THE BR2 MATERIALS TESTING REACTOR PAST, ONGOING AND UNDER-STUDY UPGRADINGS

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Past, ongoing and under-study upgradings

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ABSTRACT

The BR2 reactor (Mol, Belgium) is a high-flux materials testing reactor. The fuel is 93% ^{235}U enriched uranium. The nominal power ranges from 60 to 100 MW. The main features of the design are the following :

- maximum neutron flux
  - thermal : 1.2×10^{15} n/cm² s
  - fast (E > 0.1 MeV) : 8.4×10^{14} n/cm² s;
- great flexibility of utilization : the core configuration and operation mode can be adapted to the experimental loading;
- neutron spectrum tailoring;
- availability of five 200 mm diameter channels besides the standard channels (84 mm diameter);
- access to the top and bottom covers of the reactor authorizing the irradiation of loops.

The reactor is used to study the behaviour of fuel elements and structural materials intended for future nuclear power stations of several types (fission and fusion). Irradiations are carried out in connection with performance tests up to very high burn-up or neutron fluence as well as for safety experiments, power cycling experiments, and generally speaking, tests under off-normal conditions. Irradiations for nuclear transmutation (production of high specific activity radio-isotopes and transplutonium elements), neutron-radiography, use of beam tubes for physics studies, and gamma irradiations are also carried out. The BR2 is used in support of Belgian programs, at the request of utilities, industry and universities and in the framework of international agreements.

The paper reviews the past and ongoing upgrading and enhancement of reactor capabilities as well as those under study or consideration, namely with regard to
- reactor equipment,
- fuel elements,
- irradiation facilities,
- reactor operation conditions,
- long-term strategy.

I. INTRODUCTION

The BR2 reactor at Mol (Belgium) went critical for the first time on June 29, 1961; it was put into service with an experimental loading in January 1963. On December 31, 1978 the reactor was shut down to replace the beryllium matrix. Routine operation of the reactor was resumed in July 1980.

Many upgradings and enhancements of reactor capabilities have been carried out; other ones are going on or are under study.

The BR2 reactor is part of a techno-scientific experimentation and production complex which comprises also general and peripheral support facilities, designed to optimize its utilization. A complete irradiation service can be provided, from design study to post-irradiation examination.

II. BRIEF DESCRIPTION AND SPECIAL FEATURES OF BR2

The BR2 reactor is a high-flux materials testing reactor of the thermal heterogeneous type [1]. The fuel is 93% ^{235}U enriched uranium sandwiched between aluminium plates. The moderator consists of beryllium and light water, the water being pressurized (1.25 MPa) and acting also as coolant. The pressure vessel is of aluminium, and is placed in a pool of demineralized water.

The BR2 has the following main features :

- The experimental channels are skew, the bundle presenting the form of a hyperboloid of revolution (Fig. 1). This original configuration gives easy access to the core, allowing the loading of complex instrumented devices, and it results in a compact core, source of very high neutron fluxes.

- The access to the top and bottom covers of the reactor authorizes irradiation of devices measuring up to 11 meters long, some of them being able to contain fuel rods up to 4 meters.

- Besides the standard channels (84 mm diameter), five large diameter (200 mm) irradiation channels are available, with the possibility of loading large experimental irradiation devices such as sodium, gas or water loops.

- Although BR2 is a thermal reactor, it is possible to achieve neutron spectra very similar to those obtained in other reactor types, e.g. fast reactors and fusion reactors (neutron spectrum tailoring).

- A remarkable flexibility of utilization : the core configuration and the operation mode of the reactor are adapted to the experimental requirements. Fig. 2 shows a typical core configuration.

III. OPERATION CHARACTERISTICS

The main operational characteristics are summarized in Table 1.

The reactor operation is carried out on the basis of an operating cycle. The present nominal cycle length is 4 weeks and consists of 2 weeks shut-down for loading and unloading and normal maintenance work, followed by 14 days of operation. Each year, two shut-down periods are extended for survey tests and special maintenance work. In addition, special irradiation campaigns are organized in order to carry out particular experiments such as safety tests. The total number of days of operation per year is presently 180.

The present maximum nominal heat flux at the surface of the reactor fuel elements is 470 W/cm^2, 500 W/cm^2 having been reached during special campaigns (programme MOL 7C) and 600 W/cm^2 being the maximum admissible heat flux (probable onset of nucleate boiling). The 470 W/cm^2 heat flux was tested under the circumstances of pressure loss incidents, 600 W/cm^2 having been tested for the nominal cooling flow rate.

The nominal full-power level depends on the core configuration used; at present with the configurations 10 or 12, it ranges from 60 to 80 MW, the maximum reached being 106 MW. The ultimate cooling capacity, initially foreseen for 50 MW, has been increased in 1971 to 125 MW.

IV. NUCLEAR CHARACTERISTICS

For a BR2 core operating at a hot spot heat flux of 470 W/cm^2, the maximum available neutron fluxes are :

- *in the axis of the central channel H1 with a Be plug*
  - thermal : 1 x 10^{15} n/cm^2 s

- *in a fuel element channel*
  - total : 1.4 x 10^{15} n/cm^2 s
  - fast (E > 0.1 MeV) : 7 x 10^{14} n/cm^2 s
  - fast (E > 1.0 MeV) : 3.5 x 10^{14} n/cm^2 s.

Typical neutron spectra in a reflector position and in a fuel element position are shown in Fig. 3.

It is possible to irradiate in BR2 fissile and structural materials intended for reactors of several types (fission and fusion) in such a way that irradiation effects correspond to those expected in these reactors.

V. REACTOR UTILIZATION

V.1. Facilities Available

At BR2, about 100 irradiation positions are available. It is possible to irradiate :

- *in the pressure vessel*
  - core
    - within the standard fuel elements (diameter of the experimental cavity : 17.4 mm to 51.6 mm)
    - in a driver fuel element or in a special plug (in the large 200 mm diameter channels)
  - reflector
    - in beryllium or aluminium plugs (diameter of the experimental cavity : up to 200 mm)
    - in the hydraulic rabbit
    - in the self-service thimbles.

- *outside the pressure vessel*
  - in the beam-tubes (radial or tangential)
  - in the reactor pool.

Fig. 4 shows examples of irradiation devices loaded in a beryllium plug or a standard fuel element containing 6 plates; by reducing the number of concentric fuel plates, it is possible to increase the useful diameter of the experimental cavity. Fig. 5 gives an example of a loop surrounded by a driver fuel element and loaded in a 200 mm diameter channel.

In addition to the irradiation itself, the BR2 Operating Group can provide a complete high flux irradiation service from the planning stage up to the interpretation of the final results :

- assistance in the design of experimental devices

- determination of the neutronic characteristics of the irradiation by means of 1-D and 2-D neutron transport or diffusion calculation codes, gamma heating calculations being also performed when required

- design and fabrication of irradiation equipment :
  - high performance loops,
  - instrumentation capsules for fissile and non-fissile materials irradiations at high temperatures and high power ratings,
  - retractable and reloadable devices,
  - test on pre-irradiated fuel pins,
  - power cycling devices,
  - capsules for the production of isotopes and transplutonium elements.

- testing and commissioning of irradiation equipment

- dosimetric analysis :
  - determination of optimum irradiation conditions with experimental mock-ups in the BR02 reactor, the zero-power nuclear model of BR2, or in BR2 operating at low power,
  - thermal and fast neutron detector measurements.

- post-irradiation examination and analysis :
  - dismantling of equipment
  - metallurgical and physical tests in hot cells,
  - chemical operations and analysis.

V.2. <u>Irradiations Carried out</u>

Purpose of the irradiations [1, 2] :

- *research activities*
  - study of the behaviour of fuel elements and structural materials intended for the reactors of future nuclear power stations (sodium or gas cooled fast reactors, high temperature gas cooled reactors, light water reactors, fusion reactors)
  - basic physical research within the beam-tubes (nuclear physics and solid state physics)

- *in-pile safety experiments (particularly related to fuel pin cooling and transient overpower)*

- *production activities*
  - production of high specific activity radioisotopes
  - silicon doping
  - colouration of gems (diamond, topaz)

- *peripheral activities*
  - neutron-radiography in the reactor pool
  - gamma irradiations within spent fuel elements (5 x 10’ rad/h or 140 W/kg).

VI. PARTICULAR UPGRADINGS AND ENHANCEMENTS OF REACTOR CAPABILITIES

VI.1. Reactor Equipment

VI.1.1. Major Equipment Replacement

The unloading and replacement of the first beryllium matrix of the BR2 reactor took place in 1979-1980.

The main steps of the replacement operation are described in reference [3].

At unloading time the maximum fast fluence in the hottest channel had reached about 8 x 10^{22} n/cm^2 (E > 1 MeV). Dimensional stability and swelling of the beryllium matrix have been investigated. The swelling, mainly due to the formation of gas atoms, was found a nearly linear function of the fast fluence up to a value of ≈ 6.4 x 10^{22} n/cm^2 (E > 1 MeV) at the temperature of ≈ 50°C normally existing in the matrix. For higher values of the fast fluence, several observations showed an accelerated increase of the swelling. Consequently the maximum allowed fast fluence for the second beryllium matrix has been limited to 6.4 x 10^{22} n/cm^2 (E > 1 MeV). A surveillance programme of the second BR2 beryllium matrix has been set up; it mainly concerns direct observations and measurements on the beryllium matrix itself. Dimensional measurements allow comparison of the relative swelling in axial and radial directions with the dilatation coefficients obtained for the first matrix. Visual inspections are performed on the inner surfaces of the reactor channels in order to record the beginning and the evolution of cracks and to measure the total length of cracks in function of the fast fluence. Irradiations and measurements are also performed on test samples coming from the heats which served for the manufacturing of the second matrix.

In 1971, the nine original heat exchangers of the reactor primary cooling circuit, of the classical straight tube pattern, were replaced by three units, of a helical tube pattern.

In January 1972, it was found that one tube of the new exchangers was perforated, by vibration of the unsupported straight lead-in section against a weld. After removal of the faulty tube, extensive and systematic vibration measurements were carried out, and it was found that, in two of the heat exchangers, several tubes experienced excessive vibration. As an initial corrective measure, the manufacturer installed aluminium strips around the lead-in tube bundles, to reduce the vibration of the enter tubes. Subsequently, a woven stainless steel mat, 5 cm thick, was wrapped around the bundles to break up the impinging jet of primary water which enters at right angles to the tube bundle. These modifications were carried out on all three exchangers.

Also in 1971, the original wooden cooling tower packing was replaced by plastic material. This modification of the towers and the replacement of the heat exchangers have led to a nominal cooling capacity of the system exceeding 120 MW.

VI.1.2. Nuclear Instrumentation

From the beginning of the reactor life, a great effort has been devoted to the maintenance and the improvement of

- the reactor control equipment
- the control commands and mechanisms of the safety and regulating rods
- the instrumentation of the experiments and irradiation devices
- the radiation monitoring system.

Many mechanical improvements have been made in order to increase the reliability : balling screw for the regulating rod, improved scram mechanism, position sensors,...
The first generation nuclear instrumentation of BR2 was installed in 1960. All the electronics was then driven by tubes. Therefore, the reactor control electronics has been nearly completely renewed. About 80 racks completely transistorized are now controlling the power of the reactor. More chambers have been installed around the reactor with a view of redundancy.

The radiation monitoring system comprises more than 80 ionization chambers, many GM, NaI crystals, GeLi and spectrometers. It also includes radiation monitoring of the experiments.

Three new racks improving the performance and the safety of the reactor control (neutron measurement by linear chambers) are now ready to be installed. The replacement of the very last racks still working with tubes is under study. So the reactor control will be completely transistorized by the end of 1991.

A new phase will begin with the digitalizing of many signals. During 1990 the position of some chambers controlling the reactor will be fully digitalized using absolute position encoders. The next step will be the digitalizing of the position of the control rods.

Another project concerns the monitoring of fission products in primary water by on line spectroscopy.
During 1990, fission counters and completely renewed ionization chambers will be installed around the reactor in order to increase sensitivity resulting in an enforced safety of the reactor.

The safety of the reactor and the reliability of its instrumentation have been considerably improved during the last 30 years. In 1989, only one unscheduled shut-down (scram) occurred due to an electronic failure. The goal is to keep all the nuclear instrumentation as up-to-date as possible and to keep it ready for the future.

VI.1.3. Maintenance and upgrading

A great effort is devoted every year to the maintenance and upgrading of the installations in order to maintain an optimal availability and safety during the working of the reactor.
The accent is now put on the regular maintenance, automatization, renovation, modernization of the equipments during the scheduled reactor shut-downs.

The main items which were recently covered, or are still in progress, concern :

- the complete overhaul of the three emergency power generators and their associated equipments;

- the complete overhaul of all the main electric motors of the primary and secondary cooling circuits; also the complete overhaul of the main electric motors of all the reactor auxiliary circuits;

- the renewal of the high-voltage switching equipments for the main secondary pumps;

- the renewal of tens of low voltage electric breakers for auxiliary equipments;

- the replacement of the main ventilation pipings between the process and ventilation buildings;

- the complete refurbishment of the cooling towers of the main secondary cooling circuit;

- the upgrading and duplication of the control commands for the reactor building ventilation valves.

The following items are now planned or under study for the near future (1990-1991) :

- the inspection of the main electric transformers;

- the replacement of the heat exchangers of the reactor and storage pools;

- the internal examination of the main primary heat exchangers;

- the extension of the spent fuel storage capacity to cover the reactor working period until end of 1995;

- the erection of a new shipping and decontamination area for transport containers.

VI.2. Fuel Element

Since 1971, the majority of fresh fuel elements loaded have been of the Cermet type. The standard six tube elements used contain either 330 g ^{235}U (50 mg/cm^3) together with 2.8 g natural boron (in the form of B_4C) and 1.4 g natural samarium (in the form of Sm_2O_3) as burnable poisons, or 400 g ^{235}U (60 mg/cm^3) and 3.8 g boron and 1.4 g samarium, compared with 244 g ^{235}U for the alloy elements previously used, without poison.

The generalized use of these Cermet elements has led to an increase in the reactor cycle length, a reduction in the variation in irradiation conditions during the cycle caused by the control rod movement, the possibility of overcoming increasing reactivity absorption effects of the rigs and a reduction in fuel costs by decreasing the number of fresh elements used each cycle and by increasing the mean burn-up (Fig. 6).

The fuel is presently 93% ^{235}U enriched uranium. The uranium density in the meat of the 400 g ^{235}U standard six tube elements is 1.3 g/cm^3 corresponding to an uranium concentration of 37 wt %.

Since 1978, C.E.N./S.C.K. follows carefully the RERTR activities (Reduced Enrichment Research and Test Reactor program) and has offered its collaboration. But, under the present circumstances (the BR2 experimental program, state-of-the-art LEU fuel technology), BR2 has to continue to use highly enriched uranium (90-93% ^{235}U). [4]

Increase of the uranium density from the present value of 1.3 to 1.7 g/cm^3, allowing a load of 500 g ^{235}U per standard fuel element, is under consideration to improve the fuel cycle economics.

VI.3. Irradiation Facilities

In the challenging field of irradiation testing and neutron-based production activities, thorough experience has been gained from the start of the BR2 reactor [1]. Particular features of this are the following :

- a wide range of irradiation devices for LWRs, LMFBRs, HTRs, GCFRs and fusion reactors and for radioisotope and transplutonium elements production;

- long established use of BR2 for safety experiments (Mol 7C, PAHR) and power transients (VIC loop, TRIBULATION program);

- irradiation campaigns on pre-irradiated fuel pins (without length limits) or on fuel pins with fuel cladding defects;

- remote assembly of bundles of irradiated fuel pins and remote sodium filling of in-pile sections;

- handling of circuits contaminated by fission products or tritium.

Recent developments :

- in-pile fatigue tests on fusion reactor first wall candidate materials, FAFUMA 3 experiment (Fig. 7);

- the PRF device for the irradiation of highly enriched uranium targets, with loading and unloading capability during reactor operation (Fig. 8);

- modification of the beryllium plug loaded into the central channel H1 in order to increase the number of irradiation positions (from 3 to 6) with very high thermal neutron fluxes and to allow the loading of a BR2 standard fuel element in the centre (Fig. 9).

Under development :

- the high pressure water loop CALLISTO (Capability of Light water fuel testing In Steady state and Transient Operation) for the irradiation of 3 x 9 fuel rods with a broad range of experimental conditions representative of PWR reactors (Fig. 10);

- the SIDONIE device for silicon doping, ingot diameter up to 5" (Fig. 11).

Under consideration :

- the SOLISTE loop (Sodium Loop for Incidental and Safety Transients Experiments) for the epithermal irradiation of high burn-up fuel pins pre-irradiated in fast reactors such as PHENIX with simulation of different kinds of transient incidents such as a control rod withdrawal incident (CRW) (Fig. 12);

- PAHR (Post Accident Heat Removal) type experiments in support of LWR safety analysis studies;

- to provide, on the occasion of the next beryllium matrix replacement, an experimental cavity with a diameter up to 400 mm in the central region of the reactor (Fig. 13).

VI.4. Reactor Operation Conditions

From January 1963 till December 1989, 78 different core configurations have been used. This large number of variants utilized is due to continued attempts to use the flexibility of loading to the best advantage of the greatly varying experimental charge, while still maintaining the maximum operating cycle length and keeping fuel consumption to the minimum.

The nominal full power level was regularly adapted to the experimental loading demands : 34 MW in 1963, 60 to 80 MW at present.

The highest power ever reached by BR2 (and by a research reactor in Europe) is 106 MW; this power level was attained during a special campaign in order to meet the irradiation conditions required for a particular experiment of the MOL 7C safety program (study of local blockage of the sodium flow in a fuel bundle of 30 LMFBR fuel pins).

At each routine start-up, it is customary to operate for short periods at 1%, 40% and 80% of nominal full power, in order to carry out various checks, mainly on the irradiation conditions for the experiments, to determine the optimum power level and to find the best control rod alignment, having regard to flux perturbations and imbalance. In addition, during each cycle, the reactor power is modified, if necessary, to give the optimum irradiation conditions for the experimental load as a whole, while still respecting safety limits.

Under study or consideration :

- the loading of a standard 6 tube element in the central position of the new beryllium plug loaded in the H1 channel in order to compensate for the loss of reactivity caused by the radioisotope production baskets loaded in the other positions and to cope with the ^{3}He poisoning of the beryllium matrix during the shut-down periods;

- the increase of the maximum hot spot specific power from the present 470 W/cm^2 level to 550 or 600 W/cm^2 if requested by particular safety experiments on high burn-up fuel pins.

VII. LONG-TERM STRATEGY

A major milestone in the presumable future of the BR2 reactor will be somewhere around 1995, when the present beryllium matrix has reached its maximum allowed fast fluence.
Beyond this point, one can think of different scenarios ranging from a simple replacement of the matrix up to major modifications of the reactor.
The event-tree given in Fig. 14 can give some guidance to the decision-making process.
It clearly appears that decisions will have to be made quite in advance, if operations are to be conducted successfully. The choice of a scenario to be followed will be made at latest by the end of 1991.

VIII. CONCLUSION

The BR2 reactor was first put into service with an experimental loading in 1963. Since then it has contributed greatly to the development of many large nuclear and non-nuclear projects within the European Community and other countries such as the U.S.A. and Japan. This successful result has been obtained thanks to the continuous process set up for the upgrading and enhancement of the reactor capabilities.

As far as the future is concerned, efforts will be continued in order to maintain an optimal availability and safe operation of the reactor and to adapt the irradiation capacity and the operating conditions of BR2 so as to accommodate the future expected experimental loading. In addition, consideration is given to the long term strategy after 1995, time at which the present beryllium matrix has to be replaced.

TABLE 1 : BR2 MAIN DATA

Beginning of utilization	*1963*
Maximum heat flux	
• *nominal*	*470 W/cm^2*
• *admissible*	*600 W/cm^2*
Nominal power	*60 to 100 MW*
Maximum neutron flux (for 600 W/cm^2)	
• *thermal*	*1.2 x 10^{15} n/cm^2 s*
• *fast (E > 0.1 MeV)*	*8.4 x 10^{14} n/cm^2 s*
Irradiation positions	*up to 100*
Fuel enrichment	*90 - 93 % ^{235}U*
Fissile charge at start of cycle	*9 to 13 kg ^{235}U*
Cycle of 4 weeks	
presently	*2 weeks shut-down* *14 days operation*
Total operation days per year	
• *presently*	*180*
• *possible*	*200 to 250*

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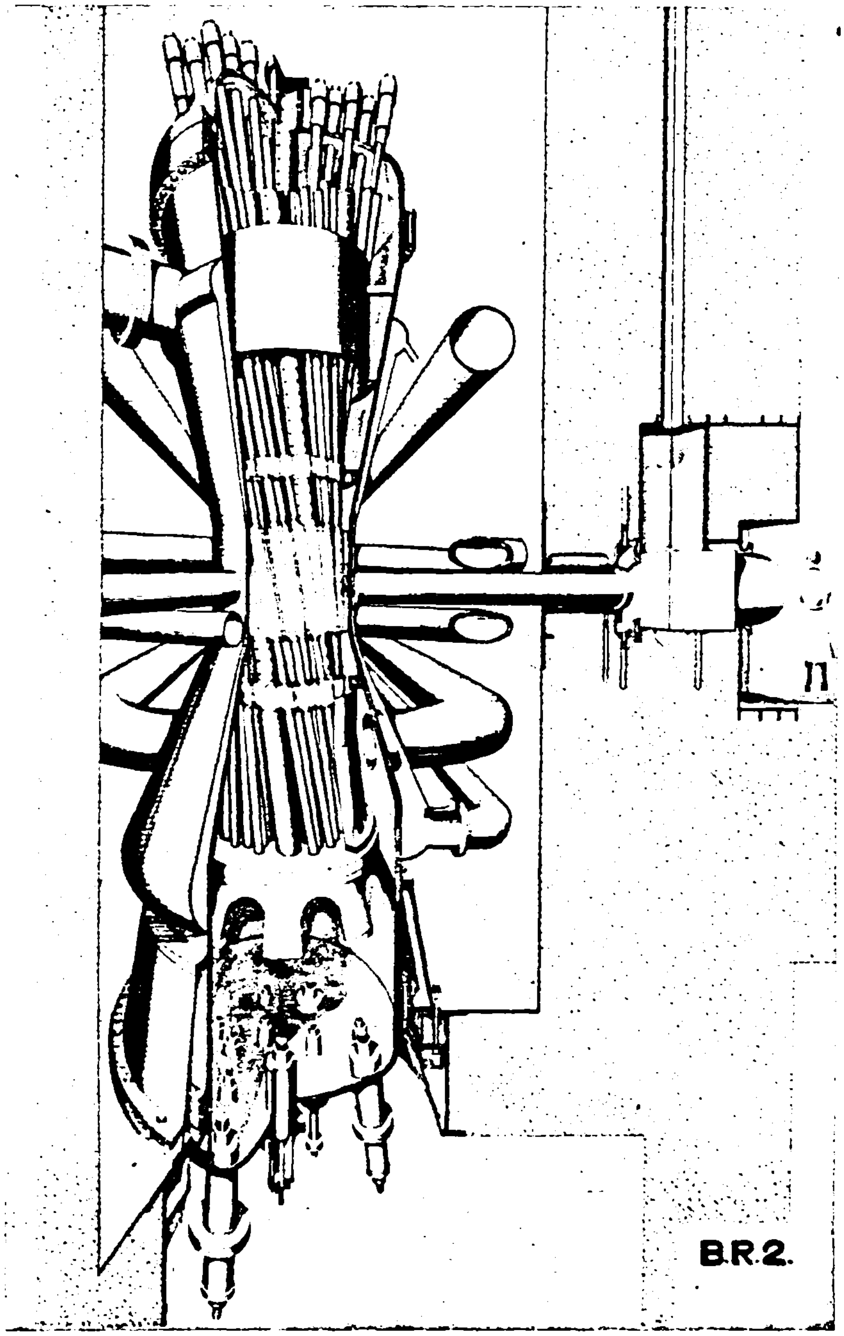
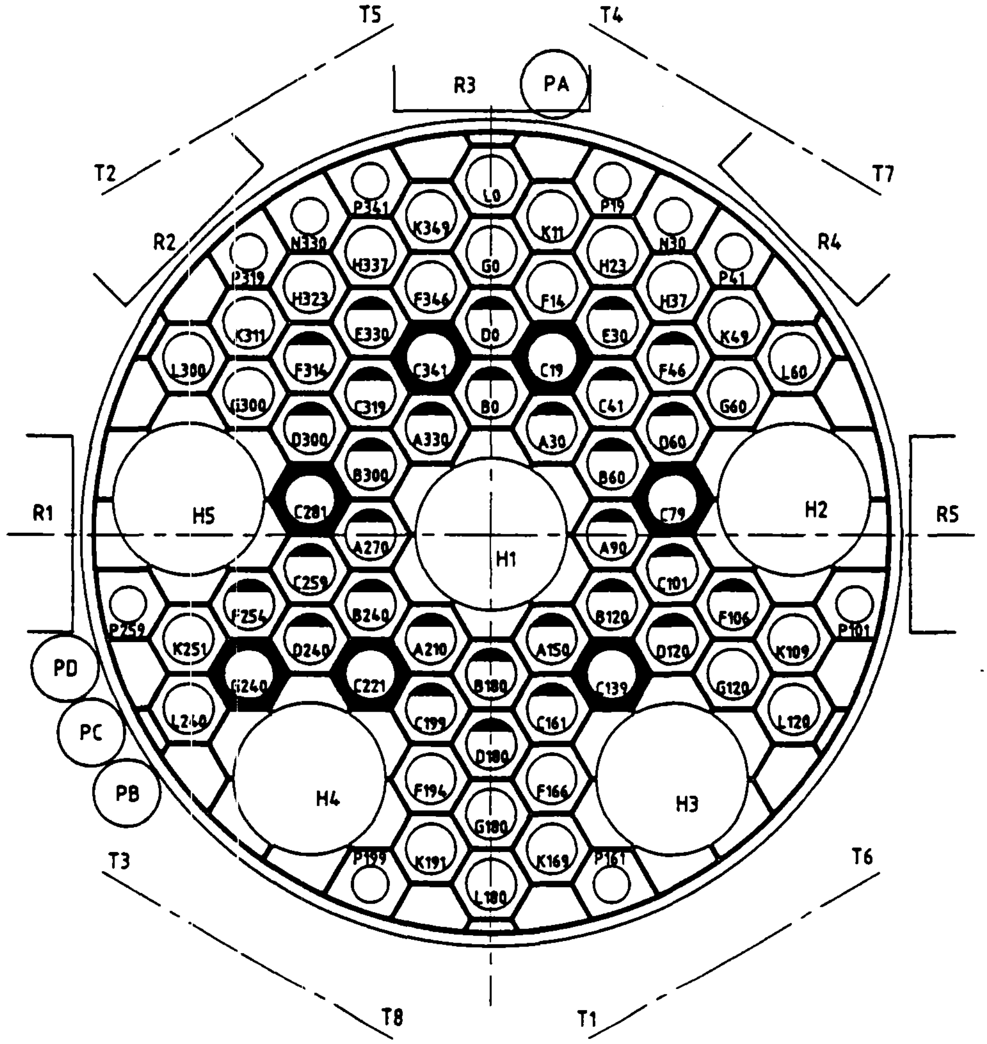


Fig.1 General view of the BR2 reactor.

CONFIGURATIE 10N



CHANNEL WITH FUEL ELEMENT

CHANNEL WITH CONTROL ROD

REFLECTOR CHANNEL

POOL SIDE TUBE

TANGENTIAL BEAM TUBE

RADIAL BEAM TUBE

Fig.2 BR2 CORE
Cross section at mid plane
TYPICAL CONFIGURATION

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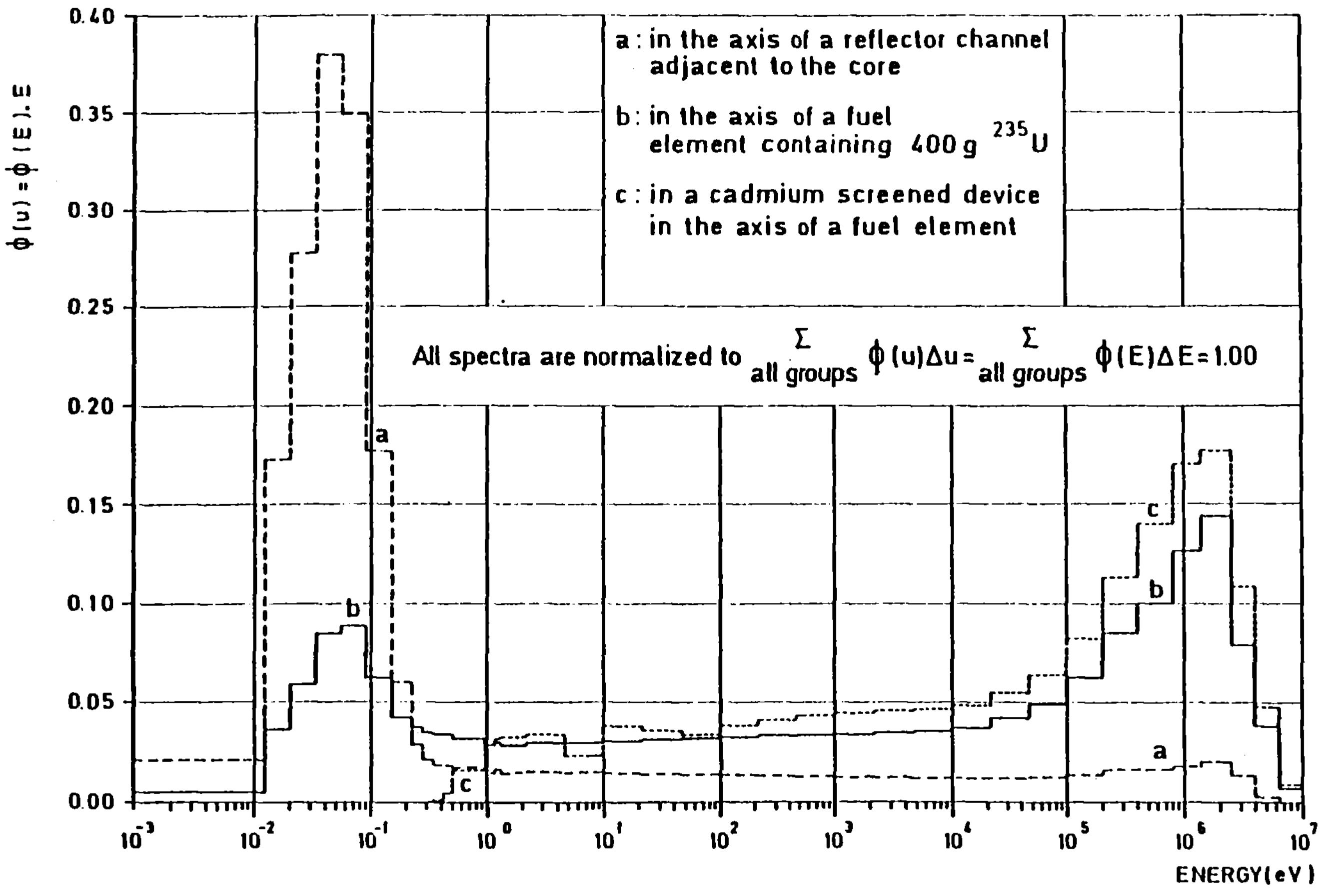
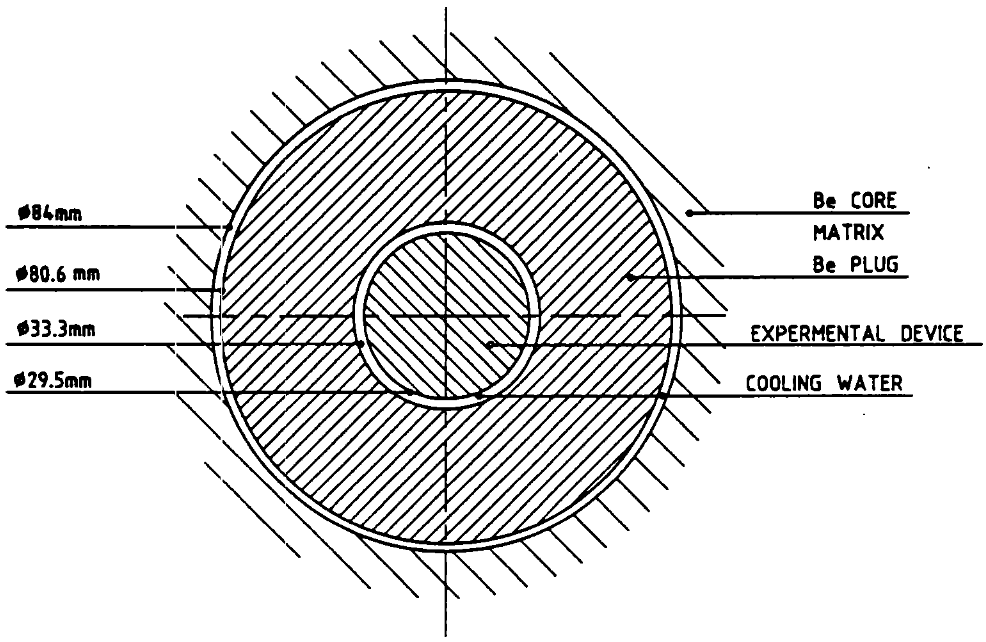
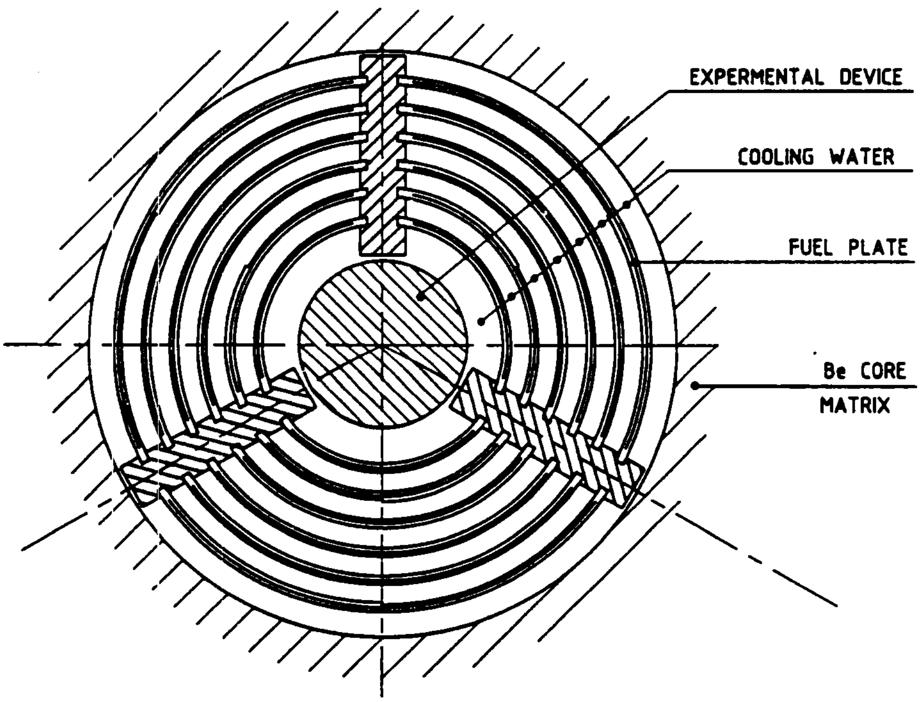


Fig.3. TYPICAL NEUTRON SPECTRA IN BR2 SCK-CEN F 602



With a Be FILLING PLUG (Cross section)



With a FUEL ELEMENT (Cross section)

Fig.4 BR2 Irradiation in a standard channel

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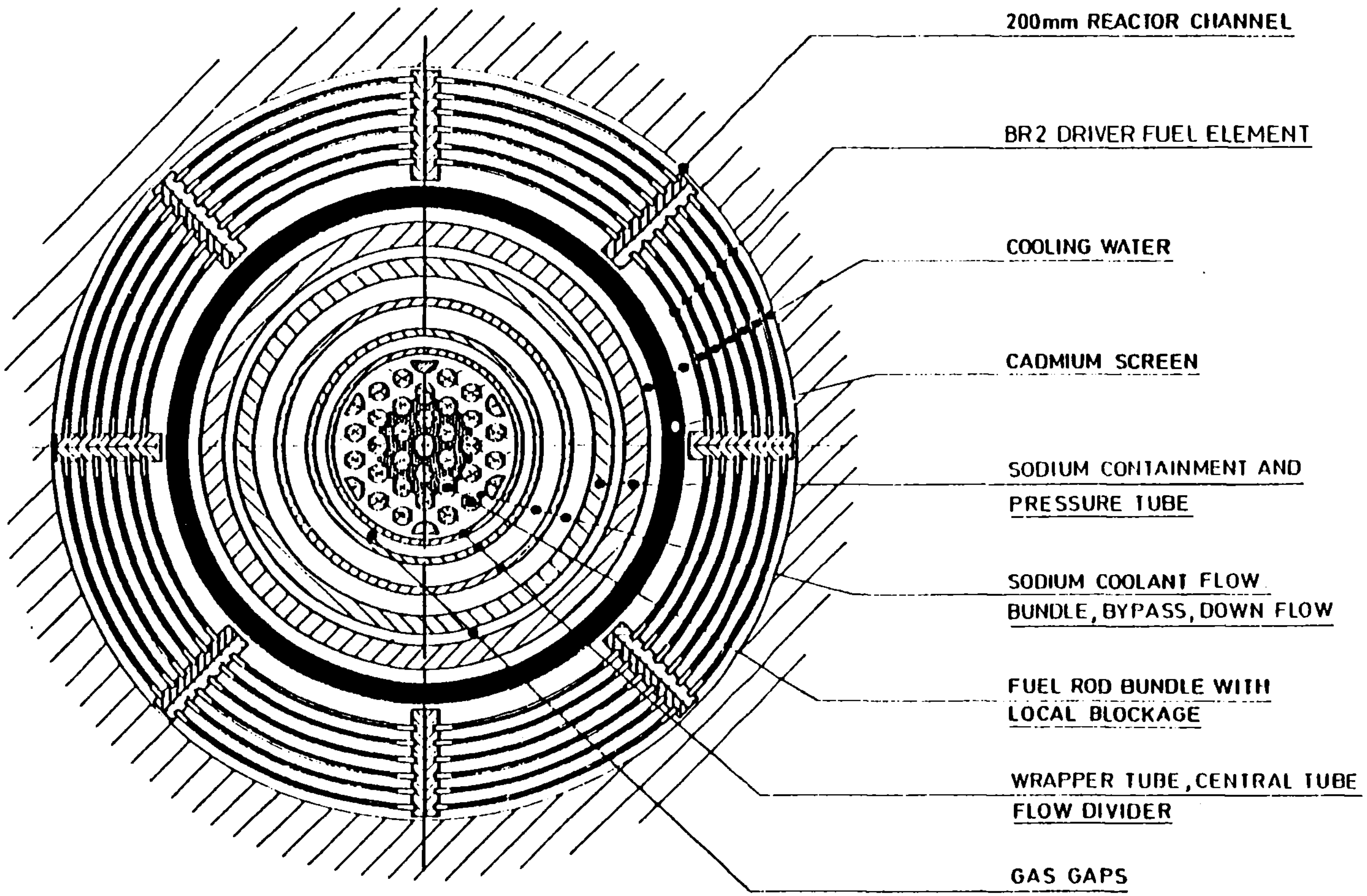


Fig.5. MOL 7C SODIUM LOOP

CROSS-SECTION AT REACTOR MID-PLANE

SCK/CEN TECHN. F. 901.

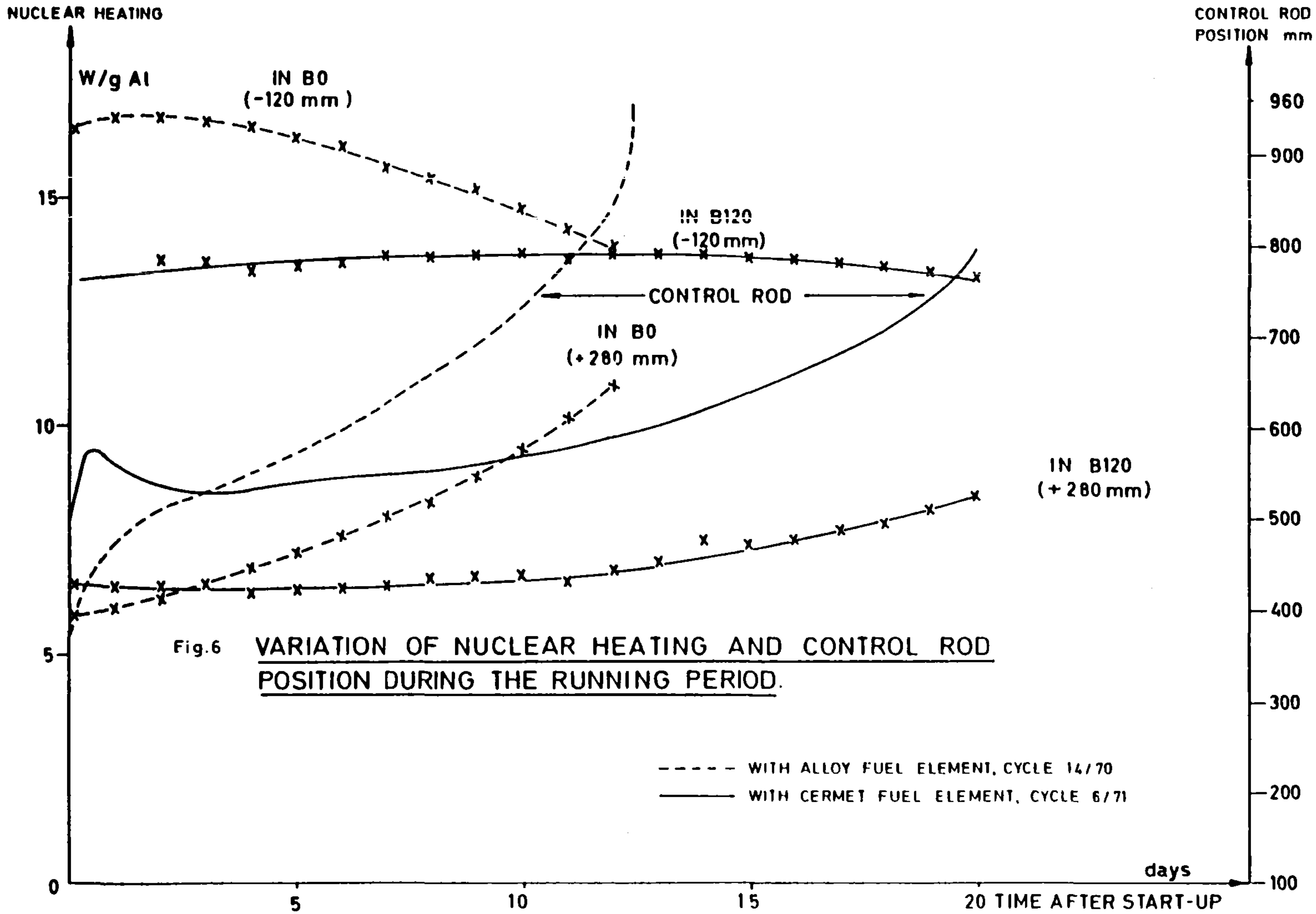
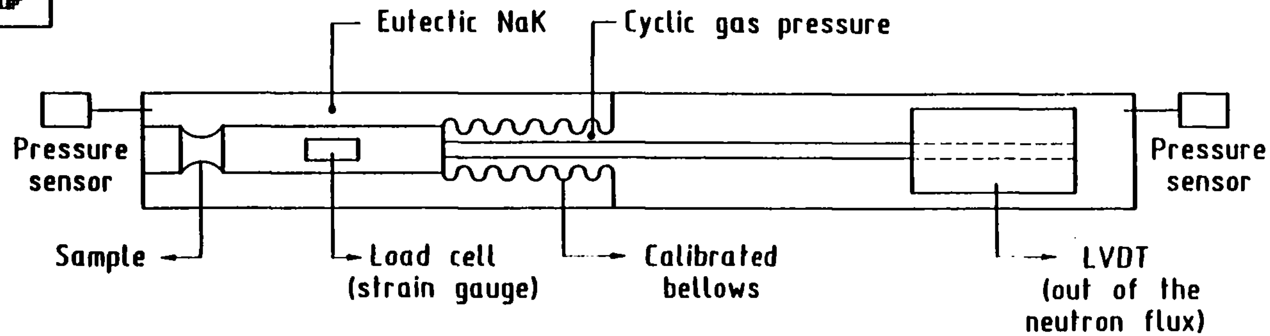


Fig.6 VARIATION OF NUCLEAR HEATING AND CONTROL ROD POSITION DURING THE RUNNING PERIOD.



MEASUREMENTS :

Load : -Pressure Δ + calibrated bellows
-Load cell

Deformation : -LVDT (Linear Variable Differential Transformer: displacement sensor)

CALIBRATIONS :

1. Bellows : before irradiation (in the actual mounted situation)
2. Pressure sensors : can be calibrated every time it is needed by connexion between static-cyclic pressure circuits
3. LVDT : during irrad. by the known clearance (Zeroing system)

Fig.7. FAFUMA-3 : MODULE FOR IN-PILE FATIGUE TESTS. SCHEMATIC VIEW

F1370

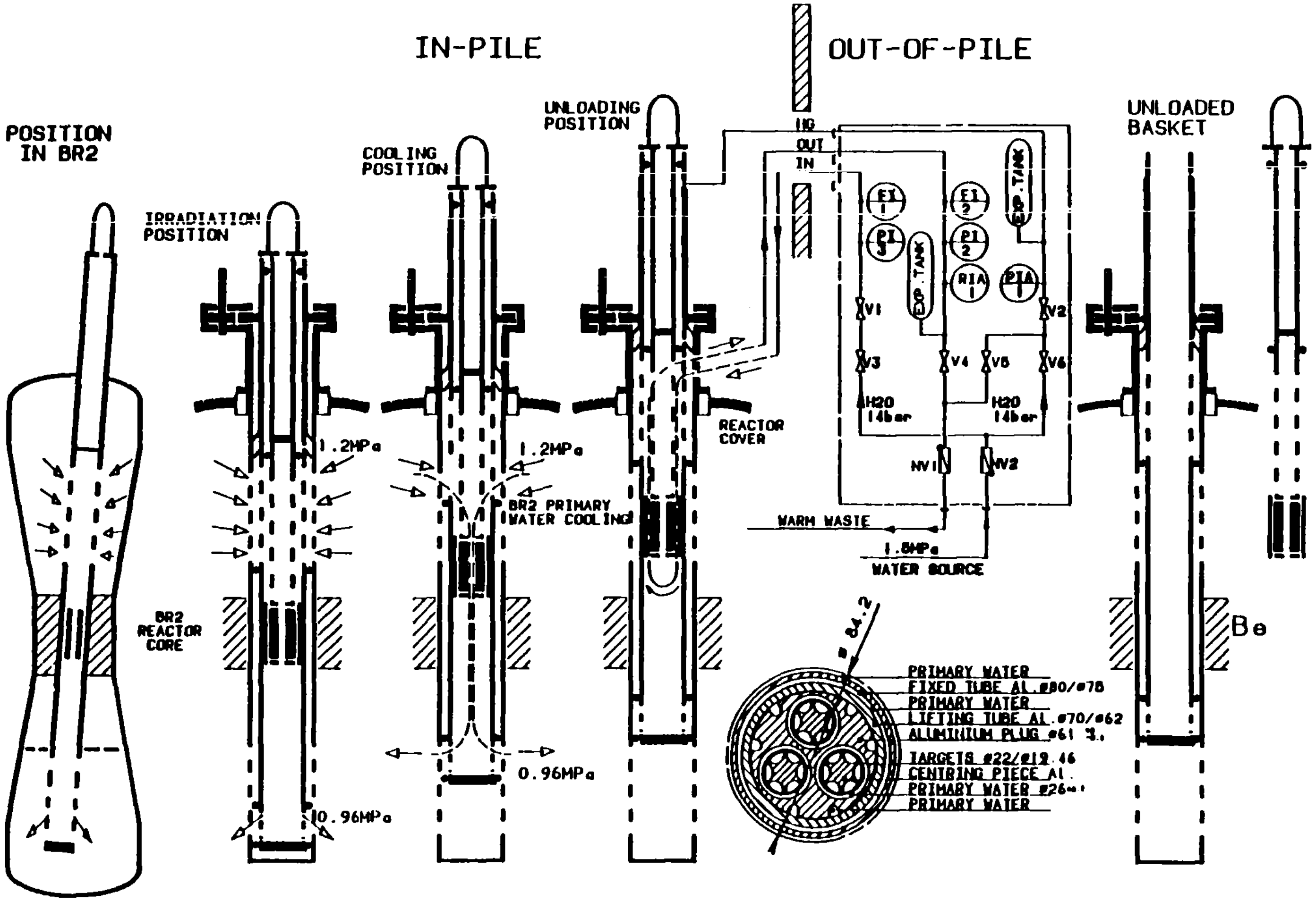


Fig.8. Xe-133 Mo-99 I-131 RADIOISOTOPE PRODUCTION IN BR2 PRF DEVICE

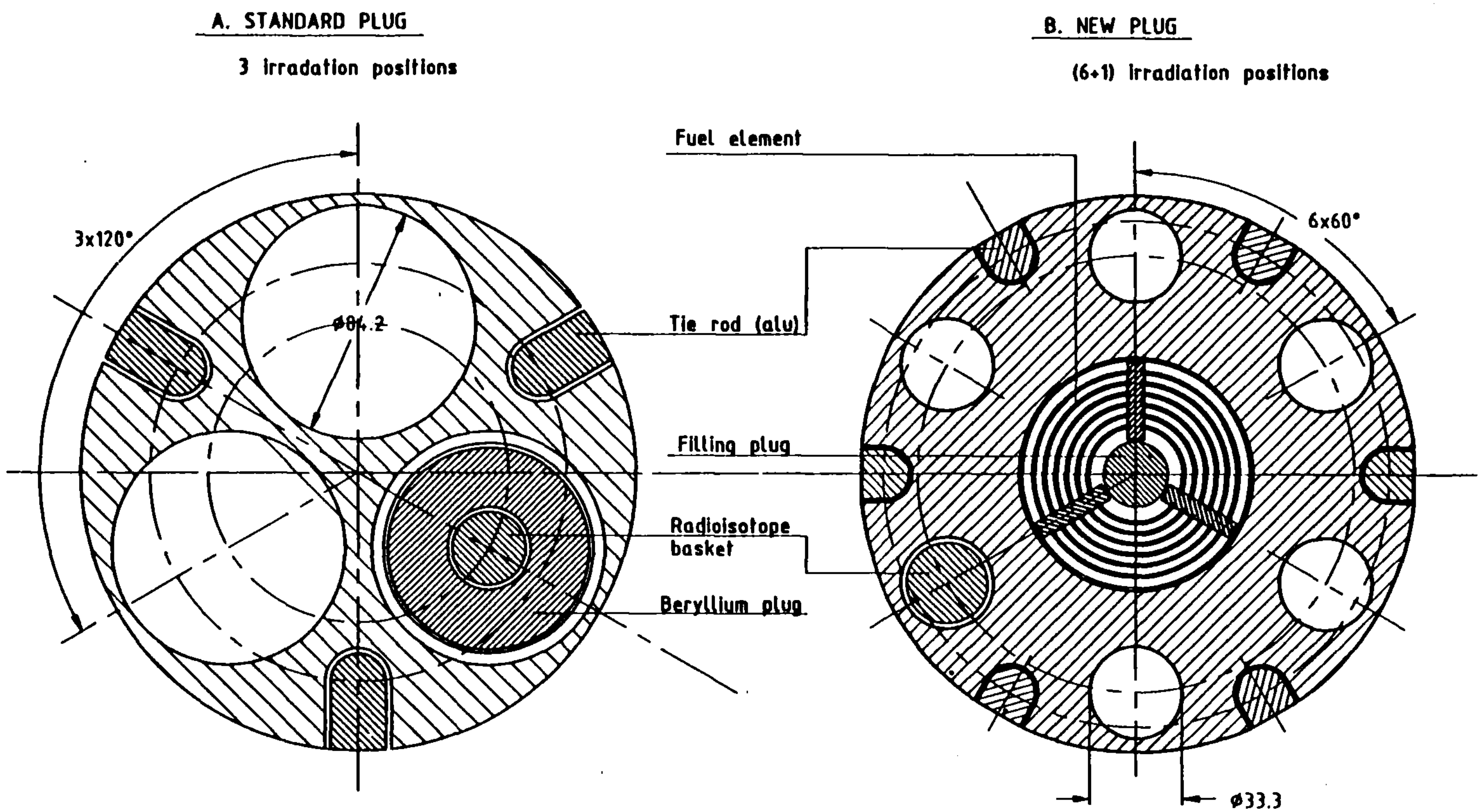


Fig.9 Central channel H1 with a 200mm beryllium plug (cross section)

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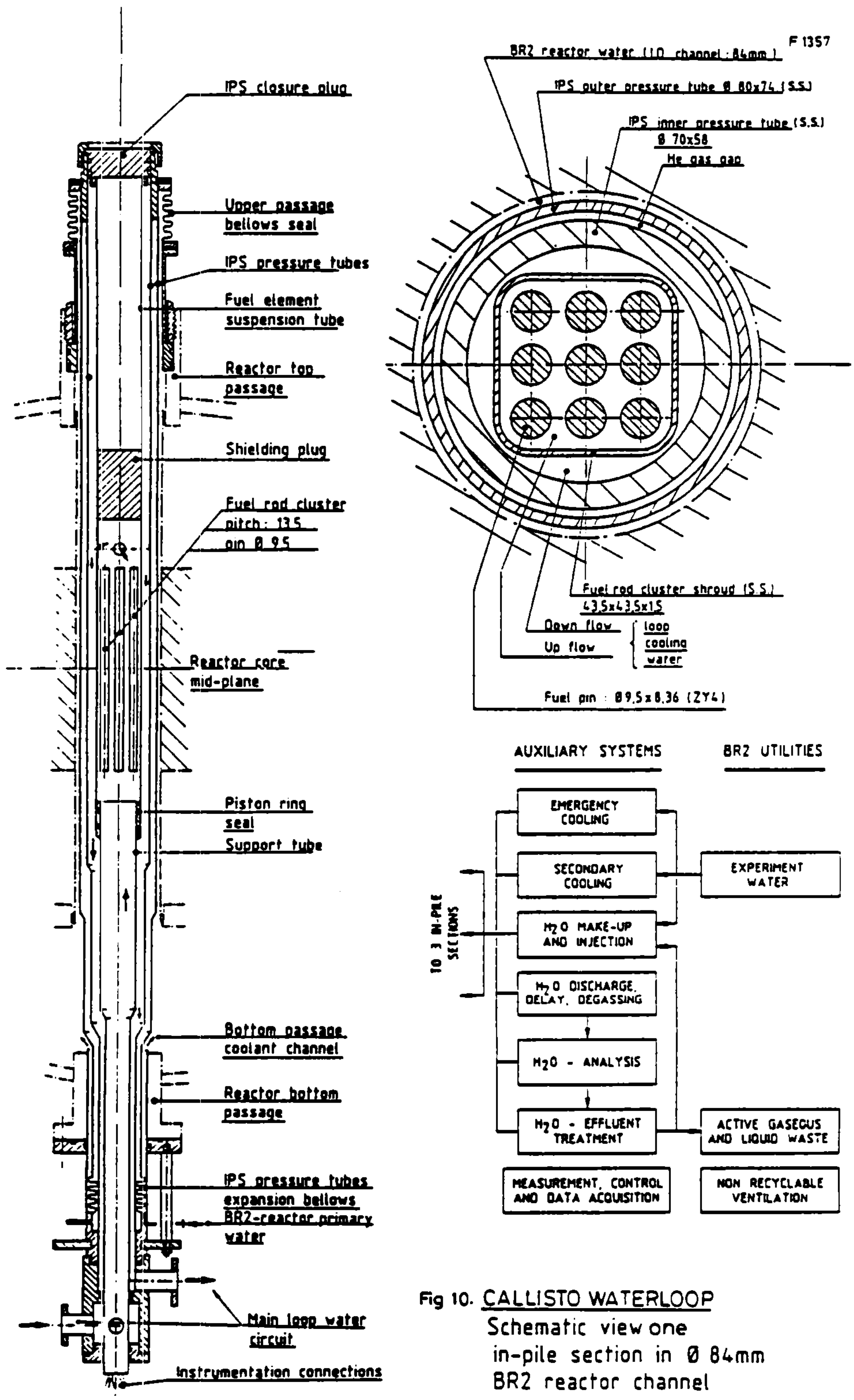


Fig 10. CALLISTO WATERLOOP
Schematic view one in-pile section in Ø 84mm BR2 reactor channel

SIDONIE

POSSIBLE LOADING SCHEMES OF THE BASKET

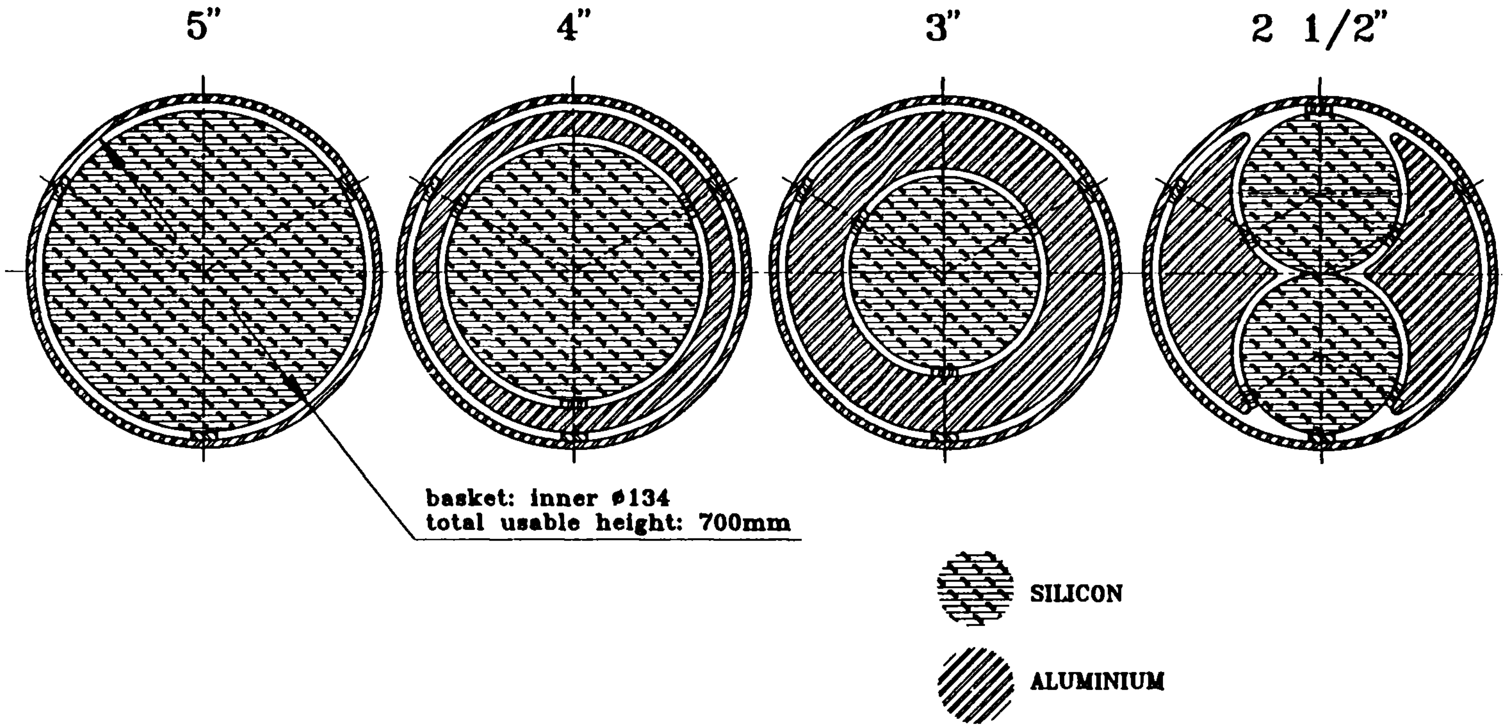


Fig.11 Silicon doping

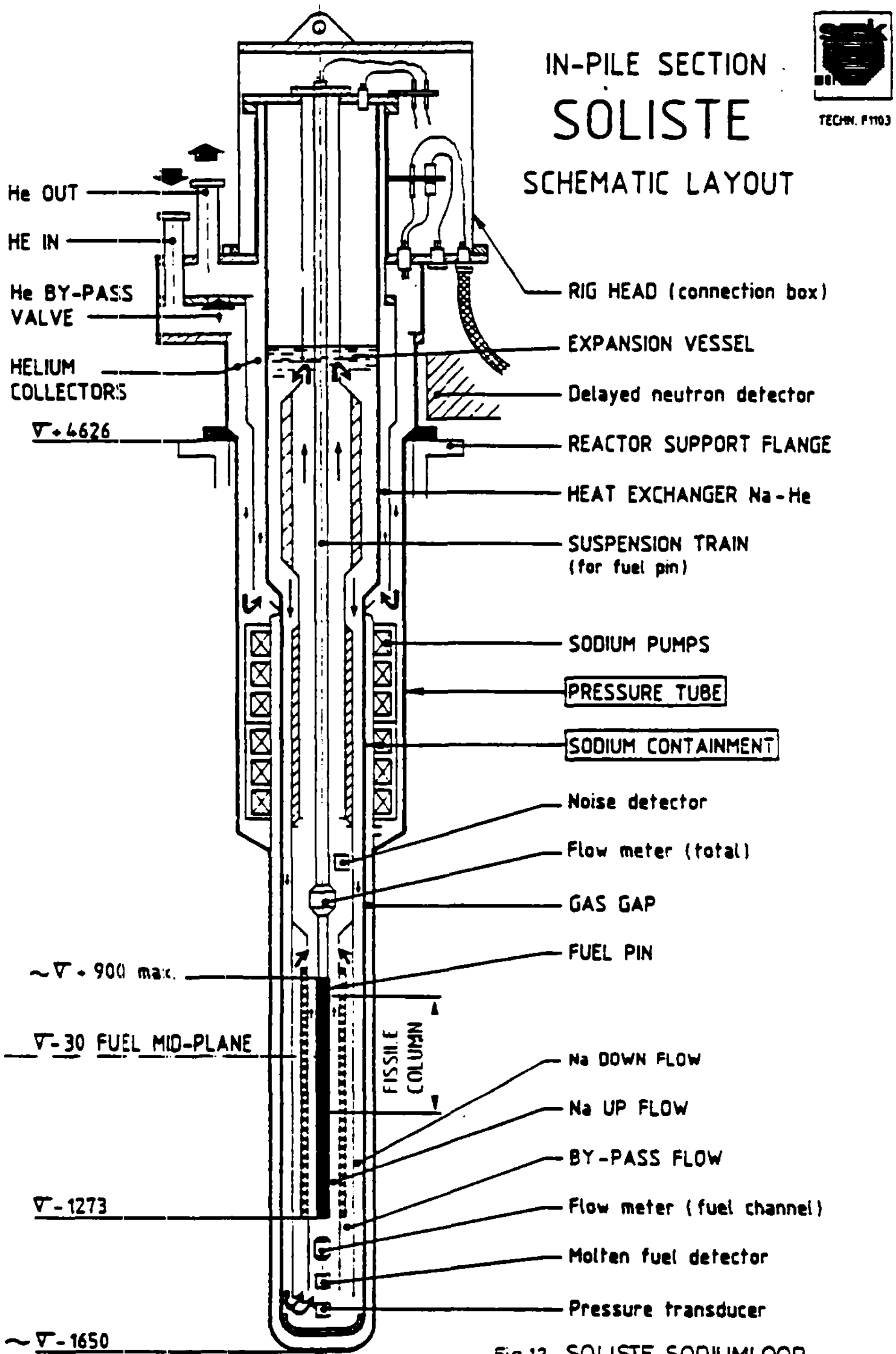
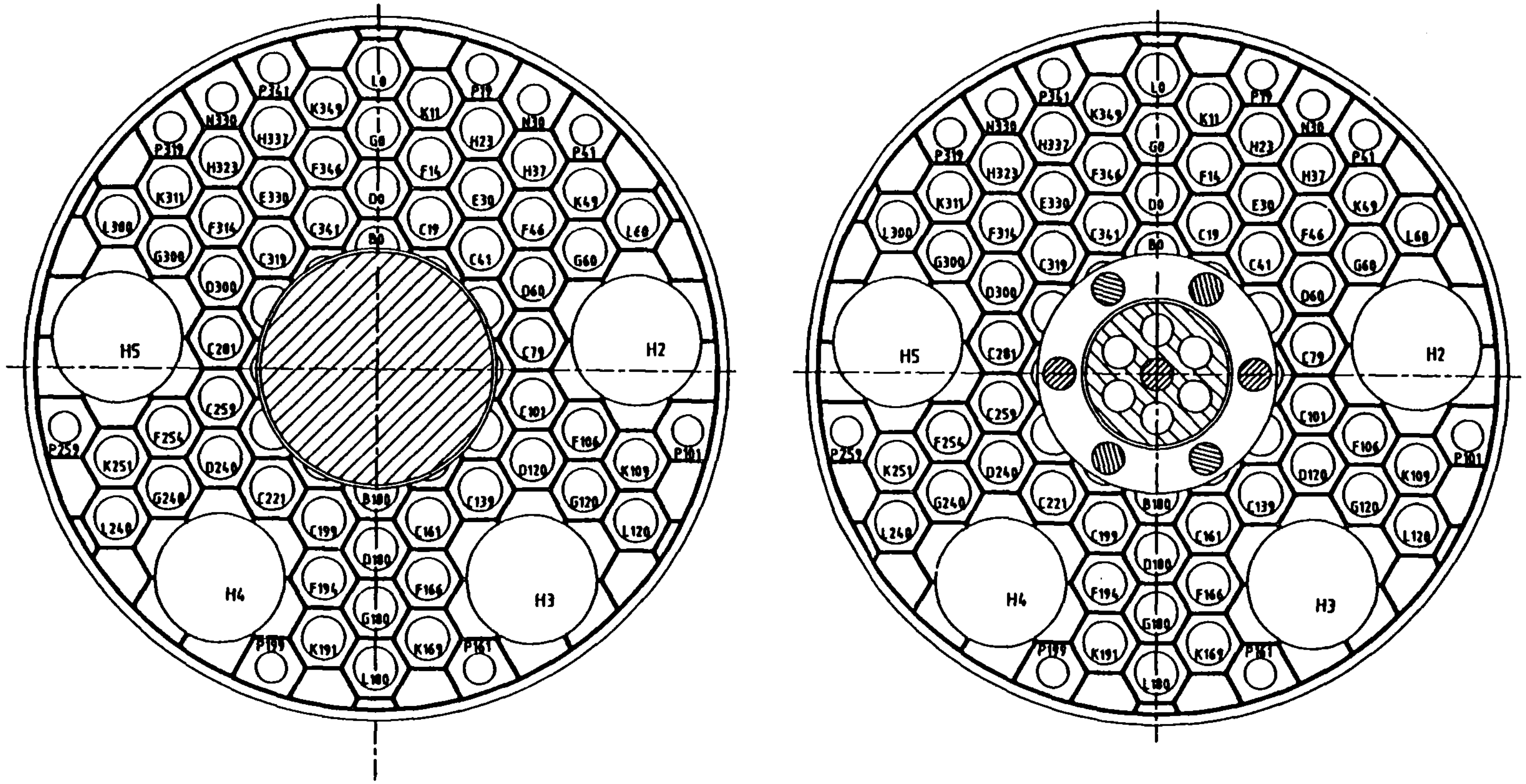


Fig.12. SOLISTE SODIUMLOOP



A. loading: large experimental device

B. loading: filling plug with
-fuel elements
-as ⌀200mm case

Fig.13 BR2 with a central hole of 400 mm diameter

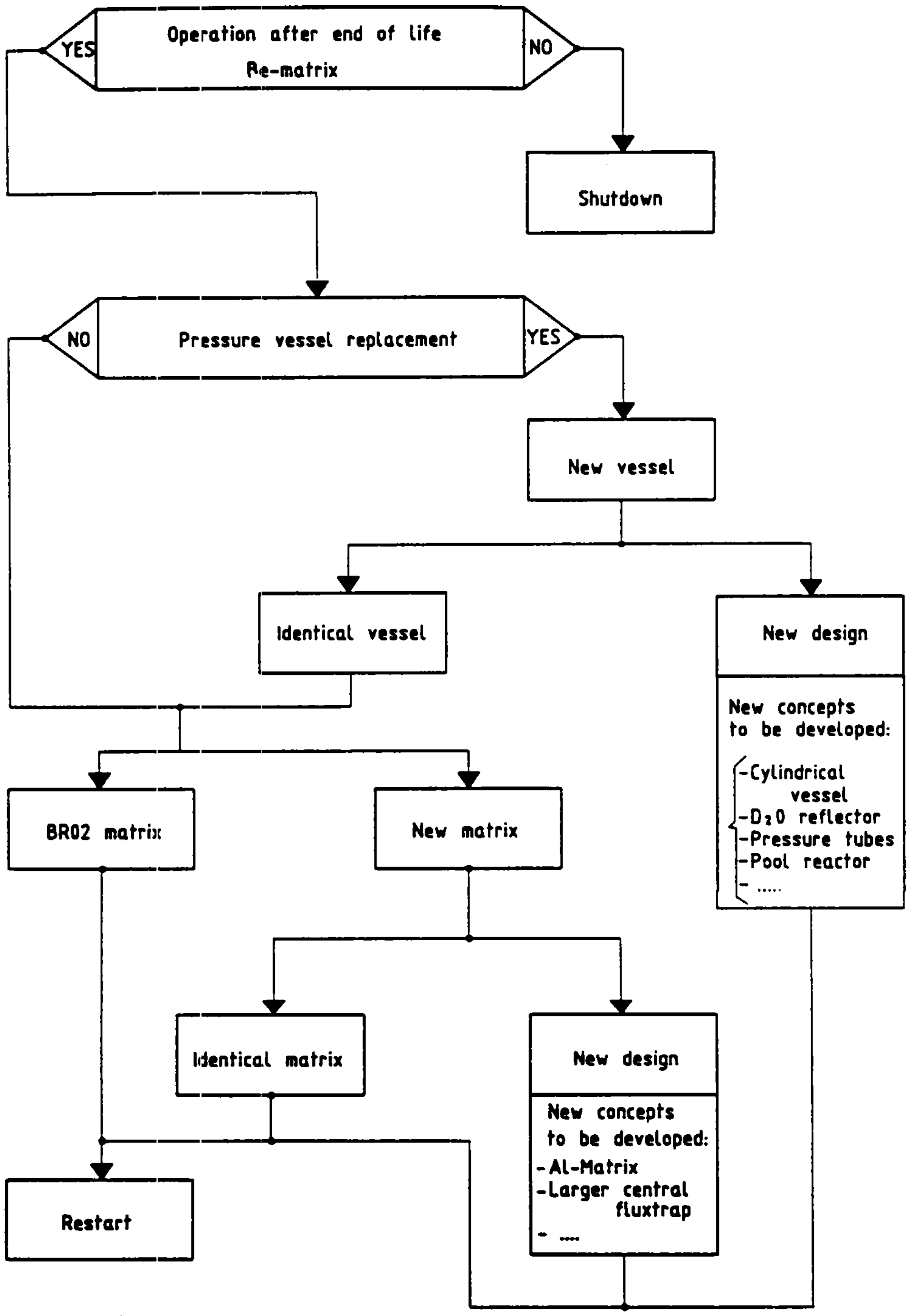


Fig.14 BR2 Long-term strategy

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