APPENDIX

Located on the banks of the Rhône River on the Marcoule nuclear site in the Gard department, the Phénix plant is a prototype of a fast neutron reactor (or a fast breeder reactor [FBR]) using a sodium coolant and equipped with a turbo-generator set to generate electricity. The Phénix plant is an "integrated" reactor type, which refers to the fact that the core, the primary coolant pumps and the intermediate heat exchangers are all located in the same vessel.

Phénix plant operations are jointly run by the French Atomic Energy Commission (CEA) and Electricité de France (EDF). The CEA contributes 80% of the plant's budget while EDF provides the remaining 20%. The plant personnel is therefore composed of employees from the two organisations. The CEA is in charge of managing this collaboration, as well as being the owner and nuclear operator of the facility.

A.1. Core

The reactor core is composed of fissile fuel from which the greater part of the reactor's power is generated, the fuel itself being enveloped in a breeder "blanket" and a neutron shielding especially designed to limit the activation of the secondary cooling sodium in the intermediate heat exchangers. The core itself – corresponding to the fissile part – barely takes up a cubic meter, whereas the combined fissile + breeder part occupies a volume similar to a 2 meter-long cylinder with a diameter of 2 meters.

The **fissile fuel** is composed of plutonium in the form of a $U0_2$ – PuO_2 mixed oxide with a central region enriched by approximately 20% and a periphery region enriched by about 25%, which is designed to "level out" the neutron flux and homogenise heating. The fissile fuel is contained in approximately one hundred fuel sub-assemblies, each containing 217 fuel pins formed by a stack of oxide pellets of a diameter of 5.5 mm enclosed in a stainless steel cladding. A stack of breeder pellets composed of depleted uranium oxide can also be found at the base of each fuel pin, which acts as a lower axial blanket. A spacer wire is spiralled around the fuel pins to guarantee the flow of sodium and optimise heat exchanges. Each fissile column is 85 centimetres long.

Each fuel bundle is placed in a stainless steel wrapper with a hexagonal cross section and also contains upper axial blankets – 37 depleted uranium oxide pins – and a combined stainless steel and boron carbide upper neutron shielding. A spike is located in the lower part of the fuel sub-assembly, which allows its vertical position in the diagrid. This spike is equipped with a gag designed to gauge the sodium flow rate in the assembly, which is generally greater in the centre than at the periphery. A series of "locks" also ensure that the assembly is not placed in a more central position than expected . The head on the upper part of the sub-assembly includes a groove that is used to handle each sub-assembly with a handling gripper. A fuel sub-assembly contains approximately 10 kg of plutonium, is 4.3 m long for a maximum diameter of 15 cm and has a total mass of 226 kg. A fissile fuel pin is 1.8 m long. This represents a total of approximately one tonne of plutonium which generates approximately 600 MWt, with a neutron flux of around 7.10^{15} $n/cm^2.s$ at the core centre.

A **radial breeder blanket** of depleted uranium oxide is also made of pellets in about one hundred sub-assemblies, with each assembly containing 61 fuel pins. The structural elements of these sub-assemblies – cladding, spikes, heads – are identical to those used in the fissile assemblies, with the sodium being fed through the spikes in the diagrid. A breeder assembly contains 2 kg of plutonium after irradiation, has a mass of 294 kg and retains the same overall dimensions of those of a fissile fuel sub-assembly. The length of a breeder fuel pin is equivalent to 1.8 m.

Experimental sub-assemblies are fissile fuel sub-assemblies and are either:

- Sub-assemblies with a central channel designed to hold an irradiation rig. These sub-assemblies generally contain 180 fuel pins only and no upper axial blanket pins,
- Sub-assemblies differing from driver assemblies by their use of different materials or structural geometry.

Other sub-assemblies carrying irradiations devices are made of steel and contain a central channel designed to hold an irradiation rig.

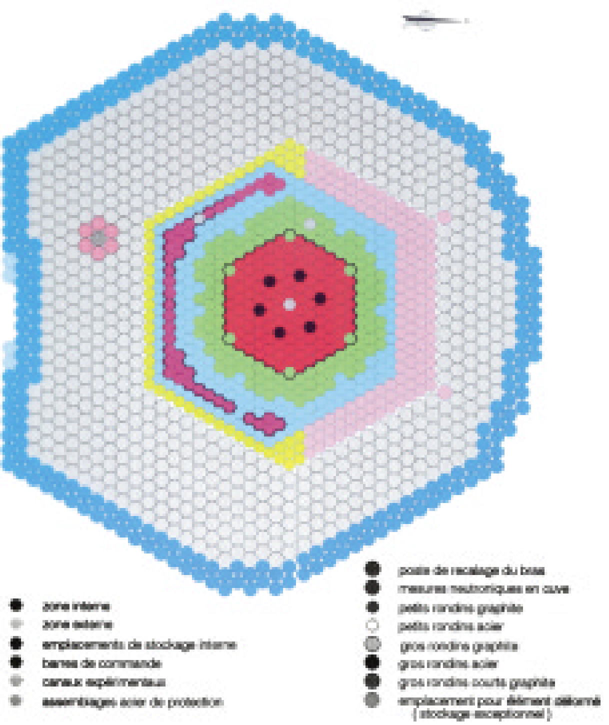
Such a sub-assembly is more commonly known as an irradiation and in-core measurement device or a DIMEP [1].

Absorber sub-assemblies are composed of a sliding control rod in a hexagonal guide tube that is handled in an independent manner. From bottom to top, the control rod of each sub-assembly is composed of: a guiding spike, 7 stainless steel cladded fuel pins each containing a stack of boron carbide pellets (in contact with sodium), a flexible rod and a bonding head to guarantee connection with the control mechanism and for handling purposes. The control rod is 4 m long with a mass of approximately 50 kg and a diameter of 12 cm. Absorber fuel pins are 1.2 m long, whereas their guide tube has a mass of 115 kg and is approximately the same size as a fuel sub-assembly sheath. A specific absorber sub-assembly acting as a complementary shutdown system has been implemented in the core centre since 1996. Its driveline assembly is composed of six 0.9 m long absorber fuel pins and is without a guiding spike.

[1] Dispositif d'Irradiation et de Mesure en Pile

Beginning with the blanket, the **lateral neutron shielding** is composed of:

- rows of stainless steel elements resembling a fuel sub-assembly from the outside (same hexagonal cross-section), placed in the diagrid and cooled by the forced convection of sodium; approximately forty spaces designed to hold irradiated sub-assemblies to be unloaded are also located here,
- rows of stainless steel billets (circular cross-section elements) placed in a structure encircling the diagrid and known as a lateral shielding support; these billets are cooled by the natural convention of sodium.



IMPLANTATION GENERALE DANS LE COEUR

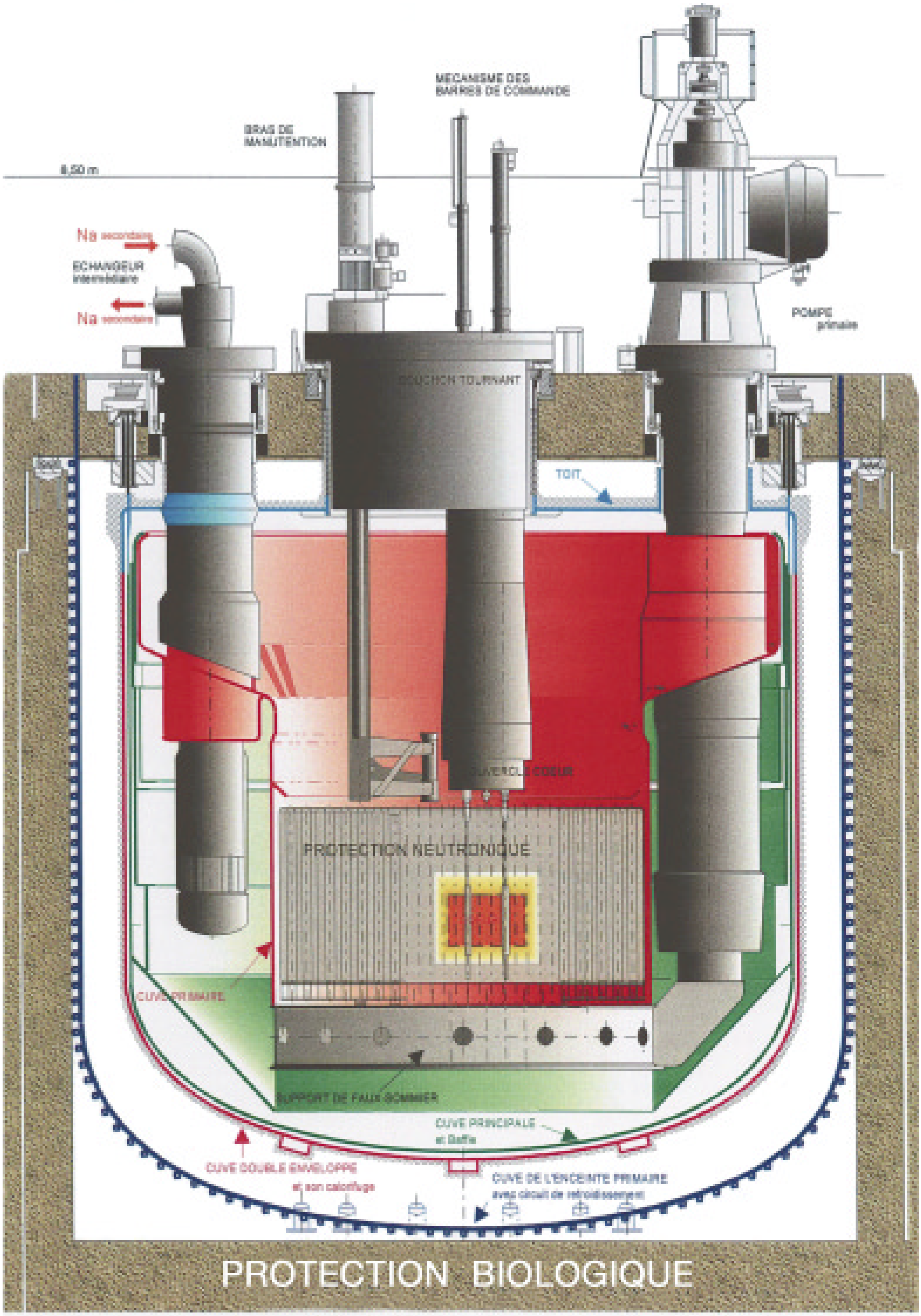
A.2. Reactor block

The diagrid includes a sodium distribution box pressurised by the primary coolant pumps, with sodium being supplied through three pipes. The diagrid guarantees the correct distribution of the coolant to the different regions in the core in relation to the thermal power to be removed from each assembly. In order to do this, the shroud tubes in which the core assembly spikes are held are fitted with six openings decreasing in size from the core centre towards the periphery. The diagrid and the lateral shielding support surrounding the core are fixed to matting that is held by the main vessel via a conical shell. This set of components supports the weight of all assemblies which is equivalent to 350 tonnes.

The **main vessel** is 10 metres high and 12 metres in diameter yet the part of the vessel resting in the sodium is nozzle-free so that risks of leakage are reduced to a maximum. The upper reinforced part of the main vessel is extended by 21 hanger rods. The main vessel is therefore supported by the slab that forms the upper part of the reactor block. This slab also bears the weight of the primary coolant pump and intermediate heat exchanger supports, as well as the rotating plug – at the centre of the slab – needed for fuel handling, whose lower part is extended via the core cover plug regrouping all of the core's instrumentation. Leaktightness between the slab and the rotating plug is guaranteed by a fusible metal seal. This seal can be described as a collector filled with a lead-bismuth eutectic alloy that remains solid while the reactor is in operation and can be fused using heat resistors in order to allow the rotating plug to turn during handling operations. The upper part of the main vessel is closed off with a flat roof equipped with pumps and exchangers penetrations. The roof is then connected to the rotating plug shell which centres everything in relation to the slab.

Inside the main vessel, the primary vessel separates the sodium coolant into two pools. The primary vessel is composed of a shell extended by a conical baffle that contains twelve channels equipped with sleeves for the primary pumps, the intermediate heat exchangers and other components. This is followed by a new shell that envelopes the core and is welded to the lateral shielding support. The hot sodium (560 °C) is therefore contained inside this vessel and exits through the intermediate heat exchangers to be pumped cold (400°C) by the main pumps that drive the sodium into the diagrid. The hydraulic baffles are supported by the conical shell and leave space for two concentric rings on the periphery of the main vessel. These two rings are supplied in cold sodium by the diagrid, thus maintaining the main vessel temperature at approximately 400°C during reactor operation.

For safety reasons, a **safety vessel** envelopes the main reactor vessel and is designed to contain any possible sodium leaks without the sodium level falling too low and hindering core cooling. The safety vessel and the main vessel roof are both insulated. A third vessel, the containment vessel, is made from ordinary steel and envelopes the first two vessels. This vessel is welded under the concrete slab and is maintained in a nitrogen atmosphere. This vessel is designed to contain any active products that may be released from the main vessel in the event of an accident. Furthermore, the containment vessel is equipped with a cooling system – more commonly called the emergency cooling system – that is cooled via a heat exchanger initially supplied with water from the Rhône River but was then connected to air coolers in 2002. This cooling system is designed to maintain the reactor pit concrete at ambient temperature when the reactor is in operation, as well as evacuate residual power in the event of the failure of the secondary sodium cooling systems.


MECANISME DES
BARRES DE COMMANDE
BRAS DE
MANUTENTION
Na
ECHANGEUR
intermédiaire
Na
BOUCHON TOURNANT
TOIT
POMPE
primaire
PROTECTION NEUTRONIQUE
CUVE PRIMAIRE
SUPPORT DE FAUX SOMMIER
CUVE PRINCIPALE
et Baffle
CUVE DOUBLE ENVELOPPE
et son calorifuge
CUVE DE L'ENCEINTE PRIMAIRE
avec circuit de refroidissement
PROTECTION BIOLOGIQUE

A.3. Reactor circuits

Owing to its integrated design, the reactor block contains the **main primary cooling circuit**. This system holds approximately 800 tonnes of sodium, which provides the system with great inertia. Argon acts as an inert blanket above the sodium. The three pumps and the six intermediate heat exchangers are positioned in the annular space between the primary vessel and the main vessel. The primary coolant pumps are vertically submerged in the cold sodium (400 °C) and suspended from the upper part of the slab. They are connected to the diagrid with hinged pipes. These pumps are driven at a continuous variable speed of 150 to 820 revolutions per minute using the main motor or at 100 revolutions per minute using an pony motor. These pipes produce a unit flow of roughly 1,000 kg/s. The intermediate heat exchangers are connected two by two to a secondary cooling circuit and suspended from the slab in a similar way. These straight-tube heat exchangers - over 2,200 pipes forming 19 rings - are fixed onto lower and upper tube plates by expansion and welding techniques[2]. The primary sodium coolant flows outside these tubes.

Auxiliary circuits are designed to store, refill, drain and purify the primary sodium, as well as control the pressure, the purification process and the release rate of the argon blanket. These circuits are constantly filled with primary sodium coolant and are located in leak-tight cells maintained in a nitrogen atmosphere to avoid active sodium fires. These circuits are equipped with a cold trap and a plugging indicator that are specifically used with sodium and based on the variation in solubility of sodium impurities in relation to the sodium temperature. The sodium is cooled in the cold trap which causes all impurities(oxides and hydrides) to precipitate and collect on a stainless steel mesh filter (KNIT wad). The temperature of the sodium circulating through the plugging indicator varies according the predefined cycles. The temperature at which the sodium no longer flows through a calibrated nozzle is measured: this is known as the "plugging temperature". This plugging temperature must be kept as low as possible by purifying sodium while the sodium flowing in the circuit must remain several tens of degrees higher than this plugging temperature.

Three completely and independent **secondary cooling** circuits guarantee the transfer of heat from the intermediate heat exchangers to the steam generators via the sodium. The sodium in these systems is not radioactive thanks to the neutron shielding enveloping the core. At the top of the intermediate heat exchangers, the secondary sodium enters a central tube and flows to the bottom of the distribution box with a convex bottom welded to the lower tube plate. This sodium then goes back up and inside these tubes. Once the sodium has passed through the bundle, it then exits the intermediate heat exchanger via a header equipped with a lateral pipe.

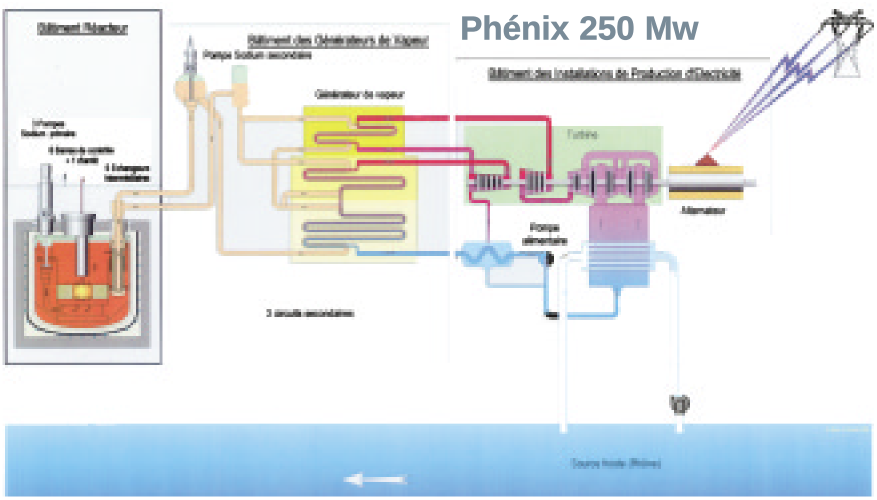
Under normal operating conditions, the sodium exits the intermediate heat exchangers at 550°C and enters at 350°C, flowing at a rate of approximately 800 kg/s and driven by a mechanical pump located in the expansion tank of each system. The main pipes - with a diameter of 500 mm - supply two intermediate heat exchangers and cross through the reactor building to the steam generator building where the secondary cooling system facilities can be found: main pumps, buffer tanks, valves, auxiliary circuits (storage, refilling and purification). The circuits are drained by gravity into storage tanks located on the bottom floor of the building. Each circuit contains approximately 140 tonnes of sodium. All remaining sodium-free circuits and tanks are filled with argon.

[2] "Expansion" refers to the mechanical operation of expanding each tube so as to force the tube wall tight against its hole in the tube plate, so keeping it in place and achieving a preliminary level of tightness. The seal is perfected with a ring of welding.

Each secondary cooling circuit is connected to a **steam generator** composed of three parts (evaporator, superheater and reheater) that are each composed of twelve modules. The hot sodium flows through the superheater and the reheater at the same time with steam exiting at a temperature of 512°C and a pressure of 165 and 34 bar respectively. The totality of the sodium then flows through the evaporator that, supplied with water at 246°C, provides slightly overheated steam at 375°C. The evaporator is made from ferritic steel whereas the superheater and reheater are made from austenitic steel. These modules are S-shaped, or two S-shaped modules in the case of the evaporator. Each module is composed of 7 tubes placed inside a shell with water flowing in the tubes and sodium flowing outside the tubes in the opposite direction. Systems detecting water leaks into the sodium protect the facility against sodium-water reactions. The steam generators can also be used as sodium-air heat exchangers to evacuate the reactor's residual power: hatches below and above the steam generator casing are opened and air flows around the modules by natural convection.

Thermal energy generated by the reactor and transported by steam into the steam generators is transformed into electrical power using a turbo-generator set (250 MWe) at 3,000 revolutions per minute, which is connected to the EDF high-voltage electric grid (225 kV). The turbine is a combined impulse-turbine composed of three cylinders on one unique 39 metre long shaft line. The superheated steam coming from the steam generators takes effect in the high-pressure cylinder. This steam then goes back through the reheater part of the steam generators, before spreading out in the medium-pressure cylinder and the two low-pressure cylinders.

The equipment in this electricity generating system - condenser, low and high-pressure reheaters, water tank, feed-water pumps, steam headers, turbo-generator set, turbine by-pass, buffer tanks and drains, etc. - are similar to those found in a conventional power plant. It is nevertheless important to point out that an evaporator steam/water by-pass circuit connected to each steam generator was added to evacuate the reactor's residual power after a turbine trip. Steam generators, of the forced circulation type, require very pure water whose total volume is filtered through a water treatment station. The condenser is cooled with water drawn from a pumping station on the Rhône River.



A.4. Handling operations

Refuelling is performed when the reactor has been shut down. A rotating arm – fixed in an off-centred fashion to the rotating plug that is itself off-centred in relation to the reactor core – is used to transfer fuel sub-assemblies from their initial position in the core to the intermediate storage area and the removal station. The combination of the rotating arm and the rotating plug makes it possible to reach all positions. After having cooled down in the internal storage area, each element is removed from the reactor using an immersed handling bucket located in the removal station. This sodium-filled handling bucket is manoeuvred by a loading carriage along the primary transfer ramp and placed in the A-framed transfer lock above the slab. This bucket is then tipped and lifted down into the transfer lock and carried down the secondary transfer ramp to a storage drum capable of holding approximately one hundred fuel sub-assemblies. Each sub-assembly remains in a bucket, with all buckets floating in the sodium in the storage drum capable of holding 180 tonnes.

Fresh-fuel sub-assemblies are stored in a storage room upon their arrival on site. After dimensional check and once thermally conditioned, these sub-assemblies are placed in the storage drum in a bucket filled with sodium . During core refuelling, fresh-fuel sub-assemblies go through the opposite procedure to that applied to spent sub-assemblies. These sub-assemblies are transferred from the storage drum to the reactor, where they are directly placed in specific positions defined by neutron calculations. Several fresh-fuel sub-assemblies are stored in the reactor's internal storage area in case a sub-assembly demonstrates cladding failure or thermal abnormality during an irradiation cycle. Faulty sub-assemblies can simply be replaced internally with fresh sub-assemblies.

Spent sub-assemblies are stored in the storage drum for a cooldown period that depends on their residual power. These sub-assemblies are then removed one by one from their bucket using a gripper that transfers them directly into the irradiated elements cell maintained in a nitrogen atmosphere. After the sodium dripping process has been completed, this sodium is destroyed using a wet carbon dioxide gas stream. Next, the sub-assembly is moved to the annex cell [3] where it is dismantled: the spike and head are sawed off, the hexagonal wrapper is milled opened at the two opposing angles and the fuel bundle is removed using a jack that pushes the bundle into a container. This container is returned to the irradiated elements cell to be sealed in two concentric cases.

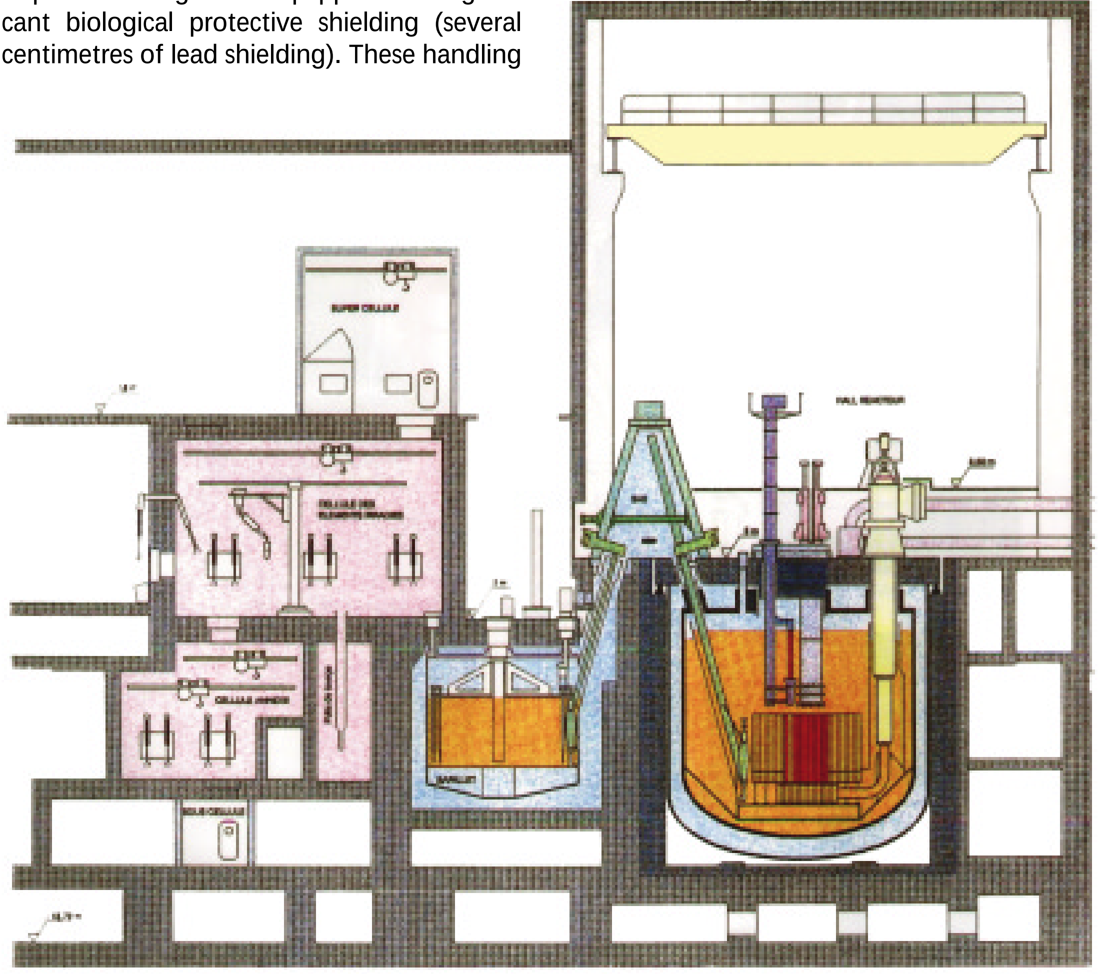
These conditioned fuel pins are then transported in a transfer cask to a storage site or fuel reprocessing plant. Sub-assembly structural waste – heads, hexagonal wrapper, spikes – are placed in bins that are transported in transfer casks to a storage unit located on site at Marcoule. Specific operations can also be performed on particular experimental sub-assemblies, such as preparing fuel pins and rigs or reconstructing rigs or sub-assemblies using previously irradiated fuel pins. All such operations are carried out using remote controlled systems by operators behind observation ports more than a metre in thickness.

A specific device known as a neutron radiography reactor is associated with this facility. Using a highly enriched uranyl nitrite solution, this reactor provides bursts of neutrons dedicated to examining the internal structures of irradiated fuel pins. This reactor provides examinations complementing other visual, radiographic and gammagraphic examinations performed on the fuel pins in

[3] The annex cell was built in 1980. Beforehand, sub-assemblies were dismantled in the irradiated elements cell using a different process to cut the hexagonal wrapper.

the irradiated elements cell. Operations on irradiated sub-assemblies are carried out independently to the reactor state, either while reactor operation or during the reactor shut-down. When such hot cells do not contain irradiated fuel pins, they can be used in an air environment, which simplifies maintenance using remote control systems.

The different **removable components** in the reactor block descending into the vessel through the slab and the rotating plug (primary coolant pumps, intermediate heat exchangers, handling arm, control rod mechanisms, etc.) can be dismantled for maintenance purposes. The lower end of such components being active, handling activities require handling flasks equipped with significant biological protective shielding (several centimetres of lead shielding). These handling flasks, the heaviest weighing 110 tonnes empty, can be connected up in a leak tight manner using mobile locks equipped with valves on top of the slab. Handling flasks are manipulated in an upright position using the travelling crane, before moving through a lock equipped with a transporter. They are then recuperated in the hall dedicated to special handling activities located in the handling building where their content is emptied into different pits to be cleaned, decontaminated, repaired and stored. Cleaning is carried out by spraying water from fixed ramps into a pit maintained in an inert gaseous environment. Decontamination is carried out through successive diluted acidic washings.



A.5. Instrumentation and Control

The nuclear power of the core is measured by a series of detectors positioned under the reactor vessel. Two detectors can also be found inside the reactor vessel, vertically positioned in the lateral neutron shielding in order to guarantee valid measurements at very low power rates and especially during reactor criticality. The control rods – a total of six – are powered by mechanisms mounted on the rotating plug. All six control rods are designed to guarantee safety functions (automatic shutdown), compensation (reactivity variations) and control operations (power adjustments). The control rod system is composed of two groups of three mechanisms each, with differing designs (pinion and rack drive or travelling nut drive), including independent control systems. Since 1996, a seventh control rod, composed of several articulated components that remain insertable even in the event of core deformation, has a safety function (the complementary shutdown system): positioned at the centre of the core and held in place with an electromagnet, this control rod handles shutdowns and maintains the reactor in a zero power state, as well as re-establishing a thermal state ensuring structural integrity (T < 450 °C) in the event of a rod drop from a rated power. The six control rods and the absorber sub-assembly of the complementary shutdown system are placed at the bottom of their housing during handling activities so that the rotating plug with the sub-assembly transfer arm can operate.

The temperature of the sodium at the outlet of each fuel sub-assembly is monitored by two thermocouples guided through the core cover plug. Other measuring devices have also been implemented to detect abnormal core operation and monitor the temperature of several structures. Detecting and locating cladding failure helps detect fuel pin leak-tight problems at an early stage, which makes it possible to assess the extent of the problem and decide whether the fuel sub-assembly in question should be unloaded or not. Primary sodium samples are taken on a continuous basis at the intermediate heat exchanger outlets (detection) and above each fuel sub-assembly (location) for scanning. Associated measuring devices detect fission products emitting delayed neutrons that reveal cladding failures when detected in the sodium.

The entire plant is monitored by operators in the control room located on the second floor of the control room and office building. Other than alarm windows and conventional control blocks, the facility is equipped with several independent data processing systems, the last of these systems being added during the plant operation, such as the:

- Rapid Temperature Monitoring System is designed exclusively to monitor sodium temperatures at fuel sub-assembly outlets and triggers safety action (automatic shutdown),
- Central Data Processing System draws on all the other measuring and signalling devices at the plant but does not trigger safety action but alarms only,
- Hydrogen Detection System specifically monitors hydrogen production rates in the secondary sodium and triggers appropriate safety action (rapid shutdown, isolation and decompression of the steam generator in question),

- Reactor Block Temperature Monitoring System draws on reactor block structural temperature measurements without triggering safety action,
- Data Acquisition Back-up System monitors all essential safety parameters as a back-up to both conventional means and the Central Data Processing system,
- Rapid Data Acquisition System rapidly receives and processes a whole set of parameters capable of providing information in the event of a negative reactivity trip.

The computer and electronic rooms are next to the control room and house the main monitoring computers and electronic equipment. The relay circuitry takes up part of the first floor in this building, whereas the medium and low power electrical distribution panels are located on the ground floor. A back-up room located in an underground passageway is used by the shift team to monitor and control the shutdown reactor if a problem, such as fire or attack, was to prevent them from using the control room.

Other than external electric power sources, including the normal 225 kV power line and the 20 kV back-up power line, electric power can also be distributed by internal sources including the back-up diesel-powered generator sets and batteries. Two diesel-powered generator sets each generate enough power to supply auxiliary equipment that must continue functioning after an automatic shutdown. With each safety upgrading of the plant, various new equipment and components have been added. Therefore, in the event of the total loss of all external electric power sources and the first two generator sets, two other diesel-powered generator sets provide the power required to correctly run the back-up cooling system, decay heat removal circuits and several actuators. Four other diesel-powered generator sets designed to supply specific equipment in the event of a power loss were also implemented.

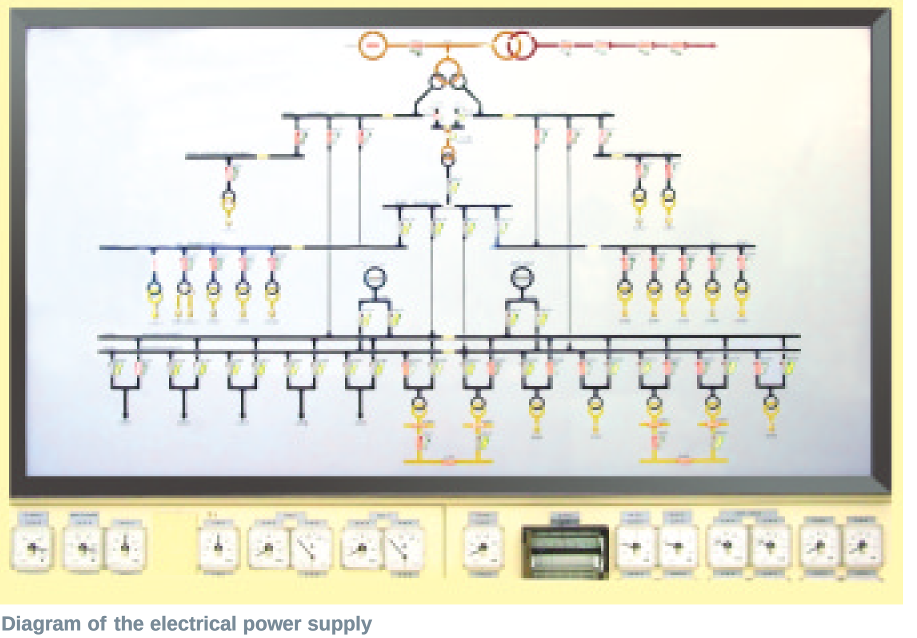


Diagram of the electrical power supply

A.6. Safety Functions

Core reactivity is controlled by manoeuvring the control rods. Fission reactions are maintained at a strictly minimum level required to generate the desired power level by inserting or removing the absorbers. The various different neutron and thermal measurements, for example, make it possible to check that this level is respected. If any parameter oversteps its normal operating range, operators are warned and can reverse the situation using the control rods. If the situation developed too quickly, the control system automatically provokes a shutdown. There are two different automatic shutdown sequences called: rapid shutdown and emergency shutdown. If an incident occurs in a secondary cooling circuits or in the electric power generation facility, the control rods are automatically inserted into the reactor core by approximately thirty centimetres in three and a half minutes. During the first minute, the nuclear power practically reaches a zero-power level. If a reactor-related incident occurs, the control rods and the complementary shutdown system rod gravitationally drop in less than a second, which brings the nuclear chain reaction to a halt. Other than the core (storage drum, irradiated elements cell, fresh fuel storage room), reactivity control is guaranteed by structural arrangements, as separation of the sub-assemblies suffices to prevent a critical scenario from occurring.

The characteristics of fast neutron reactor cores such as the Phénix core represent three main risks that must be carefully considered:

- the void coefficient is positive in the core centre, which means that reactivity increases if the sodium boils,
- the power density is very high, which renders the core sensitive to local or generalised cooling defects,
- the core is not in its most reactive configuration: compaction of the sub-assemblies increases reactivity.

Such phenomena require reinforced core monitoring. Thus, an emergency shutdown can be prompted by a) the medium-level overheating of the core or even the overheating of one sub-assembly only, b) a positive or negative variation in reactivity, c) fuel pin cladding failure, d) a earthquake or e) increase in the sodium temperature at the core inlet.

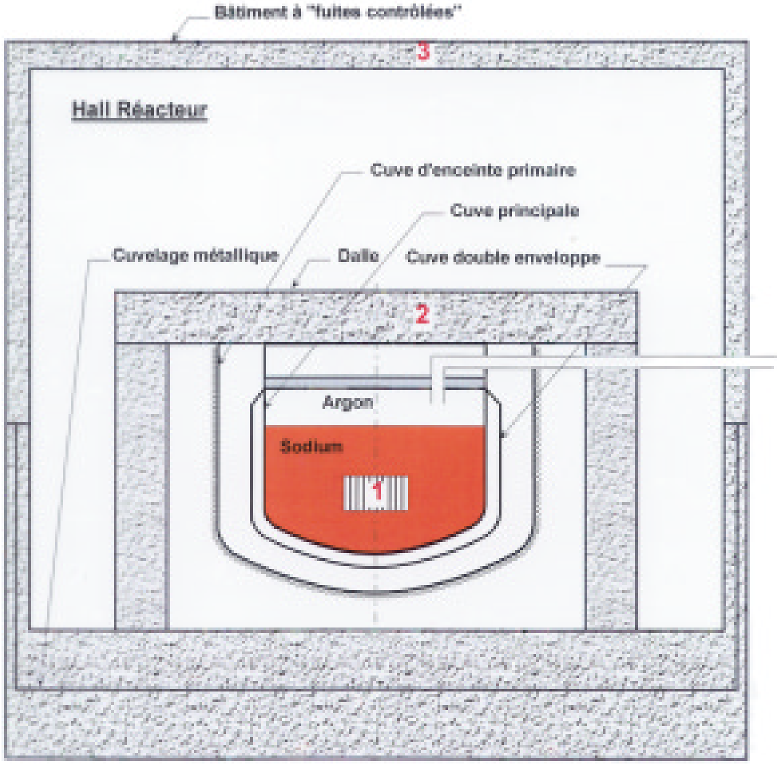
However, the Phénix core benefits from feedback effects providing the reactor with inherent safety characteristics. The Doppler effect is the first of these feedback effects, which is mainly due to the breeder nuclei: when the temperature rises, the neutron capture rate of uranium-238 also increases, which proportionally decreases the core reactivity. Other temperature effects act indirectly by globally reducing the chain reaction by expansion of the fuel and structures. The constant flow of the coolant guarantees core cooling, even in the event of an accidental situation thanks to the integrated design of the reactor. Furthermore, as xenon and samarium poisoning is non-existent, reactor operations are simplified following a shutdown, which also improves safety levels (only the accumulation of neptunium-239 has a slightly positive effect at the beginning of each cycle).

Decay heat removal in the reactor after shutdown is usually carried out by the secondary cooling circuits, the steam generators and the condenser in the turbine hall. If the condenser happens to be unavailable, the steam generator casing hatches are opened and the air flowing around the modules of only one steam generator suffices to remove residual power. In the event of an accident during which all three independent secondary cooling circuits are unavailable, the emergency cooling circuit is designed to maintain the reactor block temperature at an acceptable level while absorbing the thermal radiation emitted by the main reactor vessel. This emergency system was considerably renovated between 1999 and 2002 to guarantee its smooth running even after an earthquake of high intensity.

The residual power of sub-assemblies placed in the storage drum is removed via a specific oil-filled cooling system, which is itself cooled by water from the Rhône River. The sub-assemblies are only extracted from the storage drum when their residual power is sufficiently low so that cooling can continue naturally in a nitrogen environment in the irradiated elements cell.

The containment is designed to isolate the plant environment and staff from nuclear materials (fuel) and fission product releases, thanks to a series of consecutive barriers. The leak-tight cladding enveloping the fuel pins represents the first barrier. The second barrier is composed of several containment vessels: a) the main vessel doubled by the safety vessel for the main part and closed off in the upper part of the reactor by the roof, b) the containment vessel closed off by the concrete slab in the upper part of the reactor and c) the circuits connected to the primary cooling circuit (primary sodium purification, cladding failure detection, primary argon).The integrated reactor design (the core and all components located in the same vessel) makes it possible to integrate a second, very compact and therefore very reliable barrier, not to mention the fact that the succession of vessels ensures that the primary sodium constantly cools down the reactor core. The third barrier is composed of a controlled leak-off type reactor building. The infrastructure is integrated into a metal leak-tight liner fitted with a cathodic protection. The superstructure includes a concrete construction composed of a steel framework supporting the roof.

Other than these three barriers, it is also worth mentioning:



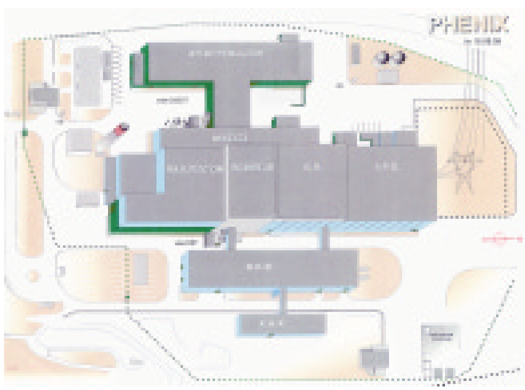
Schematic of the containment. 1 : fuel pins clad.
2 : Second containment barrier. 3 : Reactor building

- barriers containing the secondary sodium coolant (pipes, tanks, etc.),
- barriers vis-à-vis handling (A-framed fuel transfer lock, storage drum, irradiated elements cell, etc.).

Radioactive liquid effluents produced at the Phénix plant are collected in two main 20 m^3 storage tanks, then inspected and transferred by tank truck of a capacity of 8 m^3 to the liquid effluent waste treatment plant (STEL) at Marcoule where such waste is treated with waste coming from other site facilities. Gaseous effluents – mainly argon from the cover gas – are purified and deactivated before being monitored and released through a stack. Solid waste (dismantled sub-assembly structures, operational waste) is monitored and transferred towards ad hoc facilities on site at Marcoule.

Using sodium as a coolant requires taking several precautions owing to its extremely high reactivity when in contact with air and water. In terms of sodium fires, other than the quality of the piping and tanks, free sodium levels are systematically protected by an inert argon or nitrogen blanket. Leak detectors (beaded wires or spark plug leak detectors) and fire detectors (sodium aerosol analysers) equip all plant components and equipment. In terms of the primary sodium coolant, systems outside the reactor vessel pass through rooms maintained in a nitrogen environment. In the event of a leak, the faulty circuits are usually drained, except for the main vessel which is doubled by two other vessels in a nitrogen atmosphere so that sodium levels can always cool down fuel sub-assemblies. Sodium fires are not as fierce as hydrocarbon fires and can be extinguished using the “Marcalina” powder composed of sodium carbonate, lithium and graphite.

The risk of a reaction between sodium and water does exist in the steam generators as only the exchange tubes separate the two fluids. The interposition of the secondary cooling systems is uniquely designed to prevent such a reaction from occurring with the radioactive primary sodium. Hydrogen – generated during a reaction between sodium and water – is used to indicate the presence of a leak in a tube: the hydrogen content in sodium and argon in the secondary circuits is measured constantly. The plant operators are warned in the case of an abnormal generation of hydrogen. The operators shut down the plant, dry the faulty steam generator, isolate the water-steam section and then drain the sodium system. Therefore, the two reactants are no longer in contact. Such actions are executed automatically if the hydrogen content rises rapidly. Last of all, in the event of a severe tube rupture, the increase in pressure in the secondary circuit due to the excessive generation of hydrogen leads to the rupture of the bursting discs, which causes the sodium of the steam generator to empty at an even greater rate.



A.7. Building infrastructure

The Phénix plant is located north of the Marcoule site on a platform covering several hectares. The main buildings are lined up in parallel to the Rhône River and form a series of building of approximately 150 metres long and 42 metres wide. Stretching from south to north, the following buildings can be observed:

The handling building is composed of two main parts. The first is devoted to fuel aspects, and contains the storage drum, the irradiated elements cell and their auxiliary equipment. The second part is devoted to operations on removable reactor block components, including an operation and storage cell, cleaning and decontamination pits and the liquid effluent reception and control system.

The reactor building houses all active primary cooling circuits. The reactor – suspended from the slab – is positioned in a concrete pit. Primary system auxiliary equipment (cold trap, cladding failure detection system, etc.) are mainly found in the two rooms equipped with biological shielding and maintained in a nitrogen environment.

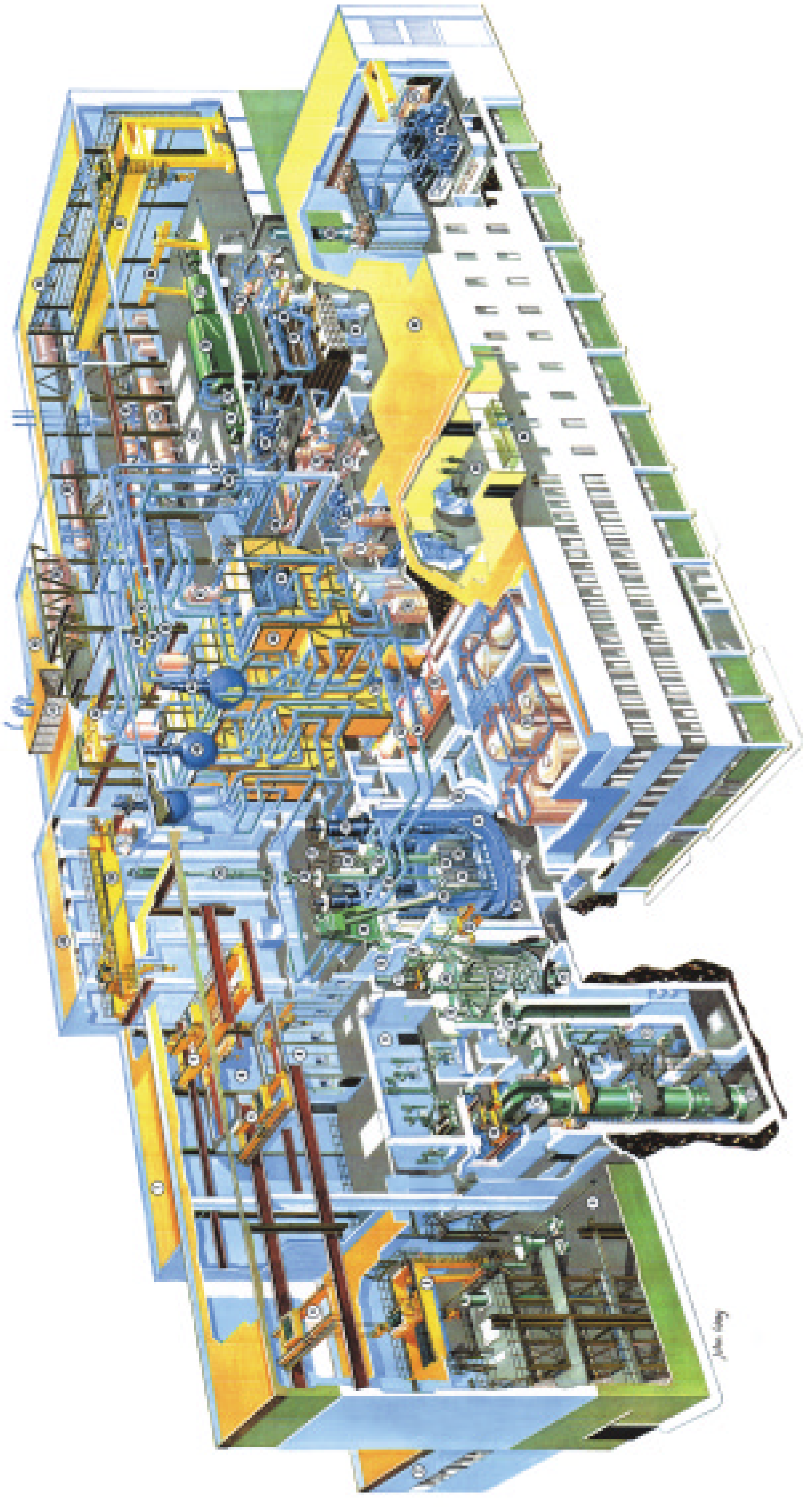
The two above-mentioned buildings form the restricted area with respect to radiation protection issues and are equipped with a special ventilation system that creates a slight vacuum pressure in comparison to the outside atmosphere. The foundations of these buildings extend 11 metres underground and their superstructures – 35 metres high – are high enough to facilitate equipment handling activities.

One half of the steam generator building contains the secondary cooling circuits, the draining tanks, the steam generators and their auxiliary equipment, whereas the other half is used for handling steam generator modules.

The turbine hall looks like any other conventional facility containing a turbo-generator set and associated auxiliary equipment (condenser, water tanks, feed water pumps, etc.), with a demineralised water treatment station next to this building. The electrical substation (transformers) is located north next to the turbine hall.

Various different buildings required during reactor operation can be found surrounding these buildings:

- The control room and office building houses two diesel-powered generator sets, electrical and electronic equipment, the control room and offices,
- The annex building houses various different auxiliary reactor equipment such as the ventilation system, cooling systems, nitrogen systems,
- The pumping station is completely underground (as much as 17 metres under) and includes two 200 metre pipes located in the Rhône River. The realise pipe for condenser water can be found a little further downstream.
- The buildings in which the pumps, generator sets and the air-coolers of the new back-up cooling system were built in 1999 on each side of the reactor building,
- The plant stack used for air ventilation and gaseous effluent releases,
- The visitors reception building including the physics laboratories and the maintenance building are used as offices, as are various other small buildings.



A.8. Plant operation

To perform a **start-up** when the facility is in a 250°C isothermal state, the plant operator raises the complementary shutdown system rod, before simultaneously raising the control rods in a curtain-like movement to a predetermined level. The control rods are then progressively raised to a level and criticality occurs when the last rod has been raised. In parallel, the condenser and the turbine are preheated thanks to steam generated by the steam supply facility on site at Marcoule. Reactor power is increased to 5 MWt, whereas its temperature is maintained at 250°C and the steam generators are progressively supplied with water. The power generated by the fuel is used to heat the plant (primary sodium coolant, secondary sodium coolant, steam generators, electric power production facility) while making sure that all thermal gradients and regulatory heating rates are respected. When a global temperature of 360°C is reached, the steam generators are switched to the steam phase. The turbine is activated when the steam meets design characteristics of 140 bar and 400°C. The generator is therefore connected to the grid seeing that the reactor is already generating several tens of MWt and all excess energy is removed by the turbine by-pass. The power increase takes place over several hours and is obtained by altering the level of the control rods as well as the primary and secondary coolant pump speeds.

The Phénix plant is not operated in relation to EDF’s needs in electricity, nor does it play a part in the frequency control of the electric power grid. Phénix’s power is generally operated at the maximum power tolerated by reactor equipment. The control rods are gradually raised once or twice per shift [4] to compensate for fuel burn-ups, while retaining approximately the “curtain” configuration. The plant can also be freely operated at two thirds of its rated power, using two of the three primary pumps, or two of the three secondary circuits. It is also possible to shut down one of the three primary coolant pumps during reactor operation. However, it is necessary to shut down the reactor when moving from three secondary systems to two secondary systems and vice-versa.

Shutdown of the Phénix plant is carried out gradually by inserting the control rods in the core. When reactor power is sufficiently low enough, the generator is disconnected from the grid and the steam is directed to the condenser. The reactor’s temperature progressively decreases and the control rods continue to be inserted until the reactor is completely shut down. Automatic shutdowns (rapid or emergency shutdowns, cf. § A.6) only take a few seconds to occur. It is worth pointing out that the plant is not equipped with a house load operator control system. A turbine trip and an automatic shutdown are initiated when a defect of a few seconds occurs in the EDF high voltage power line to which the plant supplies electricity. Once the chain reaction has been stopped, the residual power is removed via the condenser before exiting through the steam generator hatches.

Under normal shutdown conditions, particularly when refuelling, the reactor temperature is maintained at 250°C. The control rods are placed in a low position so that the absorber rods are completely inserted in the reactor core. The core is composed of fresh and spent fuel sub-assemblies and does not need to be removed as spent fuel sub-assemblies are replaced with fresh fuel ones. For component handling operations or in the event of

[4] A shift, just like on a ship, is defined as the period of time during which the same team remains at work. At the Phénix plant and other EDF power plants, each shift lasts eight hours, including the overlapping times between the two teams. Six shift teams are required to operate the Phénix plant.

a long shutdown, the reactor is cooled down to 180°C. If core residual power is insufficient to sustain this temperature, energy from the primary and secondary pumps – when the secondary circuits are operating – is used to stabilise the reactor temperature. The electric heater from the primary sodium auxiliary system can also be used for the same reasons.

Fresh fuel sub-assemblies were produced by the Cogema fuel fabrication workshop at Cadarache until its closure in 2001. These fuel sub-assemblies were transported to Marcoule site and stored at the Phénix fuel storage room in line with strict safety regulations. When these fresh fuel sub-assemblies need to be used, they are once again inspected and thermally conditioned before being loaded into the storage drum. These sub-assemblies are then transferred into the reactor during a refuelling campaign. After several irradiation cycles, during which the fuel sub-assemblies are usually moved around to optimise core management, the irradiated fuel sub-assemblies are transferred to the internal storage area located on the core periphery behind three rows of stainless steel sub-assemblies designed to reduce irradiation. When the residual power of these spent sub-assemblies has fallen below 10 kW, they are then transferred – usually during the next refuelling campaign – into the storage drum to continue their cooldown. Several months later, when these spent fuel sub-assemblies have cooled down so that their residual power is below 6 kW, they are then transferred into the irradiated elements cell to be dismantled.

NOMINAL TECHNICAL CHARACTERISTICS

Thermal power:	563 MWt
Gross electrical output:	250 MWe
Neutron flux at core centre	$7\ 10^{15}$ n/ cm^2.s
Fraction of delayed neutrons	360 pcm
Active volume in the core	1.4 m^3
Maximum temperature at pellet centre	2,300 °C
Average power density	1,200 kW/ dm^3
Maximum linear power rating of fuel pins	450 W/ cm
Maximum temperature of cladding	700 °C
Temperature coefficient	- 2.7 pcm / °C
Power coefficient	- 0.5 pcm / MW
Doppler effect in the fissile region at 1,500 °K	- 0.3 pcm / °C
Sodium temperature at core inlet:	400 °C
Sodium temperature at core outlet:	560 °C
Primary sodium flow in the core:	2,800 kg/s
Sodium temperature at intermediary heat exchanger inlets:	350 °C
Sodium temperature at intermediary heat exchanger outlets:	550 °C
Secondary sodium flow in each system:	740 kg/s
Water temperature at steam generator inlets:	246 °C
Water temperature at steam generator outlets:	512 °C
Steam pressure at superheater outlet:	165 bars
Steam pressure at reheater outlet:	34 bars
Water flow in each steam generator:	210 kg/s

Joël GUIDEZ

Director of the Phénix plant
since November 2002

A reactor that's easy to live with

Pressurised water reactor specialists are always surprised how easy it is to run a fast reactor: no pressure, no neutron poisons like boron, no xenon effect, no compensatory movements of the rods, etc. Simply, when one raises the rods, there is divergence and the power increases. Regulating the level of the rods stabilises the reactor at the desired power. The very strong thermal inertia of the whole unit allows plenty of time for the corresponding temperature changes. If one does nothing, the power will gradually decrease as the fuel ages, and from time to time one will have to raise the rods again to maintain constant power. It all reminds one of a good honest cart-horse rather than a highly-strung race horse.

Similarly, the supposed drawbacks of sodium often turn out in practice to be advantages. For example, the sodium leaks (about thirty so far since the plant first started up) create electrical contacts and produce smoke, which means they can be detected very quickly. Again, the fact that sodium is solid at ambient temperature simplifies many operations on the circuits. More generally, because of the chemical properties of sodium, the plant is designed to keep it rigorously confined, including during handling. During operation, all this provides a much greater "dosimetric convenience" than conventional reactors. In particular, a very large part of the plant is completely accessible to staff whatever power the reactor is at, and the dose levels are very low.

Because of the very high neutron flux (more than ten times as high as with water reactors), there is great demand for experiments. These experiments are performed using either rigs inside carrier sub-assemblies or using special experimental sub-assemblies with particular characteristics. All experiments are run and monitored in the core like the other sub-assemblies. Since the origin Phénix irradiated around 1000 sub-assemblies, on which 200 were experimental sub-assemblies. It is true that the Phénix is not as flexible as an experimental water reactor, in which targets can easily be handled and moved. But, with a minimum of preparation - which is necessary anyway for reasons of safety and quality - numerous parameters such as flux, spectrum and duration can be adjusted to the needs of each experiment.

Furthermore, the reactor was designed by modest people who thought in advance of everything that would be needed for intervention on the plant: modular steam generators, washing pits, component handling casks etc. All of which has been very useful and has made possible numerous operations and modifications in every domain. All this has meant that a prototype reactor built in the early 1970s is still operational in 2004, and will continue so for several years yet.

GLOSSARY OF TECHNICAL TERMS SPECIFIC TO THE PHÉNIX PLANT

Availability factor: The ratio between the electrical energy produced by the power plant over a given period of time and the product of its rated capacity (250 MWe) and the length of time concerned (= load factor), to which is added the time devoted to normal handling of the sub-assemblies (chance factors excluded) and R&D tests (handling of experimental sub-assemblies) and production time lost due to external causes (e.g. electricity grid failure). The availability factor expresses the power plant's ability to operate at the maximum of its potential for a sustained period.

Breeder: Breeder nuclides (usually uranium 238) are nuclides that can be directly or indirectly transformed into fissile nuclides (e.g. plutonium 239) by neutron capture. The term is also used to describe material containing one or more breeder nuclides, and by extension to the sub-assembly containing this material.

Breeding rate: Ratio of the number of fissile nuclei produced in the reactor core from fertile nuclei to the number of fissile nuclei destroyed during a given period of time. It is higher than 1 (otherwise the term used is burning).

Burn-up: Ratio of the number of atomic nuclei of a given element (or a given set of elements) that disappear by nuclear combustion to the initial number of nuclei.

Cladding failure or clad failure: Appearance of a defect in the cladding of a fuel pin, through which fission products can escape. A distinction is made between cladding failures that release only gaseous fission products and open ruptures which bring the fuel pellets into contact with the primary sodium

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Controlled leak containment: The containment formed by the building walls, designed to confine the radioactive materials and kept permanently at lower pressure than the atmosphere outside, by extractor ventilators. This arrangement prevents the transfer of any contamination in the buildings to the outside except via the flow of extracted air, and this air is collected, filtered and checked before release through the stack.

Cover gas: In the reactor block, the space above the free surface of the primary sodium, in between the main vessel and the roof, is permanently filled with argon to prevent oxidation of the sodium. Fresh argon is injected via the slab penetration seals. The cover argon circulates in an monitoring and purification circuit

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Decontamination: After washing a component, decontamination consists of removing contamination deposited on the component (products of erosion or corrosion of reactor structures, especially the fuel pin cladding). Decontamination is carried out in special pits using several stages of diluted acid baths. After decontamination, the component is dried and can then be worked on (stripped down, repaired, dismantled etc.) in virtually normal conditions for a nuclear area.**Démantèlement (d'un assemblage, d'un composant) :** C'est l'opération de découpage d'un assemblage irradié ou d'un composant usé du réacteur. Elle permet de séparer les déchets de différentes catégories tout en les réduisant à une taille acceptable par les châteaux de transport et les installations d'entreposage provisoire ou de stockage définitif de déchets radioactifs. Dans le cas des assemblages combustibles, fissiles et fertiles, cette opération permet de récupérer les aiguilles afin de les expédier dans une usine de retraitement.

Delayed neutrons: Neutrons emitted by nuclei in an excited state formed during beta decay of fission products. The neutron emission itself is instantaneous; the observed delay is due to the preceding beta emission or emissions. The delayed neutron fraction (i.e. the ratio of the average number of fission events caused by delayed neutrons to the total number of fission events caused by prompt and delayed neutrons together) is essential to ensure control of a nuclear reactor. In the core of the Phénix plant, this number is 0.325%, or β = 325 pcm. This is the value which, by convention, sets the value of the "dollar" ($), i.e. the level of reactivity required to make the reactor critical on prompt neutrons alone ("prompt critical").

Delayed re-heat cracking: This is a defect triggered in the root pass of a weld in the immediate neighbourhood of the contact zone, and which spreads radially between the grains when under stress in service. This only occurs with certain materials such as 321 type stainless steel, as it is caused by hardening of the steel due to fine precipitations of titanium carbide inside the crystalline structure. The hardening causes the plastic deformation capacity to be transferred to the periphery of the grains. For this to happen, the following conditions have to be met:

- a high operating temperature (> 475°C for 321 steel),
- a geometrical discontinuity at the weld root,
- strain hardening at the weld root showing significant shrinkage,
- heavy local load, which may be due to welding stresses,
- a defect in the weld root (e.g. a small shrinkage crack).

Dismantling: (of a sub-assembly or a component): Cutting up an irradiated sub-assembly or used reactor component. The different categories of waste can then be separated and reduced to an acceptable size for removal in transport casks and storage in provisional or definitive radioactive waste storage facilities. In the case of fissile and breeder fuel sub-assemblies, dismantling enables the operator to recover the fuel pins and send them to the reprocessing facility.

Dosimetry: Estimation, from individual measuring devices, of the dose absorbed by an individual or group of individuals. It is expressed in Sieverts (Sv) or milliSieverts (mSv) and, with collective doses, man-Sieverts (man-Sv). Until the early 1980s, the unit of measurement used was the rem (1 rem = 0.01 Sv = 10 mSv).

Dummy heat exchanger: A device used to replace an intermediate heat exchanger on a secondary cooling circuit that is not in use in power operation. It is basically an intermediate heat exchanger with no tube bundle. Its functions are to plug the slab penetration so as to ensure biological protection, and to provide an argon seal between the hot and cold pools.

Effective full power days or Equivalent full power days, EFPD: Ratio of heat energy produced in the reactor core (expressed in MWd) to the reactor's rated capacity (563 MWt). The number of EFPDs expresses a duration of irradiation of the sub-assemblies present in the core, regardless of their position.

Fast neutrons: The neutrons released on fission of a nucleus are emitted with high energy (around a million of electron-volts) and hence at high speed (about 20,000 kilometres per second). Using these fast neutrons without slowing them down (unlike slow neutron reactors or thermal reactors) requires a material with a high concentration of fissile nuclei (e.g. uranium 235 or plutonium 239) to offset the lower probability of fast neutrons causing fissions. Whence the absence of a moderator (e.g. hydrogen or carbon) in fast neutron reactors and the need for a coolant fluid that does not slow down the neutrons (e.g. sodium, helium, mercury or lead).

Incineration: Cf. transmutation.

Irradiation cycle: Time period between two fuel replacements. However, the core can be rearranged in the course of an irradiation cycle (in which case one speaks of successive loading plans). During the first years in operation, the average duration of an irradiation cycle at the Phénix plant was extended from fifty days at first to about ninety days. For the final irradiation cycles it has been set at 120 effective full power days (EFPD).

Irradiation experiment: Experiment in which selected objects or materials are irradiated in the reactor core for a defined period (a few months to several years) generally expressed in effective full power days (EFPD). The devices used are either experimental sub-assemblies, or rigs housed in carrier sub-assemblies.

Lagging: Insulation material placed around pipes and tanks containing a high-temperature fluid such as sodium, argon, nitrogen, water or steam, to prevent or limit heat loss. The materials used are poor conductors of heat, such as glass fibre and asbestos. Lagging may be partly or entirely removed from a pipe or tank to give access for inspection, repair etc.

Linear power rating: Thermal power produced per unit of active length of a fuel element. It is expressed in Watts per metre (W/m) or, more commonly, Watts per centimetre (W/cm).

Load factor: Ratio of gross electrical energy produced by the power plant (and of the equivalent energy supplied to the Marcoule facility in the form of steam) during a given period of time, to the product of the rated capacity (250 MWe) and the length of time concerned.

Negative reactivity trip (A.U.R.N.): Reactor shutdown automatically triggered by the three power range neutron measuring channels that monitor the core's reactivity when two of these channels measure reactivity below a value set at -10 pcm. This automatic response protects the reactor from accidents caused by largely insufficient cooling of the core, such as instantaneous breach of the connection between primary pump and diagrid.

Reactivity: In the reactor core where the chain reaction takes place, reactivity is the parameter reflecting departure from the critical state. Positives reactivity values reflect supercriticality, negative values sub-criticality. It is expressed in pcm (parts per hundred thousand) or as fractions of a dollar ($).

Safety authority: The French nuclear safety authority ASN was originally the central department for safety of Nuclear Installations (SCSIN), formed in 1973 as part of the Ministry for Industry and receiving technical assistance from

- the Institute for Nuclear Safety and Protection (IPSN) (part of the CEA),
- the NSSS control Office (BCCN),
- the regional Directions for Industry and Research (DRIR) (the bodies responsible for industry and research in each Region).

The Phénix plant came under the DRIRs for Languedoc-Roussillon (Mining Services) and Provence-Alpes-Côte d'Azur for the nuclear part.

In May 1991, the SCSIN became the Nuclear Installation Safety Directorate (DSIN) while the DRIRs took on responsibility for environmental matters and took the name Regional Directions for Industry, Research and Environment (DRIRE).

In February 2002, the DSIN became the General Directorate of Nuclear Safety and Radioprotection (DGSNR), absorbing the body formerly responsible for radiation protection (Office for Protection against Ionising Radiations or OPRI), which in July 1994 had taken over from the Central Service for Protection against Ionising Radiations (SCPRI). Alongside this, the IPSN was entirely detached from the CEA and became the Institute for Radioprotection and Nuclear Safety (IRSN).

Sodium: An alkaline metal element, atomic number Z = 11, symbol Na. It is the seventh most abundant element in the Earth's crust. At atmospheric pressure, it has a melting point of 97.5°C and a boiling point of 883°C. Its density is 0.97. It oxidises spontaneously in contact with air (in the form of a high-temperature fire) and reacts violently with water. It has a fairly low neutron absorption cross section. Under irradiation, two isotopes are created: ^{22}Na, a β^+ and γ emitting isotope with a half-life of 2.6 years, and ^{24}Na, a β^- and γ emitting isotope with a half-life of 15 hours.

Sodium aerosols: Fine particles of various compounds of sodium (oxides, carbonates etc.) resulting from the combustion of hot sodium in air and dispersed in the form of opaque white smoke and deposited on surrounding surfaces. Sodium aerosols can also be formed by oxidisation of hot sodium by traces of oxygen in the neutral gases used as cover gas in the sodium tanks (argon and nitrogen).

Specific burn-up: Total energy released by nuclear transformation of atoms when a reactor is operating (nuclear burn-up), per unit of fuel mass. Usually expressed in megawatt-days per metric ton (MWd/t).

Total loss of decay heat removal circuits (D.C.N.E.P.): This is a hypothetical accident in which all three independent secondary sodium circuits suddenly and simultaneously go out of action. In this case the residual power in the core would be removed mainly by convection through the reactor vessels to the emergency cooling system. The temperature of the reactor block would rise until the power removed by thermal radiation offset the residual power, which would decrease over time. To ensure that all the reactor structures remain undamaged, this temperature must be below 720°C.

Transmutation: Transformation of one atomic nucleus into another by nuclear reaction. This may result in a different chemical element, or simply a different isotope of the initial element. This type of reaction provides a way of transforming long-lived radioactive isotopes into short-lived or stable isotopes in order to reduce the long-term radiotoxicity inventory of radioactive waste.

Washing: This operation is carried out in pits especially designed either for the irradiated sub-assemblies, or for the extractible components of the reactor block (intermediate heat exchangers, primary pumps, control rod mechanisms etc.). Washing consists of eliminating the metallic sodium by transforming it into soda or sodium carbonate. This is done by circulating first a wet inert gas, then water.

Fast Breeder Reactors in the world

Fast Breeder Reactors in the world

Country	Reactor	Thermal power	Electrical power	First criticality	Definitive shutdown
United States	Clementine	25 kWt	-	1946	1953
	EBR 1	1.4 MWt	200 kWe	1951	1963
	EBR 2	62.5 MWt	20 MWe	1961	1994
	Fermi	200 MWt	61 MWe	1963	1972
	FFTF	400 MWt	-	1980	1992
USSR	BR 2	100 kWt	-	1956	(1958)
	BR 5	5 MWt	-	1958	(1971)
	BR 10	8 MWt	-	1971	2003
	BOR 60	55 MWt	12 MWe	1968	
	BN 350	1000 MWt	130 MWe	1972	1999
	BN 600	1470 MWt	600 MWe	1980	
United Kingdom	DFR	60 MWt	15 MWe	1959	1977
	PFR	650 MWt	250 MWe	1974	1994
France	Rapsodie	40 MWt	-	1967	1983
	Phénix	563 MWt	250 MWe	1973	
	Superphénix	3000 MWt	1200 MWe	1985	1998
Germany	KNK II	58 MWt	20 MWe	1972	1991
Japan	Joyo	140 MWt	-	1977	
	Monju	714 MWt	280 MWe	1995	
India	FBTR	40 MWt	13 MWe	1985	
China	CEFR	65 MWt	23 MWe	*2005*	

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