THE ORPHEE REACTOR CURRENT STATUS AND PROPOSED ENHANCEMENT OF EXPERIMENTAL CAPABILITIES

P. Breant

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ABSTRACT

This report provides a description of the Orphée reactor, together with a rapid assessment of its experimental and research capabilities. The plans for enhancing the reactor's experimental capabilities are also presented.

I. REACTOR GENERAL DESIGN PRINCIPLES

Orphée is a swimming pool-type reactor cooled with light water and moderated with heavy water. It was designed and built between 1975 and 1979. Initial criticality was achieved in December 1980 after a one-year testing period to verify proper operation of the reactor's functional and safety systems.

Low-power testing was carried out from December 1980 to July 1981, followed by high-power testing from July 1981 to September 1981. It was thus possible to verify neutron characteristics, core thermal performances, available neutron fluxes and their distribution, power distributions, efficiency of the control rods, reactivity effect, and efficiency of radiological protection features.

The following main criteria were used for design of the reactor :

a) Continuous, independent verification of the effectiveness of three protective barriers :

- the fuel cladding (first barrier),
- the reactor primary system and swimming pool (second barrier),
- the reactor building and its ventilation system associated with its isolation valves (third barrier).

b) Redundancy of assessment and monitoring facilities for the main reactor protection parameters with total separation of instrumentation channels.

c) Design, construction and testing of systems in accordance with a quality assurance plan employing qualified teams, facilities, suppliers and codes.

d) Definition of a design basis accident (worst-cas hypothetical accident) and assessment of the maximum allowable consequences for the environment. All reactor protection facilities are designed to effectively maintain these consequences within the prescribed limits.

e) Capability to control the reactor in case of an accident from an emergency control panel that can ensure safe reactor shutdown, i.e. :

- insertion of the control rods and verification of their position,
- core cooling with reinjection of makeup water, if necessary, to prevent core dewatering,
- reactor containment with, if necessary, planned, controlled depressurization of the containment.

II. DESCRIPTION

II.1 Reactor block (core and moderator)

As shown in Figure1, the core is relatively compact. It consists of 168 identical fuel plates contained in two types of fuel assemblies : standard (24-plate) assemblies and control (18-plate) assemblies. Each fuel assembly has a square section of 82.4 mm per side.

The fuel is placed around a central beryllium element designed to optimize power distribution in the fuel.

The core, which has a life of 100 equivalent full-power days, is completely discharged at the end of one operating cycle and replaced by a new one. For this reason, space is provided along the centerline of the beryllium element to contain an antimony-beryllium neutron source required for reactor control during the core loading phase.

The four control assemblies are placed in the corners of a Zircaloy 2 core tank. The four standard assemblies are placed at the center in relation to the four sides of the tank.

In order to improve axial power distribution, the side plates of the fuel assemblies contain a partial load of boron. During two-thirds of the operating cycle, the control rods thus move only about ± 5 mm from their assigned position (Figure 2), which provides a highly constant neutron flux distribution in the moderator.

The moderator is enclosed in a stainless steel tank about 2 m in diameter and 2 m high. It contains about 6 t of heavy water that is usually between 99.7 and 99.9% pure. Tritium content is maintained between 2 and 4 Ci/l with an exceptional maximum of 6 Ci/l.

The reactor block is located at about mid-height of a 15 m deep swimming pool designed to always contain water. The pool is divided into three areas of about the same height.

From top to bottom (see Figures 3 and 4), these areas are:

- a 4.5 m deep basin that can be drained to a tank when the reactor is shut down,
- the core, reflector and channels area, which is 5.5 m high. This area is closed off by a double-shell tank assembly with the inner tank made of stainless steel. In the event of a design basis accident (135 Mjoule), part of the mechanical energy would be absorbed by deformation of the inner tank. This deformation would not cause the tank to rupture, as demonstrated by qualification tests performed on a model.
- a decay tank, which receives water circulated to cool the core and enables disintegration of the nitrogen 16 contained in the main reactor system water.

Adjacent to the main swimming pool is a transfer canal (or service pool) where all routine service operations are performed on the fresh and irradiated fuel, as well as on all the activated products from the reactor. No hot cell is provided for the Orphée reactor.

II.2 Core performance characteristics

When equipped as described above, the reactor core is highly undermoderated. It has the following characteristics :

- MTR-type fuel with 93 % U-235 enrichment,
- UAl alloy with 34 % enrichment,
- total U-235 fuel weight : 5.9 kg,
- U-235 per plate : 0.035 kg,
- fuel core working dimensions : 0.25 x 0.25 x 0.9 m
  or a volume of 56 dm^3,
- heat exchange area : 20.68 m^2,
- core mean specific power : 0.25 MW/l,
- mean heat flux : 71 W/cm^2,
- maximum heat flux : 172 W/cm^2,
- *maximum hot channel* heat flux : 206W/cm^2,
- maximum temperature at surface of fuel plates : 123.5°C,
- available undisturbed thermal neutron flux in the moderator
  at core maximum level : 3×10^{14} $n/cm^2/s$,
- working thermal neutron flux : 2.5×10^{14} $n/cm^2/s$,
- maximum gamma flux : 6 W/g,
- gamma flux in integrated vertical devices :
  hot and cold sources < 2 W/g,
- core cooling capacity : 835 m^3/h light water,
- water flow through fuel plates : 7.5 m/s,
- maximum coolant temperatures : 35°C inlet, 49°C outlet,
- hot channel factor : approx. 1.40,
- flow capacity redistribution margin
  (all uncertainties cumulated) : 2.12,
- moderator circulation capacity : 35 m^3/h,
- moderator circulation flow in heavy water tank : < 0.1 m/s,
- total reactor power : 14 MW

. distributed in :	core	12.4 MW
	pool	0.8 MW
	reflector	0.8 MW

II.3 Horizontal and vertical devices

Vertical devices

The reactor includes two types of vertical devices : two liquid hydrogen cold sources and one hot source. These devices are considered in the reactor safety analysis.

Four channels are used for activation analysis.

Six channels enable irradiation of various materials : radioisotopes, silicon for neutron irradiation doping.

Associated experimental rigs

These devices include nine channels, eight with two beams and one with four beams. They thus provide a total of 20 beams (eight cold beams, eight thermal beams and four hot beams).

Six cold beams are associated with neutron guides.

The reactor can accomodate 25 spectrometers.

One neutron guide provides capability for use of a neutron radiography facility.

II.4 Other systems

A detailed description is not given for the primary system, swimming pool system and heavy water system. These systems are all of conventional design and include : pumps, heat exchangers, purification systems, storage vessels, instrumentation and controls.

All or part of these systems are generally considered important to reactor safety. They are built to meet precise quality criteria.

The following sections provide a more complete description of the following :

- containment and ventilation system,
- cold sources,
- hot source,
- reactor protection system.

II.4.1 Containment and ventilation system

The reactor building is made of strongly reinforced 0.60 m thick concrete. It rests on a thick foundation raft and is capped by a dome of decreasing thickness form the periphery (0.60 m) to the center (0.30 m) (Figure 5).

The foundation raft is provided with a leaktight multilayer bituminous coating up to the ground level. Leaktightness integrity is verified by means of sumps that penetrate the containment either at the upper level of the multilayer coating or at the lower level of the swimming pool linings.

The straight part of the building is lined over part of its height by a leak recovery vessel. This double-shell vessel is built to cover the fraction of the reactor building circumference that is penetrated by fluid pipes or electric cable ducts.

The containment penetrations have double walls. Their leaktightness can be tested individually.

The leak recovery vessel is designed to recover any leakage from the penetrations. It is placed under negative pressure in the event of an accident causing an overpressure inside the containment.

The ventilation systems includes the following four subsystems (Figure 6) :

- an air supply subsystem equipped with three fans, one for standby duty, capable of providing suitably humidified and conditioned air. The air supply capacity is 38,000 m^3/h for a total containment capacity of approximately 20,000 m^3 or two renewals an hour,
- a non-active air exhaust subsystem with a capacity of 20,000 m^3/h. Air is removed through high-efficiency absolute particulate filters with an efficiency of a least 1000 for dust particles of 15-micron diameter and iodine filters with an efficiency of at least 100 for methyl iodide. The premises are maintained under an negative pressure of 1 cm of water relative to the outside.
- an active air exhaust subsystem for the "technical rooms", which are subject to atmospheric contamination hazards. This subsystem has a capacity of 18,000 m^3/h and is equipped with the same filtration system as above. The rooms are maintained under a negative pressure of 1 cm of water relative to the above premises (or 2 cm relative to the outside).
- an accident ventilation subsystem with a capacity of 200 to 800 m^3/h.

By regulating valves, following objective examination of the conditions for outside discharge, the accident ventilation subsystem enables :

- depressurization of the reactor containment after an accident that would have placed it under overpressure, to a level such that direct leakage through the reactor building concrete is negligible,
- pumping into the leak recovery vessel to "treat" leakage through the containment penetrations.

All accident ventilation discharges are also filtered through absolute and iodine filters.

The reactor containment is periodically and systematically tested for leaktightness integrity. The maximum leakage allowed by safety authorities is restricted to 1 % of containment capacity per hour.

II.4.2 Cold sources (Figure 7)

The reactor includes two could sources, each contained in tubes that pass directly into the heavy water reflector. Located at about 30 cm from the core centerline, the cold sources remain in the area of maximum thermal neutron flux, but where gamma heating is moderate (< 1 W/g on average).

The vertical arrangement of the source enables separation into two distinct areas the design constraints useful for operation of the source proper and the constraints that provide the researcher an experimental device suited to his needs. Utilization and operation of the source are thus completely independent.

The two sources are supplied with liquid hydrogen via two independent systems, each of which is cooled with a hydrogen-helium heat exchanger. All of these components are completely immersed in the reactor swimming pool, which ensures active safety in case of an accidental loss of leaktightness integrity.

The two He-H_2 heat exchangers are supplied with cold helium by a common cryogenerator for the two sources through a cold box. The cold box can cross over the systems of each of the two sources.

Cold helium is obtained by reducing pressure of the gas through two fluid-bearing gas turbines. The gas is previously compressed to standard temperature at 15 bar using two double-acting piston compressors.

The effective power output obtained for each cold source is 700 watts.

Source No. 1 (SF1) supplies cold neutrons to four neutron guides. Source No. 2 (SF2) supplies cold neutrons to two neutron guides and to a facility located in the reactor hall for use of two 3-axis spectrometers.

Figure 8 shows a graph of the cold neutron gain for various wavelengths.

II.4.3 Hot source (Figure 9)

The reactor block also includes a hot source which is considered in the overall safety analysis. This source is placed in the most heavily loaded area of the reflector tank, i.e. where flux is highest (around 1.5 to 2.5 W/g) and where the available thermal neutron flux is also close to maximum.

The hot source consists of a graphite block approximately 150 mm in diameter and 250 mm high. This block is surrounded by highly effective thermal barriers formed mainly by solid shields and graphite felt ; it is placed inside a double Zircaloy 2 housing. The space between the two housings provides a gas blanket with an atmosphere that can be helium, nitrogen or a mixture of these two gases. The internal housing that contains the graphite block can also be filled by either of these two gases, or placed under a vacuum. The latter operating mode is normally used with a nitrogen gas blanket.

The temperature reached in the graphite under these conditions when the reactor is at nominal power is approximately 1450 K.

The next table shows the numbered values of the hot neutrons gain for this device.

Wavelength Å	1.1	0.7	0.5
Multiplication factor	0.8	2.5	5

The hot source supplies hot neutrons to two channels (four beams). The neutrons are used directly on spectrometers installed in the reactor building.

II.4.4 Reactor protection system

The reactor is protected by a group of redundant facilities and measures that are verified and analyzed by three independent protection channels, which enable 2/3 majority voting for all parameters vital to reactor safety. These parameters mainly cover the following functions :

- neutron verifications
. maximum and minimum counting at high and low power for each instrumentaiton range,
. positive or negative doubling time,
- maximum coolant temperature at the core inlet,
- maximum temperature difference at core inlet-outlet,
- coolant flow,
- maximum gamma activity initiating reactor containment,
- loss of electric power supply,
- maximum pressure of cold sources (hydrogen and isolating vacuum),
- maximum pressure of hot source (internal compartment and gas blanket),
- fuel clad burst (activity and flow),
- maximum shift in control rod positions,
- negative pressure of the reactor building,
- accelerometer on the reactor building (seismic monitoring).

These parameters are all associated with a loop-type logic circuit that initiates a reactor scram command in the event of a continuity break. This command is sent to the reactor through two fully independent reactor scram channels. It can be initiated manually from several locations, particularly via two independent channels connected to an emergency control panel located about 400 m from the reactor in a direction different from that of the prevailing winds on the Saclay site.

The reactor protection system has been considered in a safety study. Using the failure rates of its components, and overall availability was determined and used to establish the frequency of systematic testing of the system. The unsafe failure rates were compatible with the recommendation of IEC standard 231 A (less than 10^{-5} over three months).

III. OPERATION

The reactor is operated by the French Atomic Energy Commission (CEA) with a group of 54 operators, 24 of whom are on continuous duty in six teams of four operators. Each surveillance team includes a shaft supervisor, a mechanic, an electronics technician and an electrical technician. All continuous duty operators are individually certified to operate the reactor through constant monitoring of their technical knowledge.

The reactor operates an average of 250 equivalent full power days a year or 2.5 cycles.

The main operating activities are conducted with an organization to meet the standards established by French law, which stipulates that the reactor operator must define the list of activities for which quality must be monitored.

These activities include:

- periodic tests to comply with precise operating rules for 45 systems. These tests are usually performed by the reactor operating teams or by specialized service teams. Their results are controlled by the operating team managers for technical conformance and by the local quality assurance officer for compliance with procedures.
- maintenance activities for all operating equipment. These activities are also performed in accordance with precise written procedures.

All operating documents are systematically recorded.

IV. UTILIZATION

The French Atomic Energy Commission (CEA) and the National Center for Scientific Research (CNRS) have established a joint laboratory, the Léon Brillouin Laboratory (LLB), for utilization of the Orphée reactor neutron beams. The LLB has a board of directors and a scientific board. Proposed experiments are reviewed every year during specialized working meetings (round tables), which assemble the reactor users and the equipment managers. The reactor users mainly come from the French community, but extensive collaboration has developed at the European level:

- the Federal Republic of Germany has built and manages two spectrometers (one triple-axis thermal neutron unit and one four-circle unit).
- Belgium has installed a time-of-flight spectrometer at the end of a neutron guide,

- Hungary has designed and built a high-resolution spin echo spectrometer in collaboration with LLB teams,
- Austria has built and manages a triple-axis spectrometer installed on a neutron guide.

A total of 25 spectrometers are not installed around the Orphee reactor (Figure 11), 11 in the reactor hall and 14 in the neutron guide hall. These units are listed in Table 1. Orphee is equipped with six cold neutron guides (beam cross section of 15 x 2.5 cm^2), which penetrate the reactor containment and are arranged in an experiment hall 50 meters long and 30 meters wide. In this hall they are extended by secondary neutron guides (two at present), thus increasing the possibilities for use of wide-spectral distribution beams.

In conclusion, it should be recalled that Orphee is provided with:

- four pneumatic channels connected to the Pierre Sue laboratory, which is specialized in activation analysis. Several hundred irradiation operations are conducted in this laboratory every year.
- a neutron radiography facility placed at the end of a neutron guide on beam G4. This facility is used for industrial applications, particularly in the aircraft sector. It is also employed for certain types of non-destructive examinations, notably for ensuring uniformity of the fuel plates and burnable poison plates,
- several vertical devices capable of irradiating large quantities of monocrystalline silicon for phosphorus doping, as well as supplying radioisotopes for industry and medicine.

V. FUTURE PLANS

Orphee will have been in service for 10 years at the end of 1990, which is not very long for a reactor. For the neutron sources, these 10 years have enabled precise determination of the exact capabilities of the reactor and assessment of its few shortcomings. For its utilization, the experimental equipment is now almost fully exploited. The quality of this equipment makes Orphee an ideal complement for the potential of the high flux reactor of the Laue Langevin Institute in Grenoble.

Since nearly all experimental capabilities are being exploited and requests are being received from the European Community, a study is being conducted to enhance the quality and increase the number of usable neutron beams. Three projects are being contemplated for implementation within the next five years:

- improvement of the existing beams. Transmission capabilities of the present cold neutron guides can be enhanced by replacing the most curved neutron guides with straight ones and by changing the reflecting material. The use of Ni58 or supermirrors is under consideration.
- the creation of new cold neutron beams. This project has already been carried out with installation of the two secondary neutron guides. A third secondary neutron guide is being designed and will be installed in 1991. This enhancement of cold neutron capability also involves the startup of an annular cold source. A prototype will be tested this year under actual service conditions. Such a source would increase the number of channels capable of being supplied with cold neutrons.
- installation of a new neutron guide using the containment penetration provided during construction. This guide, which has a large cross section (about 12 x 12 cm^2), will pass through the reactor hall and into a new neutron guide hall. The beam will then be separated into three secondary neutron guides. This equipment will increase the LLB's experimental capabilities by about 30 % (see Figure 12).

These projects will not exhaust the development potential of the Orphée reactor. The second spare containment penetration could subsequently be used to provide new capabilities, which have not yet reached the design stage.

VI. REFERENCES

1. D. Cribier, B. Farnoux, P. Breant, Reactor design and utilisation. CEA/IRDI/DERPE/SPS/ORPHEE/AM 005 Np 001. May (1983).

2. J. Safieh, Cold and hot sources study in a research reactor. Thesis presented at INSTN-CEN Saclay. October (1982).

TABLEAU I

30.8.89

LABORATOIRE LEON BRILLOUIN

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RESPONSABLES D'APPAREILS
SECURITE

CANAL FAISCEAU	TYPE	TELEPHONE	EXPERIMENTATEURS
- DIFFUSION INELASTIQUE & QUASI ELASTIQUE			
1T1	Trois axes, neutrons thermiques	62 28	B. HENNION
2T1	Trois axes, neutrons thermiques	39 78	N. PYKA
4F1	Trois axes, neutrons froids	62 30	B. HENNION
4F2	Trois axes, neutrons froids, "TANGO"	62 30	D. PETITGRAND
8F-G3.2	Echo de spin, haute résolution, "MESS"	72 96	R. PAPOULAR
8F-G4.3	Trois axes, neutrons froids, "VALSE"	65 19	W. SCHWARZ
9F-G6.2	Temps de vol, "MIBEMOL"	63 55	G. CODDENS
- DIFFUSION ELASTIQUE (STRUCTURES)			
3T1	Deux axes, poudres	62 29	M. PINOT
3T2	Deux axes, haute résolution (poudres)	62 29	F. BOUREE
8F-G4.2	Deux axes, neutrons froids	65 19	M. PERRIN
5C1	Deux axes, neutrons polarisés, "POLDIF"	62 31	B. GILLON
5C2	Deux axes, quatre cercles, (monocristaux)	62 31	P. SCHWEISS
8F-G4.1	Deux axes, neutrons froids, "PYRRHIAS"	65 21	Y. ALLAIN-G. ANDRE
9F-G5.1	Laue neutrons (monochromatique)	65 19	A. DELAPALME
6T1	Deux axes, quatre cercles (textures)	62 32	R. PENELLE
- DIFFUSION DIFFUSE (SYSTEMES DESORDONNES)			
8F-G4.4	Diffusion diffuse, détecteurs multiples	65 20	R. CAUDRON
9F-G6.1	Diffusion diffuse, multidétecteur linéaire neutrons polarisés "DNPX"	65 17	G. PARETTE
7C2	Deux axes, multidétecteur linéaire, amorphes et liquides, "PHYLIKAM"	29 58	R. BELLISSENT
- DIFFUSION AUX PETITS ANGLES			
8F-G1.2	Diffusion isotrope, multicompteur à anneaux concentriques, "PACE"	62 79	L. AUVRAY
8F-G2.2	Deux axes, haute résolution, "PADA"	65 16	P. CALMETTES
8F-G2.3	Diffusion anisotrope, multicompteur XY, "PAXY"	62 22	A. BRULET
9F-G5.4	Diffusion anisotrope multicompteur XY, "PAXE"	85 18	J. TEIXEIRA
- APPAREILS SPECIAUX			
8F-G1bis	Prototype de réflectomètre "DESIR"	54 46	B. FARNOUX
9F-G5.3	Diffusion aux petits angles avec orientation nucléaire, "PAON"	62 25	H. GLATTLI
G3 bis	Réflectomètre en cours de montage	54 46	B. FARNOUX

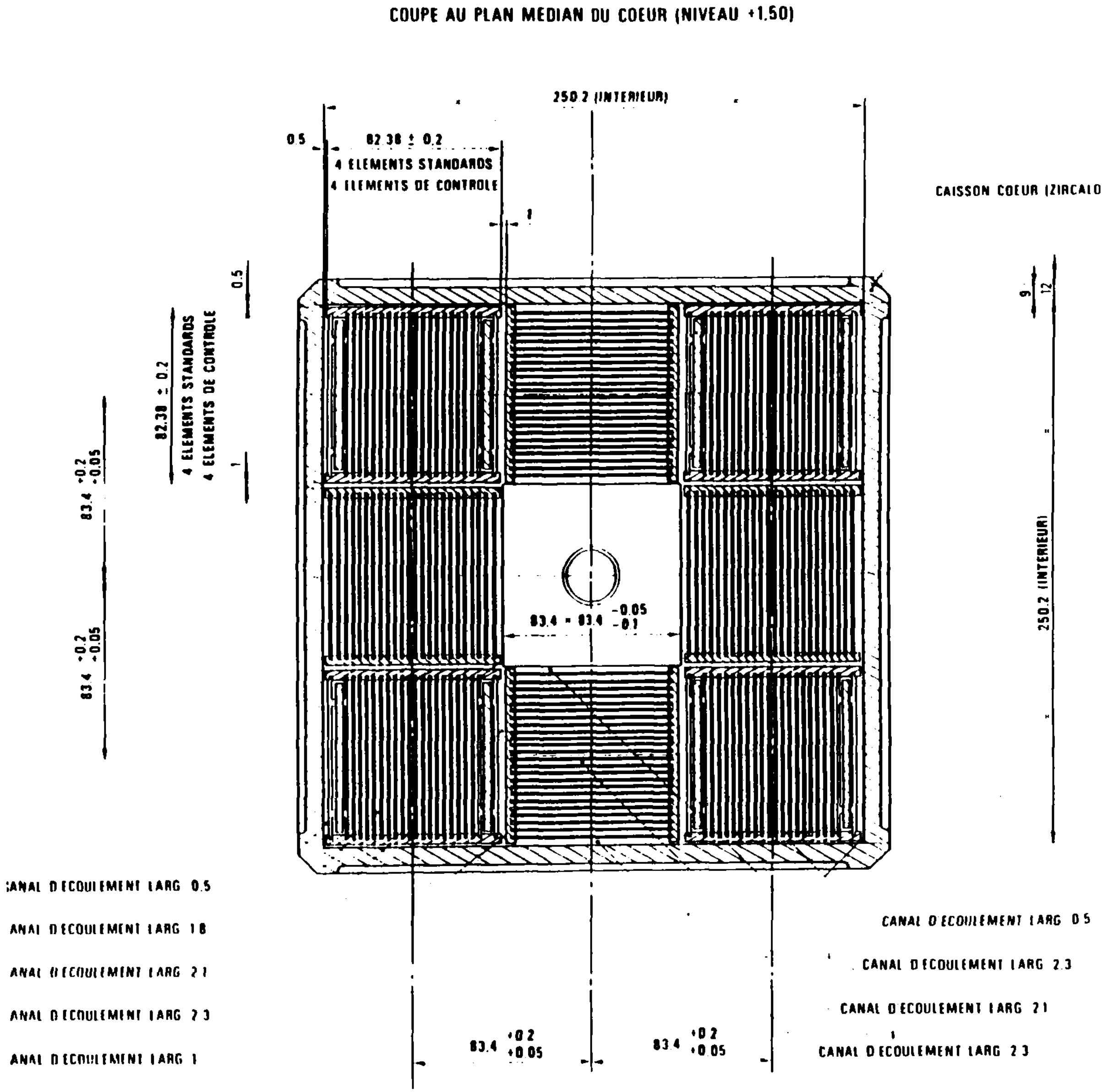

COUPE AU PLAN MEDIAN DU COEUR (NIVEAU +1.50)
250.2 (INTERIEUR)
0.5
82.38 ± 0.2
4 ELEMENTS STANDARDS
4 ELEMENTS DE CONTROLE
1
CAISSON COEUR (ZIRCALOY)
9
12
250.2 (INTERIEUR)
0.5
82.38 ± 0.2
4 ELEMENTS STANDARDS
4 ELEMENTS DE CONTROLE
1
83.4 +0.2 +0.05
83.4 +0.2 +0.05
83.4 × 83.4 -0.05 -0.1
ANAL D ECOULEMENT LARG 0.5
ANAL D ECOULEMENT LARG 1.8
ANAL D ECOULEMENT LARG 2.1
ANAL D ECOULEMENT LARG 2.3
ANAL D ECOULEMENT LARG 1
CANAL D ECOULEMENT LARG 0.5
CANAL D ECOULEMENT LARG 2.3
CANAL D ECOULEMENT LARG 2.1
CANAL D ECOULEMENT LARG 2.3
83.4 +0.2 +0.05
83.4 +0.2 +0.05

Figure 1.

ORPHEE EVOLUTION DE LA COTE DES B.C. PENDANT UN CYCLE

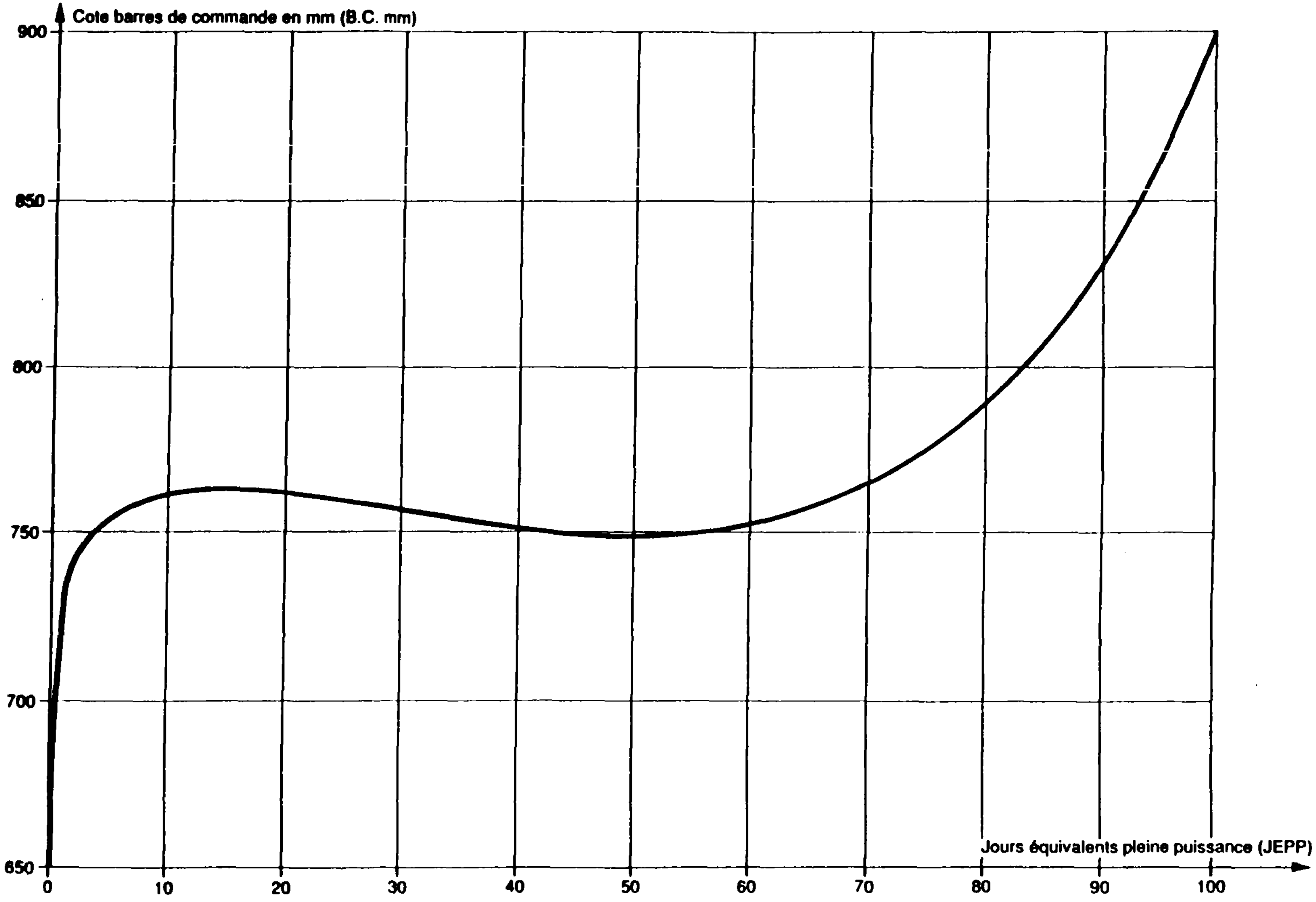
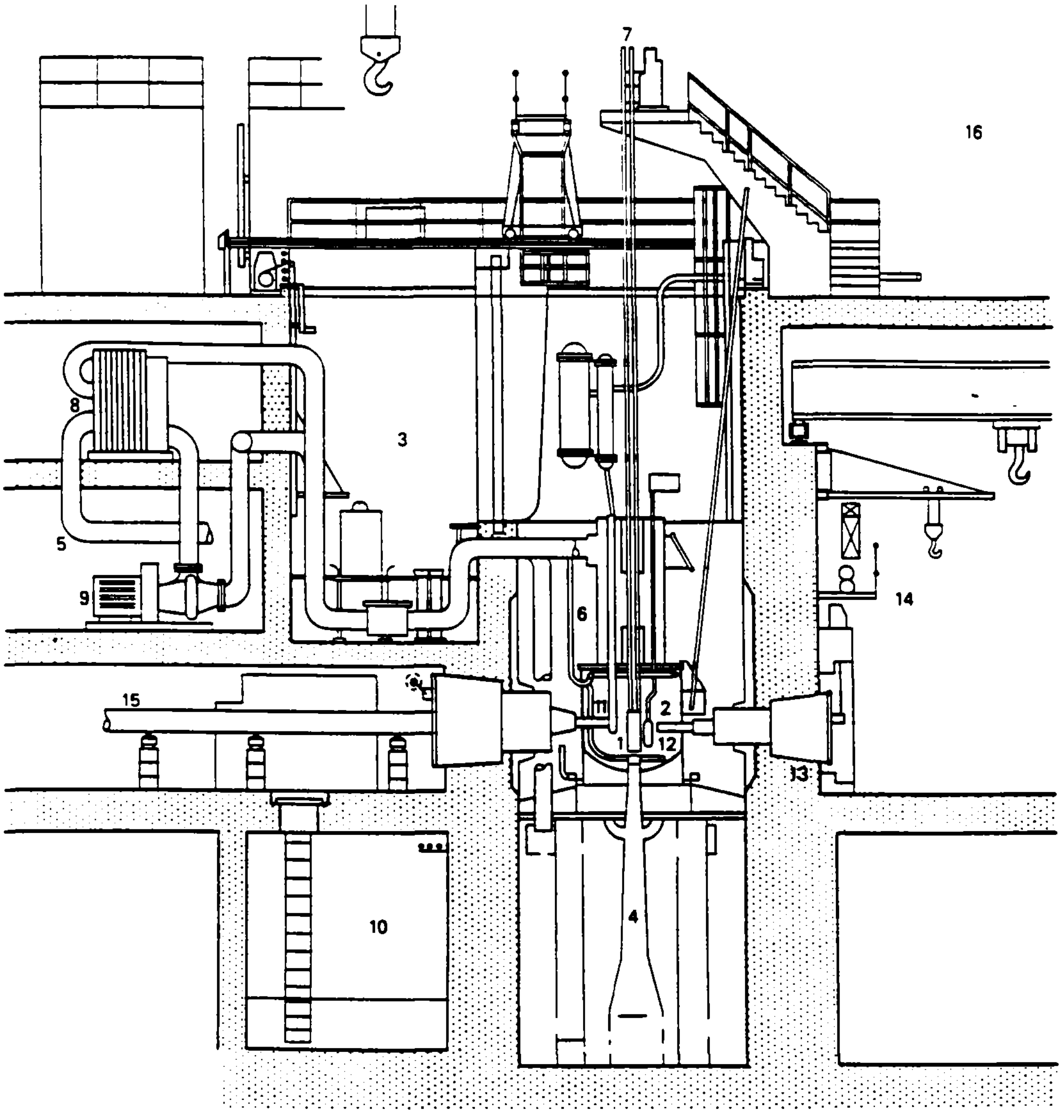
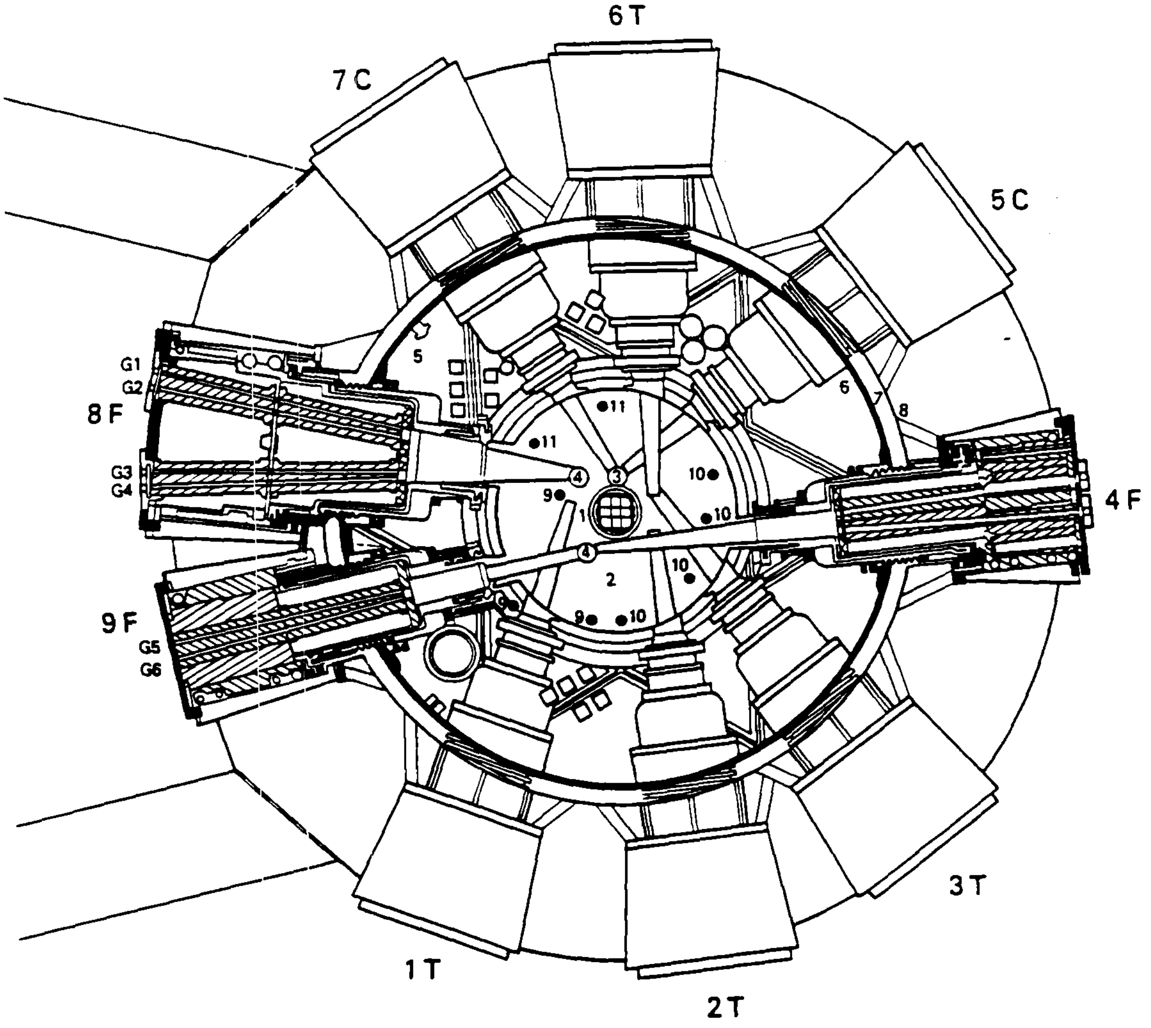


Figure 2.



1. core
2. heavy water reflector
3. pool
4. primary coolant system
5. secondary system
6. heavy water system
7. control rod drives
8. heat exchanger
9. pump
10. pool drain tank
11. low-temperature source
12. high-temperature source
13. tangential channel
14. experimenters' area
15. neutron guide
16. reactor building

Figure 3.



1. core
2. heavy water reflector
3. high-temperature source
4. low-temperature source
5. pool
6. pool inner wall
7. annular space
8. pool outer wall
9. radio-isotope production channel
10. shuttle tube
11. vertical irradiation channel

Figure 4.

SCHÉMA CONFINEMENT DU RÉACTEUR

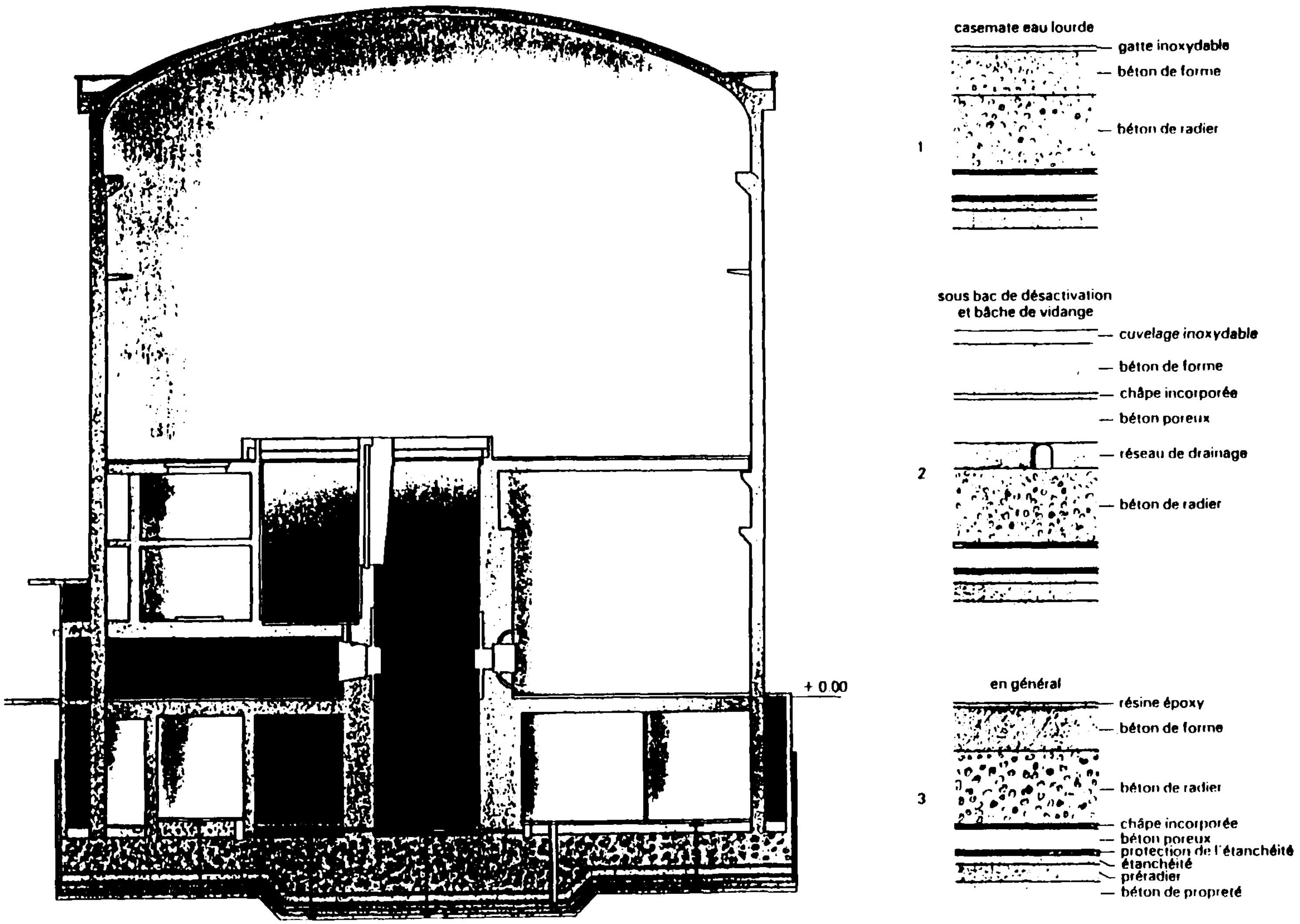


Figure 5.

SCHÉMA GÉNÉRAL DE LA VENTILATION

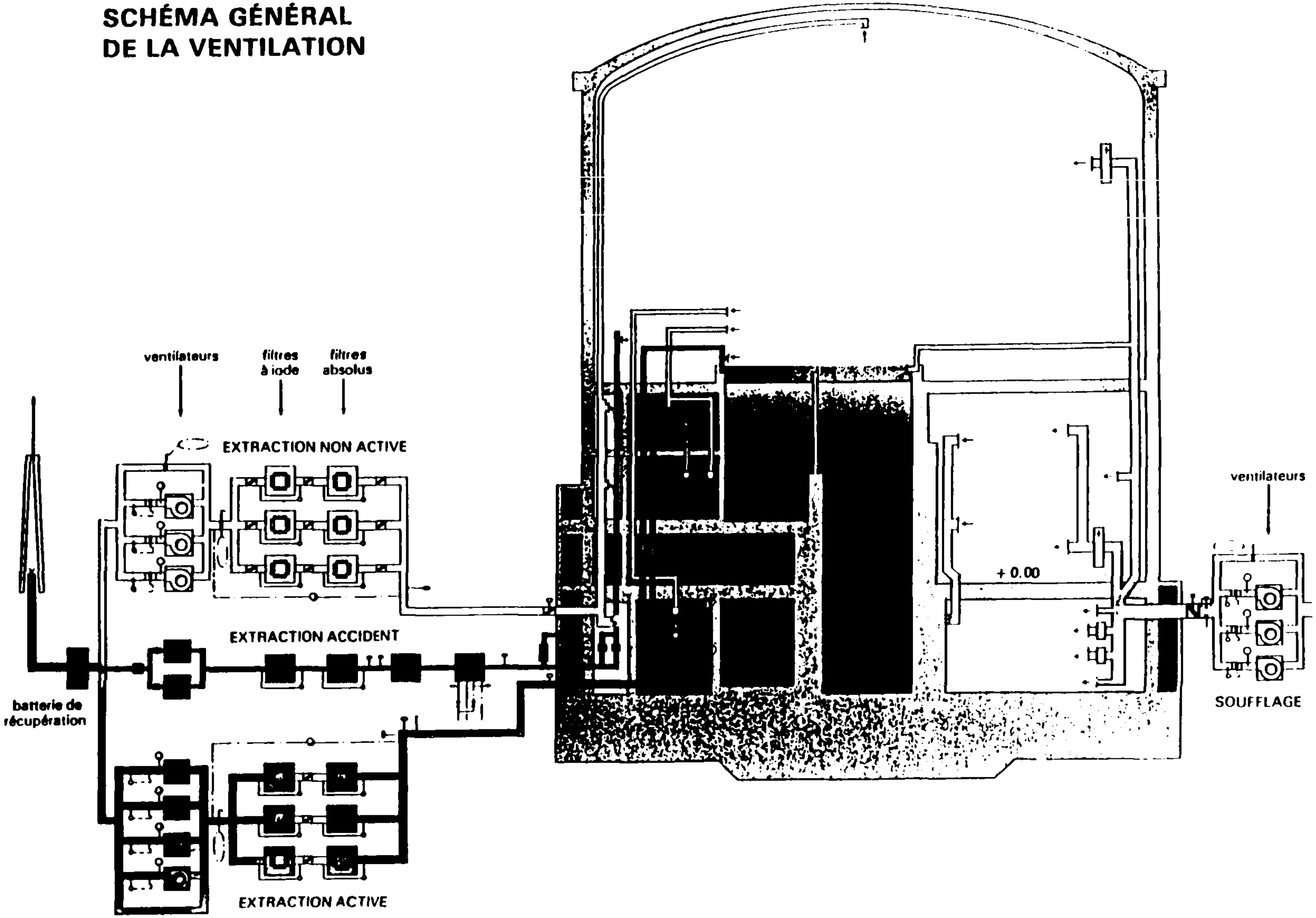


Figure 6.

SOURCE FROIDE ORPHEE

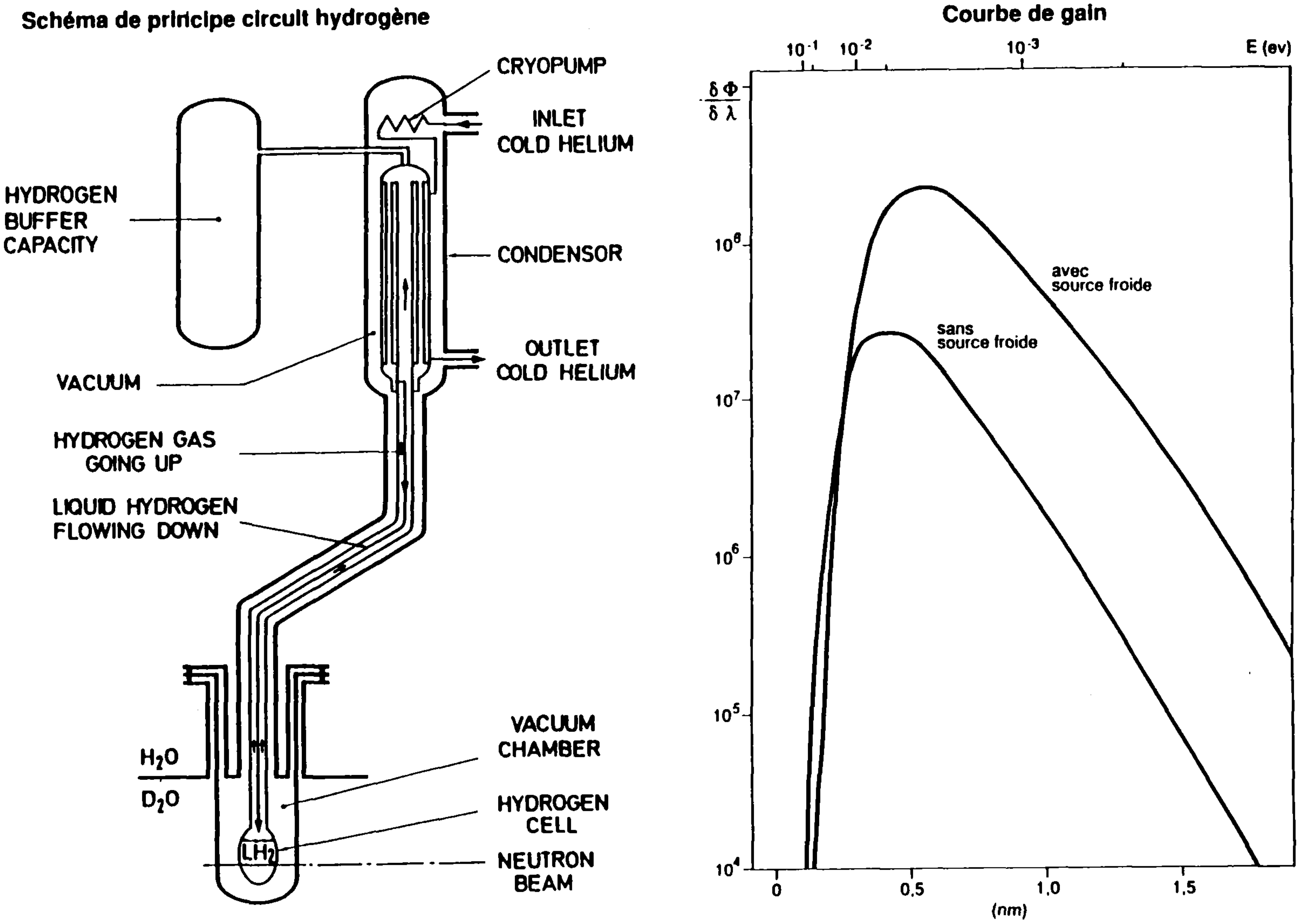


Schéma de principe circuit hydrogène

Courbe de gain

Figure 7.

SOURCE FROIDE ORPHEE
Schéma de principe circuit hélium

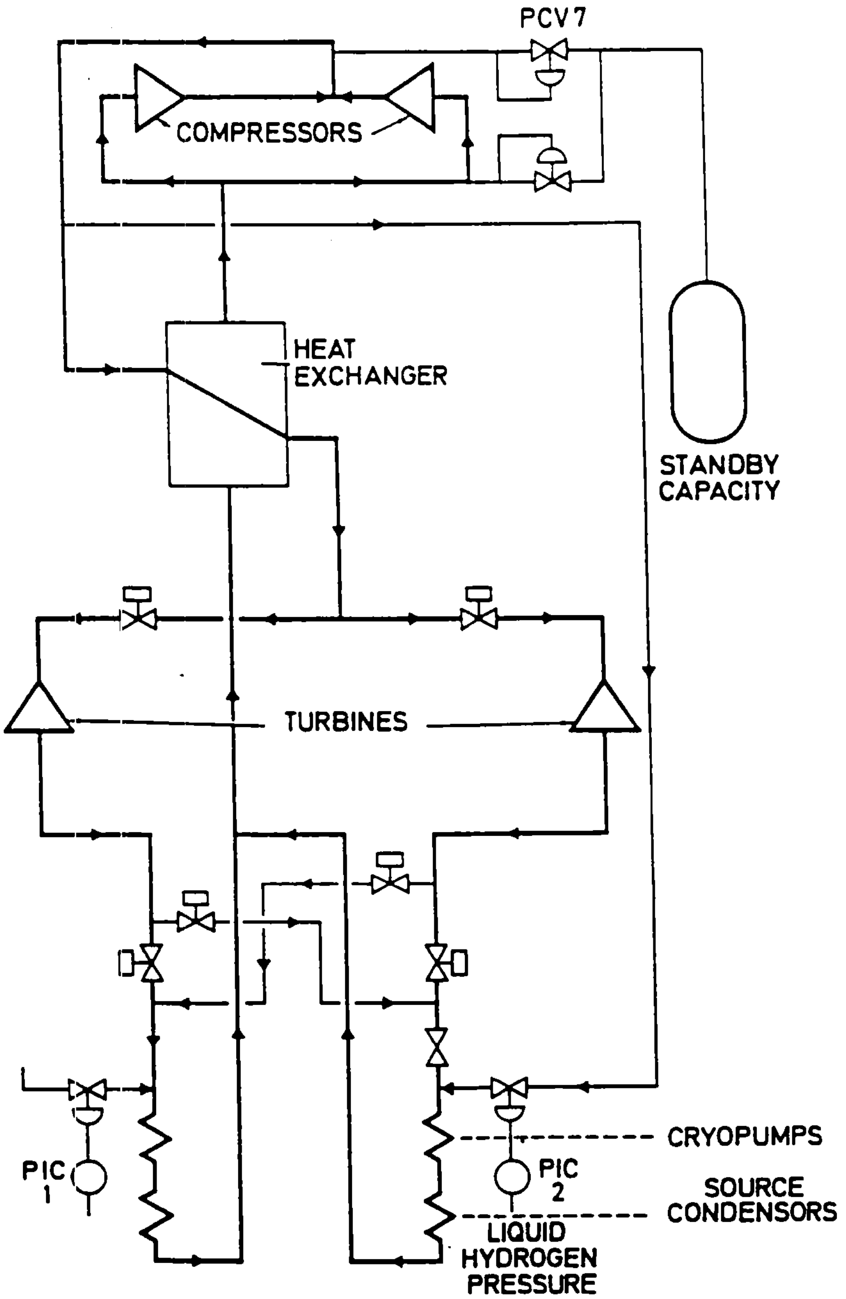


Figure 8.

SOURCES FROIDES
Courbes de gain

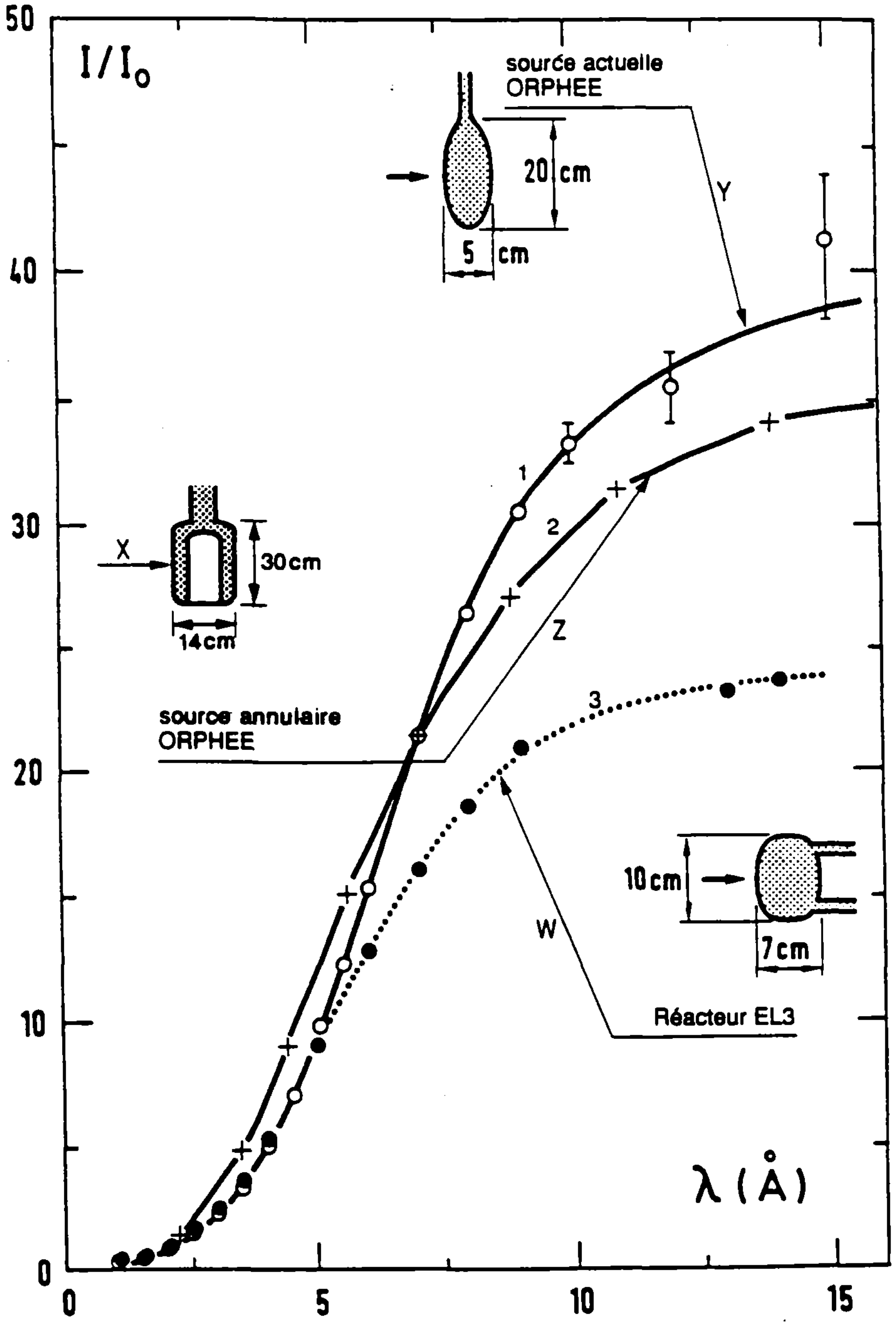


Figure 9.

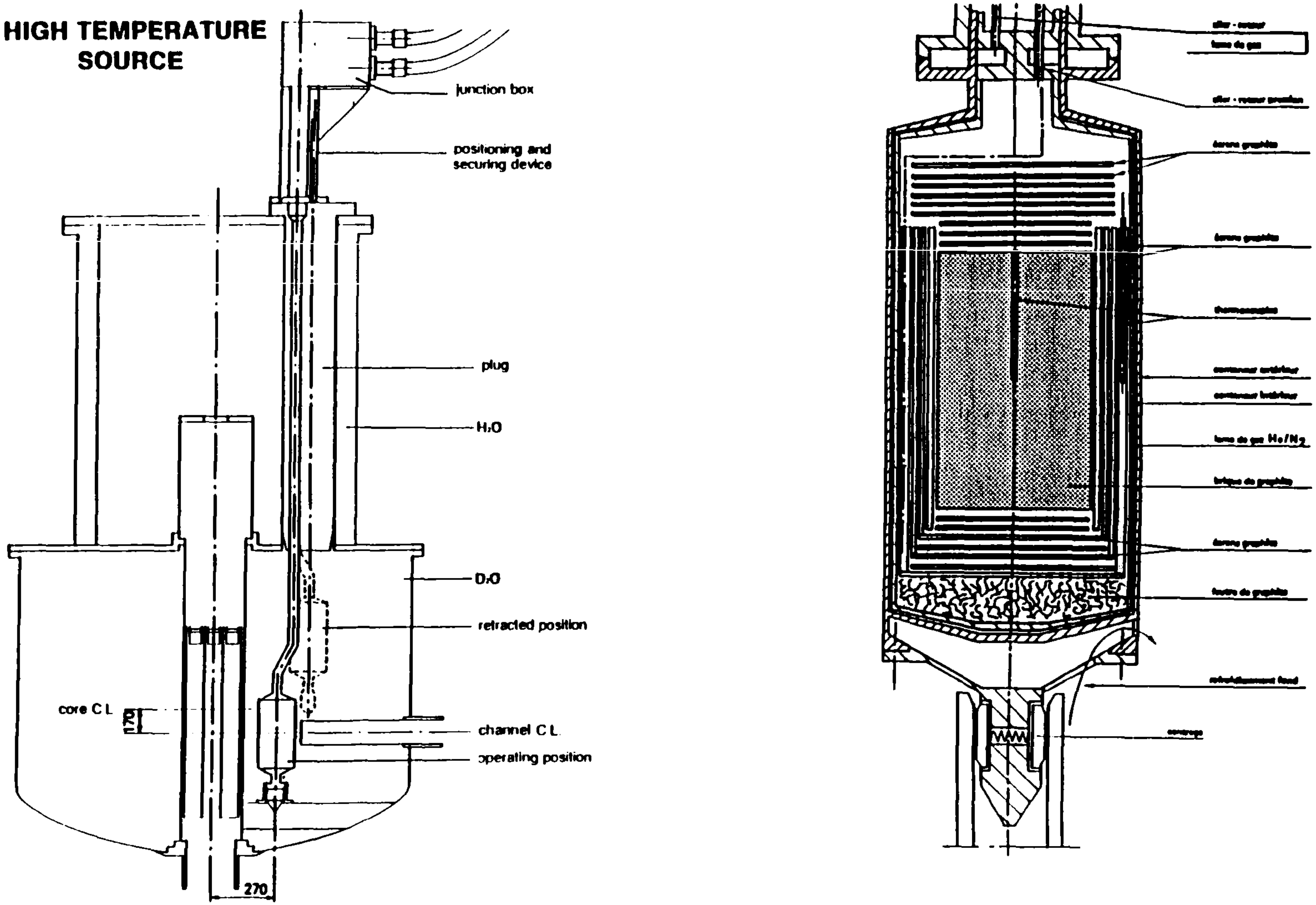

HIGH TEMPERATURE SOURCE
junction box
positioning and securing device
plug
H₂O
D₂O
retracted position
core C L
170
channel C L
operating position
270
aller - retour
lame de gaz
aller - retour pression
écrans graphite
écrans graphite
thermocouples
conteneur extérieur
conteneur intérieur
lame de gaz He/N2
brique de graphite
écrans graphite
feutre de graphite
refroidissement fond
centrage

Figure 10.

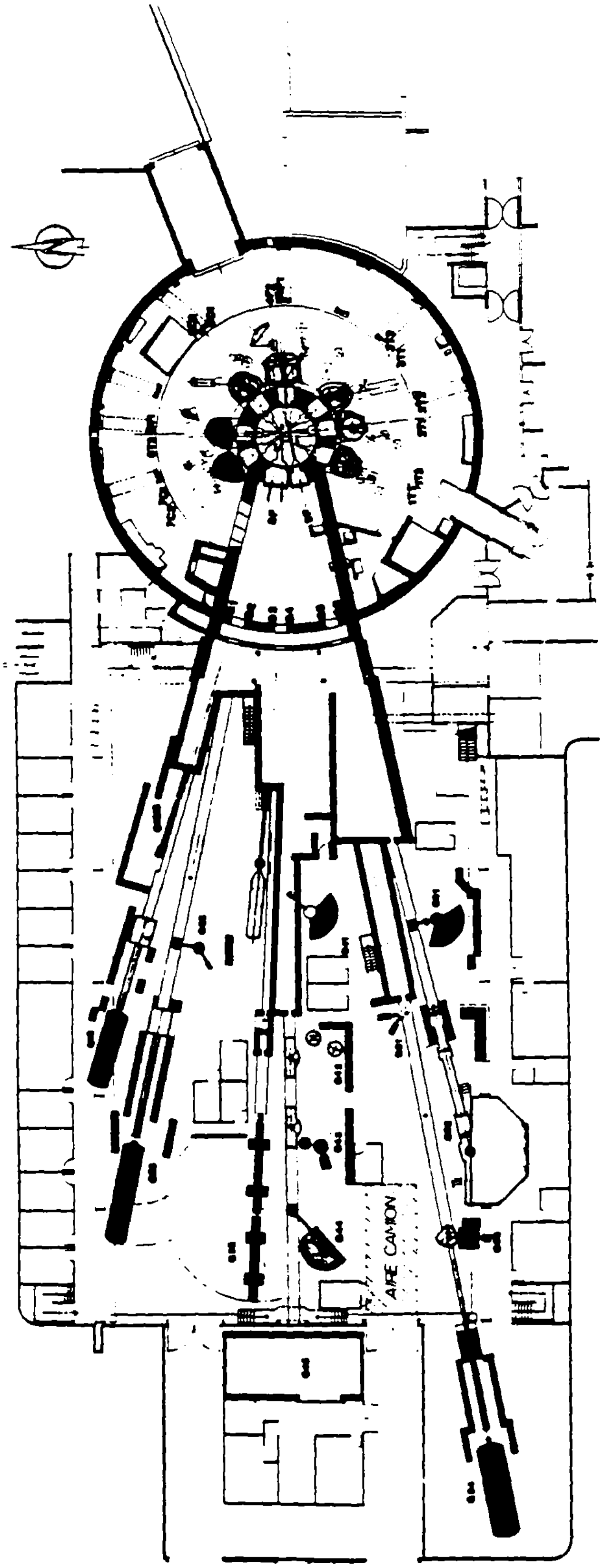


Figure 11.

PROJET DE HALL DES GUIDES EST

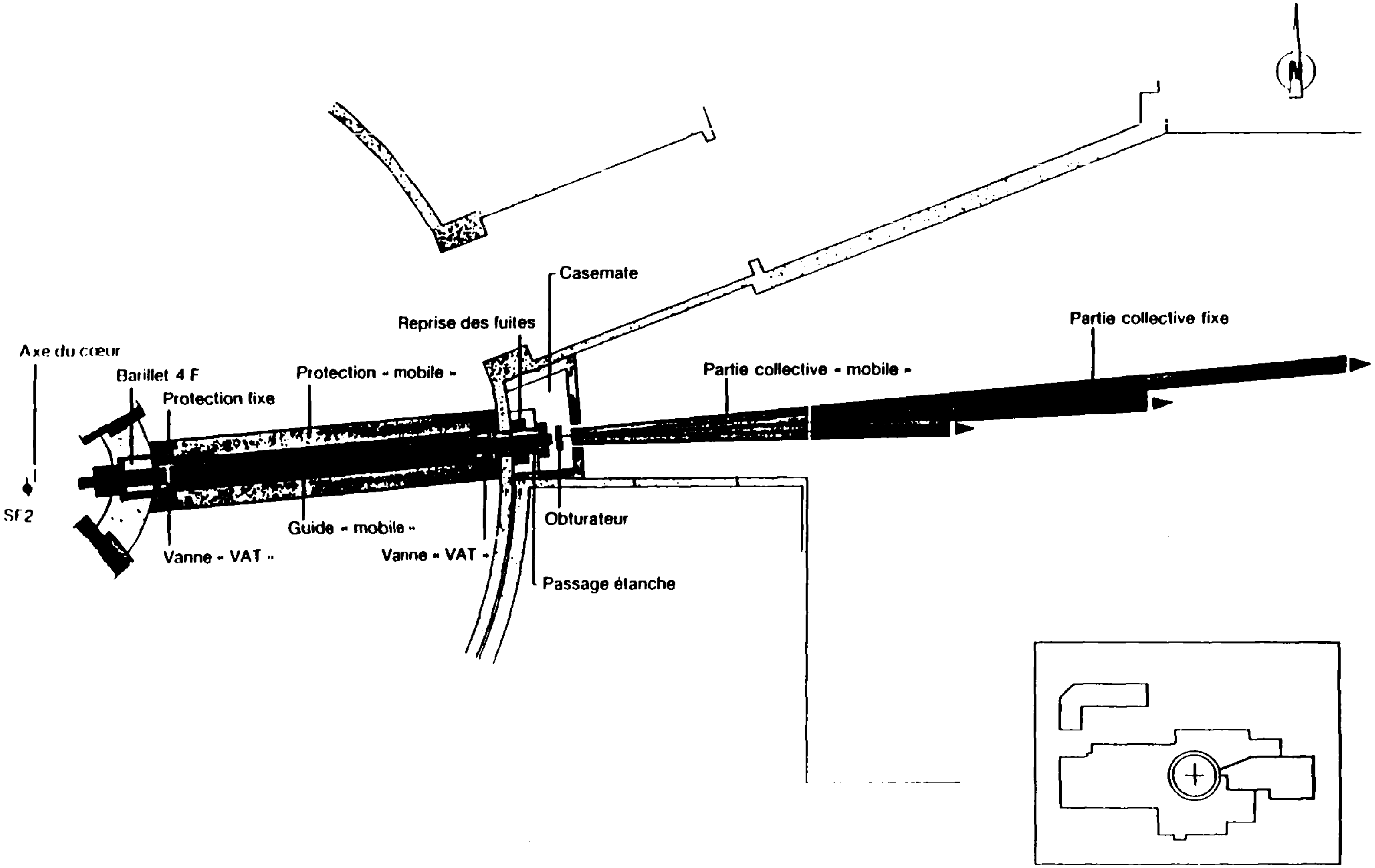


Figure 12.