protection, 29- Reactor block stool, Chambers tools, 31- Natural convection flap, 32- Suction pipe to core /deactivation tank, 33- Primary circuit return diffuser, 34- Deactivation tank baffle, 35- Access door to the deactivation tank

During dismantling, once the atmosphere in the hall had returned to an acceptable ambient dose, 187 g of uranium-aluminum alloy (enriched to 93% in uranium 235) melted, corresponding to a mass of 36.8 g of uranium 235, 18 g of which were released into the primary circuit (Photo 2.55). The complement was found in the form of corium relocated at the foot of the control element. Fortunately, the fuel element concerned had a low fission rate (FIMA (Fission per Invested Metal Atom) burn-up of 4%). Nevertheless, 2000 curies of rare gas activity (74 10^{12} Bq) would have been released. The activity of noble gases decreases rapidly with time. Fuel entrained by the

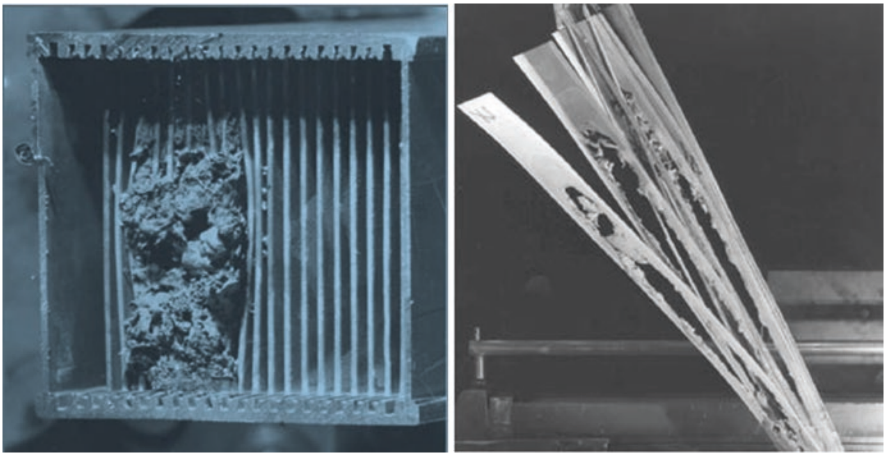


Photo 2.55 Degradation of the fuel element of Siloé in 1967 (view from the bottom). The uranium-aluminum fuel plates are simply encased in a casing (left). The plates are partially perforated by large tears after extraction from the casing (right)

cooling water was subsequently found in the deactivation tanks until 1971 (adapted and commented on from the book *Retour d'expérience des réacteurs de recherche français*, IRSN, available on the web site https://www.irsn.fr/FR/Larecherche/publications-documentation/collection-ouvrages-IRSN/Documents/RR-ReacteursRecherche_web-NB-Chapitre-10.pdf). The real cause of the accident is unclear. One immediately thinks of a local overpower, but it was not the hottest part of the core that melted. The boiling temperature of the water at the bottom of the pool (1.5 bars of pressure) is 128 °C, whereas the hot point (in water) did not exceed 115 °C at a nominal flow rate. However, in order to melt, the fuel element had to rise to at least 660 °C, the melting temperature of aluminum (the melting temperature of uranium metal is still higher than 1132 °C). In visual terms, the fuel plates do not seem particularly oxidized (Photo 2.55), which indicates a rapid degradation by drying (local exceeding of the critical heat flux). Given the thinness of the metal plates (more easily cooled than an oxide plate due to higher thermal conductivity), a significant flow loss was required in the incriminated channel. The margin should have been even greater for the incriminated element, which was not at the hot spot. The appearance of corium clearly indicates the drying of the fuel wall. As paint flakes from the structures overhanging the reactor were found several times in the pool water, a postulated scenario was imagined that a (partial?) blockage of a water channel had occurred, which would have reduced the flow. The corium would then have spread into the other adjacent channels. The principle of assembly of the fuel plates means that each cooling channel is isolated from the others. It would have been judicious to provide openings in the design to allow fluid to communicate between the channels, which would have made the assembly more resistant to instantaneous total blockage, a phenomenon much feared in fast neutron reactors, but which probably happened in Siloé.

Corrective measures were taken following the accident. Painted sheet metal was replaced with unpainted stainless-steel structures (no more risk of chipping/flaking). The facility's emergency exhaust system was redundant, and air and water sampling systems were installed for use from outside the building. In addition, a control system for activating the purification circuit was installed in the control room (thus without having to travel near the main pool). The Siloé accident, although perfectly documented by the IRSN, remains a largely unknown accident in France.

Gradually, the CEA is going to shut down all the nuclear activities of the CEA in Grenoble, the site being considered too close to the Grenoble suburb. Siloé was shut down on December 23, 1997. Decree no. 2005-78 of January 26, 2005, authorized the CEA "*to proceed with the shutdown and dismantling of the basic nuclear facility no. 20, called the Siloé reactor, in the municipality of Grenoble.*" As of September 2012, the Siloé reactor was dismantled in its entirety because repeated leaks of radioactive water made it problematic to maintain the building in its current state (tritium level). Cardem and Eurovia-Vinci were involved in dismantling the reactor (Photo 2.56). The work began with the cleaning of the elements before the asbestos removal, then the demolition of the four different buildings consisting of a technical wing, office buildings, a "crown" building, and the reactor could proceed. On January 22, 2013, an excavator equipped with a large arm (Photo 2.56) began the demolition of the 27-meter-high reactor, whose raft had previously been made safe by installing a watertight protection system and a 3.80-meter backfill above it. This raft was then demolished under containment in April 2013 to level the ground. The final decommissioning of the facility was pronounced on January 8, 2015, by the ASN.

Photo 2.56 Dismantling of the Siloé reactor building (CEA-Grenoble) (photo Cardem and Eurovia-Vinci)

Lucens, Partial Fusion of a Fuel Rod (Switzerland, 1969)

In the early 1960s, Switzerland wanted to create a 100% Swiss nuclear reactor type, like its French neighbor with its Natural Uranium-Graphite-Gas (UNGG) reactor type, using heavy water as a moderator and carbon dioxide gas as a coolant. This technological choice allows the use of natural uranium that the Swiss hope to find in large quantities in the Alps, a hope that will prove to be disappointed. The heavy water could be produced using electricity from its many hydraulic dams. The basic idea being to use unenriched natural uranium (0.711% in uranium 235), the neutron balance is then very tight, and one can only use graphite or heavy water as a moderator. The parasitic capture of neutrons by light water is too great to hope to operate with natural uranium. The Canadians have developed a national reactor type (CANDU) where the moderator and the coolant are made of heavy water. If the moderator is stored in a calandria without flow in which the fuels are bathed, the coolant circulates in a primary circuit to exchange its heat with a secondary circuit of light water that will produce steam to turn a turbine. This circulation inevitably leads to fluid losses that are very costly when it comes to heavy water. The Canadians will realize this by replacing the heavy water in the coolant with light water. The Swiss retained the idea of a heavy water calandria but, like the French and the British, decided to cool the reactor with carbon dioxide.[29] CO_2 in pressure. This design will lead to the realization of the

[29] Carbon dioxide is an inorganic compound with the chemical formula CO_2. Its form is gaseous above −78.48 °C. Carbon dioxide is produced by human respiration, but also by the combustion of carbonaceous materials (graphite, wood...) in the air. The air outside nowadays contains about 0.04% CO_2. From a given concentration in the air, this gas is dangerous or even deadly for humans because of the risk of asphyxiation or acidosis, although CO_2 is not chemically toxic strictly speaking. Unlike vegetable plants, mammals cannot dissociate the CO_2 molecule to use oxygen. The exposure limit is 3% over a period of 15 minutes. Beyond that, the health effects are all the more serious as the CO_2 content increases. Thus, at 2% CO_2 in the air, the respiratory amplitude increases. At 4% (i.e., 100 times the concentration in the atmosphere), the respiratory frequency accelerates. At 10%, visual disturbances, tremors and sweating may occur. At 15%, there is a sudden loss of consciousness, and at 25%, respiratory shutdown leads to death. Regardless of the risks to humans, carbon dioxide has significant industrial benefits. Thanks to its low impact on the environment compared to other refrigerants currently used (up to 3800 times less impact on the environment than the Hydrofluorocarbons HFCs initially used in the refrigeration industry), carbon dioxide is used in the industry because it has no impact on the ozone (it has an ODP (Ozone Depletion Potential) index of 0) knowing for example that the R404A fluid has a GWP of 3800, and little direct impact on the greenhouse effect (GWP index (Global Warming Potential) of 1) knowing also that the R12 fluid has a GWP of 10,900. It is non-flammable (used as a gas in fire extinguishers), non-corrosive, compatible with all materials and non-chemically toxic. However, it forms acids when mixed with water, which suggests extensive dehydration of the circuits before commissioning. To become a good heat transfer medium (modest thermal capacity at 20 °C of 840 J/kg/K against 5193 J/kg/K for helium, even air has a better thermal capacity of 1004 J/kg/K but air feeds fires), it is necessary to increase its pressure inducing well protected circuits.

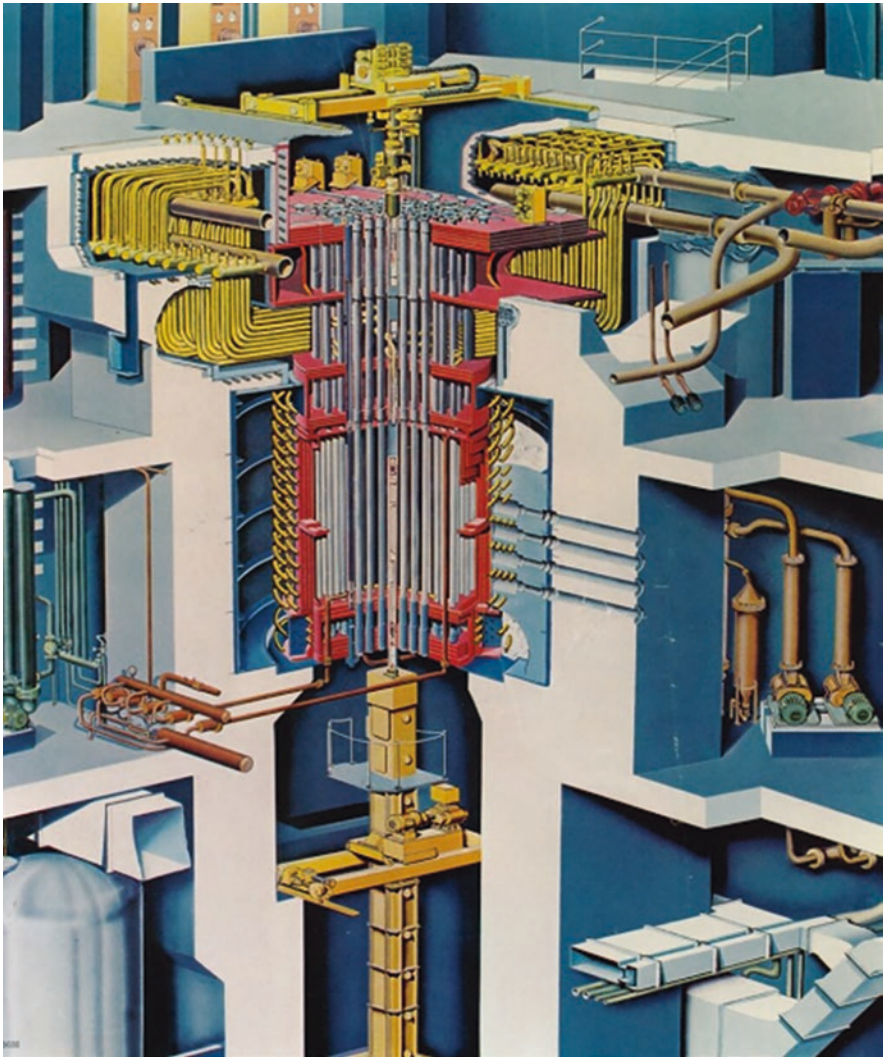


Fig. 2.54 The Diorit reactor at the Paul Sherrer Institute in Würelingen. Moderated and cooled with heavy water and with a power of 30 MWth. It was started in 1960 and operated until 1977. It is the first reactor of Swiss design and construction. Diorit is the direct ancestor of the Lucens reactor

underground reactor of Lucens (pronounced *Lussan*) started in 1968, with an electrical power of 6 MWe.

Lucens is not the first reactor installed in Switzerland. In August 1960, researchers put into operation the "*Diorit*" reactor » (Fig. 2.54, Photos 2.57, 2.58 and 2.59) on the site of the Federal Institute for Reactor Research (IFR) in Würelingen. This facility was used to test various reactor concepts and to produce radioactive isotopes for medicine, research and industry. In 1957, the

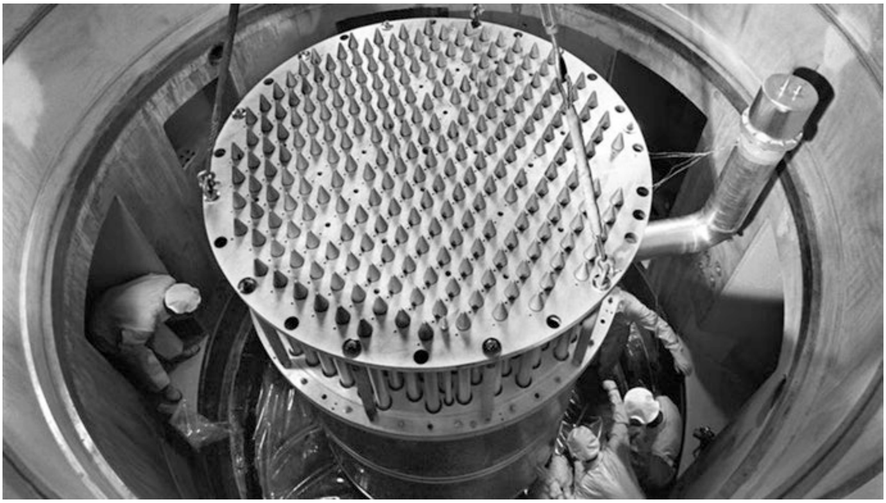


Photo 2.57 View of the top of the Diorit reactor in its vessel pit at the level of the pressure tubes-(1959) (photo IFR)

Würelingen site saw the commissioning of another experimental reactor, the "*Saphir*". The "Saphir" reactor was not a development of Swiss industry, but had been acquired from the USA. The reactor used light water as a moderator. Rudolf W. Meier, a renowned Swiss physicist and president of the Swiss Federal Commission for Energy Research (CORE) from 1986 to 1991, summarized the importance of the Diorit project for the development of nuclear know-how in Switzerland as follows: "*The construction of Diorit took place at a time when there was a strong desire to develop the use of nuclear energy in Switzerland from our own industrial power plant. Entrepreneur Walter Boveri and ETH Professor Paul Scherrer were very determined to support this concept, and their credibility in business and scientific circles provided the necessary additional weight in political circles.*" Werner Zünti and other pioneers (Fritz Alder, Walter Hälg, Paul Schmid) launched the P34 project for an experimental-skill acquisition reactor. The preliminary project was completed in 1955. The foundation of the Reactor AG with Rudolf Sontheim as director ensured the financing and construction of a completely new institute in Würelingen within five years, until the first commissioning of Diorit (1960–1977) (source https://www.nuklearforum.ch/fr/actualites/e-bulletin/il-y-40-ans-diorit-etait-mis-en-service). This nuclear reactor was operated by the EIR from 1960 to 1977. The moderator was heavy water (D_2O). In addition, heavy water was used as coolant. The initial reactor, commissioned in 1960, had a thermal power of 20 MWth without producing electricity. The fuel used in the research reactor was initially natural uranium, then enriched uranium. The 2-meter-long, aluminum-clad, nickel-clad fuel elements were manufactured by the Canadian company AMF Atomics Canada Ltd.

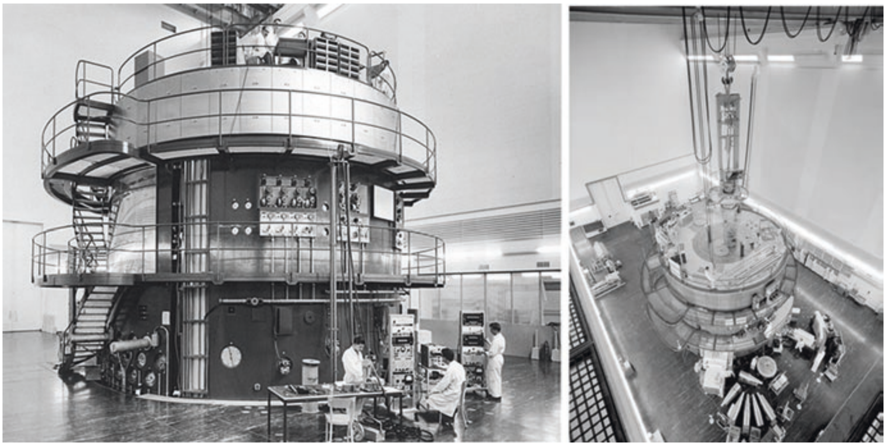


Photo 2.58 View of the service desk of Diorit. This part is very similar to what will be Lucens. Reaktor AG was founded in 1955 on the initiative of the two large Swiss companies Sulzer Winterthur and BBC Brown Boveri Baden. Among the shareholders were more than 100 Swiss companies. According to its articles of association, the company's purpose is "*the construction and operation of experimental reactors for the creation of scientific and technical bases for the construction and operation of industrially usable reactors …*". Reaktor AG received financial support from the Swiss federal government from the beginning. The company had a heavy water reactor built, which went into operation in 1960 and was called Diorit. The reactor was to serve as a precursor to a Swiss power reactor, i.e., a Swiss nuclear power plant technology was to be developed, which was not only to be used for domestic power generation, but also for export. Relatively quickly, however, it became clear that the financial outlay for private industry was becoming too high. The facilities of Reaktor AG—including the experimental Diorit reactor—were handed over to the federal government in 1960, which established the Swiss Federal Institute for Reactor Research (EIR) as an adjunct institution of ETH Zurich. The issue of what happened to the plutonium produced by Diorit in its early days was the subject of controversy in Switzerland in 2016, as was the transfer of 20 kg of unpurified plutonium powder (less than 92% plutonium) to the United States for safe storage. The very existence of this plutonium shows an initial desire by Switzerland to produce an atomic weapon

Switzerland's interest in nuclear power was then expressed in projects launched by three industrial groups. Many people supported the idea that the district heating plant at the ETH Zurich should be replaced by an atomic reactor to produce thermal and electrical energy. The "*Consortium*," a group of companies, took on the task of implementing this project. The model followed was that of the ÅGESTA plant (natural uranium oxide moderated with heavy water and cooled with light water), which went into operation in 1954 near Stockholm. It was then decided to build the reactor in a cavern 42 m underground, near the main building of the ETH. Cooling was by means of an overhead cooling tower drawing water from the Limmat River. At the same time, electricity producers were working on the construction of a nuclear power plant. In 1957, the project company "Suisatom A" was founded. This

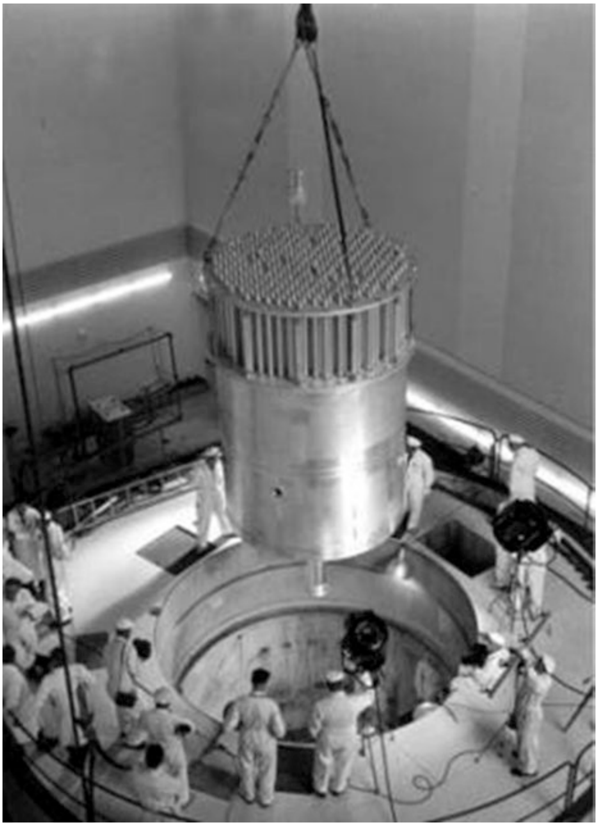


Photo 2.59 The vessel (calandria) of Diorit (Photo PSI-Würelingen)

plant was also to be housed in a cavern near Villigen, but in contrast to the Zurich project it was to be used exclusively for electricity generation. The third project was carried out by the industrial group "Enusa." This project aimed to build an experimental nuclear power plant for the Expo 1964. The equipment was to be installed in a cavern dug in the rock, near Lucens. The structure of the sandstone of the local geological layers was homogeneous and facilitated the excavation of the cavern. The reactor should have been built according to American plans.

But in September 1959, the Federal Council asked Enusa, Suisatom and the Consortium to merge their projects to develop a Swiss experimental reactor. Thus, in July 1961, the National Society for the Promotion of Industrial Atomic Technology (SNA) was created. The experimental plant was to be the intermediate step for the later development of a large nuclear power plant for commercial use "made in Switzerland" with export ambitions.

Fig. 2.55 Location of the Lucens plant in Switzerland

In May 1962, the SNA, as project owner, decided to build the Lucens Experimental Nuclear Power Plant (CNEL), with a thermal power of 30 MWth, for a gross electrical power of 8.5 MWe and a net power (after removal of the electricity used on the plant itself) of 6 MWe. For five years, the plant was built two kilometers southwest of Lucens (Fig. 2.55, Photo 2.60, Fig. 2.56), 25 km north-east of Lausanne and 60 km from Bern, on the left bank of the Broye, the river that was to supply the secondary cooling circuits of the reactor.

An access gallery 100 m long (Photos 2.61 and 2.62) led to three caverns respectively for the reactor (Fig. 2.57), the turbine and the fuel element storage pool (Photo 2.63, Fig. 2.58). A ventilation chimney dug in the mountain allows the ventilation of the underground parts. A chimney on the surface evacuates the stale air at altitude. The supplier of the reactor was Ther-Atom. Ther-Atom was also part, with three engineering offices of the *Groupe 8 de Travail de Lucens* (GTL). Their mission was to supervise the studies, the construction management, and the tests of the CNEL. From a technical point of view, the CNEL reactor was a development of the Diorit reactor already mentioned. The Federal Commission for the Safety of Nuclear Installations, founded in 1960, was the first nuclear supervisory authority of the Swiss Confederation (CSA). It accompanied the licensing process of the CNEL from the beginning. However, the CNEL was a real challenge, because the

Photo 2.60 The surface buildings of Lucens in 1969

CSA could only rely on very limited experience in reactor core design and containment layout.

The Lucens reactor (Fig. 2.59) used slightly enriched uranium (0.93%) as fuel, 99.75%-pure heavy water as moderator contained in a calandria, and carbon dioxide (CO_2) as coolant. A light enrichment is still necessary because the small size of the core induces significant neutron leakage (13,000 pcm leakage). By increasing the size of the core to reduce these leaks to 5000 pcm, one could have used only natural uranium. The fuel assemblies were made in the same way as those used by the British and French graphite-gas reactor

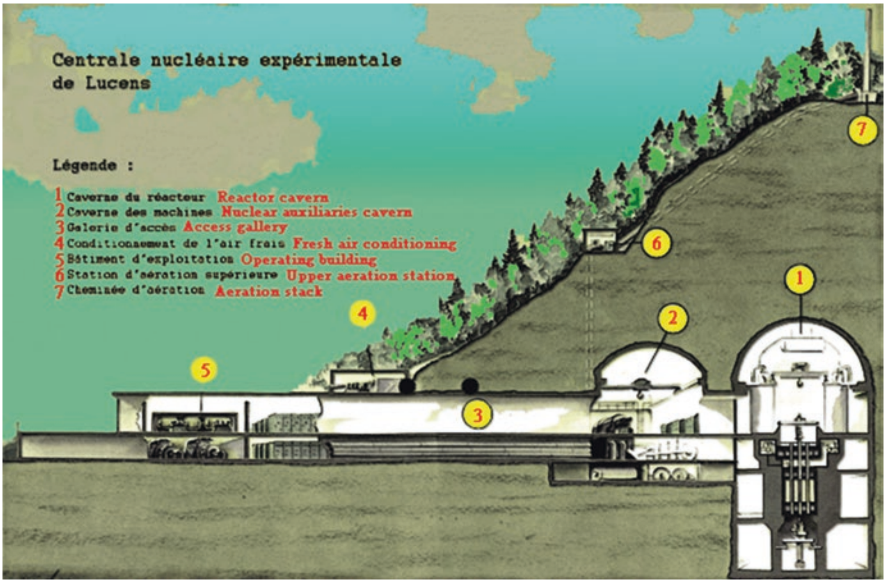


Fig. 2.56 Section of the underground plant of Lucens (Switzerland)

Photo 2.61 The access tunnel to the cavern reactor

types, that is, the uranium metal rods were housed in magnesium alloy cladding. Each fuel element was itself housed in its own pressure tube where the coolant circulated. This design made it possible to obtain a particularly compact reactor, requiring a containment of restricted dimensions. This containment consisted of a wall of concrete, asphalt, and aluminum about 60 cm thick that lined the artificial reactor cavern. The reactor core contains 73 fuel elements that are bathed in the heavy water calandria made of aluminum, 3.10 m in diameter and 3.16 m high (Photo 2.64, Fig. 2.60). The core is

Photo 2.62 View of the operating building on the surface of the Lucens plant (photo 24 Heures)

divided into two concentric regions of different assembly pitch to flatten the radial power sheet by playing on the moderation ratio. The pitch of the outer region (29 cm) is wider than the pitch of the inner region (24 cm).

The heavy water in the calandria must not exceed 80 °C and must not boil. The heavy water does not have a heat removal function in nominal operation, it is the role of the carbon dioxide to ensure this function. Above the calandria there is a metal caisson of light water, whose function is the biological protection of the service desk area where the operators are located. Water is a very good "shielding" against neutrons.[30] The calandria and the biological protection caisson are penetrated vertically by 73 aluminum tubes (channels) 14.5 cm in diameter welded to the bottom and top of the calandria. It is in each of these tubes that a complex system will be inserted assembling a pressure tube that channels the flow of carbon dioxide under pressure (60 atmospheres), the 7 axial nuclear fuel rods per element, a column of graphite support which rigidifies the fuel rods and also serves as a moderator, a system of bayonet coupling in the upper part and a double connection of the inlet

[30] Protections against gamma rays are usually made of heavy materials such as lead. On the other hand, hydrogenated materials protect against neutrons: water is a cheap and very effective representative.

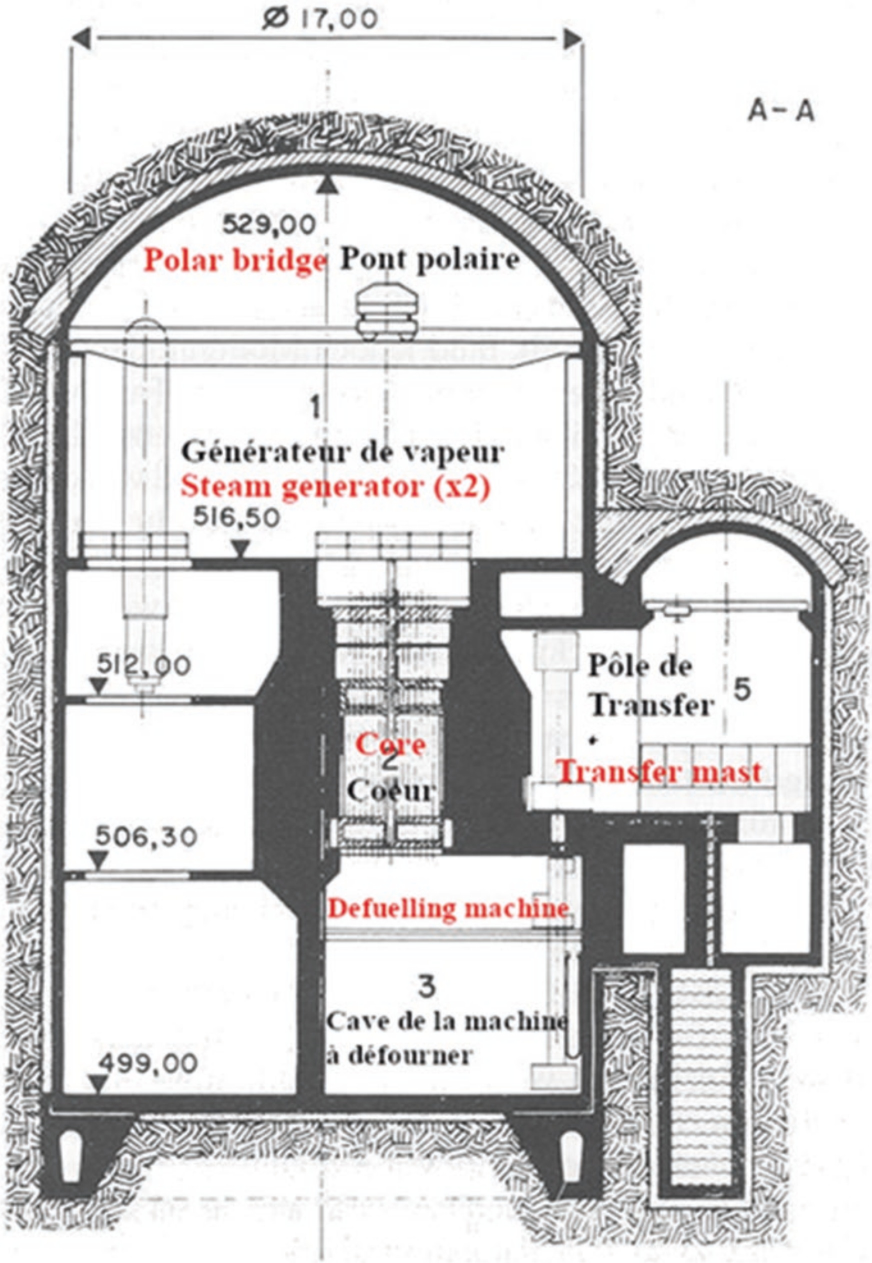


Fig. 2.57 Axial section of the Lucens reactor cavern

Photo 2.63 Model of the reactor cavern and the turbine cavern. One recognizes well above the reactor the two vertical steam generators of great height

and outlet pipes of the gas coolant. The double connections are connected to cold gas manifolds (headers) for the inlet and hot gas manifolds for the outlet. Customized valves per assembly allow for individual dosing of the carbon dioxide flow to each fuel element (Photo 2.65).

The diameter of the pressure tube is of course smaller than that of the channel into which it is inserted, and the gap between the two tubes is filled with carbon dioxide, which acts as a thermal insulation against the heavy water in the calandria. The cold coolant (220 °C) descends into the assembly, licking the inner face of the pressure tube, and is then forced upwards to contact the fuel rods to cool them. The gas is heated up to 385 °C even though the primary circuit is sized up to 520 °C. The pressure tubes are therefore closed at the bottom. The graphite support is inserted into the pressure tube and locked at the bottom by a bayonet device. The support is pierced by 7 channels in which the 7 fuel rods are inserted (Fig. 2.62). The graphite support serves as a guide for the coolant and to support the rods. Each fuel rod is an assembly of 4 segments screwed one on the other with a height of 2.765 m. The rods are

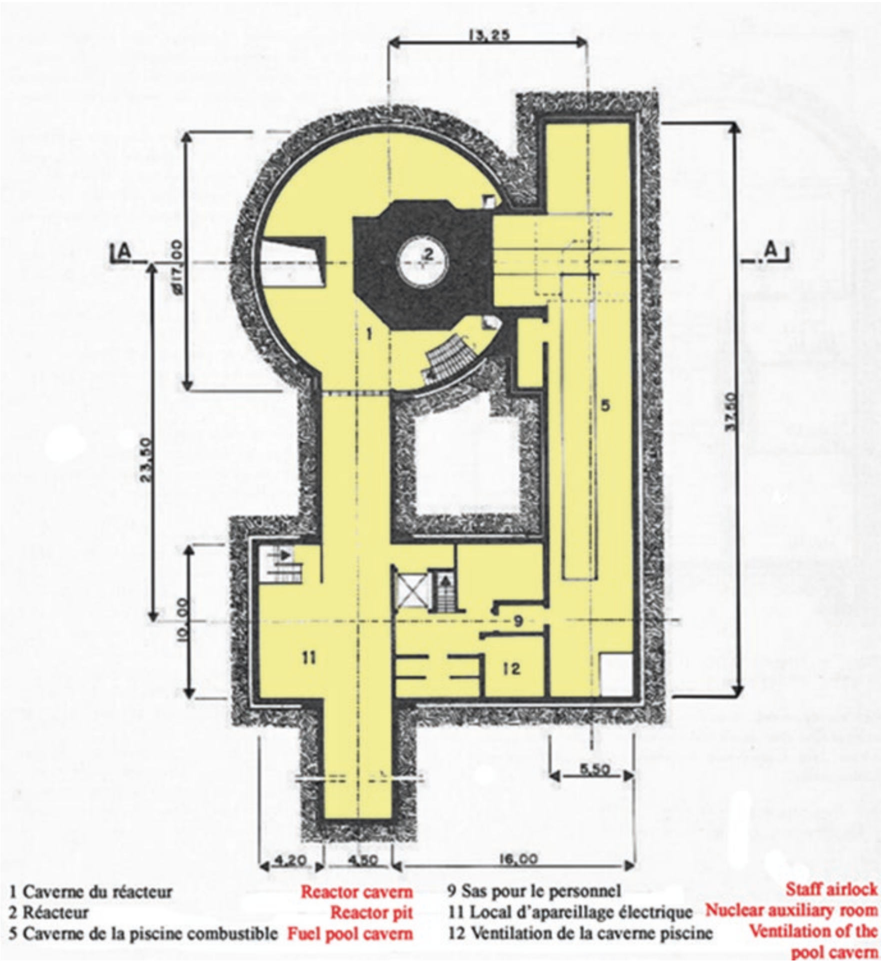


Fig. 2.58 Map of the Lucens cavern at elevation 508.30

integral with the graphite support at the bottom and free to expand at the top. The segments are made of low-alloy uranium metal (1% Molybdenum) 17 mm in diameter and 650 mm high, isolated from the carbon dioxide by a 1.75 mm magnesium cladding. Once heated by the rods, the CO_2 transfers its heat to a secondary circuit through two Steam Generators (SGs) that work as a heat exchanger to vaporize light water (Photo 2.66, Fig. 2.60).

The superheated steam from the secondary circuit then feeds a turbine, which is itself coupled to an alternator to produce electricity. The vessel is radially surrounded by cylindrical steel shields (gamma protection) placed inside a 2.8 m thick concrete caisson (biological shield against neutrons

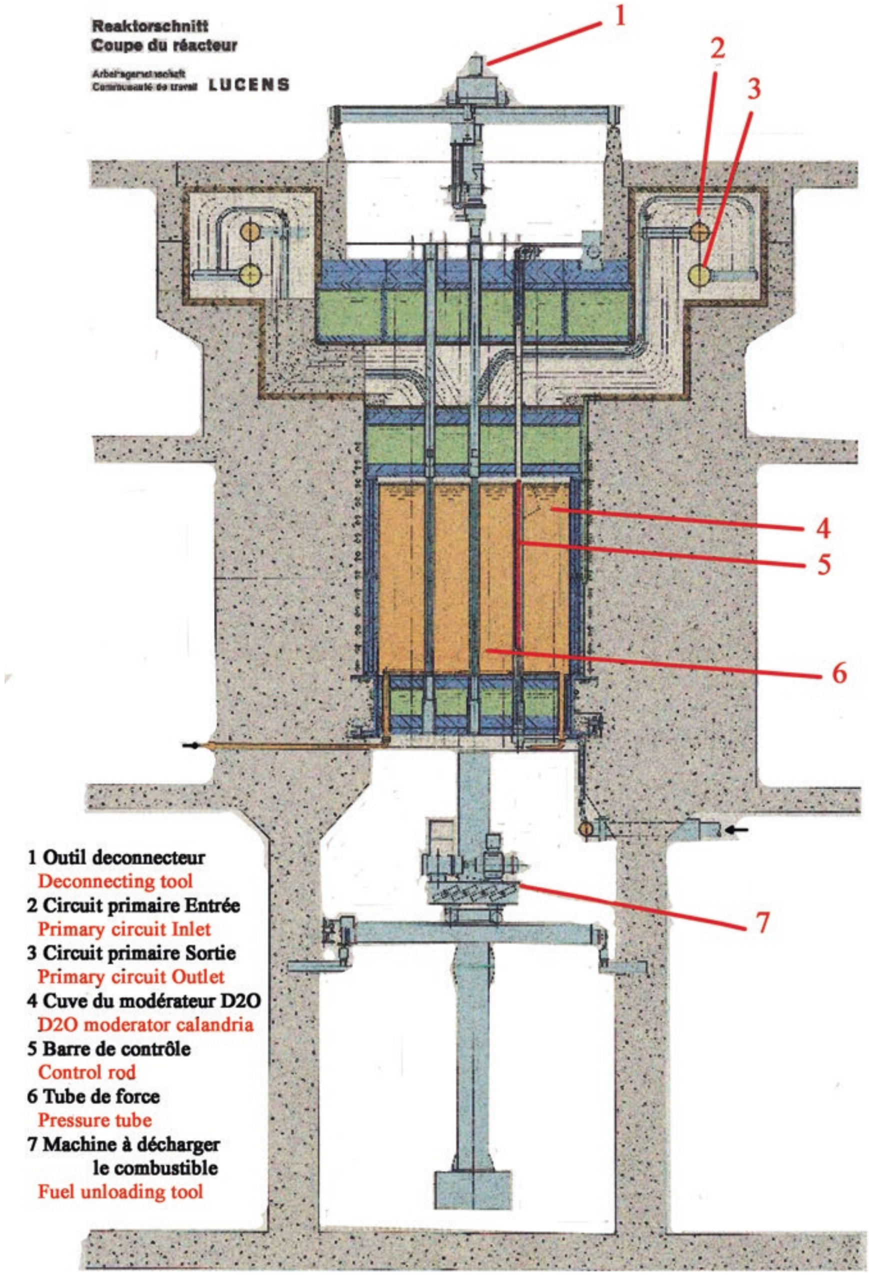


Fig. 2.59 Section of the Lucens reactor (Switzerland). The nuclear fuel is "bathed" in a calandria of heavy water that slows down the neutrons. The cooling is ensured by pumps blowing carbonic gas which circulates in pressure tubes. A carbon dioxide channel can be isolated to insert fuel (adapted from *Bulletin Technique de la Suisse Romande* n°13 of 30 June 1962)

Photo 2.64 Placing a fresh fuel assembly in a storage rack. The core contains 73 such assemblies. The spent fuel assemblies are evacuated without contact by the unloading machine to the deactivation pool

because concrete contains about 6% water) (Fig. 2.61). The gap between the steel shields, the concrete and the pipe room, is in a slightly over-pressurized stagnant CO_2 atmosphere to prevent air ingress. Towards the bottom, a lower caisson protects from radiation the unloading machine room, which allows the extraction of a spent fuel element. This area is inaccessible during nominal operation, as is the vessel pit of a Pressurized Water Reactor. The pressure tubes and their fuel element are deflected together by the unloading machine after a burn-up of about 3000 MegaWatt-days/ton and after disconnection of the pressure tube from the top by the disconnection machine. For this purpose, the gas pressure in the shutdown reactor is lowered, and the residual

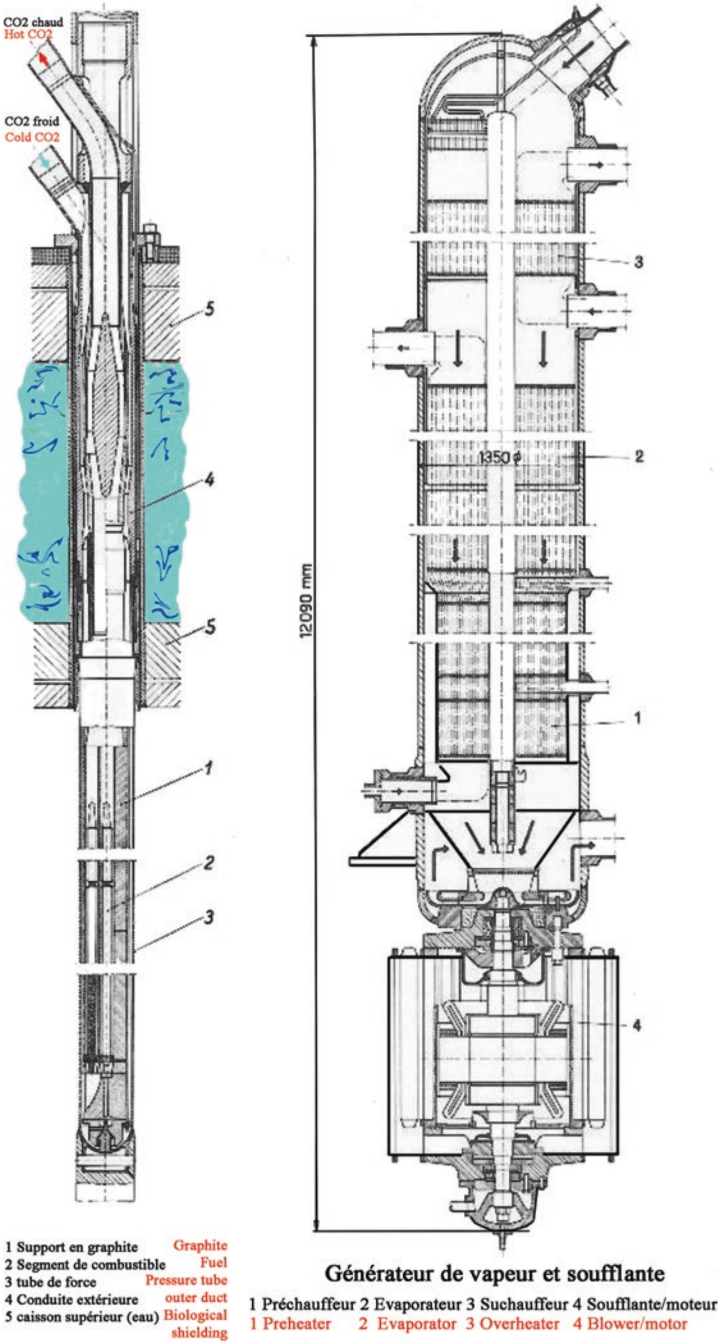


Fig. 2.60 Fuel assembly (left) and steam generator (right) at Lucens

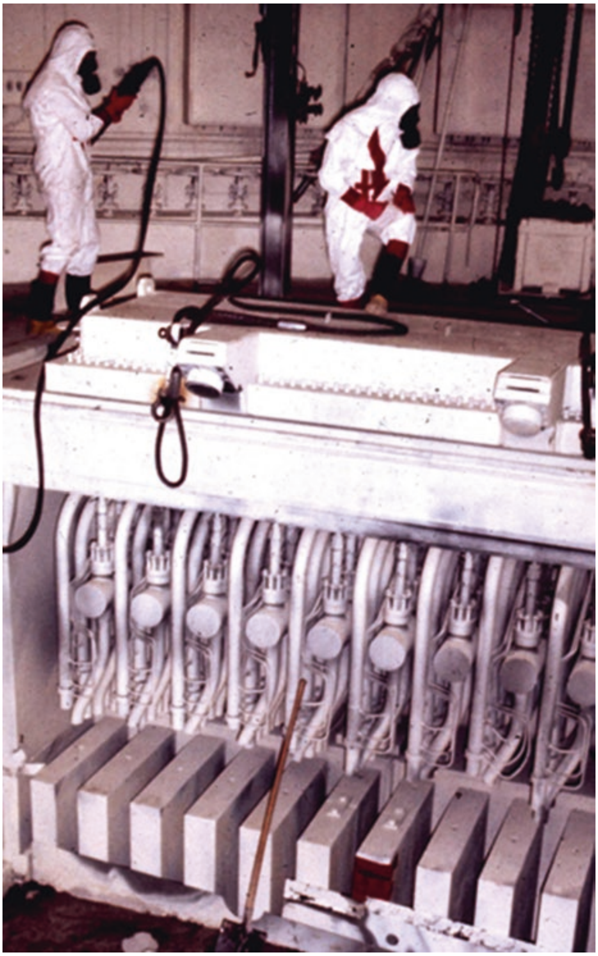


Photo 2.65 CO_2 control valves for assemblies

power decreases for several hours. The unloading machine is positioned below the orifice of the fuel to be unloaded. The tube is then sealed to prevent radioactive leakage in the case of leaking cladding, and the machine then takes it to a transfer pit with a hood in which the pressure tube enters, towards the deactivation pool. The heavy water calandria rests on this lower caisson, and the whole assembly is constructed in such a way that the vessel can be lowered into the unloading machine room in the event of major repairs. At the service desk above the reactor is the disconnect tool that operates the bayonet fasteners that fix the pressure tubes to the dual connection heads. There are also the winches for operating the 12 control rods located in the intermediate ring.

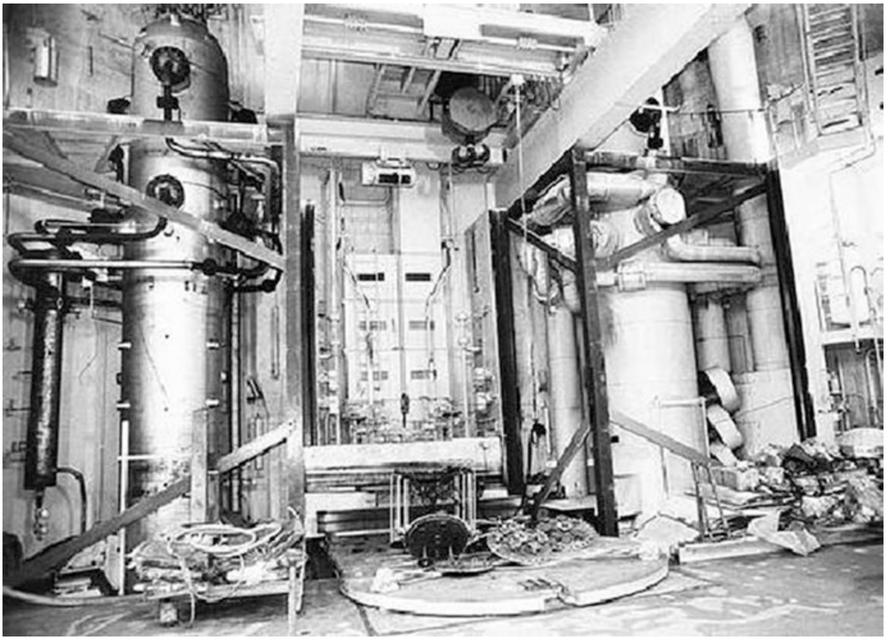


Photo 2.66 The floor at SGs level after the accident

Four shutdown rods by gravity drop are located more in the center of the reactor (Photo 2.67). The rods consist of two concentric tubes, the central part containing a cadmium-silver alloy, two materials that are highly neutron absorbers. The rods are cooled by a flow of CO_2.

The hot gas (temperature 385 °C mainly limited by the nature of the fuel and its cladding) is sent to two steam generators to vaporize light water. The SGs have centrifugal steam dryers. The light water circulates from bottom to top in helical tubes. CO_2 flows in counter-current. Steam is produced at 370 °C under 21.5 atmospheres. The gas blowers are located just below the SGs. The flow rate of the throttle valves at the outlet of the blowers can be adjusted. The blowers are connected by flanges to the SGs, which allows room for differential expansion between SG and blower. The rest of the primary circuit is fully welded. The blowers are driven by asynchronous motors at 6 kV and 3000 rpm. The turbine produces 8.55 MWe net at 3000 rpm. After letdown in the turbine, the steam passes through a condenser. After reheating at low pressure, the water is sent to a feeding tank which serves as a third reheater, then the water is injected by two feeding pumps which send it back to the two SGs at 147 °C. A tertiary circuit cools the condenser by taking

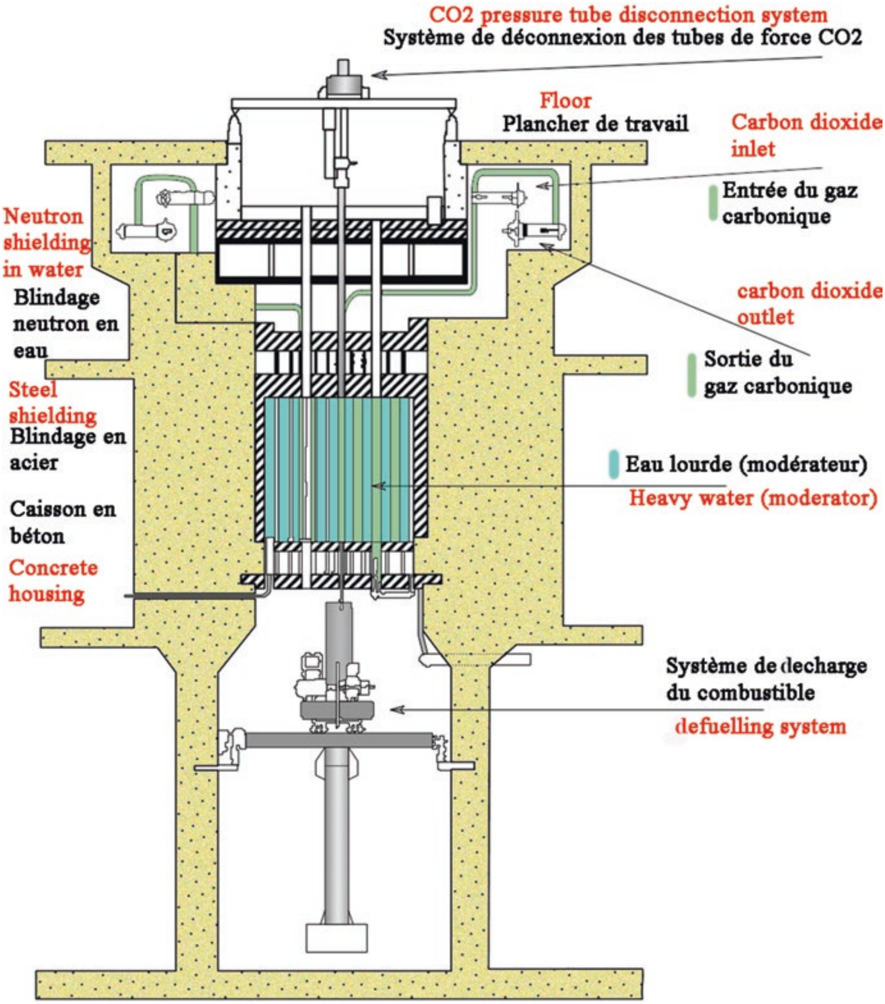


Fig. 2.61 Axial section of the Lucens reactor

water from the Broye (100 liters/s). A tank of 500 m^3 can continue to supply the tertiary circuit in case of loss for a short time allowing the scram (Fig. 2.62).

The air for the ventilation of the cave is sucked, filtered, and air-conditioned in a room located above the entrance of the access gallery. The necessary flow of 12 m^3/h is provided by a fan with a second one as backup (Photo 2.68). Some of the air is sent to the access gallery, the equipment room, and the decontamination room. The turbine building, the deactivation pool room and the electrical equipment room are each equipped with a closed-circuit ventilation system. These closed circuits evacuate the heat up of the electrical

Photo 2.67 View of the upper side of the Lucens reactor vessel (photo IFSN). The control rods and shutdown control rods, wrapped in transparent plastic, can be seen emerging from the vessel cover

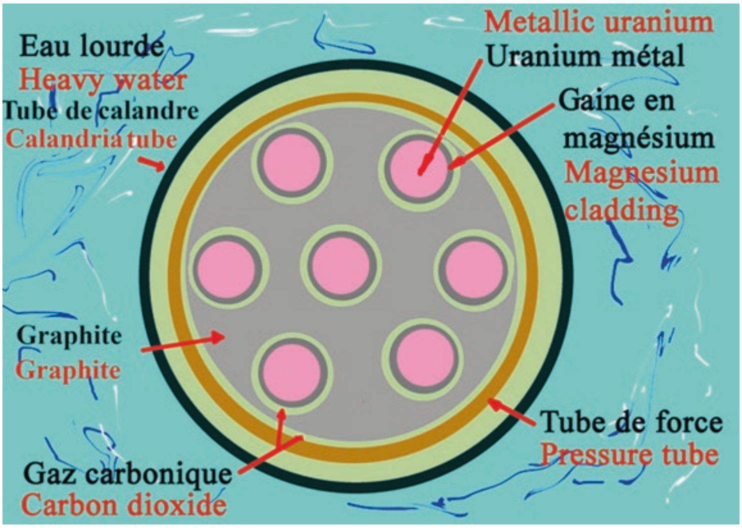


Fig. 2.62 Pressure tube and fuel element principle (dimensions are not respected)

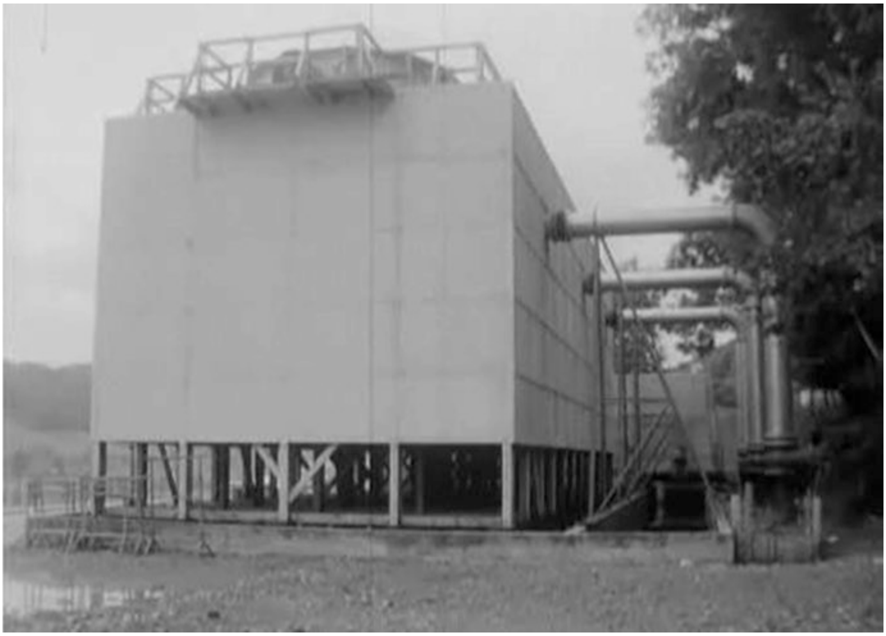


Photo 2.68 View of the aeration station of the Lucens reactor. The reactor is located in depth (photo IFSN)

equipment by cooling with the tertiary circuit. The reactor hall is supplied with fresh air directly from the air intake. Tightly sealed safety valves are installed in the fresh air line and the exhaust cladding to hermetically isolate the reactor hall. In the event of a shutdown, the contaminated air is treated by a closed emergency circuit with fans and particle/aerosol filters located in the turbine building, before being released to the outside stack for dispersion (Fig. 2.63) (adapted from the *Bulletin Technique de la Suisse Romande* n°13 du 30 juin 1962).

For the design of the reactor vault, SSN took into account the "*hypothetical worst-case accident*" (by hypothetical, it is meant reasonable) in terms of pressure, temperature and radioactive releases, and not, as in the rest of the world, the "*worst-case accident imaginable*," i.e., a massive loss of primary coolant. During the licensing procedure, the CSA imposed various conditions and obligations on the developer. For example, the commission demanded that pressure and leakage tests be carried out on the reactor cavern. When the measurements later failed to confirm the desired almost complete tightness, an emergency effluent venting system with activated charcoal filters was installed. These filters are placed to filter out the most dangerous aerosols, such as iodine and cesium. The aerosol-bearing gases are sent to a chimney

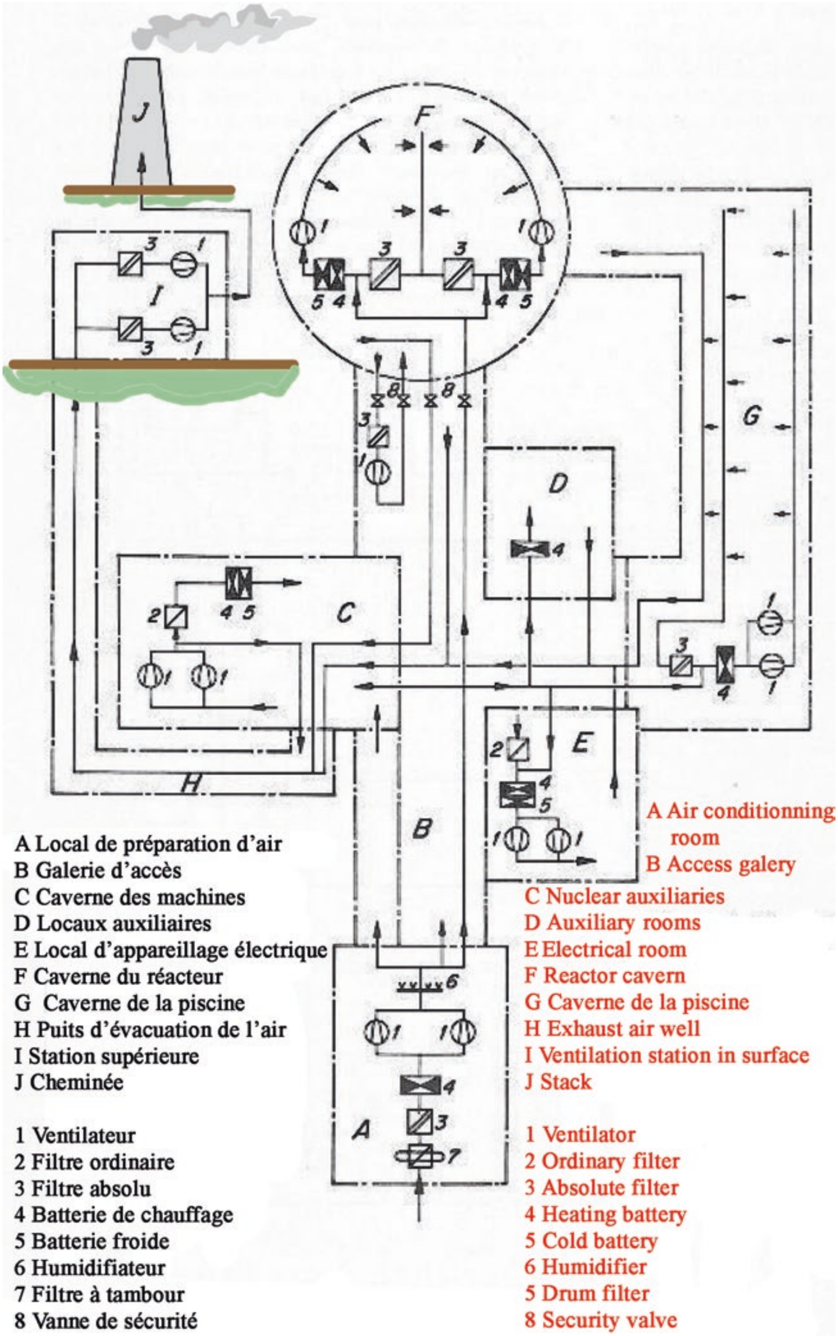


Fig. 2.63 Ventilation system of the underground plant in Lucens. This system will play its role well by isolating the contaminated caverns from the beginning of the accident

equipped with these filters at the base. This equipment created the conditions necessary to respect the limit values at the time of the releases with a safety margin considered sufficient, even for extreme accidents. Since May 1966, tests had been carried out in the helium circuit of "Diorit" with a fuel element of the Lucens type. The aim was to gain the first experience under operating conditions with this new type of fuel. On November 16, 1966, during a power increase in the reactor, a partial melting of the uranium and the magnesium[31] cladding occurred. CSA required a thorough analysis of the anomaly, which concluded that the incident was due to the rapid power increase. Based on this result, Therm-Atom recommended slow start-up power and speed changes for CNEL operation.

The reactor reached criticality for the first time on December 29, 1966. The following year was devoted to commissioning tests under the supervision of the CSA and to various finishing and improvement works. From 1968, the power of the reactor was gradually increased. In April/May 1968, a ten-day endurance test at nearly two-thirds of the maximum power was carried out. The test phase of the CNEL was thus completed, and the operation of the experimental plant was transferred to *Energie Ouest Suisse* (EOS) for industrial operation on May 10, 1968. From mid-August to the end of October 1968, the plant operated under a temporary continuous regime up to its maximum thermal power of 30 MWth. The operation was then interrupted by a period for repairs and improvements. During the experimental reactor tests in 1967 and 1968, the circulation system was the source of repeated difficulties. The biggest problems concerned the two carbon dioxide blowers, the term used to describe the large fans of the cooling circuit, specially designed for Lucens. Indeed, to ensure the tightness of this primary circuit, the two blowers had been equipped with water-lubricated slip rings as bearings. It should be remembered that CO_2 is a gas that is fatal to humans, hence the strict control of leaks. The seals were specially designed for this application and tested in a test rig for a long time. However, during a test under operating conditions, which began in May 1967, some of the water that seals the rotary joints migrated into the primary circuit. It should be remembered that water and

[31] Magnesium (symbol Mg) is a light alkaline earth metal (density 1.738) with atomic number 12, white-gray in color. It has been known since the dawn of time (Magnesia is the name of a region of Thessaly in Greece), but recognized as a chemical element by Joseph Black in 1755 and isolated in its pure metallic form by Sir Humphry Davy by electrolysis in 1808 from a mixture of magnesia MgO and mercury oxide HgO. The melting points of magnesium (650 °C) and aluminum (660 °C) are relatively low, but above all magnesium ignites easily (it was used historically for the flashes of the first cameras). While its low weight is a definite advantage in the cladding of nuclear fuel assemblies, its low melting point and pyrophoric properties have caused it to be phased out in modern nuclear fuel designs.

carbon dioxide produce carbonic acid according to the following reaction for which K_h is the chemical production constant:

$$CO_{2(aq)} + H_2O_{(liq)} \rightarrow H_2CO_3(aq),$$
$$\text{with } K_h = [H_2CO_3]/[CO_2] \approx 1{,}70 \times 10^{-3} \text{ à } 25°C.$$

In October 1968, the reactor had to be shut down again after an extended endurance test following a new water intrusion in the primary circuit. On October 24, 1968, the blowers were modified and improved during work that lasted several months. On December 23, 1968, *Energie Ouest Suisse* received the final operating permit, based on an expert opinion from the CSA, among others. In its report, the safety authority considered the fuel elements used in the reactor to be rather unreliable (risk of magnesium fire), but finally agreed with Therm-Atom's proposals to operate the reactor with the least possible brutal thermal cycles. The safety authority was finally to give the final operating license, but not without ensuring that the safety measures to protect the population had been taken. The reactor was to operate until the end of 1969. The date of January 21, 1969, corresponds to the definitive start-up of the experimental installation. At about 4:23 a.m., the reactor reached criticality, then the power was gradually increased. The primary circuit had undergone hot drying the previous two days because of excessive humidity. At about 6.15 a.m., the operators in the control room noticed a small defect in the cyclic monitoring of the carbon dioxide temperatures in the core and a strong background noise on some channels due to the supposed detection of cladding rupture. All this was corrected at the end of the morning without any disturbance to the test phase. The power was then increased from 9 to 12 MW and at 5:14 p.m. the 12 MWth was reached. At 5.20 p.m., the pressure in the primary circuit suddenly dropped and the carbon dioxide, which acts as a coolant, escaped into the cavern. At the same time, a large loss of heavy water showed that the aluminum vessel of the moderator could be damaged. The instrumentation recorded a significant increase in radioactivity in the containment. The emergency shutdown was triggered to the surprise of the operators in the control room (Photo 2.69), and the control rods droped into the core. The ventilation check valves are closed to isolate the cavern. In the control room, the shift operators applied the appropriate emergency procedure and called back the team they had just replaced. This shutdown was associated with the tight closure of the ventilation pipes in the reactor cavern due to the detection of radioactivity. At 5:40 p.m., Jean-Paul Buclin, technical director of the plant, was notified by telephone while he was in Würenlingen for a

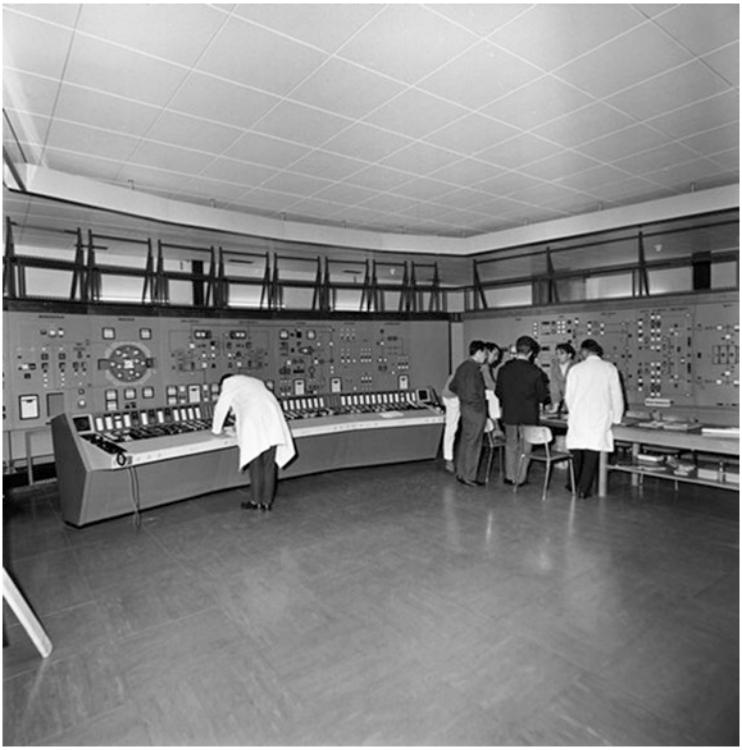


Photo 2.69 Control room of the Lucens plant. Clearly, the operator must be standing

meeting of the nuclear safety commission. For half an hour, he went over the events and emergency procedures in detail with the control room. He decided to carry out a rapid draining of the heavy water and "*to save 20 million Swiss francs.*" He arrived in Lucens at 9:30 p.m. and in the meantime, the personnel had put on masks and protective clothing following an increase in radioactivity in the access gallery. At 9:45 p.m., the cooling of the reactor was well underway, and the radioactivity in the access corridor was decreasing. From 0:00 to 3:00 a.m., experts checked and copied all records, while others measured the radioactivity outside the site. At 6:30 a.m., a press release was issued. Afterwards, the accident was brought under control and Jean-Paul Buclin declared: "*This was a perfectly controlled incident.*" He will also say: "*We would never have acquired such a complete, fast, and basically inexpensive experience without Lucens. There is no reason to be embarrassed by this adventure,*" an a posteriori justification that will not prevent the development program of the heavy water reactor type from being literally and figuratively buried.

Let us return to the accident phase itself, to focus on the state of the core. At the same time as the pressure drop in the primary circuit, the latter let out a gaseous mixture with a large proportion of highly radioactive contaminated CO_2 into the cavern, empty of any human presence, immediately suggesting a degradation of the fuel cladding. This outgassing process lasted nearly 15 min until the primary circuit, operating at 60 atmospheres, had released enough coolant into the reactor cavern to reach the common equilibrium pressure of 1.2 bar. It seems that the cause of the Lucens accident dates back to October 24, 1968. Indeed, it was on this date that maintenance work had taken place on the rotating joints of the coolant recirculation blowers. It was at this time that several liters of back pressure water from the rotating joints,[32] would have escaped into the primary circuit. After the water infiltrated the primary circuit, carbonic acid was produced. Carbonic acid is a weak acid found in carbonated beverages and produces the “pungent” effect on the tongue. Carbonic acid is also the cause of the acidification of the oceans due to the production of CO_2 by man.[33] This acidic water attacked the magnesium cladding of several fuel elements. The equation for the oxidation of the cladding by water vapor is given by:

$$Mg_{(\text{metal})} + H_2O_{(\text{steam})} \rightarrow MgO_{(\text{solid})} + H_{2(\text{gas})}$$

This oxidation produces hydrogen gas release and flammable magnesium oxide powder. Magnesium oxide is known to be unstable. Moreover, its instability tends to increase with high temperatures. The corrosion products formed then fell into the heat transfer gas circulation channels. It is postulated that the debris fell to the bottom of the pressure tubes and partially clogged them, reducing the flow in some channels. Fuel element 59 was insufficiently cooled due to the reduced CO_2 flow rate inherent in the pressure tube plugging. Several of the seven fuel rods in fuel element 59 (Photo 2.70) thus underwent an overheating that went unnoticed at first because not all the fuel

[32] The seal back pressure technique isolates the downstream portion of the seals from the upstream portion that contains a potentially radioactive liquid or gas. A higher pressure is applied downstream of the seal labyrinth to contain the radioactivity by imposing a flow from downstream to upstream of lower pressure, in the direction of decreasing pressure. This is what is successfully applied on the primary pumps of Pressurized Water Reactors, but in this situation, one has to inject non-active water into a circuit of possibly active water. In this case, the backpressure water must not penetrate the primary circuit of carbon dioxide, at the risk of acid formation, hence the complex technology of the implementation of the backpressure.

[33] The more than 40% increase in atmospheric CO_2 concentration from 280 ppm (parts per million) in 1750 to 400 ppm in 2015 and 403.3 ppm in 2016 increased the dissolved CO_2 in the form of carbonic acid in the ocean, increasing its acidity by 26%, as measured by its pH, which decreased by about 0.1 from 8.2 to 8.1 (source https://reseauactionclimat.org/acidification-rechauffement-ocean-dangers-demultiplies/)

Photo 2.70 Impressive view of the cladding of fuel element 59. The cladding is completely torn

elements were equipped with a temperature probe in the uranium. When the temperature reached 600 °C, the magnesium cladding of the central fuel rod melted, followed shortly after by the uranium metal (melting at 1135 °C) that it protected. Thus, a column of molten metal was formed (with the heavy uranium at the bottom of the column and the magnesium above). This melting process then spread from one to the next to the neighboring fuel rods (Photo 2.71). And the metal eventually ignited in the CO_2, causing a massive release of radioactive fission products into the coolant and the Automatic Reactor Shutdown (ARS). The ARS shut down the nuclear chain reaction, but not the fire in fuel element 59. The graphite column bent, met the nearby pressure tube, overheated it and caused it to burst under the effect of the 50-bar pressure that prevailed there when the temperature reached between 700 °C and 800 °C. This explosion initially ruptured one of the five rupture discs responsible for limiting the pressure of the heavy water tank (the calandria). Through this opening, 1100 kg of heavy water, a molten mixture of magnesium and uranium, and contaminated coolant were projected into the reactor cavern. About a second later, a thermal reaction between the heavy water and the molten metal triggered a second explosion. This is called a corium-water interaction or steam explosion. The shock wave caused the control rods, which had already been lowered during the scram, to jam in their guide tubes, but without touching the particularly well-protected (by reinforced tubes) safety

Photo 2.71 Double connection of channel 59 (left) and channel deformation (right)

Photo 2.72 Channel 59 in top view

control rods. The overpressure led to the rupture of the four other rupture discs of the moderator calandria tank, with new projections of radioactive material into the biological shield made of water. This process continued over the next few minutes until the decompression of the primary circuit in the reactor vault was completed. (adapted and commented from https://www.ensi.ch/fr/2012/05/31/serie-de-lucens-analyse-profonde-de-laccident). Post-mortem examinations showed that the cladding of fuel 59 had completely burst. The dismantling from above showed the damage caused by the explosion on the double connection of channel 59 (Photo 2.72).

The investigation report, published in 1979, revealed to the public that there had been a partial meltdown of the core. The cause was said to be moisture in the cavern (!!!) and leaking seals that caused water to accumulate. The part between the humidity and the water intrusion in the previous test was not specified. The accident would have been classified at level 4 of the INES scale nowadays, the scale having been created only in 1990 (accident not involving significant risks outside the site). Clearly, the cavern has saved from a more severe classification. During the accident, it is true that all safety devices worked as intended. Neither the operating team quickly equipped with self-contained breathing apparatus, nor the environment, were exposed to unacceptable radiation doses. The ASPEA (*Association Suisse Pour l'Energie Atomique*) declared that this "*unintentional breakdown was rich in lessons learned*." The word breakdown is a mild euphemism in this case. The official investigation report mainly details the technical causes of the accident and not much about its radiological consequences. However, the measurements taken that night and in the following days show that the level of radioactivity did not increase significantly. Moreover, the contamination of the access corridor immediately after the accident was due to two isotopes with a half-life not exceeding three hours. Radioactive gases did escape into the cave but were contained in the rock. The Federal Office of Public Health, responsible for monitoring radioactivity in the Swiss environment, has been monitoring radioactivity around the Lucens plant since the accident. Drainage water samples from the former plant are collected every two weeks and analyzed at the Institute of Radio Physics in Lausanne. The radionuclides monitored are tritium (present in the irradiated water, half-life 12.32 years), strontium 90 and gamma emitters. The strontium 90 contents (half-life 29 years) measured over the last ten years are below the detection limit, which is about five milliBecquerels per liter (tolerance value for drinking water: 1000 millibecquerels per liter). Tritium activity is detectable and averages around 10 Becquerels per liter (tolerance value for drinking water: 10,000 Becquerels per liter). Gamma emitters such as cesium 137 (half-life 30.1 years) and cobalt 60 (half-life 5.27 years), for example, have not been detected. Some studies, which show an increase in intestinal cancers in the Broye district between 1970 and 1990, are, however, used to contradict the official version. Professor Matthias Bopp, co-author of one of these studies, said: "*In men, the general excess mortality in the Broye has the same components as in neighboring regions,* i.e.*, diseases related to alcohol consumption, accidents and lung cancer. In women, heart disease was the cause of the additional deaths. It is therefore impossible to deduce a link with the nuclear accident of 1969, especially since intestinal cancer is not among the cancers suspected to be caused by irradiation*."

The post-decommissioning monitoring program consisted of collecting two samples of water from the drainage system every 15 days, one from the pond collecting drainage from the nine main drains in the cavern (Fig. 2.64). The second is in the control chamber, which is located just before the release into the Broye. Until the beginning of 2010, the measured tritium contents were between 10 and 20 Bq/l (average value of approx. 15 Bq/l), whereas surface water usually does not exceed 3 Bq/l. At the end of 2011, a notable increase in tritium activity was noted (up to 230 Bq/l, Fig. 2.65) relayed by

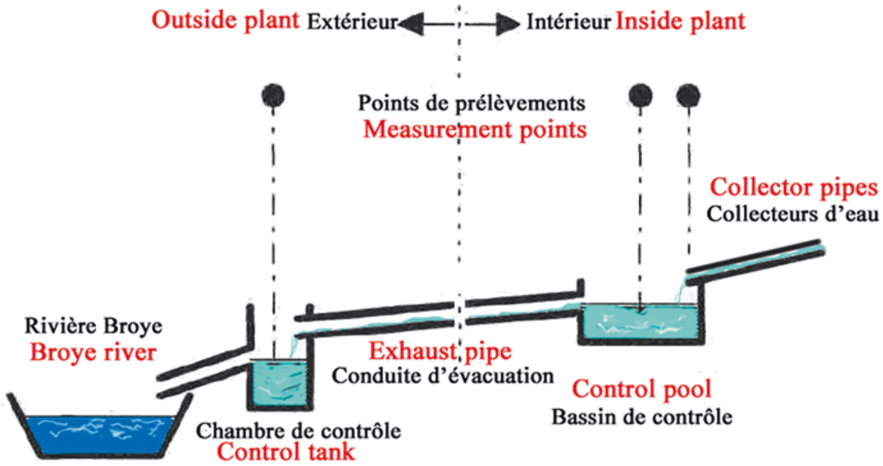


Fig. 2.64 Activity measurement points (every 15 days) of the collected water from the Lucens plant

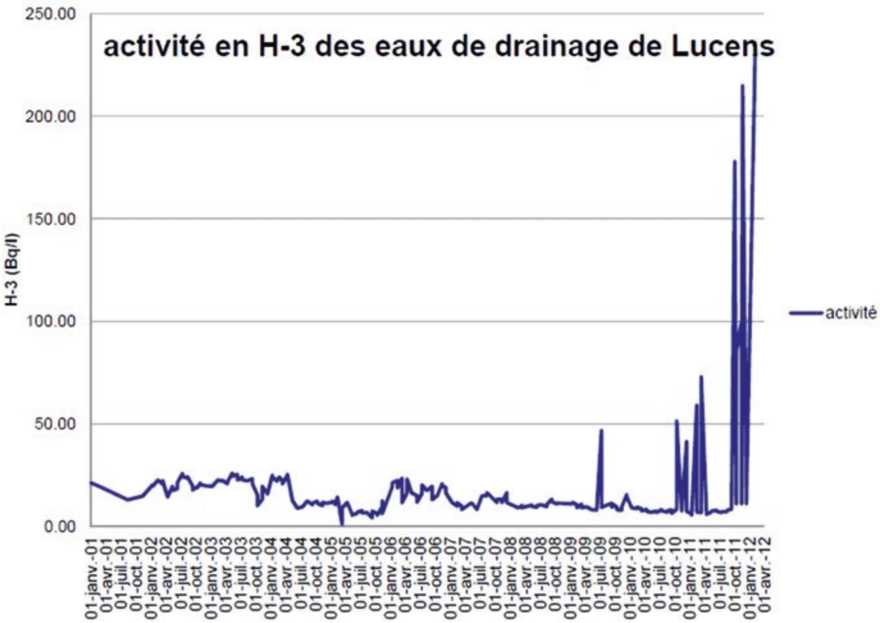


Fig. 2.65 Tritium activity measured at the release in the Broye. A strong increase is noted from October 2011 onwards, which has caused a controversy in Switzerland

the Press (newspaper 24 heures) and anti-nuclear associations. However, it is not dangerous for the population because it is well below the regulatory limits of 10,000 Bq/l or 20,000 Bq/day. The variability of a drainage water depends of course on the rain regime and on the intrusion water towards the contaminated cavern which evolve according to time. It will take about 100 years from the accident for the tritium produced by the reactor to disappear almost completely.

The dismantling of the Lucens plant, led by the Director Jean-Paul Buclin,[34] began a year after the accident. It was necessary to wait for the regulatory authorizations, and some people had crazy ideas, such as drowning the cave, which would have been counterproductive given the very likely exfiltration of radioactive water that this would have generated. Patiently, the workers protected by suits (of the "*Mururoa*" type with ventilation) dismantled and cleaned the plant (Photos 2.73, 2.74, 2.75 and 2.76). The working conditions were Dantean, with workers losing up to 4 liters of sweat per hour of work. The dismantling of the plant lasted until the end of 1972.

The fuel assemblies were sent to the Eurochemic plant in Mol, Belgium. Most of the radioactive waste was transferred to the Paul Scherrer Institute, except for various large parts. However, it was not until September 2003 that the last low-level radioactive elements left Lucens for the temporary storage center for nuclear waste at Würenlingen in the canton of Aargau. The work for the decommissioning consisted essentially of the installation of a drainage system around the underground structures (caverns), the installation and commissioning of a specially protected pipe for the direct discharge of the water collected by the drainage system into the Broye, the filling of some of the caverns with concrete in 1992, the installation of a fence delimiting the

[34] This recognized expert was later contacted by the Soviet Union during the Chernobyl accident to delimit the dangerous zones. He is nowadays considered as an expert in the field of dismantling and remains one of the great craftsmen of the feat that was the accidental plant of Lucens.

Jean-Paul Buclin interviewed on Swiss television RTS.

Photo 2.73 Verification of breathing apparatus for cleaners

Photo 2.74 Dressing of the cleaners in ventilated protective suits

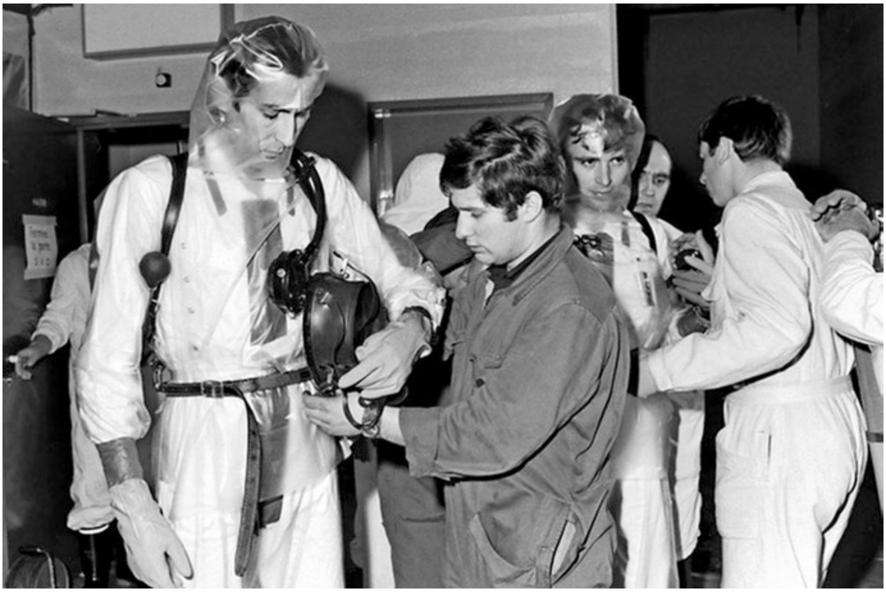


Photo 2.75 Preparation of the cleaners. Checking the ventilation systems

Photo 2.76 Two operators from Lucens are waiting in their uniforms to enter the contaminated area. They appear to be wearing a dosimeter on their chest and a radiation detector in their hand

plot intended for the casks and controlling access to it, with the construction of a shield wall intended to complete the radiological protection against radiation from these casks. Most of the plant was decommissioned in April 1995 and the Federal Council decided on December 3, 2004, that the former experimental nuclear power plant in Lucens was completely decommissioned and no longer constituted a nuclear installation within the meaning of the former Atomic Energy Act. The cost of the final decommissioning was 16 million Swiss francs. Since October 1997, the premises have been used as a storage facility for various museums and cultural institutions in the canton of Vaud. The site is reconverted into storage for stuffed animals! (Photo 2.77).

The Lucens accident, although little known by the public, is considered as one of the most serious accidents in the field of civil nuclear power in the world. The personnel and the local population were not irradiated, or only slightly. The radioactivity measurements carried out after the accident did not reveal any significant contamination of the environment. However, the cavern was largely contaminated. During the following years, the reactor was dismantled, and the cavern was decontaminated. In 1992, the cavern was partially filled with concrete.

Lucens sounds the death knell for the hopes of a Swiss national reactor type. Following the Fukushima accident, the Swiss Federal Council

Photo 2.77 The present of Lucens. A decontaminated part is used to store stuffed animals (DR)

confirmed, on May 25, 2011, the gradual phase-out of nuclear power by deciding not to renew the nuclear power plants in operation and opting for their definitive shutdown once they have reached 50 years, i.e., between 2019 and 2034. On September 28, 2011, the Council of States confirmed the shutdown of the construction of new nuclear power plants while demanding the continuation of research in the nuclear sector, a wishful thinking which does not really make sense insofar as the competences disappear very quickly due to the lack of job opportunity.

What lessons can be learned from the Lucens accident? The main cause of the accident was the use of a magnesium cladding, which is highly oxidizable by water, has a relatively low operating temperature and is likely to "burn" in an unfavorable atmosphere. Magnesium was quickly abandoned by fuel designers throughout the world in favor of zirconium. A highly aggravating phenomenon is the fact that the geometry of the rod cluster is not open, unlike in PWRs. Any total or partial blockage cannot be compensated by coolant from another nearby channel. This is a defect that is also found in the Canadian CANDU or Russian RBMK reactor design. Let's recall that operators use this property to flatten the power sheet by playing on the opening of the carbon dioxide valve in each assembly. This tactic is also used in fast neutron reactors cooled with sodium or lead-bismuth, where the assemblies are isolated from each other by a hexagonal tube. Detection of these blockages requires instrumentation of each assembly with thermocouples capable of rapidly detecting an abnormal increase in temperature, which was not the case for the Lucens reactor (economy?). The penalty was immediate and definitive for the operator. The cavernous situation in which the reactor is housed, nevertheless, allowed the avoidance of significant radioactive releases and spared the population from certain contamination. In France, only the Chooz-A reactor, shut down in 1991, had this core cavern configuration.

Saint Laurent des Eaux A1 (France, 1969), Saint Laurent des Eaux A2 (France, 1980)

The most serious accident that took place on French territory remains without question the partial fuel meltdown accident in the A1 reactor of the Saint-Laurent des Eaux plant on October 17, 1969. The Saint-Laurent-A1 plant, located on the banks of the Loire (Photos 2.78 and 2.79), is part of the last wave of Natural Uranium-Graphite-Gas (UNGG) construction in France, coupled to the grid in 1969 and shutdown in 1990, for a capacity of 1662 MWth (480 MWe net).

Photo 2.78 Saint-Laurent-des-eaux site. The two Natural Uranium-Graphite-Gas (UNGG) reactors are located at the far left, recognizable by their cubic shape. Two air-cooling towers in operation are located at the end of the site on the right. The two PWRs that they cool in addition to the Loire River are located just to the left of the towers, recognizable by the hemispherical shape of the reactor buildings and the next large parallelepipedal turbine buildings

Photo 2.79 The two reactor blocks of Saint-Laurent-A1 and A2. The welded structures that surround them are characteristic of the French Natural Uranium-Graphite-Gas (UNGG) of the late 1960s

The reactor (Fig. 2.66) contains 446 tons of natural uranium in the form of metal clad with a magnesium-zirconium alloy (43,865 fuel elements called cartridges in the core, 600 mm long, hollow rod 23 mm internal, 43 mm external, surrounded by a graphite fuel jacket 112 mm internal, 137 mm external). The moderator, designed to slow down the neutrons that become more efficient, is made of a stack of 2572 tons of graphite 9 m high (Photo 2.80).

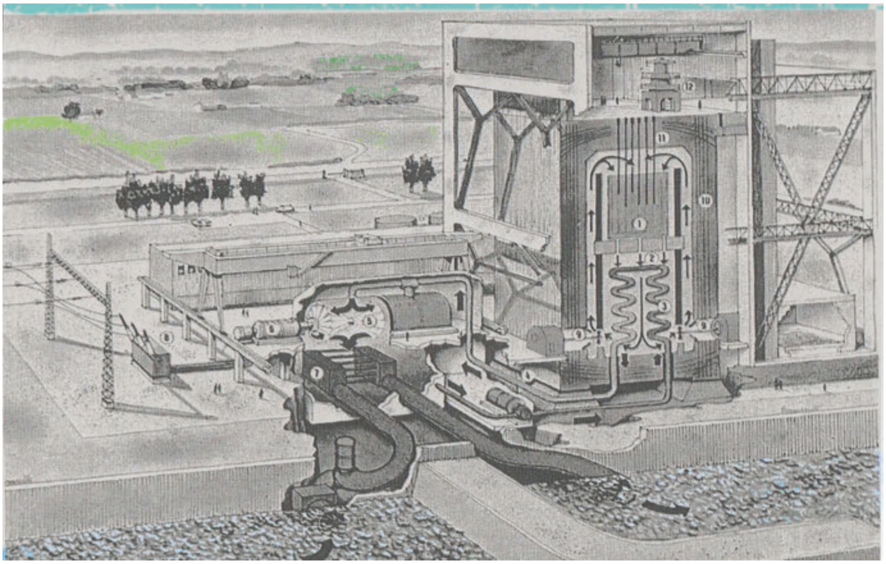


Fig. 2.66 Artist's cut view of the Saint Laurent-A1 plant. The interior of the concrete caisson shows the core (1) and the CO_2/water exchangers (3). Note that the direction of the carbon dioxide flow is from top to bottom, which may seem surprising at first, because it is the opposite of the chimney effect of hot gases. But the idea here is to cool the inside of the concrete biological protection caisson. The blowers that circulate the gas are shown in 9, the condenser in 7 and the turbine in 5

Photo 2.80 Building the graphite pile: channels through the graphite sleaves are clearly visible

The flow of CO_2 gas cooling the core is 8747 kg/s at a pressure of 26.5 bars. The inlet temperature of the gas is 217 °C for an outlet temperature of 400 °C. The circuit contains 185 tons of carbon dioxide. The plant produces 2178 tons/h of steam at 390 °C and 33.6 bars at turbine inlet. The reactor is controlled by 138 absorber rods, including 3 safety rods, 24 neutron flux-shape control rods, 12 pilot rods, 81 short-term reactivity compensation rods and 18 long-term reactivity compensation rods. The upper desk slab has 109 loading holes that can be opened by the fuel loading machine under pressure. The concrete caisson is cooled by water flowing through tubes between the sealing plate and the concrete.

On October 17, 1969, at 7:08 a.m., seven months after the coupling of the plant, during the handling of fuel elements in channel n°21 of the pit in naval battle position F9 M15, the reactor was at 80% of nominal power. The loading/unloading device (Main Handling Device DPM controlled by a punched card displacement system in the computer context of the time) mistakenly places a flow control device, normally intended for other uses, above ten fuel elements already loaded, on top of which five graphite logs have been placed. The flow control device consists of a graphite rod with a 20 mm hole, which causes a pressure drop at the passage of the carbon dioxide, a pressure drop 40 times higher than that of a normal fuel. The classic use of these carbon dioxide flow reduction devices allows to play on the flow between different channels to homogenize the temperatures radially in the pile; The DPM is located above the loading platform and moves on a guide rail to be placed above the pit to be unloaded (Photos 2.81 and 2.82). The machine connects to the channel pit to be treated, unscrews the sealing plug and then, thanks to a telescopic arm, removes the cartridges and replaces them with new fuel placed on standby in a barrel of the DPM.

The partial obstruction of the channel, caused by this loading error, was sufficient to cause a rapid increase in temperature (less than 10 s) such that it led to the melting (and ignition in the CO_2 coolant) of the magnesium-aluminum fuel cladding, then the melting of the uranium fuel (Photos 2.83 and 2.84). The contamination of the channel with fission products was immediate, leading to an increase in activity measurements at 7h08min00s by the activity measurement system of the fuel loading machine still in position, then by the general cladding rupture detection system at 7h08min10s, the loading being carried out during operation of the reactor. This detection led to an emergency shutdown at 7h08min11s. Tests were underway in a hot test channel in which so-called degaussing logs were tested, i.e., graphite logs (3 different types) without fuel elements. The objective of the test was to find out if these logs did not present any disadvantages in operation. In fact, the core

Photo 2.81 Natural uranium graphite gas reactor (first French reactor type). The Saint Laurent-A loading platform and the Main Handling Device (DPM). The rails of the fuel loading machine and the tulip-shape plugs (with circular top) closing the CO_2 channels are visible in front of the photograph (photo: Bouchacourt-Foissote-Valdenaire-ENSIB)

was not loaded in the usual way. The core and hot channel were loaded and unloaded by the same fuel loading machine that had had many failures in the past. It is probable that a human error took place on the hot channel, consisting in removing a false graphite fuel jacket (empty fuel log). The discovery of a missing element on October 8 led to the fabrication of a punch card for the fuel loading machine program. This card had to contain the location address that was not detected on rereading, and channel 21 was loaded by a fuel jacket

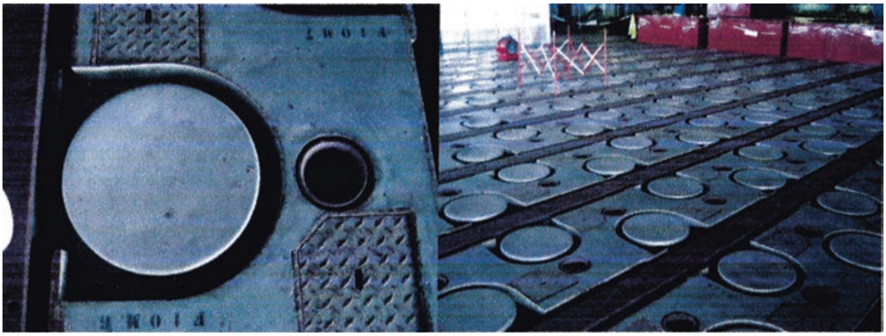


Photo 2.82 "tulip-shape" plug of a channel and load face. The damaged channel is isolated by the access barrier (photo: Bouchacourt-Foissote-Valdenaire-ENSIB)

with a reduced passage section. The continuation of the loading operations alternated manual and automatic phases so that a cell of the barrel of the reloading machine was found empty of logs, whereas it should have contained 5. The operator then thought of a shift in block on 6 cells. Only a weighing system placed on the fuel loading machine could have detected this error, but the operator had not yet been trained to interpret this indication. Unfortunately, probably to save time due to numerous delays, no flow measurement was made once the wrong fuel cartridge was placed, and the heat up occurred. The F9 M15 channel was first gassed with 60 °C CO_2 at the time of loading, which delayed its heat up, then it was increased to 225 °C (at the nominal CO_2 circulation temperature), which precipitated the accident. As soon as the control rods dropped, the reactor caisson was "deflated" from 35 bars to 1 bar of CO_2. Analysis of the measurements of the leak detection system made it possible to locate the incriminated channel and the releases were filtered by iodine filters. The dosimeters of the EDF agents present measured 2.3 mSv for the safety officer on duty, 0.6 mSv and 0.2 mSv for two operators and less than 0.1 mSv for all the others. At the time, the public exposure limit was 5 mSv/year.

The corium fell into the "*debris catcher*," also called the "*garbage can*" placed at the bottom of the channel and spurted out through the holes (orifices) of the catcher, normally intended for the passage of carbon dioxide. The attack on the steel of the corium catcher by the molten corium led to the erosion of the "*garbage can*" (that is the official term) at its weakest point, namely the holes in the core catcher, which are pierced in "lace-like" fashion to allow the carbon dioxide to pass. CO_2 (Photo 2.85). Human error was most likely the cause of the accident. The DPM was programmed by a punch card system that was difficult to verify and the plant did not have in-house

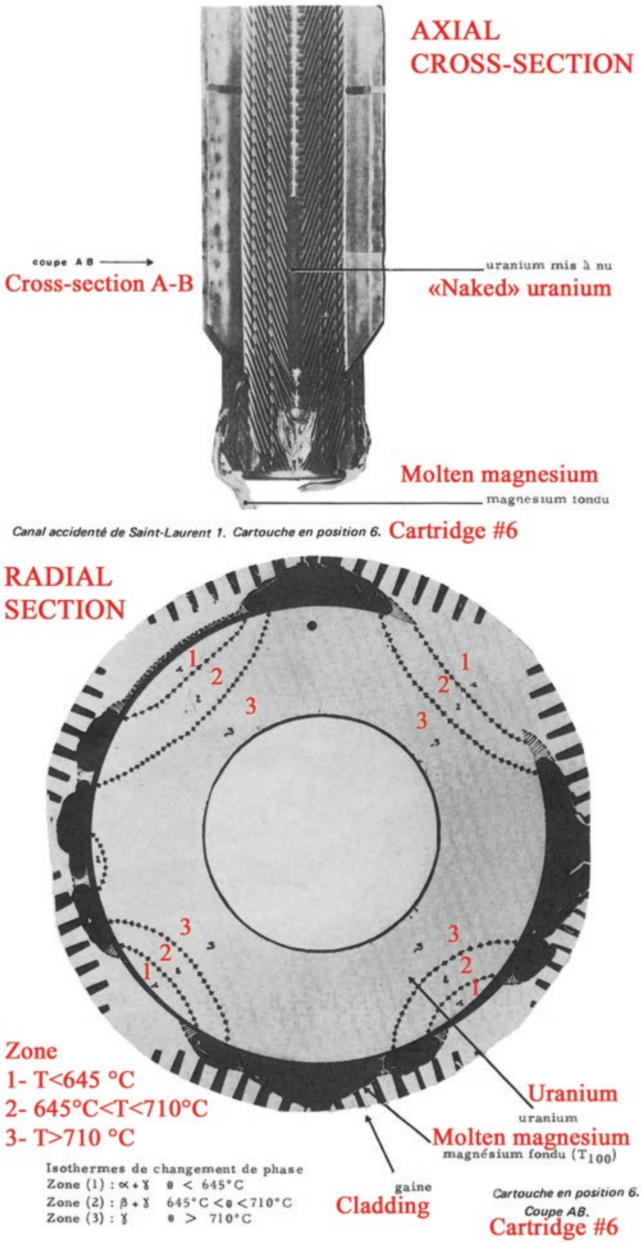


Photo 2.83 Degradation of a fuel cartridge (vertical section and section) analyzed by the CEA. On the top picture, we see the melt magnesium flows. On the lower picture, we see the radial extent of the magnesium flows as well as the cooling blades around the cartridge (in black)

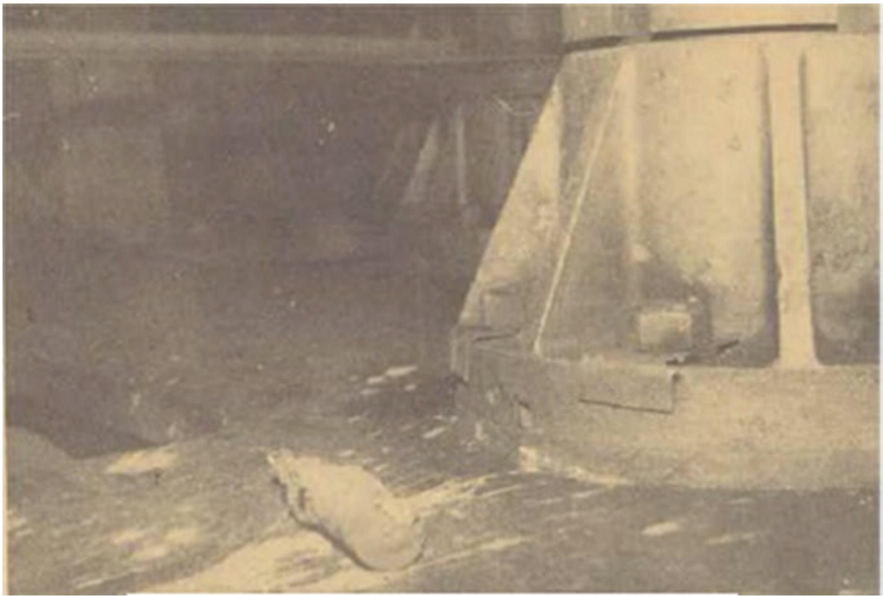


Photo 2.84 A fuel jacket debris placed on the support area in front of the heat exchangers and below the core (the exchangers are placed below the active core). Large debris such as this could be removed by remotely operated tongs. The finishing work had to be done manually after re-entering the caisson. The fuel, almost fresh, was (relatively) not very radioactive

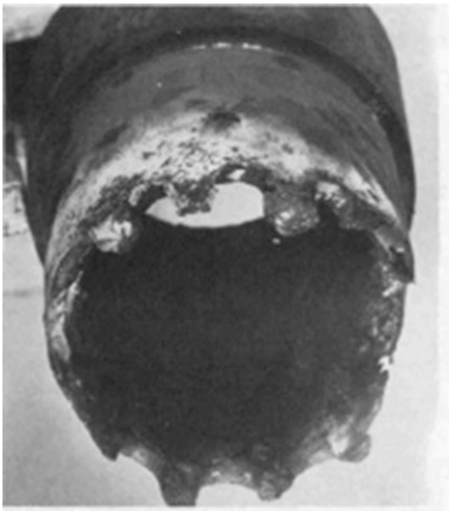


Photo 2.85 Photo of the damaged "trash can." The "recuperator" part has completely disappeared when all the full zones of the circular honeycomb part have melted

computer-trained specialists. It was also claimed that there was a fuel loading pattern error that could never be proven. Five elements in the lower part of the core (out of a column of 10) were destroyed, producing about 50 kilograms of corium. 14 kg were retained by the debris collector located below the active core. The rest was thrown out and spread to the surrounding structures (the support area) and to the lower structures (the heat exchanger tubes) by gravity (Fig. 2.67). At high temperature, the uranium was partially oxidized by contact with the CO_2, and uranium oxide dust was carried by the gas and deposited on the intact fuel elements, causing significant pollution. This pollution resulted in a strong increase in the background noise of the cladding rupture detection device (DRG), which measures the radioactivity of the fission gases leaking from the fuel cladding. The fact that the fuel that had just been loaded into the channel was fresh meant that its fission products content was very low.

After the accident, the pollution of the reactor was estimated at 100 grams of uranium deposited on the surface of the cladding, instead of 6 grams for a new core (there is always some uranium powder on the surface of new fuel because of the manufacturing process). This had the consequence of increasing the count rates by a coefficient of fifty.[35] As a result, the DRG had to be recalibrated to ensure that it was still capable of performing its function.

The rehabilitation of the reactor required the solution of several problems: the cleaning of as much corium and uranium debris as possible (Photos 2.86 and 2.87). EDF used to the maximum the devices controlled remotely from the upper slab such as suction hoses and remote-controlled gripping (pneumatic clamp) of the most voluminous pieces (47 kg of large debris, of which 15 kg were collected thanks to a scraper allowing to make heaps accessible to the clamp). But a human intervention was necessary to remove some debris adhering to the structures. Each of the people who entered the caisson stayed there less than 8 minutes. Because of the limitation to 3 rems per person, 105 people[36] intervened in the caisson maintained under vacuum, after preparation on a scale model, as well as on reactor no. 2 then under construction. They passed through the top of the exchangers after dismantling and cleaning the cell closest to the damaged channel. Dose rate predictions were carried out by the CEA on this occasion, to program the shifts between the teams. The operators entered the caisson through airlocks located at the height of the

[35] A. Grauvogel, J.P. Le Noc: *Saint-Laurent 1 – Incident du 17 octobre 1969, Pollution du réacteur et modification de la DRG*, Bulletin d'information de l'association technique pour l'énergie nucléaire n°92 (1971).

[36] Possibly women (secretaries?), according to one of the former participants in the affair, a detail that I have not been able to confirm from other sources. Perhaps it is an urban legend that captures the attention of listeners! I personally find it hard to believe.

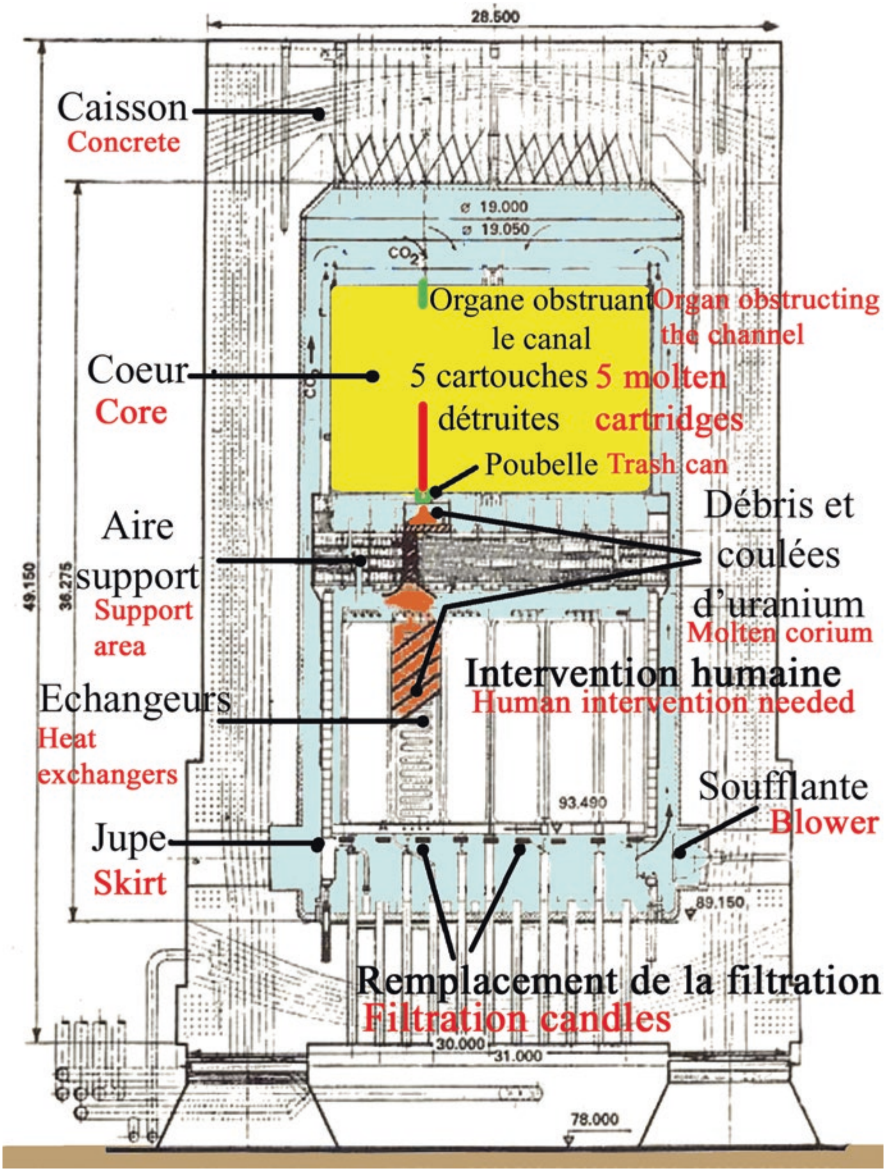


Fig. 2.67 Plan of the core and the damaged channel of Saint-Laurent-A1. The carbon dioxide rises around the core and then passes through the core from top to bottom before passing through the heat exchangers. Note that the core is placed above the heat exchangers, which is antagonistic to natural convection, but which allows the concrete of the caisson to be cooled by cold carbon dioxide, compared to a situation where the core would be placed below the heat exchangers with a cold gas rising and then hot gas descending on contact with the concrete (*jupe* = skirt, *poubelle* = garbage can, *soufflante* = CO_2 blower, *coeur* = core, *échangeurs* = heat exchanger)

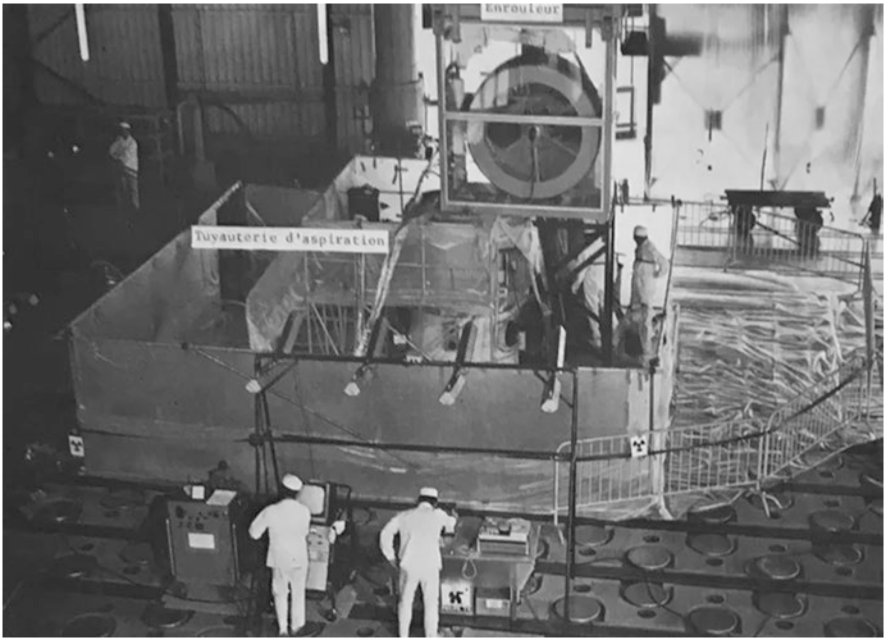


Photo 2.86 Installation of a suction system from above around the damaged channel at the level of the reactor slab. A controlled zone surrounds the whole. One can clearly see on the ground the displacement rails of the fuel loading machine and the circular plugs of the access pits. "Tuyauterie d'aspiration"=venting duct

Photo 2.87 Cutting operation on Saint Laurent-A1 during post-accident repair. The operators are wearing ventilated clothing indicating a possible source of contamination

turbofans. Climbing along the heat exchangers in total darkness except for a little artificial lighting, they had access to the lower support area of the reactor, and, after 2 weeks of cutting work in a containment and extremely stressful environment, they were able to access the damaged channel.

The dust around the incriminated channel could then be sucked up. The risk of ignition of the uranium debris in the air following the opening of the caisson (uranium and in particular its hydrides can ignite in air) was also considered before being invalidated. At the end of these cleaning operations, 47 kg were removed from the reactor, which left about 10 kg, including 5 to 8 kg of uranium, trapped in the exchangers and certain cells. Pierre Way, at the time a technician in the uranium store, reported[37] that the Pegasus casks, intended to transport the spent cartridges to La Hague, were poorly adapted to mate with the orifice of the container system (known as *Mecca*): "*With two colleagues with strong nerves, we tied a sailor's knot around the blocks and rushed everything into the cask. Everything happened very quickly. We were not irradiated.*" The fit-up system was adapted later. It was then necessary to create a sufficiently efficient filtration system to prevent the reactor from becoming polluted again over time. This filtration, made of cartridges (known as *glass wool candles*) and metal sieves, had the task of recovering the residues partially oxidized by the CO_2 at 400 °C, which would not fail to be carried away by the heat transfer gas. This filtration proved to be disappointing as only 1.5 kg of material could be recovered. The remaining material was never located more precisely. Are they the cause of the pollution of the Loire? The last filters were removed in 1978. Thermochemical studies have shown that oxidation only in the presence of carbon dioxide (i.e., without oxygen) was finally quite slow. A granulometric analysis of the debris made it possible to predict approximately the rate of de-scaling of the core from the knowledge of the flow of CO_2 (9 tons per second). A metal casing was then introduced under the exchangers with a seal against the skirt (the structure that channels the gas flow). On this frame were fixed baskets containing about ten filtering candles (so-called because of their shape) of 17 cm diameter and 75 cm height, for a total of 1600 candles. Beyond design basis tests were performed to evaluate the efficiency of this device outside the core. As a last resort, the DRG cladding breakage measurement system had to be adapted to take into account the high level of parasitic noise due to the dust, the quantity of which decreased over time. Indeed, the restart of the reactor was conditioned to the possibility of detecting cladding failures later. Tests at low power showed that the DRG could still perform its function effectively, without even renewing the contaminated fuel. An "auxiliary computer" was developed to check the punched

[37] As reported in *Génération SPT* n°21, *Journal de la production thermique d'EDF*, July-August 1988.

cards of the fuel loading machine, i.e., a card reading system that shows the fuel loading pattern as actually punched. In addition, the fuel loading machine was equipped with a continuous weighing system and a camera for identifying the elements being loaded.

The time required to rehabilitate the reactor, resulting from effective collaboration between EDF and the CEA, was short enough for the reactor to be reconnected to the grid on 16 October 1970, exactly one year after the accident. The filtration allowed the removal of an additional 1.5 kg of dust, in a very localized area vertically above the damaged channel. By today's standards, this accident would probably have been classified 4 on the INES scale for describing nuclear accidents (see Appendix 1). Indeed, when the caisson was opened and ventilated, contaminated carbon dioxide was released into the atmosphere after filtration, and it is estimated that the presence of Very High-Efficiency filters retained most of the particles with a diameter greater than 0.3μm.

The financial cost of the rehabilitation is estimated at ten million francs in 1969, to which must be added the cost of the loss of operation (electricity sales), which is about the same. Measures to improve safety were taken afterwards: the damaged channel was simply condemned, perforated bells were installed at the head of the channel to ensure permanent cooling by CO_2, a gas turbine was added to secure the electrical source. A last resort panel was settled, and an additional cooling pump was installed. The reactor was then able to operate without any particular problems until its final shutdown in 1990.

A new partial meltdown accident occurred on March 13, 1980 at 5:40 p.m. in the other Natural Uranium-Graphite-Gas (UNGG) reactor Saint Laurent-A2 (Fig. 2.68). Following an increase in radioactivity in the coolant indicating the presence of fission gas, the reactor was shut down. Visual inspections showed that a pressure transducer holding plate of about 0.5 m^2 which had become loose because of corrosion and obstructed a dozen channels in the F05 M19 cell and in neighboring cells, out of 3,000 cooling channels. This obstruction led to a major melting of two fuel elements, about 20 kg of uranium and magnesium.

Corrosion is a major problem in Natural Uranium-Graphite-Gas (UNGG). It is due to radiolysis[38] by carbon dioxide, which produces oxidizing free radicals.

[38] Radiolysis consists in the decomposition of a molecule under the effect of radioactive radiation. Thus, liquid water can be transformed into hydrogen and oxygen, and carbon dioxide into carbon and oxygen. It is oxygen that corrodes metal structures. The oxidation is exacerbated by the temperature: the higher the temperature, the faster the oxidation.

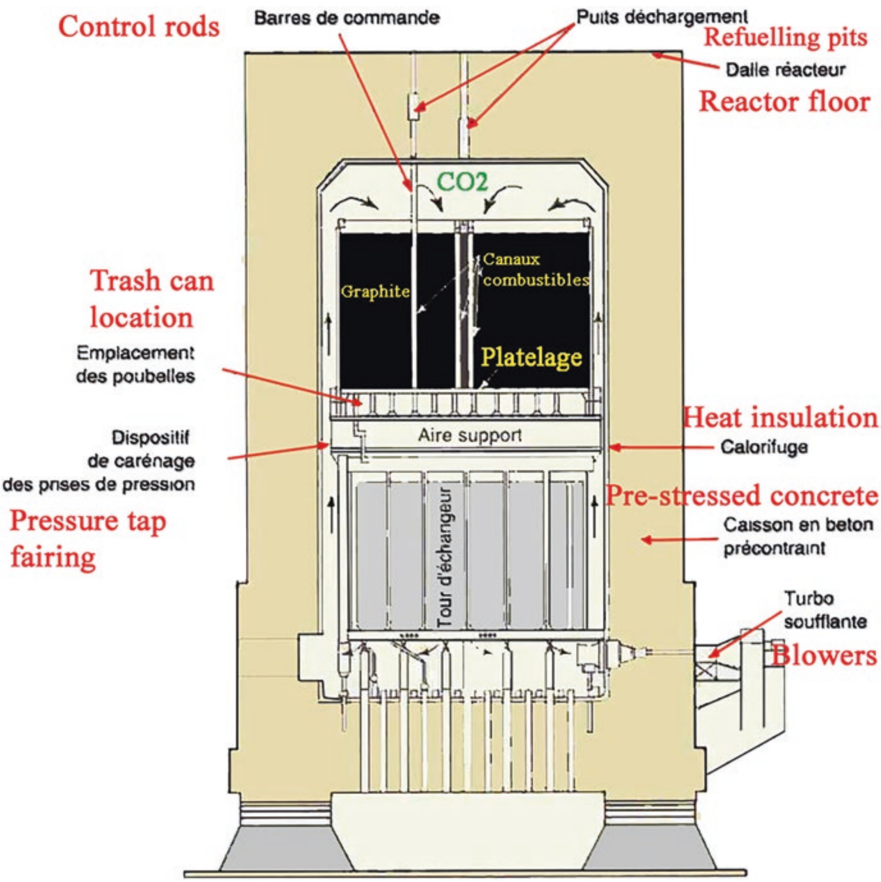


Fig. 2.68 Axial section of the Saint Laurent des Eaux-A2 reactor

$$CO_2 \rightarrow CO + \underbrace{0}_{\text{radical libre}}$$

This accident rendered the plant unavailable for two and a half years and was rated 4 on the INES scale. Although less uranium was melted in this accident than in 1969, the fuel was much more burned-up, resulting in a greater release of radioactivity. Early signs of corrosion had been reported in September 1976 at the twin plant of Vandellos in Spain, but in a report in Spanish that did not attract the attention of the French. Deterioration in January 1980 of the pressure sensors of Saint Laurent-A2 due to unidentified corrosion/detachment of the fairing sheets did not attract attention either.

After the accident in March 1980, the plant was authorized to restart in October 1983, after 500 people had intervened,[39] cleaning of the support area under the core (as in 1969). The cumulative releases remained low because the deflation of the caisson was delayed, knowing that the fuel was spent fuel. Releases were limited to 1.5 mCi of iodine and aerosols (for authorized weekly maximums of 15 mCi and annual maximums of 0.2 Ci) and 775 Ci of noble gases (for maximums of 1200 Ci weekly and 8000 Ci annually). As in 1969, glass wool candles were placed to filter the carbon dioxide, making it possible to recover mainly small pieces of graphite. The final shutdown of the plant took place in 1992.

To complete the history of abnormal situations in the French Natural Uranium-Graphite-Gas (UNGG) plants, a level-2 incident occurred on January 12, 1987, following the freezing of the water supply from the Loire River, the cold source for the condenser of the Natural Uranium-Graphite-Gas (UNGG) turbofans (problem of supercooling of the liquid water to a temperature below 0 °C explaining the very large quantity of ice at the water intake). The cooling function of the condenser was no longer ensured, and there was a leak of steam from the condenser, detected by the fire systems as a fire outbreak, which led to the last liquid water resources in the auxiliary building being emptied by automatic spray. The water supply was re-supplied by demineralized water from the neighboring PWR plant. Afterwards, the army men destroyed the ice dam and restored the water supply. This incident clearly illustrates the problem of the reliability of the cold source on river plants, whether in extreme cold or in low water conditions during a period of severe drought.

It is for technical reasons, but above all for economic reasons, that Natural Uranium-Graphite-Gas (UNGG) will come to an end in France. Indeed, the operating costs per kilowatt and per year were twice those of PWRs (440 French Francs/1988 for 200 French Francs/1988). Moreover, due to a lack of standardization, each plant used a different fuel, which posed specific problems for each plant. The aging of the plants justified their shutdown. Chinon-A1, very recognizable thanks to its steel sphere, became a museum in 1985, accessible to the public.

On May 4, 2015, the encrypted French television channel *Canal* + presented a program entitled " *Nuclear power, the politics of lies*?" This program presents the accidents of October 17, 1969, and March 13, 1980, as a scoop on alleged severe accidents hidden and buried by the EDF and the government. This very "tabloid" presentation of the facts is rather curious since the

[39] Because of the radioactivity, the exposure was limited to 20 minutes in order not to exceed 30 mSv.

first French edition of this book dates from 2011 and was largely based on public facts, so it could not decently be called a scoop. The government responds to these accusations with a mission of inquiry requested by Ségolène Royal, the French Minister of Ecology, Sustainable Development, and Energy, to Philippe Guignard, Chief Engineer of the bridge, water, and forests corps, and Serge Catoire, Chief Engineer of mines corps. While the mission agrees that there was no concerted plot, it appears that the decree that governed the releases of alpha emitters did not mention precise limits on March 13, 1980, and on December 13, 1980, new decrees were issued for the start-up of two new PWR reactors at Saint Laurent, vaguely specifying that "*these liquid or gaseous releases must in no case add alpha emitters to the environment,*" which is scientifically impossible to respect insofar as small quantities of fuel remained trapped in the caissons. The discovery of traces of plutonium (less than one gram in total, 10–20 milliCuries of activity, and 10 Sv/mg of radiotoxicity) in the sediments of the Loire (in millions of tons) and its average water flow (1000 m^3/h raises the question of the origin of this pollution, although everyone agrees that the risks for the environment and the population are almost nil. Was it the bursting on 21 April 1980 of a cask that had transported a damaged fuel element, or was it the water from the desiccation of the carbon dioxide released into the Loire by the Natural Uranium-Graphite-Gas (UNGG) plants, which could certainly have contained traces of plutonium? It should be noted that the isotopic analysis of the plutonium makes it possible to know whether it is military plutonium from atmospheric fallout dating from the time of atmospheric testing (the plutonium is then practically pure in plutonium 239), or plutonium produced in power reactors (the plutonium then contains isotopes 238 to 242 and americium 241, and the plutonium 239 isotopy is much lower than that of military plutonium). The mission noted the good faith of the operator and of the authorities in the administrative context of the time, while noting an uncertainty about the norms concerning releases of alpha emitters, an uncertainty that has been slow to be resolved.

As a matter of curiosity, a forum was set up during the fiftieth anniversary of the 1969 accident by an association from Orléans of the "1901 law" type, somewhat pompously called the "*Collège d'Histoire de l'Energie Nucléaire et de ses aléas*," proposing to reveal alleged "secrets" about the accidents at Saint Laurent des Eaux. Not having participated personally, I cannot give my opinion on the level of information delivered, but the sensationalism of the poster (Photo 2.88) bodes well for information that is, to say the least, biased. Let's bet that this association had at least read the first 2011 edition of this book!

Photo 2.88 The poster of a forum on the accidents of Saint Laurent. Not so secret as that! The teasing is the following: "*Did you know it? 50 years ago, on October 17, 1969, there was a NUCLEAR FUSION accident involving 50 kg of uranium, as at Three-Mile-Island, which was kept secret for over 40 years! What was the contamination of the living and the environment? Few know*". The words "*NUCLEAR FUSION*" are rather misleading in this context

Bohunice A1: (Czechoslovakia, 1976, 1977)

Czechoslovakia embarked on a nuclear program in the late 1950s. The site chosen was Jaslovské Bohunice, 60 km from Bratislava (Photos 2.89 and 2.90). Besides the A1-reactor, 4 WWER-440 reactors of Russian design (2 models 440/230 and two more recent models 440/213) were built in 1972. The construction of the reactor, a model called “KS-150” of Soviet design but entirely manufactured by the Czech company Skoda, began in 1958 (Photo 2.89). The reactor (Fig. 2.69) used natural uranium (4.5 tons in all) contained in an assembly 12 m high (!), moderated with heavy water contained in a calandria (Photo 2.91) and cooled by carbon dioxide at 65 atmospheres (65.9 bars) which passes through pressure tubes. The reactor went into operation on December 25, 1972. The reactor has a power of 143 MWe gross (93 MWe net, 560 MWth), which heats the primary circuit of carbon dioxide (Fig. 2.70) at 410 °C. The secondary circuit is composed of 6 SGs, the steam of which turns three turbo-alternators of 50 MWe each. The core can be loaded continuously, with the reactor running, just like the French Natural Uranium-Graphite-Gas (UNGG) or English MAGNOX models. A fuel loading machine moves on the loading side to

Photo 2.89 Beginning of the A1 reactor construction (circa 1959)

Photo 2.90 The site of Bohunice. The A1 reactor is recognizable with its very high hall with white roof and by the chimney on its left. The eight air coolers in operation serve the 4 WWER-440 reactors on the right of the picture

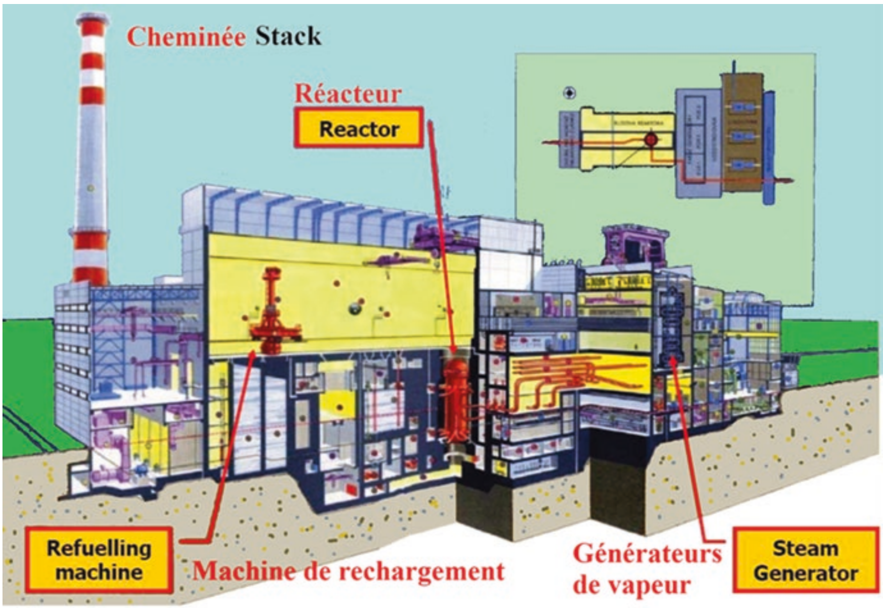


Fig. 2.69 The A1-reactor. The fuel loading machine being very high to contain assemblies of 12 m high, the hall must be very important in size

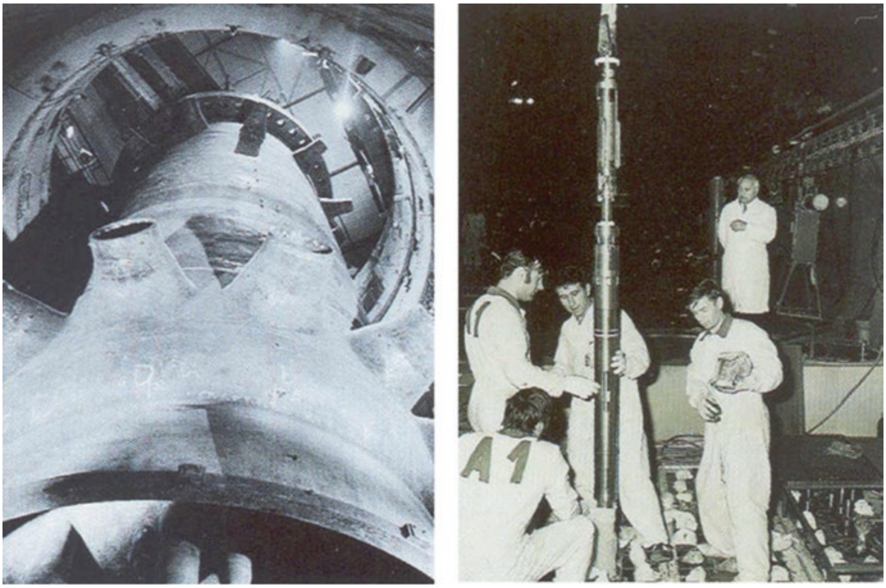


Photo 2.91 KS-150 reactor calandria inserted into its housing (left) and manual insertion of fresh fuel for the start-up core (right)

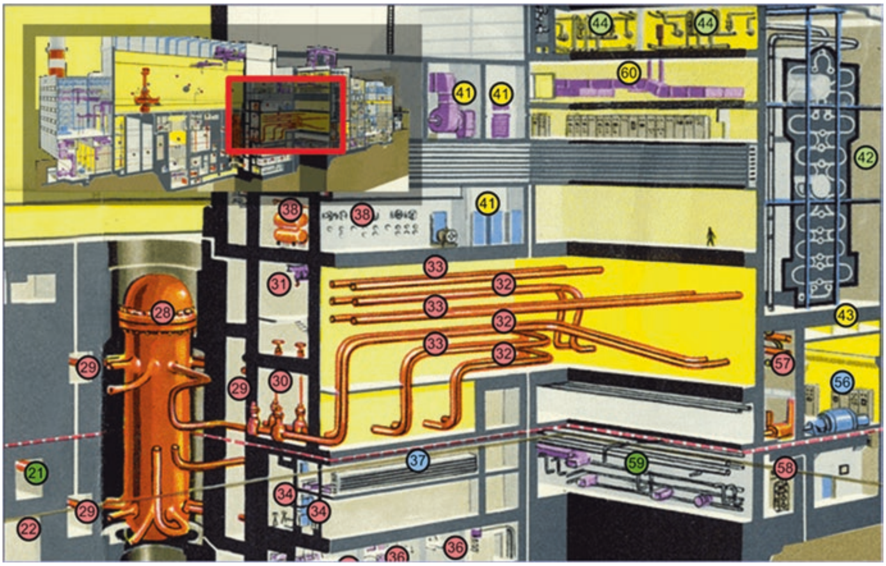


Fig. 2.70 The primary circuit of the A1 reactor: 28- Reactor pressure vessel, 29- Primary pumps of carbon dioxide, 32- Six cold loops of carbon dioxide, 33- Six hot loops of carbon dioxide, 42- one of the 6 steam generators (image adapted from the site of the Slovak company Javys). The reactor vessel has 6 cold inlets at the top of the active core and 6 hot outlets at the bottom of the active core, which means that the primary circuit is complex and winding because the SGs are located far from the core, requiring an extremely large amount of plumbing, and welding work inducing very significant risks of leakage

connect to a pressure tube in a tight way and inserts or extracts an assembly (Photo 2.92 and Fig. 2.71).

A serious incident took place on January 5, 1976 during the reloading of a pressure tube by a new fuel. The shift supervisor, Viliam Pačes, directs the loading maneuver. The electronic control on the loading mast, which tests the correct closing of the pressure tube, shows that the connection is tight. In fact, operator Martin Slezàk lifts the fuel assembly slightly as required by procedure. However, the connection was not tight, and the pressurized carbon dioxide (65.86 bars) ejected the assembly, which was 12 m high. The failure of the closing system of the carbon dioxide channel thus causes the ejection of the new fuel that had just been placed. The force of the flight is such that the ejected fuel will hit the crane of the fuel loading machine. Even some of the steel cubes used to block the assembly start to fly away. The whistling sound of the carbon dioxide depressurization is frightening, far superior to a full-powered alarm siren. After a moment of fright, the shift supervisor rushes into the control room to alert and retrieve gas masks, then returns with a man from the radiation protection team to the reactor hall. Operator Slezàk is injured more seriously and evacuated. For 10 to 15 min, Pačes, assisted by Milan Antolík, will heroically struggle to evacuate the fresh fuel assembly around the fuel loading machine and close the channel despite the flow of gas which cannot be stopped because it must evacuate the residual power, even if the reactor is shut down. The radioactive carbon dioxide then escapes into the reactor hall during this time. As the fuel is fresh, there is little irradiation of personnel outside the reactor hall, but two unmasked operators near the hall airlock who did not evacuate were asphyxiated to death by the carbon dioxide. This accident will remain largely ignored in the West until 1998 and 2006.[40] It would probably have been classified at level 3 on the INES scale. The reactor will be shut down until the end of 1976 for modifications. An investigation of the accident by the Czechoslovak security services was conducted. Antolik explains: « *We all knew why. It was simply impossible for Soviet technology to fail. Even when we were later debriefed by the StB secret service and the criminal police, all questions were directed towards finding a culprit. They pushed the search for a saboteur in order to be able to qualify the accident as a deliberate act of sabotage. At that time, it was inconceivable to say that a Russian reactor had been damaged*». Viliam Pačes spent his entire career on Slovakian reactors. Pačes apparently received a high dose during the accident, as he experienced nausea afterwards, but he is still alive today. He is currently retired. When Fukushima, he was asked about the 1976 accident. He reports some elements on what would have turned to an even bigger tragedy:

[40] An excellent synthesis of Jozef Kuruc and Lubomir Màtel: *Thirtieth anniversary of reactor accident in A-1 Nuclear Power Plant Jaslovcske Bohinice*, XXVIII Dny radiačni ochrany, November 20–24, 2006, Luhačovice, Czech Republic, Sbornik rozsirenych abstraktu, pp. 159–162, ISBN 80-01-03575-1, from which we draw most of the illustrations in this paragraph.

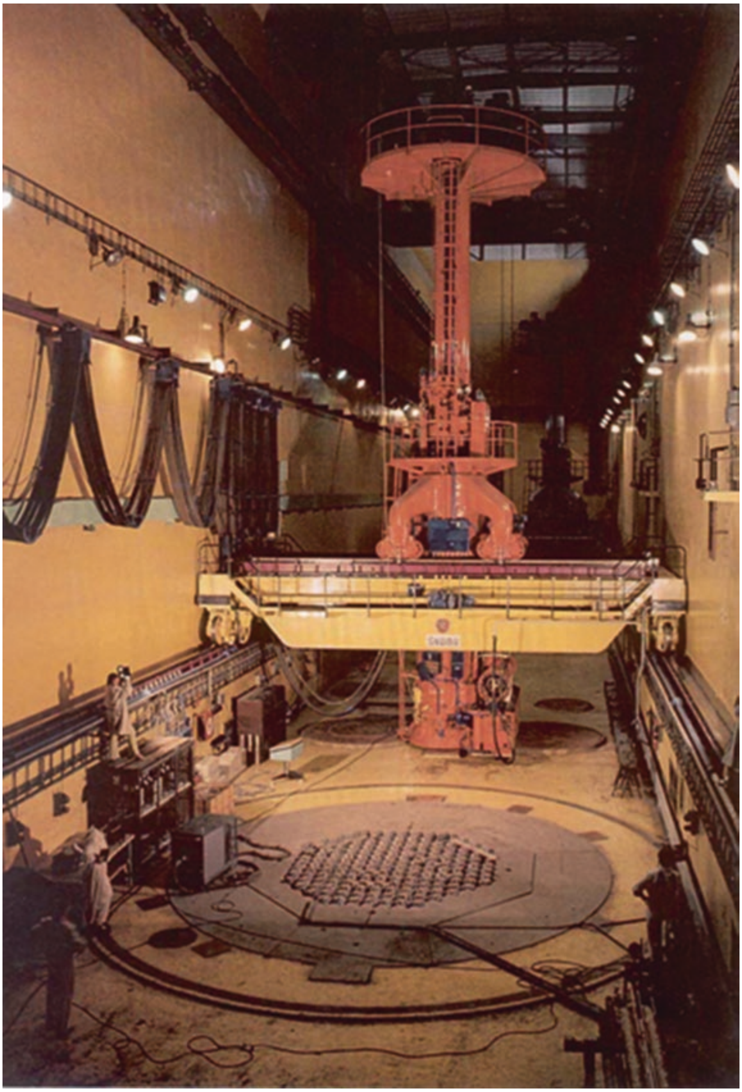


Photo 2.92 The reactor hall. The fuel loading machine (in orange at the bottom of the photo) moves on the loading floor and is connected to a pressure tube of which one sees the tight closing system. Contrary to the French system where the fuel loading machine moves on rails, this machine moves thanks to the crane (yellow) which runs on rails placed at about 3 m from the ground and clearly visible along the walls. A lateral movement along the crane allows to reach all the pressure tubes that fill the octagon of the core. The height of the machine (and its weight) is considerable because of the height of the assembly (12 m), whereas the French have chosen a fuel in the form of a cartridge, which is much easier to handle

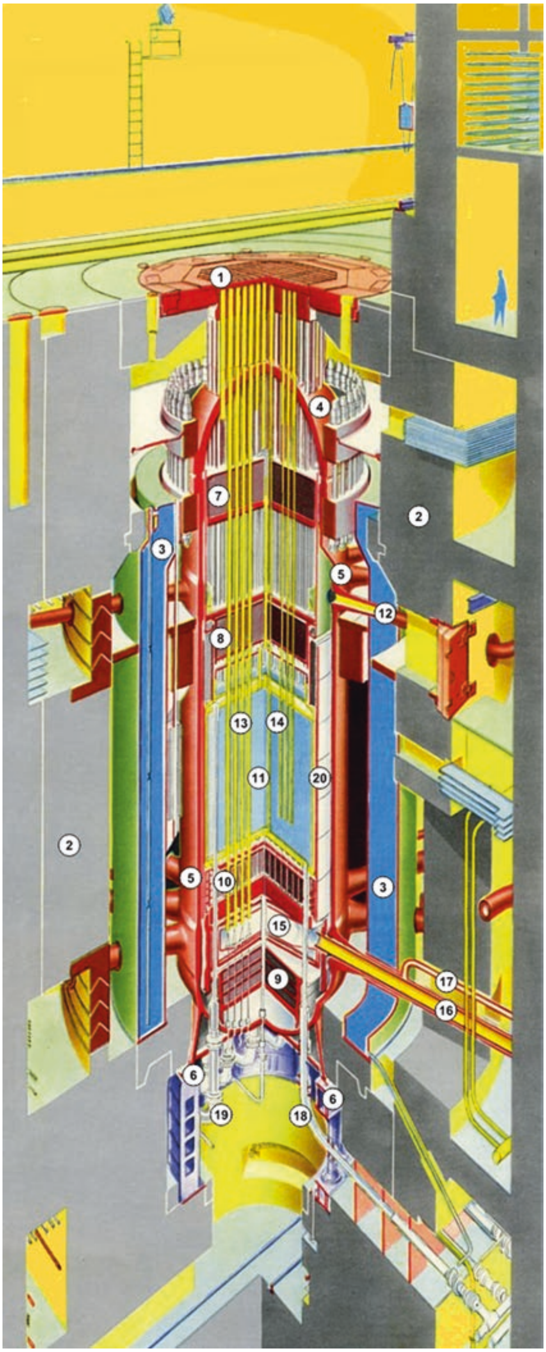


Fig. 2.71 KS-150 reactor: 1- Loading face, 2- Concrete biological protection caisson, 3- Biological protection water tank, 4- Pressure vessel cover, 5- Pressure reactor vessel, 6- Pressure vessel support, 7- Upper biological protection, 8- Middle biological protection, 9- Lower biological protection, 10- Graphite reflector of the core support plate, 11- Heavy water calandria in the active zone of the core (about 12 m high), 12- Cold leg for carbon dioxide entry from the steam generators, 13- Pressure tubes containing the

*« At the time the fuel assembly came out of the reactor and the gas escaped, I didn't have an oxygen mask. So, of course, I inhaled some. But I got exhausted pretty quickly and I had to get out of the hall, otherwise I wouldn't have survived. Then the evacuation started in the reactor building. We agreed with the plant management that the only way to avoid a catastrophe was to seal the leaking pipe. So, I took an oxygen breathing apparatus and went back quickly, because the gas was leaking at a tremendous rate under high pressure. The dosimetrist went with me, but there was not much he could do on the spot. The radiation in the reactor hall was so enormous that it exceeded the capabilities of the measuring instrument he was using. Carbon dioxide was escaping through the leak, so there was a risk of that some reactor components could melt. The dosimetrist told me to leave immediately. Later, however, he realized that someone had to do it. I knew that I could receive a dose of radiation that could kill me. Other people told me later that they thought I would not come back and that if I survived, I would have long-term effects. But when a person is at work and the rescue is up to them, they think differently than when they are at home on their couch. I couldn't tell myself to let someone else do it. Because there was no one else who could seal that pressure tube in the reactor. I also imagined how many people would be threatened by the disaster. I knew from my industrial training that radiation could endanger them. Among these people in my imagination were my wife and children. All this made me go further. I don't know how much dose I received. I didn't take my personal dosimeter with me in the rush. Measurements were taken later, but I didn't know the results. However, we can deduce a clue. For a year after this procedure, I was forbidden to go into the reactor hall so that I would not receive any further doses. When I left there, I didn't feel well. After a while, however, it passed. I also forgot that I had to get a checkup. It was a completely different time; the measuring instruments weren't that good, and a lot of things were kept secret. We also didn't have enough experience back then and we weren't well trained. Today, the requirements are much higher. My superiors and colleagues thanked me and shook my hand. That's all, no one gave me a bonus. Then, only on the fifteenth anniversary of the founding of Slovakia in 2008, President Ivan Gašparovič awarded me and Milan Antolik the Milan Rastislav Štefánik Cross (*Photo 2.93*). However, my great reward was that, although there was a lot of material damage, nothing worse happened».*

On February 22, 1977, a severe accident occurred leading to fuel melting. The loading of a fuel that did not allow sufficient passage of CO_2, for reasons that are not well known, led to a local heat up that resulted in the melting of the fuel and

Fig. 2.71 (continued) fuel elements, 14- Control rods and emergency shutdown rods, 15- Hot carbon dioxide collection chamber, 16- Hot carbon dioxide evacuation pipe to the steam generators, 17- Injection of cooling CO_2, 18- "Cold" heavy water injection channel, 19- "Hot" heavy water extraction channel to a heat exchanger for cooling the heavy water (image adapted from the Slovakian company Javys)

Photo 2.93 Viliam Pačes (on the right of the left image) receives the Milan Rastislav Štefánik medal from the hands of Slovak President Ivan Gašparovič in 2008 for his courage during the accident at the A1 reactor in Bohunice (photo Slovak TV), Milan Antolik is also awarded (on the right of the right image). In 1987, both received a medal from the Prime Minister Lubomír Štrougal for services to construction during the Soviet era. Antolik reported that Štrougal was sweating profusely, his hands were shaking, and he seemed to be afraid of the contamination that the two former operators might have passed on to him 10 years later!

the piercing by the corium of the pressure tube separating the fuel and the CO_2 from the heavy water in the calandria. The mixture of heavy water brought to saturation by the corium and carbon dioxide contributed to the oxidation of the fuel cladding and the steam generator tubes. 132 assemblies (!) partially melted. The primary circuit, the secondary circuit and the reactor hall were contaminated. The contamination was such that the Czechoslovak government decided to close the reactor in 1979, which had produced a total of some 916 GWh in 5 years. 439 of the 571 spent fuel assemblies were evacuated to the Soviet Union from 1984 to 1990. The 132 badly damaged assemblies were sent to the Mayak site in Russia in 1999. The accident was classified 4 on the INES scale.

In June 1978, heavy rains at the site spread contamination to the Dudvah River, a tributary of the Vah River which itself flows into the Danube 90 km away, because no isolation action had been taken after the accident due to lack of funding. Dismantling operations did not really begin until 1995. The mass of deposits in the primary circuit was estimated at 14.3 tons, which is considerable. The gamma contamination is estimated to be between 10^{14} Bq and 10^{15} Bq. The alpha activity is between 10^{11} Bq and 10^{13} Bq. Starting in 1997, pits were dug around the reactor to pump tritium-contaminated water from the water table and limit leakage to the biotope (Fig. 2.72). ^{137}Cs activity (half-life 30.1 years) was measured at the site in 2004 (Fig. 2.73).

Constituyentes RA-2 (Argentina, 1983)

The Constituyentens accident falls into the category of criticality accidents in experimental reactors, like those of Vinča and SL-1 seen previously.

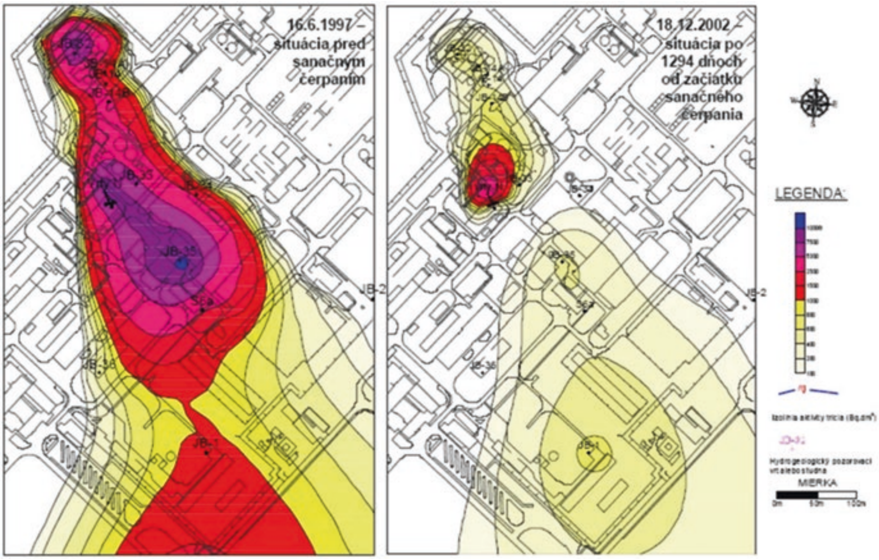


Fig. 2.72 Tritium contamination (in Bq/liter) of groundwater after the installation of pumping pits in 1997 around the reactor

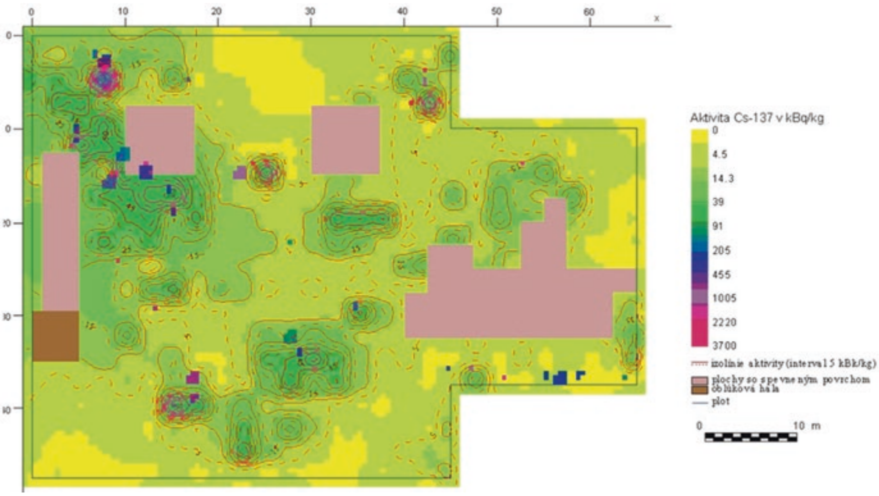


Fig. 2.73 Ground activity of ^{137}Cs on the site. A higher concentration is observed around the reactor building and the circular stack

The *Centro Atómico Constituyentes* (CAC) is located in the district of San Martín, Buenos Aires, Argentina (Photos 2.94 and 2.95). The center houses several facilities, such as the first nuclear reactor in Latin America (RA-1), RA for *Reactor Argentino*. A second RA-2 reactor was built with the objective of testing core arrangements for a more powerful reactor: the RA-3, which will be located at the Ezeiza Atomic Center. The CAC also has a heavy-ion gas accelerator TANDAR13. The CAC also houses a plant for the manufacture of uranium powder and a plant for the manufacture of fuel elements for research reactors, initially under the direction of the physicist Jorge Alberto Sabato (1924–1983. he founded in 1955 the Metallurgy Department of the *Comisión Nacional de Energía Atómica*—CNEA).[41] The center hosts laboratories dedicated to nanotechnology, solar energy, research and materials testing. Argentina's nuclear development began in the early 1950s. In 1957, it was decided to build the first research reactor. The RA-1 reactor, built in just nine months (design power 120 kWth, now authorized to operate at 40 kWth), began operation in January 1958. It was the first reactor in South America to diverge, which is a legitimate source of pride for Argentina. Originally, the RA-1 was an *Argonaut* reactor of American design operating with enriched uranium supplied by the Americans. The RA-1 is an open vessel reactor, reflected by graphite (imported from France), and whose moderator and coolant are demineralized light water. The maximum neutron flux is 2 10^{12} neutron/cm^2/s against an average neutron flux of 3 10^{14} neutron/cm^2/s in a large PWR. In the early 1960s, the core of RA-1 was modified. Fuel rods (20% ^{235}U enrichment) were introduced in place of the old Argonaut core design. The RA-1 facility was also the first to produce domestic radioisotopes for medical and industrial purposes. RA-1 is still used today for material activation testing, radiation damage and research onto new therapies in nuclear medicine, among other areas (Photos 2.96 and 2.97).

A critical facility called the RA-0 zero-power facility was first built at ACC and then transferred to the University of Cordoba. The RA-0 core has a circular ring geometry formed by two concentric and separable tanks made of anodized aluminum (Photo 2.98). It houses the fuel elements, composed of 20% enriched uranium in the form of rods, and demineralized water used as a moderator. The control rods are made of cadmium cladded with stainless steel. A rapid draining of the water from the vessel completes the safety measures. As this is a very low-power reactor (maximum neutron flux of 10^7 neutron/cm^2/s), no coolant is required and there is virtually no wear and tear on the fuel, so it does not need to be replaced. The RA-0 is used to train the

[41] The CNEA was created on May 31, 1950, by President Juan Domingo Perón to oversee Argentine work in the field of the peaceful use of the atom.

Photo 2.94 The *Centro Atomico Constituyentes*

Photo 2.95 The tower of Constituyentes is emblematic and "watches over" the site

Photo 2.96 The RA-1 reactor known as "Enrico Fermi" in honor of the builder of the first-ever reactor in Chicago

Photo 2.97 Operators working on the loading face of the RA-1 reactor

operators of the two power reactors Atucha-1 and Atucha-2. A digital reactimeter (numerical inversion of the Nordheim equations from a neutron flux measurement) was implemented at the start-up of the RA-0, which is the only reactor in the country to have such an instrument.

Photo 2.98 View of the Argentinean reactor RA-0

After that, the RA-3 project began to build a 5 MWth multipurpose nuclear reactor of the pool type Material Testing Reactor (MTR), for radioisotope production and research. For this reason and to define the characteristics of the RA-3 core, another critical zero-power facility was built, the RA-2. Initially, RA-3 was a 90% enriched fuel reactor, and its operation began in 1967 at the Ezeiza Atomic Center. The maximum fast neutron flux of RA-3 is 2.5 10^{14} fast neutron/cm^2/s and thermal neutron flux of 8 10^{13} thermal neutron/cm^2/s. RA-3 operates 4 days a week just for medical isotope production (Photo 2.99). When the Atucha-I nuclear plant project began, a German-designed power reactor, a small homogeneous reactor, was offered by the German government to Argentina (1969). It was the RA-4 reactor of the University of Rosario (20% enrichment, 1 W). In 1982, the pool reactor RA-6 of the Bariloche Atomic Center reached criticality. It is a 500 kW reactor with MTR fuel elements enriched to 90%. In 1990, the RA-3 began operating with 20% enriched fuel. In 1997, the RA-8 (a multi-purpose critical facility located at Pilcaniyeu) began operation. The RA-3 reactor is CNEA's most important reactor for the development of Argentine research reactors. It is the first of a series of Argentine MTRs built by CNEA (and INVAP Se) in Argentina and other countries: RA-6 (500 kW, Bariloche-Argentina), RP-10 (10 MW, Peru), NUR (500 kW, Algeria), MPR (22 MW, Egypt).

The RA-2 reactor, in charge of testing the RA-3 configurations, is much less documented (if none!) since it is the one on which the criticality accident occurred. Even today, government agencies and the CAC are more than

Photo 2.99 The RA-3 reactor whose main function is the production of medical isotopes such as metastable technetium 99

discreet about this reactor, which is never presented on official sites, as if they had wanted to erase this history so as not to harm the export effort. The RA-2 is a critical installation which diverged in July 1966 and of very low power (0.1 W) whose objective is the study of fuel lattices. The RA-2 reactor uses fuel in the form of enriched uranium plates clad in aluminum. The lattice is easily changeable for research in reactor physics. The core of RA-2 has a cross-section of 305 mm × 380 mm and an active height of 655 mm. In this geometry, different configurations of MTR fuel elements made of uranium enriched to 90% in ^{235}U are inserted, arranged in 19 uranium plates for the standard elements (width 75.5 mm× thickness 1.6 mm× height 655 mm), and 15 uranium plates interspersed with 2 cadmium plates for the control elements, both cladded in aluminum alloy. The power of the reactor is controlled by 4 cadmium control rods covered with stainless steel. The fuel casing is surrounded by a graphite reflector about 75 mm thick. The reactor vessel is entirely filled with demineralized light water, which acts as a coolant and moderator. Cooling is by convection and natural circulation of water inside the reactor core. On May 17, 1967, a mock-up core of RA-3 reached criticality in RA-2, in order to verify the configuration of the fuel assemblies. After the successful test, the work necessary for the inauguration of the RA-3 on December 20, 1967 was accelerated. Thereafter, the RA-2 continued to be used for various types of tests until the time of the accident. One can get an idea of the shape of the RA-2 by looking at the RA-1 pile.

On Friday, September 23, 1983, Osvaldo Rogulich, (Photo 2.100), chief operator in electro-mechanic of the RA-2 reactor of the CNEA with 14 years of experience, was waiting for the end of his shift at 5:00 p.m.. Since everything went well in the morning, he gave leave to his assistant around 2:00 p.m. since there was no more work, thus giving him an early weekend departure. However, around 3:00 p.m., Rogulich was asked to load a new core configuration for an experiment using a pulsed source and given his competence, he decided to do it alone. The procedure required a complete draining of the moderator fluid before any change of configuration of the fuel assemblies, to avoid any criticality risk. But complete draining means complete reflooding, which takes time. Probably voluntarily (?), Rogulich only half emptied the vessel of its water, convinced that the new half-full vessel geometry would be subcritical. At this level of progress in the change of configuration, he was right; but the fuel substitution operations that he was going to carry out will cruelly disabuse him of this belief. In direct view of the core, he could not ignore the presence of water. However, he violated the safety rules. Unfortunately, the partial removal of water from the moderator was not the only violation of safety procedures. Contrary to standard practice, two standard MTR fuel elements were left transiently near the graphite reflector but were not completely removed from the core. In addition, two control elements without their corresponding cadmium plates were inserted. The criticality of the lattice was reached at 4:10 p.m. when he tried to insert the second element. This second fuel element was found partially inserted afterwards, which suggests that it was at this moment that the power excursion took place. This consisted of a very short pulse of about 3×10^{17} fissions, which released about 10 MJ of power in the form of gamma and neutron radiation. This energy release occurred in about 50–70 milliseconds, long enough for Rogulich to see the flash of light emitted in the visible spectrum.

Since Rogulich was not wearing a dosimeter (?), the dose he received is estimated at 2000 rad (20 *Gray*) of gamma rays and 1700 rad (17 *Gray*) of neutrons, or a minimum dose equivalent of 37 *Sievert*, when the lethal dose is about 5 *Sievert*. The absence of a dosimeter shows how unaware the operator was of the risks he was running, especially alone. The other people on the site also did not have dosimeters. One of the conclusions of the investigation was that, probably because of several years of incident-free operation of the

Photo 2.100 Osvaldo Rogulich's official card as an agent of the CNEA. Rogulich was a methodical, cautious man who did not talk much. Married with three daughters, he lived in the working-class neighborhood of San José. He had joined CNEA as an electromechanical technician, and when one day, one of his daughters asked him what his job was on the RA-2 reactor, he replied, "*I turn a handle*." (as reported by his daughter Marcela)

reactor, overconfidence may have played a role in simplifying steps and neglecting key safety factors. Thirty minutes after the irradiation, Rogulich experienced headaches, vomiting and diarrhea. Between 2 and 26 hours after the accident, "*the latency phase was observed, with no general clinical manifestations*" described scientists Dorval, Lestani and Marquez of the Balseiro Institute in a 2004 paper analyzing the accident. *"I saw him that night at the Policlínico Bancario de Caballito where he was hospitalized, and he was perfectly lucid*" recalled a retired operator who worked alongside Rogulich. A few hours after the radioactive accident, the president of the CNEA, the physicist and vice-admiral Carlos Castro Madero, visited Rogulich at the *Policlínico Bancario*, shortly before he lost consciousness. "*Workers use hammer and sometimes they get a hammer on their finger*," the president reportedly told him cynically. This is probably the first act of scapegoating that Rogulich will be made to bear. 28 hours after the event, Rogulich went from the latency phase to the acute phase and began vomiting again. For the next 6 hours, he experienced anxiety and elation, although he remained lucid. Then the neurological syndrome started with loss of consciousness, and a symptom of vascular damage caused by radiation. He had convulsions, suffered three cardiac arrests, and finally died of acute radiation syndrome exactly 48 hours and 25 minutes after the nuclear accident at the RA-2 reactor. France, notified before his death, immediately offered to treat Rogulich in the department of Professor

Georges Mathé, where he could be given a bone marrow transplant like the Vinča accident victims, but when the French understood the level of radiation he had received, they declined: « *No need, he'll be dead before he gets there!* » they would have said prophetically. Moribund, he would not have been able to withstand the heavy operation of a transplant anyway. Eight other employees who were in the vicinity of the reactor at the time of the accident were affected by radiation, but at much lower doses that did not affect their health, according to evaluated dosimetry and subsequent follow-up (adapted and commented from an article of Facundo Di Genova in the Argentinean newspaper « *La Nacion* »). It was said that the alarms of the RA-2 reactor had not been triggered, unlike those of the RA-1 reactor, this prompted the operators of the neighboring reactor to take refuge in the RA-2 hall! If this is true, fortunately for them, the power peak was very short, and everything ended well before they had time to enter the hall.

Despite the seriousness of what happened, the 1984 annual report of the CAC (already in democracy, under the administration of President Raúl Alfonsín) did not mention the accident, and the only mention of the reactor is that the tasks of "updates" were going on. The RA-2, without giving reasons, was dismantled between 1984 and 1989. It will disappear completely from the history of Argentine nuclear power. Rogulich's daughter, who also worked for the CNEA, also felt that her father was being blamed, although the operational procedures were far from precise and their application was generally questionable. In 2007, the inventory of all the spent and unused fuel assemblies of this reactor was evaluated at 19 assemblies of highly enriched uranium and 91 plates of bent fuel, which had been made from highly enriched uranium (90% in ^{235}U supplied by the United States, the almost military enrichment made it possible to build a very small core). Fuel was sent back to the United States under the aegis of the US Department of Energy. These fuels had been kept until then in dry storage conditions on the site itself. Nowadays, it is very difficult to find detailed information about this accident, probably because Argentina had commercial interests in the sale of experimental reactors abroad. Although the remains of Osvaldo Rogulich lie in the cemetery of Lomas de Zamora, the RA-2 continues to haunt Argentina.