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LIQUID METAL REACTOR COOLING SYSTEMS

by Myriam ABERDAM and Gilbert GROS

CONTENTS

FOREWORD

The purpose of this report is to describe the various elements of the cooling systems in the principal liquid-metal-cooled reactors now operating, being constructed, or in the design stage.

Our aim has been to bring together details of the construction and operating characteristics of these liquid metal reactors so as to facilitate their comparison. We do not claim to provide all the details on each subject; for these, reference should be made to the works shown at the end of each sub-section.

In spite of the care taken in compiling the original texts, errors undoubtedly remain; we trust that they are not numerous and ask the reader's indulgence. We should be particularly grateful to anyone drawing our attention to significant omissions or inaccuracies, thereby helping us to complete our work.

The information given here is drawn from reports or publications received during or before September 1964. Periodical revisions, to incorporate new documents or enlarge sections which may appear too brief, are envisaged later.

The report is separated into two volumes. Volume I, "Text", has five parts.

Part I, entitled "General observations on liquid metal cooled reactors", contains the history of these reactors and a description of their general characteristics.

Part II, "Primary cooling systems", is divided into four sections corresponding to the various components of the primary systems.

Part III, "Secondary cooling systems", is divided into three sections corresponding to the various components of the secondary systems.

Part IV, "Miscellaneous", contains a description of the purification systems and measurement techniques.

Part V contains the references.

Lastly, an alphabetical index shows the pages on which the various subjects are dealt with.

In each section the reactors are described in the following order :

I. Fast reactors :

1. EBR 1
2. EBR 2
3. EFFBR

4. PFFBR
5. LAMPRE
6. DFR
7. RAPSODIE
8. BR 5
9. SEFOR

II. Thermal reactors :

10. SRE
11. HNPF
12. SGR (current technology)
13. SGR (advanced technology)

For the last two projects we have only given general details.

After each description will be found, according to the case :

- one or more numbers corresponding to the bibliographical references (all the references mentioned in the text are brought together by components and by reactors in section V B).

- one or more numbers referring to the figures.

- one or more numbers referring to the specifications.

- one or more numbers referring to the comparative tables.

These figures, specifications and comparative tables are to be found in Volume II.

I. GENERAL OBSERVATIONS ON LIQUID METAL COOLED REACTORS.

1. EBR I

Construction of Experimental Breeder Reactor I (EBR I) was started in 1949 by the Argonne National Laboratory (ANL) at the National Reactor Testing Station (NRTS) in Idaho, on the basis of a design produced by Enrico FERMI and Walter ZINN in 1945.

The reactor became critical in August 1951 and was the first to produce electricity from nuclear energy on 22 December 1951.

It was also the first to produce electricity with a plutonium core, in May 1963.

This reactor was principally used for examining the possibilities of breeding and for confirming the hypothesis by which a reactor can function effectively in a high neutronic energy field, by using a high temperature liquid metal cooling system.

It is the only NaK cooled fast reactor to have been in operation for several years. Its thermal capacity is 1200 kW and its electric capacity 200 kW (efficiency 17%).

EBR I operated with four cores. In the first three cores the fuel was uranium 91% enriched with U 235, and in the last an alloy of plutonium and 1.25% aluninum. The first two cores (Mark I, 1951 and Mark II, 1954) had a mean capacity in the core of 170 kW/liter and a specific rating of 20 kW/kg of uranium; their operation was unstable (power oscillations as the result of the positive coefficient of reactivity produced by the bowing of the fuel pins under the effect of the radial thermal gradient), and in November 1955 partial fusion occurred with Mark II. The operation of Mark III was stable, as was that of Mark IV which became critical in November 1962 (mean capacity in the core : 182 kW/liter; specific rating : 33.5 kW/kg of plutonium).

EBR I was finally halted at the beginning of 1964, after 12 years' operation.

References : 1, 2, 4, 5, 6, 7, 16, 60, 120, 158, 160.

Figure I-1 : Layout of the reactor.

Table I-1 : Capacity of the reactor.

Comparative table I : Cost of the reactor

II : General characteristics.

2. EBR II

Construction of Experimental Breeder Reactor II (EBR II), undertaken by the Argonne National Laboratory (ANL) in the framework of the Civilian Power Reactor Development Five Years' Program, was started in 1957 on the same site as EBR I, at the National Reactor Testing Station (NRTS) in Idaho. The plant was completed in August 1961, and dry criticality experiments, i.e. without sodium, began in September 1961.

It became critical, with sodium circulation, in 1963, but had to be halted following trouble with a pump shaft. It will become critical again in May 1964 and should produce electricity in August 1964.

The nominal thermal rating is 62.5 MW (th); net electric power production (16.5 MW e) is used by the NRTS. The net thermal efficiency is 26.4%. The mean specific rating is 311 kW per kg of U 235, and 735 kW/l.

The thermal performance and the size of the components of the system are such that it is possible to extrapolate directly to electric power plant construction. The principal fields of research in which EBR II is used are :

1. Obtaining an economic fuel cycle.
2. Obtaining reactor safety without prejudicing the economic potential.
3. Improvement and simplification of liquid sodium technology.

The first core uses an alloy with 95% uranium containing 48% U 235. Plutonium is to be used in the second core.

This is the first reactor in the US Power Reactor Demonstration Program to operate with a closed fuel cycle; this means that the recycling of the fuel and the fuel element fabrication plant form part of the nuclear power plant itself.

References : 1, 4, 5, 6, 8, 9, 10, 13, 55, 56, 57, 70, 152, 158, 160.

Table II-1 : Capacity of the reactor

Figure II-1 : Diagram of the systems

II-6 : Cross-section of the primary system

Comparative table I : Cost of the reactor

II : General characteristics.

3. <u>EFFBR</u>

Construction of the Enrico Fermi Fast Breeder Reactor (EFFBR) was started in 1956 at Lagoona Beach (Michigan).

In addition to the AEC, three separate organisations are taking part in this work. They are : Atomic Power Development Associates (APDA), Power Reactor Development Co. (PRDC), and Detroit Edison Co.

With an initial scheduled capacity of 300 MW (th) and 90 MW (e), this will be the largest fast breeder reactor in the world. (However, it should be mentioned that EFFBR core A, scheduled for 90 MW (e), has had to be modified because of difficulties which arose with the fuel subassemblies). Consequently, a new subassembly which is thermally more stable but has higher charge losses has had to be designed, restricting the capacity to 200 MW (th) and 65 MW (e). The systems, however, are calculated for the maximum capacity of the reactor (430 MW).

In the first case, the nominal specific rating was 635 kW/kg U 235; with the new subassembly it is only 350 kW/kg U 235. Similarly, the mean capacity in the core has dropped from 850 kW/l to 460 kW/l.

The net thermal efficiency is 30.5%.

A number of incidents delayed the completion of the reactor. It became critical for the first time on 23 August 1963. Nuclear tests are continuing until July 1964 at the authorised rating of 1 MW (th). Provided that further authorisation is obtained from the Atomic Energy Commission, the reactor will subsequently be raised to a rating of 110 MW (th) (28 to 30 MW (e)) until July 1968, for system and fuel tests with a maximum sodium temperature of 300°C. The core will then have to be changed in order to reach the nominal rating of 200 MW (th).

Since the fuel used at present (an alloy of enriched uranium and zirconium) has not given satisfaction, other possible fuels are being examined.

The electric power produced by the reactor will supply the grid of the Detroit Edison Co., which serves south-east Michigan. The Detroit Edison Co. has announced the installation of a conventional boiler which will permit the production of electricity even when the reactor is used for research purposes.

References : 1, 4, 5, 11, 12, 13, 14, 15, 71, 126, 158, 160.

Figure III-1 : The leakproof building with the reactor and primary systems.

Table III-1 : Capacity of the reactor.

Comparative table I : Cost of the reactor

II : General characteristics.

4. PFFBR

The Plutonium Fueled Fast Breeder Reactor (PFFBR) is being designed by Atomic Power Development Associates (APDA).

Its construction (to begin, theoretically, in 1965) is likely to be based largely on that of EFFBR, but certain alterations are to be made in order to reduce capital costs, chiefly under the following four heads :

- protection of the reactor vessel
- reloading of the core
- cooling systems
- neutronic protection.

The thermal rating will be 775 MW (th) and the reactor will produce 300 MW (e). The thermal efficiency will be 36.7% and the specific capacity in the core will be 420 kW/l. A second survey has been made for an electric capacity of 150 MW.

Numerous types of fuel has been considered for PFFBR :

1. PuO_2 - UO_2
2. PuO_2 - UO_2 in a matrix of uranium alloyed with 15% molybdenum
3. an alloy of plutonium and uranium with fission products
4. a plutonium and uranium carbide
5. a uranium nitride.

Most detailed consideration has been given to the first type of fuel.

Reference : 18

Figure IV-2 : Layout of the systems

Comparative table I : Cost of the reactor

II : General characteristics.

5. LAMPRE I

The Los Alamos Molten Plutonium Reactor Experiment I (LAMPRE I) is a homogeneous experimental fast neutron reactor using molten fuel. It was built for the AEC at the Los Alamos Scientific Laboratory, Los Alamos (New Mexico).

Criticality tests without sodium took place in January 1960 and the reactor became critical in April 1961 with a thermal rating of 1 MW released into the atmosphere via an air exchanger. (There is no secondary system).

The mean specific rating is 40 kW/kg.

The purpose of the reactor is :

1. To experiment with the use of molten metal fuels (Pu-Fe or Pu-Co-Ce eutectic)

2. To determine suitable recipients for these fuels

3. To analyse the emission of fission gases obtained from these molten fuels

4. To consider the adaptability of this type of reactor to future power breeder reactors.

The fuel is a molten alloy consisting of 90% Pu and 9.5% Fe by weight, enclosed in tantalum cladding.

The reactor was shut down in February 1964. A third core consisting of a plutonium-cobalt-cerium alloy was scheduled, but this project was abandoned due to welding problems with the tantalum and because better manpower utilisation was expected in laboratory work than in operating the reactor. All the necessary information on the physics of the reactor, and its control, are considered to have been obtained; research on the new fuel alloy will be done in the Omega West research reactor.

References : 1, 4, 6, 16, 19, 20, 158, 160.

Comparative table II : General characteristics.

6. <u>DFR</u>

Planned in 1953 to obtain further experience in the design of semi-industrial fast reactors, construction of the Dounreay Fast Reactor was started at Dounreay (Caithness, Scotland) in 1955 for the United Kingdom Atomic Energy Authority. The reactor became critical for the first time on 14 November 1959. The first fuel used was an alloy of chromium and uranium 45.5% enriched with isotope U 235. Problems concerning entrainment of the blanket gas and purification of the liquid metals had to be solved. Since July 1962 the reactor has operated with a new fuel (molybdenum and uranium alloy). Its thermal rating was 30 MW for a year, and it was then raised to 50 MW on 5 July 1963.

The thermal and electric capacities are 72 MW (th) (60 in the core, 12 in the blanket) and 12 MW (e) respectively. The thermal efficiency is 20% and the mean specific rating is 286 kW/kg U 235 and 460 kW/l in the core.

The main future objectives of DFR are :

1. Investigation of the operating and safety characteristics of this class of reactor.

2. Examination of the kinetic behavior of the reactor when subjected to changes in reactivity or coolant flow.

3. Obtaining fast neutron fluxes for the testing of fast neutron reactor fuel and structural material.

4. Later development of active liquid metal systems.

5. Examination of general problems connected with the use of plutonium fuel.

It should also be mentioned that Great Britain is about to start construction of its power fast reactor prototype (PFR). The reactor is likely to have thermal and electric capacities of 600 MW (th) and 250 MW (e), using plutonium as the fuel element. Completion is scheduled for around 1970. This construction will be a step towards a 1500 MW (th) power reactor.

References : 4, 16, 22, 23, 24, 25, 26, 27, 79, 158, 160.

Figure VI-1 : General layout of the plant

VI-2 : Reactor and primary systems

Comparative table I : Cost of the reactor

II : General characteristics.

7. RAPSODIE

Design of Rapsodie, the first French sodium-cooled fast breeder reactor, was begun in 1957 at the Commissariat à l'Energie Atomique. The initial project appeared in December 1958, and construction work started at Cadarache (Bouches-du-Rhône) in 1961. It is scheduled to become critical with sodium in 1967. In July 1962 the CEA and Euratom concluded an agreement whereby Euratom shares in the research and development work involving this reactor. The mock-ups for 1 and 10 MW capacity systems have been built.

The maximum scheduled thermal capacity is 20 MW; this power will not initially be converted into electricity. The mean specific rating is 450 kW/l, and the maximum specific rating at the center of the core is particularly high, 700 kW/l, which should permit a valid study to be made of the technological problems of future reactors of this type. It should also enable static and dynamic behavior to be studied and its rather high neutron flux (10^{15} neutrons/cm^2.s) will permit the irradiation of fuel elements for future reactors under advantageous conditions.

The choice of fuel lay between two formulae : a metal uranium-plutonium-molybdenum alloy, and a ceramic composed of a mixture of uranium and plutonium oxides (UO_2-PuO_2), 75% UO_2, 25% PuO_2. The oxide ceramic was selected. This choice only affects the charge for the first Rapsodie core, and in no way precludes later testing of other fuel formulae (mixed carbides, plutonium and uranium alloys).

The objective is the construction of a 1000 MW (e) power plant; this rating is suitable for the French grid. An intermediate 80 MW (e) reactor is scheduled, to provide experience in industrial construction and permit fuel preparation, reprocessing, and refabrication.

References : 4, 28, 158, 160 and private communication

Figure VII-11 : Cross-section of the reactor block

Comparative table : General characteristics.

8. BR 5

BR 5 (fast reactor 5) was intended as an intermediate stage between the 0.1 MW (th) experimental reactor BR 2 and the 200 MW (th) power plant BN 50. The latter (50 MW (e)) was abandoned in favor of a larger project (1000 MW (th), 350 MW (e)).

To reduce the time required for its construction, BR 5 was set up at Obminsk on the site of dismantled reactor BR 2, thereby enabling part of the equipment from the latter to be used. The reactor is not enclosed in a leakproof building.

Completed in 1958, it became critical in the summer of 1958 and operated on power in 1959.

Its thermal capacity is 5 MW and it does not produce electricity, the heat given off being discharged into the atmosphere and the water coolant. The mean specific rating in the core is 460 kW/l and 100 kW/kg of plutonium.

The reactor is designed to solve the following technological problems :

- sodium cooling under irradiation
- behavior of fuel elements
- possible irradiation rate
- material tests in a fast neutron flux

The problems of neutronics, control, the conversion rate, etc., were solved with preceding reactors.

The fuel used is plutonium oxide.

References : 3, 4, 16, 29, 30, 72, 158, 160.

Figure VIII-1 : Lengthwise cross-section of the reactor

Comparative table II - General characteristics

BN 350

After their experimental reactor BR 5, the Russians had planned to build a power reactor BN 50 (200 MW (th), 50 MW (e)) with sodium input and output temperatures of 315 and 450°C respectively and U-Mo alloy fuel.

In 1960 this intermediate project was abandoned in favor of a plan for a more powerful reactor operating with much better parameters; this is the 1000 MW (th), 350 MW (e) BN 350. The sodium temperatures are 300 and 500°C.

The fuel selected is a UO_2-PuO_2 ceramic. The specific capacity is 500 MW (e).

The central part of the subassemblies contains the fuel; the ends of the subassemblies, enclosing depleted UO_2, act as the axial blanket.

The next project is a 1000 MW (e) power plant BN 1000; the fuel is likely to be uranium monocarbide, permitting a regeneration rate of 1.75 to be reached. Steam would be produced at 580°C and 240 bars.

To examine the technological problems which occur at high temperatures, it was decided to build pilot fast reactor BOR. Its thermal capacity is likely to be from 40 to 60 MW, with a power density of 1500 kW/e. The sodium output temperature will probably be between 630 and 650°C.

Reference : 165.

9. <u>SEFOR</u>

The Southwest Experimental Fast Oxide Reactor (SEFOR) will be built near Fayetteville (Arkansas) for Southwest Atomic Energy Associates (SAEA) in collaboration with General Electric (G.E.), the Karlsruhe Nuclear Research Laboratory, the Atomic Energy Commission (AEC), and Euratom.

The details of this new fast reactor project were settled in May 1963. It will be an experimental plant with a 20 MW thermal capacity, not producing electricity (the heat produced in the secondary system will be discharged into the atmosphere). The construction contract for SEFOR was signed in May 1964.

The SEFOR reactor will be the first of a string of large fast reactors using a PuO_2-UO_2 (U 238) mixture as fuel (fast ceramic fuel reactors).

This reactor is designed :

- to study the operating characteristics of PuO_2-UO_2 large fast reactors.
- to determine and study Doppler effect under normal operating conditions.
- to determine Doppler arrest effect under transient conditions.
- to establish technological safety criteria for large industrial plants.

SEFOR is also referred to as EFCR (Experimental Fast Ceramic Reactor). Its construction will be followed by that of a 100 to 300 MW (e) prototype (completed in 1970) and then that of a 500 MW (e) reactor (FCR) in service in 1975 (scheduled thermal capacity : 1400 MW; the reactor and the primary system, consisting of four sodium circuits, will be set up in the primary tank, 12 m. in diameter).

References : 149, 150, 151, 158, 160.

Figure IX-1 : Cooling systems

Table IX-1 : Reactor characteristics.

SODIUM-COOLED GRAPHITE-MODERATED REACTORS

General Observations

When North American Aviation Inc. (NAA) was charged by the AEC in 1949 with designing a string of reactors providing plutonium and electric power at competitive prices, its choice fell upon sodium-cooled graphite-moderated thermal reactors. (The utilisation of graphite, with its excellent high temperature characteristics, in a sodium cooled reactor enables maximum benefit to be obtained from the coolant properties of sodium; heat fluxes in the core of around 3.5 MW/m^2, and power densities of the order of 10 kW (e)/kg U, can be produced).

This choice was approved by the AEC and it was decided to design and construct these types of reactor in the framework of the US AEC Civilian Power Reactor Program.

Development of the sodium-graphite string for the production of a profitable power reactor is backed by a vast research and development program of which the Sodium Reactor Experiment (SRE) and the Hallam Nuclear Power Facility experimental reactor are part.

At the same time this general program for the development of the sodium-graphite reactor (SGR) has given rise to research on current and advanced technology reactors, which should produce the data required to execute a 1000 MW (e) power plant project.

References : 33, 38, 45.

10. SRE

Atomics International (AI) (Division of North American Aviation Inc. (NAA)) was charged with the design and construction of the Sodium Reactor Experiment (SRE), which is financed by the AEC with a substantial contribution from NAA (the plant belongs to the AEC which meets the cost of operation involving AI personnel).

Design of the reactor began in July 1954, construction started in April 1955 in the Santa Susana Mountains, near Los Angeles (California), and SRE became critical for the first time on 25 April 1957 with sodium at 177°C in the core. It operated on power on 21 May 1958. The fuel elements were damaged in July 1959 following a tetraline leak from the primary pump. The reactor became critical with the second core on 5 September 1960. Its thermal capacity is at present 20 MW, and it is planned to raise this to 45 MW (th) later. The thermal efficiency was 28% with the first core, and with the new core it is 31%. In the new core, the mean specific rating has increased from 255 to 275 kW/kg U 235.

The net electric power produced by SRE (5.6 MW (e)) supplies the network of the Southern California Edison Co.

SRE was specially constructed to demonstrate the practical value of the sodium-graphite string. Although it is primarily an experimental plant, and not a proper pilot station, it has a large number of the features which are desirable in an industrial-scale plant.

The results from four years' operation are very satisfactory. Over this period, the relatively small power plant (6 MW (e)) produced 15,331,050 kW/h of electric power. SRE has operated for 3000 hours at a core output temperature of 530°C. Shorter tests were also carried out at core output temperatures of 570°C, in order to determine the characteristics of the steam generator at a steam temperature of more than 538°C.

The system appeared stable and reliable under these conditions.

The fuel used in the first charge was 2.8% enriched non-alloyed metallic uranium. Power density in the core : 4.2 kW/l. The charge of the second core, in use at present, is composed of pellets of a uranium-thorium alloy containing 7.6% uranium; this enriched uranium contains 93% U 235.

The third core will consist of uranium monocarbide clad with zircaloy 3 Z 1 (an alloy developed by AI). This substance will enable a capacity of 40 MW (th) to be attained; in addition, it tolerates continuous operation at a sodium output temperature of 650°C and a steam temperature of 538°C (which was experimentally obtained with the first core); by this alteration, SRE will become a plant for experimental work under really advanced conditions on the fuels and structural elements of sodium-cooled reactors.

References : 1, 6, 31, 32, 33, 34, 35, 36, 37,
38, 39, 158, 160

Figure X-7 : Cross-section of the reactor

Table X-1 : Capacity of the reactor

X-4 : Comparison of present and as-altered SRE

Comparative table I : Cost of the reactor

II : General characteristics.

11. HNPF

Design of the Hallam Nuclear Power Facility (HNPF), designed and constructed by Atomics International, began in 1955.

The contract between the AEC and the Consumers Public Power District (CPPD) was signed in September 1957, authorising construction, and building began at Station Sholdom, at Hallam near Lincoln (Nebraska), in April 1959, reaching completion in July 1961. Dry criticality tests took place on 19 January 1962. The reactor became critical with sodium on 25 August 1962, and produced electricity for the first time on 29 May 1963.

Its thermal and electric capacities are 240 MW (th) and 76 MW (e) respectively. The plant's net efficiency is 31.5%.

The mean specific rating is 240 kW/kg U 235 (4.8 kW/l).

The prudent design of this reactor is based on the experience and data obtained from the construction and initial operation of SRE.

The purpose of this reactor is to demonstrate the economic and technical possibility of producing a power plant using a sodium-graphite reactor and operating the plant so that it will produce the maximum quantity of electric power (there is little hope, however, that the cost price per kWh for this relatively small reactor will be competitive).

The temperature of the Na coolant and the fuel surface, as well as the steam pressure and temperature, are higher than in the other reactors in the first section of the AEC demonstration program.

The fuel used in the first charge will be 3.6% enriched uranium with 10% molybdenum; the elements will gradually be replaced with elements containing uranium monocarbide for higher temperatures.

The chief differences between SRE and this reactor are :

- the far more economic utilisation of stainless steel for the moderator cladding (the SRE cladding is zirconium). This alteration also gives better resistance at the operating temperatures.
- the installation of three recycling-type steam generators instead of the non-recycling generator in SRE.

The sodium temperature will be 507°C (but it is thought that it will be possible to raise it to 538°C and reach a capacity of 91 MW (e)).

References : 1, 33, 39, 40, 41, 42, 43, 44, 76, 89, 121, 158, 160

Figure X1-1 : Preliminary design of the reactor hall

XI-9 : Detailed diagram of the reactor

Table XI-1 : Capacity of the power plant

Comparative table I : Cost of the reactor

II : General characteristics.

12. SGR - Current technology.

Atomics International have prepared an initial design as an intermediate stage in the gradual development of sodium-graphite reactor technics.

This is an atomic power plant consisting of a sodium-graphite reactor with steam generators and turbine, of a nominal capacity of 300 MW (e). The thermal capacity is 855 MW.

The fuel used will be uranium with 10% molybdenum.

The design of this plant has a sound basis in the experiments made with SRE and the research and development data obtained from the HNPF program.

There are two important differences between this design and that of the HNPF :

- utilisation of single-wall tubes in the steam generator, instead of the double-wall tubes in the HNPF.
- use of expansion blowers in the sodium circuit instead of the expansion filters used at Hallam.

These two alterations reduce costs considerably.

The design of the reactor is comparable to that of the HNPF.

Operation is normal at a pressure of 86 bars at 455°C at the turbine inlet. Under such conditions, overall thermal efficiency of 37.8% may be obtained.

References : 45, 46.

Figure XII-1 : Diagram of the systems

Comparative table I : Cost of the reactor.

13. SGR - Advanced Technology.

Atomics International has also designed an advanced sodium-graphite reactor. This plant is scheduled to have a thermal capacity of 606 MW and an electric capacity of 265 MW. The specific rating is 1400 kW/kg U 235. The steam will be produced at 170 bars, superheating will raise it to 565°C with reheating at 538°C. The net thermal efficiency will be approximately 43%.

The fuel selected is slightly enriched (2.75%) monocarbide. The Calandria, a stainless steel tank inside the reactor vessel which is also stainless steel, contains hexagonal blocks of unclad graphite for moderation and reflection.

As in EBR II, the primary system is immersed in sodium.

Reference : 47.

Figure XIII-3 : Reactor (piping and apparatus)

Comparative table I: Cost of the reactor.

Other SGR Projects (sodium-cooled graphite-moderated reactors).

There are further projects for sodium-graphite reactors, such as the 200 MW (e) one designed by General Electric and another 500 MW (e) one. Both reactors could be built by 1968-69. They would be the prototype for a 1000 MW (e) reactor. The 200 MW reactor would have a single system, the 500 MW reactor two systems in parallel, and the 1000 MW reactor five systems in parallel (possibly with supercritical steam).

References : 136, 137.

II. PRIMARY COOLING SYSTEMS

II A GENERAL OBSERVATIONS

1. EBR I

The primary cooling fluid is NaK. There is only one primary circuit and the pile input and output temperatures are 228 and 316°C respectively. The volume flow is 65 m^3/hr. In this circuit there are two pumps (a main electromagnetic pump and a centrifugal emergency pump) and an intermediate exchanger with a non-removable tube system. The NaK is purified by means of sintered stainless steel filters and a cold trap. Argon acts as blanket gas, at a pressure of 0.35 bars.

The NaK flows from the top downwards in the blanket, and from the bottom upwards in the core.

The coolant enters the reactor vessel above the radial blanket, spreads through the collector, crosses the upper centering plate, flowing through the upper holes of the subassembly, and goes down the radial blanket pins to the bottom of the vessel. The direction of flow is then reversed and the fluid rises through the fuel subassemblies, crosses the support plates, discharges via the upper holes into a collector, and leaves the vessel laterally through a pipe situated above the admission pipe.

The reactor is supplied with NaK from a supply tank on charge. The NaK flows successively through the reactor, the intermediate exchanger and the storage tank, and then returns to the supply tank.

As the cooling fluid is NaK, a pre-heating system is not necessary.

The materials used are 347 stainless steel, inconel, nickel-chrome steel, and A nickel.

Most of the reactor and system components are made of 347 stainless steel. The tubes of the intermediate exchanger are A nickel, the piping of the electromagnetic pump is nickel-chrome, and the safety tank is made of inconel.

References : 2, 5, 60, 69, 120

Figure I-1 : Diagram of the circuits

I-2 : General diagram of the reactor

I-3 : Cross-section of the internal vessel

Table I-2 : Cooling systems

Comparative table III : Primary systems.

2. EBR II

The reactor and the primary system (pumps, heat exchanger) are inside the primary vessel and operate immersed in sodium.

There is only one primary circuit and the coolant fluid is sodium. The reactor input and output temperatures are 371 and 482°C respectively and the flow rate is 1860 m^3/hr.

This primary circuit has two centrifugal main pumps in parallel, an electromagnetic auxiliary pump and an intermediate exchanger with a removable tube system. A cold trap purifies the sodium.

The casing of the intermediate exchanger is permanently fixed to the primary vessel cover, but the tube system, collectors and sodium connections, and the protection cap can be dismantled vertically in one unit.

Argon is used as the blanket gas.

The sodium flows from the bottom upwards in the reactor. The two identical pumps in parallel draw the sodium from the primary vessel and drive it into the high and low pressure collectors of the reactor. The sodium rises from these collectors through the subassemblies to the common outlet collector in the upper part of the reactor, leaves by a single pipe and goes towards the heat exchanger, through which it passes on the casing side before returning to the sodium mass in the primary vessel. The auxiliary pump is between the reactor and the exchanger.

The sodium is electrically preheated to at least 300°C by means of immersion heaters.

304 stainless steel is used. The maximum carbon content of the steel is limited to 0.08%. Cobalt and tantalum are considered undesirable.

References : 8, 9, 70, 78, 152

Figure II-1 : Diagram of the circuits

II-5 : Diagram of the argon primary circuit

II-6 : Cross-section of the primary system

II-8 : Diagram of the systems and apparatus

Table II-2 : Primary systems

Comparative table III : Primary systems.

3. EFFBR

The coolant fluid is sodium. There are three primary systems.

The reactor input and output temperatures are 288 and 427°C, and the total volume flow is 4560 m^3/hr. Each of the three primary systems has a centrifugal pump with a one-way valve and an exchanger with a removable tube system.

The three circuits have a common cold trap (connected by a branch circuit to the overflow vessel of the primary system).

The space above the sodium is filled with argon.

In the core the sodium flows from the bottom upwards. The primary sodium flows gravitationally from the upper part of the reactor vessel towards the casing side of the intermediate exchanger, goes to the pump tank and then returns to the reactor. Approximately 90% of the flow goes towards the collector serving the core, and about 10% goes through the collector serving the radial blanket. Flow through the blanket is controlled by means of limited closure regulator valves.

The sodium supply to the sub-assemblies is divided into two zones, high and low pressure, corresponding to the core and the blanket, with separate inlet pipes (whence 6 sodium inlets although there are only 3 systems).

The whole of the primary system is enclosed in a secondary vessel to prevent any sodium loss.

Preheating is generally effected by inductive winding fed with a 60 Hz current. Since the greater part of the sodium-containing apparatus is made of magnetic steel, direct heating by induction is not possible. Magnetic steel cladding, into which the heat is released, has therefore been provided around the stainless steel piping.

The sodium storage tanks are heated by means of resistor heaters.

The reactor vessel, intermediate exchangers and the piping of the primary system are made of 304 stainless steel.

References : 5, 8, 14, 71, 126

Figure III-1 : Leakproof building with reactor and primary systems

III-2 : Diagram of the systems

III-3 : Inert gas supply system

Table III-2 : Primary systems

Comparative table III : Primary systems

4. PFFBR

Sodium is used in the three primary circuits. The reactor input and output temperatures are 344 and 538°C respectively, and the total volume flow is 13,740 m^3/hr.

Each primary system has a centrifugal pump, the casing side of a reflux-type exchanger with U tubes and a one-way valve.

There is one cold trap for all three primary systems.

To prevent sodium leaks, the whole of the piping is enclosed in a secondary casing.

Argon is used as the blanket gas.

In the reactor core the sodium flows from the bottom upwards.

The piping is preheated by induction with conventional insulation.

304 stainless steel is used for the piping.

Reference : 18

Figure IV-1 : Diagram of the primary and secondary systems

IV-2 : Layout of the primary and secondary systems

IV-3 : Primary piping and tank

IV-4 : Diagram of the primary gas system

Table IV-1 : Primary systems

Comparative table III : Primary systems

5. LAMPRE I

The fluid used in the single cooling system is sodium, which enters the reactor at 450°C and leaves it at 600°C.

The total volume flow is 23.4 m^3/hr.

This system has two electromagnetic pumps in parallel, a sodium-air exchanger which is an ordinary air radiator, a cold trap on the draining tank, and three hot traps in parallel on a branch circuit.

Helium is used as the blanket gas.

In the reactor the sodium flows from the bottom upwards.

Preheating may be effected either :

1. by surrounding all the system components and piping with tubular electric heaters, or

2. by using a transformer and a part of the sodium system built so as to form the secondary loop of the transformer. This apparatus enables the sodium to be kept at 450°C and 40 kW (th) to be added to the system.

The piping is made of 316 stainless steel.

References : 1, 19, 20

Figure V-1 : Diagram of the systems

Table V-1 : Cooling systems

Comparative table III : Primary systems

6. DFR

The primary system consists of 24 circuits which are cooled by NaK, but can be used with sodium. To make the various primary and secondary circuits independent, each pair of primary pumps and their corresponding secondary pumps are supplied with electric current by separate generators. The electricity supply operating the reactor is provided by 12 diesel engine generating units, with an appropriate number of emergency units.

The reactor input and output temperatures of the NaK are 200 and 350°C respectively, and the total volume flow is 1610 m^3/hr. Each of the 24 primary circuits has an electromagnetic pump and an exchanger with fixed uranium coaxial tubes.

The primary circuits have 15 hot traps and 5 cold traps. The use of volves was avoided. The primary system contains approximately 50 T of NaK and the expansion tanks are connected to the primary circuits to permit the NaK to expand in relation to the temperature.

To prevent coolant loss, the primary circuits and tank are enclosed in leakage recovery casings. Each casing is filled with nitrogen, with a leak detector at the lowest point.

Nitrogen was initially used as the blanket gas, but it was decided to replace this with argon, which has the advantage of being heavy and preventing nitriding of the steels and cladding (Nb and Va). Trouble caused by considerable entrainments of gas in the NaK was eliminated in 1961 by alterations to the defective parts. The fuel cladding is pierced with holes to allow the fission gases to escape, and the activity of the argon system is therefore considerable : 0.3 curie per liter of argon.

The NaK flows from the top downwards in the reactor core.

The vessel and the 24 circuits are preheated by pyrotenax; the melting temperature of the 70-30 NaK alloy is 40°C.

The piping is made of 321 stainless steel (18-8-1).

Note: For the PFR power reactor it is planned to use sodium, flow from the bottom upwards in the reactor, and only 3 or 4 circuits in parallel.

References : 24, 26, 28, 79, 119

Figure VI-2 : The reactor and primary systems

VI-12: Diagram of the systems

Table VI-1 : General points and primary systems

VI-2 : Primary pumps and auxiliaries

Comparative table III : Primary systems.

7. RAPSODIE

The coolant fluid is sodium and there are two primary systems in parallel. The reactor input and output temperatures of the sodium are 250 and 340°C respectively, and the total volume flow is 686 m^3/hr (operation at 450 and 540°C with a 750 m^3/hr flow is also planned).

Each primary system has a centrifugal pump and an encased exchanger with removable tube system. There is a purification system, comprising two cold traps in parallel, for the whole of the primary system. The primary systems have no valve and the atmosphere in the primary circuit chambers is nitrogen enriched to prevent sodium combustion in the event of leakage. Argon is used as the blanket gas.

The two primary systems and the common storage tank are beneath flooring 1.6 m thick. The primary systems are designed in such a way that the apparatus likely to be removed (exchangers, pumps) is accessible from the ground, through detachable protection caps, without having to touch the system.

The reactor has two symmetrically positioned sodium outlets, each primary system having a connection pipe between the reactor and the intermediate exchanger. The sodium enters the reactor through a single pipe, however, the two systems being connected just before the entry to the safety vessel.

The sodium flows from the bottom upwards in the reactor.

The sodium is preheated to 150°C by means of a hot nitrogen flow in the double safety casing with which the whole of the primary installation is equipped. Preheating power is approximately 125 kW. The nitrogen flow is approximately 6560 m^3/hr at 175°C.

The piping is made of 316 L stainless steel (Z6 CND 17.13).

Reference : 28

Figure VII : Diagram of the primary argon system

VII-2 : Diagram of the systems

VII-10: Preheating of the primary systems

VII-15: Overall view of the reactor block

Table VII-1 : Primary systems

Comparative table III : Primary systems.

8. BR 5

The coolant fluid is sodium. There are two primary systems, with one reactor inlet and one outlet. There is a third, removable system, which can be placed in the center of the core and operated at 600°C (power 100 kW).

The reactor input and output temperatures are 375 and 450°C respectively, and the total volume flow is 240 m^3/hr.

In both primary systems there is a vertical centrifugal pump, a non-removable exchanger with a U-tube system in the casing, a cold trap, a one-way valve and valves permitting separate use of each of the primary loops.

There is no second casing for the sodium systems.

Argon is used as the blanket gas. The sealed chambers containing the primary system equipment are filled with nitrogen. The operation of the equipment inside these chambers is supervised by means of television devices.

The sodium flows from the bottom upwards in the core.

The sodium is automatically heated by electricity as soon as its temperature drops. There is air heating around possible leakage points (welded joints).

The pipes are made of 321 stainless steel. All the welds are enclosed in jackets and have leakage detectors whose readings are shown on the control panel.

References : 29, 72, 81

Figure VIII-1 : Longitudinal cross-section of the reactor

VIII-2 : Diagram of the circuits

Table VIII-1 : Primary systems

Comparative table III : Primary systems.

9. SEFOR

There is one main primary system using sodium, which enters the reactor at 370°C and leaves the core at an average temperature of 440°C. The flow is 1020 m^3/hr.

On leaving the reactor the sodium goes into an intermediate exchanger and then an electromagnetic pump.

There is an auxiliary cooling system in case of a breakdown of the main system.

Argon is used as the blanket. Before entering the system it passes through a scrubber which removes its impurities (oxygen, water). A sodium vapor trap is situated on the argon pipes discharging above the free level of sodium. Stainless steel argon pipes have been installed wherever there is a likelihood of their coming into contact with sodium vapor or fission products. There is also a gas compressor and two decay tanks in the primary argon system. These permit the radio-active gases to be stored until activity has dropped to a level at which it is possible to discharge them into the atmosphere by means of a ventilation shaft.

Blower-type valves with safety packing-boxes, and remote-controlled valves are used.

304 stainless steel is used for the systems.

Reference : 149

Figure IX-1 : Cooling systems

Table IX-2 : Primary and secondary systems

10. SRE

Sodium is used to cool the reactor. The primary system is divided into a main circuit and an auxiliary one.

The sodium enters and leaves the reactor at 260 and 515°C respectively. The total volume flow is 240 m^3/hr. (SRE is in the process of being modified for operation with a reactor output temperature of 650°C; the sodium flow will probably rise to 442 T/h). In each circuit there is a vertical centrifugal pump and a non-removable exchanger with a U-tube system.

There are, in all, two hot traps and one cold trap.

The blower valves have been replaced by solid joint valves.

The blanket gases are nitrogen and helium. (The helium covers all the components of the systems, while the galleries containing the piping, and the reactor recess, are in a nitrogen atmosphere).

The reactor and the two primary circuits are beneath the working floor, and the circuits are in separate concrete galleries. The motor units for the mechanical pumps are above the floor for easy maintenance.

The inlet pipes of the main and auxiliary primary circuits enter the reactor vessel above the graphite sub-assemblies and descend vertically to the collector situated between the bottom of the vessel and the bed. In this zone they have double walls acting as thermal barriers.

The sodium then rises through the axial tubes, cools the fuel elements, and discharges into the 1.83 m high sodium mass surmounting the core.

Separate outlet pipes for the two primary circuits leave the reactor vessel above the graphite blocks.

137 mm thick steel thermal shielding surrounds the reactor vessel.

A safety tank surrounds this thermal shielding to collect any sodium leak from the core vessel. This tank is insulated and is situated in a concrete recess equipped with steel-plate casing on the outer surface of which are welded cooling pipes through which toluene flows.

The vessel and the circuits are equipped with immersion heating elements and tubular heating elements with electric resistors; they are also insulated.

All the parts of the primary system are made of 304 stainless steel except for the cold trap and the packing tank, which are of a carbon steel.

References : 1, 36, 72, 76, 82, 142

Figure X-2 : Diagram of the circuits

X-3 : Solid joint valve

X-7 : Cross-section of the reactor

Table X-2 : Primary system

Comparative table III : Primary system

11. HNPF

Sodium flows through the three independent primary systems, which are separately connected to the reactor vessel. The reactor input and output temperatures are 321 and 507°C respectively, and the volume flow is 4626 m^3/hr.

Each primary system has an adjustable-speed centrifugal pump, a vertical exchanger with non-removable tube system, a one-way valve, a shut-off valve, and a regulator valve (used during reactor shut-downs to regulate dissipation of the residual heat).

The sodium is purified by means of cold traps. Helium is used as the blanket gas in and around the reactor vessel, while the galleries containing the equipment are in a nitrogen atmosphere.

The heat from the core fuel elements is dissipated by an ascending flow of sodium coming up from the collector beneath the bed. After passing through the elements the sodium discharges into a free surface swimming-pool above the core.

Three primary sodium pipes enter the reactor recess via diaphragms which separate the helium atmosphere in the recess from the nitrogen atmosphere of the galleries. The inlet pipes enter the reactor recess above the moderator, and go down to the bottom of the recess, where they join the lower collector.

There is a safety casing surrounding the reactor vessel to catch sodium leaks and keep the coolant at safety level.

The cooling systems are equipped with preheating units capable of maintaining a sodium temperature of 177°C.

All the parts of the primary systems are made of 304 stainless steel, except for the cold traps and the packing tank, which are of a carbon steel.

References : 1, 42, 68, 76

Figure XI-2 : Diagram of the systems

XI-9 : Detailed view of the reactor

Table XI-2 : Primary cooling systems

Comparative table III : Primary systems.

12. SGR - Current Technology

There are four primary cooling systems, using sodium. The reactor input and output temperatures of the sodium are 330 and 507°C, and the total mass and volume flows are 13,280 T/hr and 16,400 m^3/hr.

There are valves on the suction and return pipes of each system; in the event of an emergency shut-down of the reactor the pumps are halted and the valves regulate the flow to reduce thermal shocks. The valves are also employed to prevent flow reversals when one system is halted.

The four primary pumps are of the free level, vertical centrifugal type. There are several cold traps and a hot carbon trap. Each primary system has two intermediate exchangers of the reflux type, with casing and tube systems. Helium or nitrogen is used as the blanket gas, according to the zone.

The sodium flows from the bottom upwards.

The pipes are preheated by means of tubular resistance heaters with U elbows, reflector, thermal insulation, and steel outer casing.

The metal used for the primary systems is 304 stainless steel.

Reference : 46

Figure XII-1 : Diagram of the circuits

Table XII-1 : Primary systems

13. SGR - Advanced Technology

The primary system, entirely contained within the reactor vessel, has three parallel circuits through which there is a total flow of 5,670 T/hr of sodium, which enters the vessel at 343°C and leaves it at 651°C.

Each of these primary circuits has three electromagnetic pumps and one reflux-type exchanger.

The primary sodium is purified by two cold traps.

Nitrogen and helium are used as the blanket gases.

The sodium flows from the bottom of the tubular core upwards.

The sodium coming from the calandria core passes through the neutronic protection wall and then the intermediate exchangers. On leaving the exchangers it enters the suction opening of the electromagnetic pumps, which drive it through 9 tubes into the input collector above the calandria core.

Preheating, either by electric resistor or by Joule effect in the wall, is used for all the piping and apparatus.

The piping is made of 304 stainless steel.

Reference : 47

Figure XIII-1 : Diagram of the heat-balances

XIII-2 : Intermediate exchanger

XIII-3 : Reactor (piping and apparatus)

Table XIII-1 : Primary system

Comparative table III : Primary system.

II B COOLING SAFETY

1. EBR I

In the event of the primary pump stopping, and it not being possible to put the emergency pump into operation within two minutes, there is automatically an emergency shutdown of the reactor. The cooland continues to flow, by gravity, from the supply tank, whose high capacity (10 m^3) permits operation on full flow for nine minutes.

An emergency cooling circuit (natural convection of NaK) is put into operation by the automatic (or, if necessary, manual) opening of a valve. Heat dissipation takes place in an NaK-air exchanger with fin tubes equipped with a blower (although the natural convection of the air is sufficient to dissipate the residual power).

If this emergency circuit cannot be put into operation, the NaK flow from the supply tank is regulated so as to provide, for eight hours, a flow adequate for dissipation of the heat.

In the event of all these measures failing, direct cooling of the reactor is possible by forced circulation of air.

References : 69, 120

2. EBR II

Two minutes after an emergency shut-down of the reactor operating at 62.5 MW (th), the residual power is 1.8 MW (th), or 3%.

After the reactor is shut down, the coolant fluid running through it may be kept flowing either :

- by the operation of one or both main pumps,
- by use of the auxiliary pump (which can operate on batteries), or
- by natural convection.

The heat held in the sodium coming out of the reactor may be discharged in two different ways :

- by transfer to the secondary system
- by transfer to the sodium mass in the primary vessel, followed by dissipation by means of bayonet coolers.

When the reactor cover is closed, the flow of sodium through the reactor according to one of the first three methods mentioned above follows the "normal circuit" via the intermediate exchanger to the sodium mass.

When the heat is dissipated by heat transfer to the secondary system, an intermediate exchanger is used in which the primary sodium transfers the heat to the secondary sodium which, in its turn, transfers it to the steam generator from which it is discharged by passing through water condensation cooling towers.

When the heat is not dissipated by heat transfer to the secondary system, it is transferred to the sodium mass in the primary vessel. The heated sodium coming out of the reactor is mixed with the sodium mass by release either towards the secondary exchanger or, if the reactor vessel cover is raised, towards the top of the reactor. The heat in the sodium mass is then dissipated by bayonet coolers which, in their turn, transfer the heat to the atmosphere by passing through an air exchanger with fin tubes. The bayonet cooler is an intermediate bayonet exchanger of the immersion type. It consists of two concentric pipes approximately 7.8 m long; the outer pipe is closed at its base. The inner pipe is thermally insulated from the annular section to obtain a greater temperature gap for the natural convection. The cooler is placed in a vertical sheath immersed in the primary vessel sodium mass with a thermal link of sodium in the space between the sheath and the bayonet exchanger. (This sodium lessens thermal stress and forms a barrier between the primary sodium and the NaK coolant).

The NaK enters via the top of the bayonet cooler, flows down to the bottom where it changes direction and enters the annual section where the heat is transferred to the NaK, which then goes to the top of the bayonet cooler.

After leaving the latter, the NaK goes up into an air exchanger with fin tubes which is situated in a throttled air jacket, and goes down again to the bayonet exchanger inlet.

The advantage of this method is its independence of all sources of power (the whole circulation takes place by natural convection).

The heat dissipation rate is very simply checked by the position of the registers regulating the air flow (there is a very slight NaK flow when the registers are closed).

Fully welded apparatus, without valves, is used.

References : 3, 8, 65, 70, 152

Figure II-3 : Shutdown cooler

3. EFFBR

In the event of the sodium flow stopping, there is automatically an emergency shut-down of the reactor. With natural sodium convection alone, a temperature of 1000°C would be reached in the core; this is far in excess of the boiling point of sodium (882°C). An auxiliary motor (not originally planned) was therefore installed on each pump motor; this is supplied from a stand-by power supply system, and starts up automatically when the speed of the primary pumps falls to 70 r.p.m. The motors produce 10% of the full flow. Under such conditions the core temperature would just reach the boiling point of sodium. To avoid this temperature, the emergency shutdown of the reactor is faster (10 MW/s); the maximum temperature, without the auxiliary motor, is then 550°C.

For flow to be possible, the sodium level in the reactor must not fall below that of the 762 mm outlet pipe branches. To prevent this, three measures have been taken : double casing for the whole primary system; siphon-breakers; no drainage system.

When only one of the three cooling systems stops, the other two continue to operate. Two pumps can provide approximately 85% of the total flow. If two pumps stop, the third one stops automatically, and there is an emergency shutdown of the reactor.

References : 8, 14, 65, 71, 126

4. PFFBR

In the event of an emergency shutdown of the reactor operating at 775 MW (th), the residual power decreases exponentially and reaches 4% after 10 seconds. This residual heat is dissipated by a low speed sodium flow through one or more of the three cooling systems.

Small auxiliary motors are used to drive the primary and secondary pumps. Supplied by a stand-by power source, these motors drive the pumps through a gear-down mechanism and a clutch which is normally disengaged.

During stand-by cooling, the steam is discharged into the atmosphere and a small auxiliary pump, also supplied by the stand-by electricity source, drives the supply water to the steam generators.

Reference : 18.

5. LAMPRE

When the pumps stop there is automatically an emergency shutdown of the reactor. Calculations show that, without coolant flow, the core temperature would reach 685°C.

In the event of a breakdown in the mains, two diesel stand-by generating units provide electricity for the measuring instruments, one pump, and the terminal exchanger ventilator.

When the reactor vessel remains full of sodium, the residual power coming from the reactor vessel after an emergency shutdown can be dissipated from the surface of the vessel by heat transfer to the ambient air. When it is necessary to halt the reactor under conditions in which the residual power is inadequate to keep the fuel in a molten state in the core, electric heating of the sodium in the reactor vessel makes it easier to keep it at a high temperature.

In view of the importance of having sodium constantly in the reactor vessel, two precautions have been taken against coolant loss :

1. the coolant inlet and outlet are both at the top of the reactor,

2. the reactor vessel is equipped with a double casing.

Reference : 21.

6. DFR

Thirty minutes after an emergency shutdown of the reactor operating at 60 MW (th), the residual power is 1.8 MW (th) (or about 3%).

To dissipate this heat, NaK is driven through the various primary circuits; since the electromagnetic pumps of the 24 primary circuits are supplied by 12 separate diesel units, a general halt of the primary cooling system is unlikely.

When an electromagnetic pump breaks down, the 72 m^3/hr flow is partly reversed and the flow is reduced by about 100 m^3/hr. But operation of the reactor is still possible when three or four loops have stopped.

In the event of an accident bringing coolant flow through the core to a complete halt, there are four independent thermal siphon circuits, in which NaK 22-78 (solid at -11°C) flows by natural convection between the primary exchangers and air exchangers at the bottom of a stack. The NaK-air exchanger consists of stainless steel tubes fitted with aluminum fins.

Reference : 24.

7. RAPSODIE

After a complete reactor shutdown, the residual power - a few hundred kW - can only be dissipated by natural convection. The center-line of the intermediate exchanger is therefore 65 cm above that of the core; the terminal exchanger, in turn, is above the intermediate exchanger.

Every measure has been taken to prevent untimely draining-off of the primary sodium (draining pipes forming siphons, closed by valves and obturated with solid sodium).

As a precaution against leakages, the whole of the primary system has a double casing.

In the event of fracture of the main piping, emergency cooling is possible by a gas flow in the cladding surrounding the vessel.

References : 28 and private communication

8. BR 5

A method using two liquid circuits was adopted for the first loop; in the event of an accident in one of the circuits, this permits the reactor to be cooled by a sodium flow in the other circuit.

In the event of a reactor shutdown, the residual heat is dissipated as follows:

In the first few minutes following shut-off of the current, cooling is effected by a forced sodium flow in the primary loop, using a pump supplied with power by the stand-by unit, and by natural convection NaK flow in the secondary loop, with the heat being discharged into the air by the stack effect.

After a few minutes of forced sodium flow, the primary loop pump stops and further cooling of the reactor is effected by natural convection of Na and NaK through all the loops. This natural convection was examined with great care.

To produce it, there are 2 m intermediate exchangers above the reactor core. The outer radiator and the steam generator are 2 and 1.5 m respectively above the intermediate exchanger. Draught in the outer radiator results from a stack 25 m high.

The cooling system adopted for BR 5 will eliminate 600 kW, which is far in excess of the residual power of the reactor in the few minutes following an emergency shutdown.

Note : Flywheels installed on the pumps originally provided the sodium flow for 40 to 50 seconds after the current was cut off. They were removed (excessive wear on the bearings).

References : 30, 67

Table VIII-3 : stationary operation with natural flow.

9. SEFOR

In the event of a drop in power causing a reactor shutdown, the residual heat can be dissipated by natural convection.

An auxiliary cooling system has also been provided for use in the event of the main system stopping. The primary auxiliary circuit, which has an electromagnetic pump, is of similar design to the main circuit, but has a lower thermal capacity (1 MW).

The secondary auxiliary circuit has no pump. The sodium flow is maintained by a thermal siphon, produced by the raised position of the air exchanger. The main circuit may be drained without any need to stop the auxiliary circuit.

Valves are used so that it is possible, if necessary, to isolate the auxiliary system from the main one. The auxiliary system is connected to the same purification and blanket gas systems as the main cooling system.

Reference : 149

Figure IX-2 : Auxiliary system.

10. SRE

In the event of an emergency shutdown, an air-cooled 1 MW (th) auxiliary system is set in operation.

If this emergency system does not operate, the sodium flows by natural convection through the primary and secondary systems. This flow is possible because the intermediate exchangers are higher than the core; the air exchangers are even higher.

At normal operating temperatures, it is calculated that at least 2000 kW can be dissipated by natural convection in the main system.

In addition, eddy current electromagnetic brakes have been installed in the main primary and secondary systems; this enables the drop in flow to be adjusted to the reduction in power produced by a safety shutdown.

(This flow is adjusted so as to avoid excessively rapid temperature variations which could produce considerable thermal stress; the rate was set at 28°C per hour).

Braking is produced by a continuous current electromagnet which sets up a powerful magnetic field through a section of 304 stainless steel piping. The eddy currents, which are formed in the sodium by its movement in the magnetic field, initiate the braking. With 2400 watts, the flow after an emergency shutdown is reduced from 240 m^3/hr to 0.24 m^3/hr, in spite of a 0.2 bar charge due to convection.

This braking device makes it possible not to stop the main pumps in the event of an emergency shutdown (they are simply brought down to minimum flow) and also permits power to be regained very rapidly after a halt.

References : 31, 36, 146.

11. HNPF

When one of the circuits is out of action, the reactor can operate with the two remaining ones. In the event of two circuits stopping, the reactor is shut down and the third circuit is more than adequate to dissipate the residual power of the reactor.

In the event of an emergency shutdown of the reactor, the speed of the pumps is automatically brought down to zero. The sodium then flows by natural convection; under these conditions each circuit can dissipate 4% of the total power of the reactor: one circuit is enough to dissipate the residual heat.

The flow control system acts on the regulator valves to keep the fuel channel outlet temperature constant.

Reference : 68.

II C PRIMARY PUMPS

1. EBR I

The pump in the primary system is a direct current conduction pump. Its capacity is 18 kW.

The pump conduit is made of nickel-chrome; its approximately rectangular cross-section is 75 x 43 mm^2. The magnetic pole parts surrounding the conduit are 100/350 mm.

The magnetic field is set up by the 125 x 125 copper rods attached to the pump and in fact representing 2½ turns. These rods are silver-brazed to the pump conduit, which is fitted with heavy bellows at each end to allow thermal expansion.

The whole of the pump (magnet and pump conduit) is enclosed in a thick-walled stainless steel chamber as a safeguard against sodium leaks to the atmosphere in the event of the conduit being fractured. The copper input rods are connected to this chamber by bellows 125 mm in diameter, with high electric resistance. The current by-passed is 600 to 800 amperes at maximum pump flow. The pump chamber is fitted with an electric detector for NaK leaks from the pump tube. This chamber is under argon pressure.

The current supplied to the pump through a copper-magnesium-sulfur rectifier is 25,000 amperes with a 1.5 volt potential difference. For a 20,000 ampere current and a 1 volt potential difference, the pump flow is approximately 125 m^3/hr with a delivery pressure of 1.75 bars. Thermocouples attached to the safety system check the temperature of the rectifier and the pump tube. This pump has operated satisfactorily for ten years.

The mechanical stand-by pump is similar to the secondary system pump; it is centrifugal, with a vertical shaft, and has a capacity of 10 kW.

References : 8, 69, 120

Figure I-5 : Primary electromagnetic pump

I-6 : Mechanical pump

Table I-2 : Cooling systems.

2. EBR II

a) - The two main pumps in the primary system work in parallel. While it has originally been decided to use electromagnetic DC pumps in the primary system, free-level, detachable, one-stage, vertical centrifugal mechanical pumps were finally adopted for reasons of safety, efficiency, and economy. (Tests with electromagnetic pumps are anticipated later, however).

These pumps use a fluid bearing of liquid sodium, on the driving shaft of the pump, and are directly coupled to 480 volt AC motors in leakproof chambers. Labyrinth-type joints are fixed on the shaft to reduce the quantity of sodium vapor in the motor compartment. The frequency of these motors is adjustable in a gear range of 1 to 10. Protection in the pump cap is effected by means of carbon steel dust to a depth of 850 mm, then insulation over 200 mm, and finally high density concrete over 850 mm.

The diameter of the central part of the protection cap, and that of the pump shaft, are reduced so as to lessen radiation leaks along the vertical shaft.

The shaft of the 255 kW motor has a maximum diameter of 137 mm.

The distance between the upper thrust bearing and the radial bearing and the lower hydrostatic bearing is 1200 mm.

At the top of the protection cap, the pump shaft is connected to the motor shaft; it goes through the protection cap and the collar, and comes out inside the casing where it is positioned radially by means of a hydrostatic bearing.

The pump wheel is suspended from the shaft, just below this bearing. The distance between each bearing on the portion of the shaft in the pump is 3200 mm, and maximum diameter of the shaft is 237 mm. A diameter of this size was selected to prevent instability caused by vibration. The pump shafts were precision balanced. The sodium supply to the bearing comes from the pump delivery. The hydrostatic pressure in the bearing casing is used to center the bearing within the scheduled bearing play. There are supports inside the hydrostatic bearing chambers to provide additional hydraulic centering, which is desirable during the start-up of the reactor when the pressure supplied is not enough to produce satisfactory hydrostatic bearing action.

To prevent wear, the surface of the bearings is covered with Colmonoy.

The maximum flow per pump is 1100 m^3/hr at 5.8 bars. The capacity of each pump is 255 kW.

In 1963 there was some trouble with a pump shaft; the buckling of a shaft housing produced friction at one point, and the ensuing heating caused the shaft to buckle. It had to be changed.

b) - <u>The auxiliary pump</u> operates in series with the two main pumps. It is situated in the piping between the upper collector of the reactor and the intermediate exchanger casing.

It is a permanent magnet DC electromagnetic pump, with a capacity of 114 m^3/hr at a pressure of 0.01 bars with a sodium temperature of 482°C. For this capacity, the pump needs 8100 A at 1.0 V. The pumping section is incorporated in the 350 mm reactor outlet pipe without any alteration to the cross-section thereof (at the expense of the yield, which is of little importance).

The electric power required to supply the auxiliary pump is provided from a series of metal rectifiers and storage batteries. The batteries work in parallel with the rectifiers to supply the pump in the event of a complete failure of the power supply to the system. During normal operation these batteries are on permanent charge from the supply network. In the event of extended breakdown, the pump operates until the batteries run out, thus reducing the flow progressively and producing an ideal transition to natural convection.

The primary aim of the auxiliary pump is to increase natural convection under certain reactor shutdown conditions.

References	:	8, 9, 70, 152
Figure II-9	:	Mechanical pump
II-10	:	Electromagnetic auxiliary pump
Table II-2	:	Primary system.

3. EFFBR

The three primary pumps are centrifugal ones with vertical shafts, and are set up on tanks. Each tank is 1.6 m in diameter and 8 m high, and is connected to the intermediate exchanger by a 750 mm diameter tube. Delivery is made by a 400 mm tube which runs off from the bottom of the tank. The piping is welded on to the system. A one-way valve, with a trip-disc, was originally set up on the delivery tube; a new type of one-way valve (with dash-pot) has been installed, as the first one produced undesirable clicking and overpressure.

There are two sodium-lubricated fluid bearings. The mechanical parts are oil-lubricated.

The protection cap, shaft, wheel and casing of the pump are so designed that they can be withdrawn in one unit from the pump tank, without draining the primary system; a sliding assembly in the delivery tube makes this separation possible.

Every part of the pump which comes into contact with sodium or its vapor is made of 304 stainless steel, except for the bearings, which are coated with Colmonoy.

The pumps are driven by triphase electric motors operating on 4800 volts. The sodium flow may be adjusted by varying the speed of the motor (done by varying rotor resistance by means of liquid rheostats).

An auxiliary motor running on 120 volts is set up on each main motor. The motor for the first circuit is supplied from a different network to that of the motors for circuits 2 and 3; they are used in the event of the 4800 volt supply failing.

References : 8, 12, 14, 126

Figure III-3 : Primary sodium pump and first type of one-way valve

Table III-3 : Primary pumps.

4. PFFBR

The three main primary pumps are detachable centrifugal ones with vertical shafts and single suction. The shaft has inert gas leakproof packing.

Contrary to the EFFBR pumps, the cladding in the PFFBR pumps is integral with the casing of the pump tank, which makes it possible to reduce the number of interchangeable parts. The one-way valves are separate from the pumps.

The flow is 4484 m^3/hr per pump, total manometric head 88 m, and the yield 80%.

The motors are coiled rotor electric ones, with a unitary capacity of 1117 kW. (The pumping capacity (per pump) is 923 kW). The speed of the pumps is 870 r.p.m., which can be varied from 50 to 100%.

The pumps are made of 304 stainless steel.

A 3.7 kW auxiliary motor enables the heat to be dissipated in the event of an emergency shutdown or breakdown.

Reference : 18

Figure IV-6 : Primary Na pump

Table IV-3 : Primary and secondary pumps.

5. LAMPRE

The two primary pumps, which run in parallel, are single-phase AC conduction electromagnetic pumps.

Adjustable auto-transformers driven by a motor control the power of the pumps. One-way valves of the clapper type are situated at the outlet of each pump. The nominal flow is 22.6 m^3/hr at a pressure of 1.4 bars.

Reference : 19.

6. DFR

There are 24 primary pumps. They are flat linear induction electromagnetic pumps with no detachable parts, consisting essentially of a flat, thin-walled (2 mm thick) 316 stainless steel pump tube welded on to the circuit; a detachable linear stator made of magnetic plates, with triphase induction motor type coils, is fixed to each side.

The pump flow is controlled by varying the terminal voltage by means of an induction regulator. The flow can be varied from 0 to 100%.

Electricity is supplied by 12 independent diesel units of unitary power 14.7 kW and 410 V potential difference.

With NaK, the yield of the pump is 24% (it would be 32% with sodium). Each pump discharges 65 t/hr NaK at a delivery pressure of 1.65 bars.

The maximum permissible temperature is 240°C; the pumps are therefore situated between the intermediate exchanger and the reactor.

Note : Mechanical pumps are planned for the PFR power reactor.

Reference : 24

Figure VI-3 : Electromagnetic pump

Table VI-2 : Primary pumps and auxiliaries.

7. RAPSODIE

There are two primary pumps, of the centrifugal type, leakproof with gas, comprising :

- a fixed outer ring
- the pump itself, which is detachable and includes a protection cap.

The fixed ring, which will be made of type 316 stainless steel, is a vertical cylinder suspended by its upper end at ground level. Cladding forming a double casing will allow it to be heated by a hot nitrogen flow.

The pump itself is an axially vertical centrifugal pump with a free sodium level. Delivery is axial and suction lateral.

The shaft is installed between two bearings, an upper bearing formed by a conventional roller bearing situated directly below the motor, and a lower bearing of the hydrostatic type, bathed in sodium which comes from the delivery pump. Bolted to the base of a vertical cylindrical jacket is the scatterer with the hydrostatic bearing at its center.

The shaft is hollow and has a maximum outer diameter of 230 mm, which is necessary for the critical velocity to be high enough to obviate the presence of an intermediate bearing.

At the base of the scatterer is a guide rod which fits into the lower end of the ring and thus permits the pump to be centered. This guide rod also contains a one-way valve which resists any fluid flowing in the opposite direction to the normal one, i.e. any flow produced by the other circuit working in parallel.

The protection cap closes the pump in the upper part; iron dust is used for the protection.

Two continuous level indicators are situated in the pump.

Sealing on the revolving shaft between the argon over the free sodium level and the atmosphere is effected by two equalised carbon grain joints operating in oil, the flow of which is ensured by a spiral pump integral with the shaft.

The motor has a capacity of 60 kW, and its speed can be varied in a ratio of 1 to 6 approximately. At 20 MW the nominal operating point is 375 m^3/hr with a delivery head of 32 m. The yield of the pumps is 70%.

References : 28, 164 and private communication

Figure VII-3 : 375 m^3/hr primary pump

VII-10 : Mechanical mountings.

8. BR 5

The two primary pumps are centrifugal, free-level ones with a suspended vertical shaft, roller bearing and mountings in argon.

The pressure in the motor chamber is higher than that in the pump, so that any leak through the mechanical lining is towards the inside.

The wheel is housed in the pump ring, below the coolant level, in a 0.6 m^3 space. The stator of the electric motor is hermetically sealed off from the outside by a steel casing. The gas surrounding the casing is in communication with the gas in the pump ring. The main parts of the pump which determine its period of uninterrupted operation before repair or replacement are the bearings, whose life is restricted to a few thousand hours. After additional cooling of the body of the upper pump bearing with water, the life of the pumps rises, on average, to 8,000 hours. The pumps alone work for 14,000 hours before replacement becomes necessary.

When the pumps are replaced there is local drainage of the system; the sodium which remains is solidified (this effectively reduces oxide pollution).

Gas entrainment due to the formation of gas-metal emulsions in the pump tank were observed; following research, a number of alterations were made to the design of the pump to ensure a direct flow of sodium to the pump wheel and obtain an even metal surface in the tank.

Inertia flywheels were set up on the pumps to ensure cooling safety in the event of the current being shut off; but they had to be removed because of excessive bearing wear.

References : 72, 109

Figure VIII-3 : Diagram of a pump.

9. SEFOR

The primary pump is a triphased AC linear electromagnetic pump whose flow can be varied.

Air is used to cool the pump winding.

The nominal flow of the pump is 1140 m^3/hr at a pressure of 5 bars.

Reference : 149.

10. SRE

There are two primary pumps (one main one and one auxiliary). These pumps are detachable, solid joint centrifugal mechanical ones. Since the primary pump mountings go through the gamma shielding, the wheels of these pumps are situated in housings in the main and auxiliary galleries respectively. However, since the secondary pump casings do not require any shielding, these pumps are installed above the nominal level.
The diameter of the main pump wheel is 337 mm, and that of the auxiliary pump wheel is 250 mm. To prevent contact between the solid sodium joint and the oxygen in the air, a helium atmosphere (at a delivery pressure of 0.7 bars) is maintained constantly in the pump casing.

The pumps were originally cooled with tetraline (especially the solid joints). As a leak contaminated the primary sodium and fuel rods, tetraline was completely abandoned and NaK is now used. The design of the joints was altered so as to reduce the likelihood of leaks.

When the pump is running at 1000 r.p.m., the flow is 240 m^3/hr and the manometric pressure 0.96 bars.

The motors run on DC and their speed can be varied between 0 and 1500 r.p.m. The capacity of the main motor is 18.6 kW, and that of the auxiliary motor 3.5 kW. The pumping capacity of the main pump is 9.5 kW.

The wheel and the pump shaft are made of 316 stainless steel, while all the other parts which come into contact with sodium are made of 304 stainless steel.

In the modified SRE these primary pumps are to be replaced with other mechanical pumps which are also centrifugal but have a free surface, a hydrostatic bearing with an AC motor, and an eddy current coupling.

The planned flow is 702 m^3/hr at a manometric head of 23 m with a 150 kW pumping capacity. The pump will work at 900 r.p.m.

References : 73, 76, 82, 162

Figure X-5 : Cross-section of the main secondary pump

Table X-2 : Primary system.

11. HNPF

The three primary pumps are detachable centrifugal mechanical ones, with a vertical shaft, free surface, and a sodium bearing situated close to the wheel. These pumps are fixed in the protected cells of the intermediate exchangers, and their motors are in the reactor hall, at floor level.

There are double mechanical mountings at the top of the pump. They are filled with oil and include an oil tank and drip trap to prevent any leakage of oil to the pump casing.

In the event of the lower mechanical joint breaking down, oil leaks are retained by the first oil sump and are visible through the gaged glass. The capacity of this sump is higher than the normal volume of the oil joint. There is a second oil sump with gaged glass as a precaution against the unlikely event of an oil leak from the first sump. A differential pressure alarm on the oil system draws attention to any drop in the oil indicating a leak.

Each of the pumps is driven by a 250 kW capacity AC induction motor with electromagnetic coupling; the speed can be varied from 0 to 102%.

Each pump has a flow of 1632 m^3/hr with a delivery pressure of 3.7 bars.

References : 42, 43, 68, 74, 75, 111

Figure XI-3 : Primary pump

Table XI-2 : Primary system

II D. INTERMEDIATE EXCHANGERS

1. EBR I

The single intermediate exchanger is a device with a baffled tube system and a cylindrical body; all its joints are welded. It has one horizontal baffle and twelve vertical ones. The outer casing is 4.6 m long and 0.43 m in diameter.

The 102 tubes are in the form of hair-pins; their outer diameter is 19 mm and their total outer surface area is 45.85 m^2. They are made of nickel A, and have a wall thickness of 1.5 mm. They are set up on a circular plate which is also made of nickel A; this plate is welded on to a 347 stainless steel tank which acts as the exchanger casing.

The primary NaK flows through the tubes; the secondary NaK flows in the opposite direction through the casing.

The capacity of the exchanger is 1.15 MW.

References : 2, 120, 217

Table I-3 : Intermediate exchanger.

2. EBR II

The single intermediate exchanger is suspended from the cover of the primary tank and is almost completely immersed in primary sodium. It is of the one stage, reflux type. The casing has a double wall with inert gas between the two to produce thermal insulation between the exchanger and the sodium mass in which it is immersed. The exchanger tube system and its support can be vertically detached in one piece, but the exchanger ring is permanently fixed to the cover of the reactor vessel.

The total length of the exchanger is 6.09 m.

The primary sodium flows down through the casing and at the bottom discharges directly into the sodium mass in the vessel. The secondary sodium rises again through the tubes.

The secondary sodium input and output temperatures are 321 and 454°C. Pressure on entry to the exchanger is 4.3 bars, and pressure loss inside it is 0.5 bars.

304 stainless steel is used.

References : 8, 70, 90, 152

Figure II-2 : Intermediate exchanger.

3. EFFBR

The three intermediate exchangers are of the reflux type, with casing and tubular system. This system can be removed without it being necessary to dismantle the sodium piping or drain off the primary sodium. The secondary sodium input and output branches are separated by a plate and leakproofing is ensured by piston segments. This permits slight leaks between the ingoing and outgoing liquids. To obtain a small

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reduction of thermal stress in the central tube, it is lined inside and out with stainless steel plate. Leakproofing between the tubular plate and the casing is produced by a stainless steel ring joint of circular cross-section, which prevents the secondary sodium leaking to the primary sodium. The ring is hollow and filled with nitrogen at high pressure, which increases its strength. The joint ring is compressed by 254 mm inconel springs, which transfer their charge to the tubular plate via the protection cap.

The casing comes through the working floor to facilitate access to the upper cover, so as to make it possible to remove the tube system. The caps are filled with serpentine which acts as the protection.

The primary sodium flows on the casing side, and the secondary sodium inside the tubes. The secondary sodium enters the exchanger through the 300 mm upper branches, goes down in the central tube to the floating head, rises again through the tubes and leaves via the 300 mm lower branches.

The exchangers are made of 304 stainless steel.

References : 8, 14, 91, 126

Figure III-8 : Intermediate exchangers

Table III-6 : Intermediate exchangers.

4. PFFBR

The three intermediate exchangers are of the reflux type, with U-tubes. These exchangers are suspended by their tops from the biological shielding frame.

In the PFFBR exchangers, contrary to the EFFBR ones, the protection is separate from the exchangers themselves. Flanges with welded joints give access to the tube systems for purposes of maintenance or replacement. A set of U-tubes replaces the floating head, eliminating some of the thermal barriers required in the EFFBR exchanger.

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Introduction of the primary sodium through the central column reduces thermal stress along the casing wall. The primary coolant side has inert gas blankets at the inlet and outlet. These blankets act as thermal insulators, preventing contact between the sodium and the tubular plates.

The heat transferred by the exchanger is 259 MW.

The overall height of the casing is 8.2 m and its diameter is 2.1 m. The system of tubes, with a 25-37 mm pitch, contains 1200 25 mm diameter tubes with walls 1.05 mm thick.

The primary sodium enters the exchanger casing through an opening 500 mm in diameter, near the top, and goes down through the tube system. When it reaches the lower part, the coolant rises to the top again, guided by the baffle, and flows down through the central outlet piping. The secondary sodium enters through the upper collector. It goes down through the tubes to the lower part and rises towards the outlet collector.

The exchanger input and output temperatures of the primary sodium are 538 and 343°C, and the flow per exchanger is 3760 t/hr.

The casing and the tubes of the intermediate exchanger are made of 304 stainless steel.

References : 18, 51

Figure IV-8 : Intermediate exchanger

Table IV-4 : Intermediate exchangers.

5. LAMPRE I

There are no intermediate exchangers since there is no secondary circuit. The sodium is cooled in an air exchanger (see terminal exchangers).

6. DFR

The 24 intermediate exchangers are assembled around the reactor vessel in a thick concrete gallery.

These exchangers are not removable, and each have an inner pipe 91 m long and 101 mm in diameter enclosed in an outer pipe 152 mm in diameter, in the form of 7 complete hairpins. The inner and outer pipes are kept concentric by means of centering pieces butt-welded on to the inner pipe. The central point of each branch of the exchanger is attached to a steel frame which is held by a book through a pivot joint fixed to the roof of the gallery. This enables the exchanger to be moved radially. The exchangers are enclosed in a 62 mm thick rock wool insulator covered by galvanised mild steel cladding.

Each exchanger has a thermal capacity of 3 MW; the exchanger area is 32 m^2. The primary fluid flows (upwards) in the inner pipe, and the secondary fluid flows in the opposite direction in the annular space surrounding the inner pipe. The exchanger input and output temperatures of the primary sodium are 350 and 200°C, and the exchanger input and output temperatures of the secondary sodium are 175 and 325°C.

The material used in the fabrication of the intermediate exchangers is 316 stainless steel.

Reference : 24

Figure VI-7 : Intermediate exchanger.

7. RAPSODIE

Each of the two intermediate exchangers has a fixed ring and a detachable tube system with a protection cap integral with it. The tube system is held in the vertical cylindrical ring, which is suspended from its upper flange and closed by a dish-end at the bottom.

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The sodium inlet is in the vertical part of the cylinder, and the outlet at the lower dished end. Cladding surrounds the ring in the part of the apparatus used for the nitrogen flow which pre-heats the plant before filling. The tube system consists of 888 tubes arranged in 12 concentric circles; they are expanded and welded at the ends to two tubular plates.

The upper plate is fixed; the lower plate, which forms a floating head, allows the system to expand freely. An expansion band at the upper end of each tube absorbs differential expansion between tubes.

To prevent sodium pressure impulses setting off resonance in the tubes, the latter are inter-supported by two sets of belts 1 m apart. While preventing radial displacement, these belts permit any lengthwise displacement of the tubes.

The inlet collector in the system is formed by a dished end welded to the lower tubular plate. This plate also has the secondary sodium inlet tube which is in the center of the tube system and runs through the whole device.

The outlet collector of the system is formed by the upper tubular plate and a dished end placed above it.

Vertical cladding encases the tube system so as to guide the sodium flow outside the tubes. A ring welded on to the cladding and abutting on another ring welded to the fixed ring ensures leakproofing adequate for a proper sodium flow around the system.

Three holes in the crown-ring inside the fixed ring allow the sodium to flow out of the annular space during draining. The protection cap closes the device at its upper end. Iron dust is used for protection.

The diameter of the tubes is 12/14 mm and that of the casing is 884/900 mm. The exchange length is 2.15 m and the exchange area is 84 m^2. The stainless steel weighs 4500 kg. The fluids flow as follows : the primary sodium enters the ring, spreads through the annular space which the ring forms, enters the tube system through the upper openings made in the cladding, flows down the tubes, leaves the system by the lower openings in the cladding, reaching the outlet at the inner bottom.

The secondary sodium, brought by tube to the lower collector, flows upwards inside the tubes, discharges into the upper collector, and is then evacuated via the annular space around the secondary sodium input tube.

The exchanger input and output temperatures of the primary sodium are 340 and 250°C respectively for the first rate, and 540 and 450°C respectively for the second rate.

The intermediate exchanger input and output temperatures of the secondary sodium are 220 and 310°C respectively for the first rate, and 420 and 510°C respectively for the second rate.

The intermediate exchangers are made of 316 stainless steel.

References : 28 and private communication

Figure VII-9 : 10 MW intermediate exchanger.

8. BR 5

The two intermediate exchangers are not removable. They are each composed of a tube system in a ring, with the tube-and-ring unit in the form of a U to allow the tube system to expand freely.

The intermediate exchanger input and output temperatures of the secondary NaK are 300 and 430°C, and those of the primary sodium, 450 and 375°C.

References : 3, 66.

9. SEFOR

The intermediate exchanger is of the type with stainless steel wall casing and tube system.

It is planned for a pressure of 14 bars and a temperature of 590°C.

The heat exchange area is based on an average temperature difference of 55°C.

304 stainless steel will be used.

10. SRE

There are two intermediate exchangers, namely :

- a main exchanger and an auxiliary one.

The main exchanger

We shall indicate first of all the characteristics of the main exchanger at present used in SRE, and then those of the main exchanger planned for modified SRE (1965).

SRE main exchanger, 1st version

It is of the reflux-casing type and U-shaped, placed horizontally. The tubes have unwelded single walls 19 mm in outer diameter and 1.5 mm thick. It is approximately 5.7 m long. The exchanger has 316 tubes and its total exchange area is 107.3 m^2. The scheduled thermal capacity is 20 MW for an average logarithmic temperature difference of 34°C and a flow of 220 t/hr. Pressure on entry to the exchanger is 1.89 kg/cm^2, and the pressure loss inside it is 2.5 kg/cm^2. The exchanger input and output temperatures of the primary sodium are 515 and 260°C. The exchanger input and output temperatures of the secondary sodium are 227 and 482°C.

The primary sodium flows in the tubes, and the secondary sodium in the casing.

304 stainless steel is used.

Main exchanger of modified SRE

The U-shaped unit is no longer horizontal but vertical. The average logarithmic temperature difference across the exchanger at full power is 25°C with primary sodium input

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and output temperatures of 650 and 393°C respectively. These conditions are calculated for a 442 t/hr flow and a 45 MW thermal capacity. 200 mm branches are provided and there are baffles before the tubular plates as a precaution against thermal stress.

Auxiliary exchanger

It is of the type with U-shaped tubes and casing, set up vertically; there are 38 tubes 19 mm in diameter and 1.5 mm thick in the casing. This exchanger is planned for a heat transfer of 1 MW with a logarithmic temperature difference of 34°C for an 11 t/hr flow.

References : 36, 73, 76, 93

Figure X-8 : Main intermediate exchanger

Table X-3 : Secondary system.

11. HNPF

The three intermediate exchangers are installed vertically. They are of the reflux type, with tubes and casing. There is an expansion band at about the middle of each exchanger casing to prevent fracture caused by different thermal expansion of the tubes and the casing. Each exchanger is equipped with a bracket which serves to support the exchanger and displace the weight of the apparatus towards the lower part of the installation, and permit vertical expansion at three points along the exchanger. This exchanger can only be displaced vertically to eliminate torsion charges from the baffles. The nominal pressure and temperature are 7 bars and 550°C respectively. The nominal pressure loss on the tube side is 0.35 bars, and on the casing side, 0.5 bars. Pressure on entry to the intermediate exchanger is 3.7 bars.

The exchanger input and output temperatures of the primary sodium are 507 and 321°C; those of the secondary sodium are 292 and 480°C. The primary sodium flows in the tubes, and the secondary sodium in the casing. 304 stainless steel is used.

On 18 November 1962 there was a tube fracture caused by vibrations near the secondary sodium inlet. The tubes in the inlet zones have been fixed by setting them in a lattice of stainless steel rods, which prevents vibration.

References : 62, 68, 159, 161

Figure XI-6: Intermediate exchanger.

III. SECONDARY SYSTEMS

III A GENERAL OBSERVATIONS

1. EBR I

There is only one secondary cooling system, in which NaK is used. (The secondary system has about 3.7 m^3 NaK, while the primary system contains 14.8 m^3).

The intermediate exchanger input and output temperatures of the secondary NaK are 216 and 306°C, and the steam generator input and output temperatures are 290 and 216°C. The total mass flow is 55.4 t/hr (the volume flow being 63.5 m^3/hr).

Heat may be dissipated either through fin-tube coolers, or through the steam generator which is of the forced flow type. An ordinary mechanical pump, identical to the stand-by pump in the primary circuit, carries out all the pumping.

The coolant flows from the storage tank to the intermediate exchanger via the 90 kW heating system; then, according to the method of operation used, the coolant either passes through the fin-tube coolers or through the single steam generator, afterwards returning to the storage tank.

A small fraction of the flow is by-passed through a purification circuit containing a sintered steel filter and a cold trap.

The 90 kW electric heating system is used in special experiments which require an increase in the coolant temperature at zero power.

The secondary system is made of 347 stainless steel, except for the NaK-water exchange walls, which have three nickel-chrome-nickel layers.

References : 69, 83, 93, 120

Figure I-1 : Layout of the systems

Table I-2 : Cooling systems

Comparative table IV : Secondary systems.

2. EBR II

Sodium is used in the single secondary system. The intermediate exchanger input and output temperatures of the secondary fluid are 321 and 454°C. The volume and mass flows are 1370 m^3/hr and 1170 t/hr respectively, and the pressure loss for the whole system is 4.6 bars.

The main elements of the secondary system are : the electromagnetic pump, the superheater, the evaporator, and the expansion and storage tanks.

The triphased current, linear induction, electromagnetic pump is in the sodium housing (about 15 m from the reactor housing), which also contains the secondary purification system and the storage tank. This tank is below floor-level and can drain off all the secondary sodium except that contained in the intermediate exchanger.

The expansion tank connected to the piping at the inlet to the pump maintains constant pressure in the pump.

The sodium flowing through the purification system (flow : 4.5 m^3/hr) is driven from the storage tank to the expansion tank, thus ensuring a constant sodium level. The overflow returns to the storage tank through an inner overflow pipe situated in the expansion tank.

The sodium in the expansion and storage tanks is covered with argon kept at a pressure of approximately 0.7 bars.

The steam generator housing is approximately 30 m from the reactor housing. The steam generator plant is arranged so as to allow drainage towards the storage tank. The secondary sodium passes through the sections of the heater and evaporator placed in series.

All the piping in the secondary system is designed so as to absorb thermal expansion caused by the changes in temperature from 0 to 550°C.

The piping is heated by induction (60 Hz).

304 stainless steel and steel with 2.1/4% Cr - 1% Mo are used. The evaporator and superheater are of Cr-Mo steel, and the baffles are of 304 steel.

References : 8, 9, 152

Figure II-1 : Layout of the systems

II-8 : Layout of the systems showing positions of the measuring apparatus

Table II-3 : Secondary system and steam system

Comparative table IV : Secondary systems.

3. EFFBR

Sodium is used in the three secondary cooling circuits. The intermediate exchanger input and output temperatures of the secondary sodium are 270 and 408°C. The total volume and mass flows are 4560 m^3/hr and 4020 t/hr respectively. The total pressure loss in the secondary system is 0.97 bars.

The three secondary pumps (1 per circuit) are centrifugal ones with vertical shafts. Since each secondary circuit is independent of the others, failure of one of the pumps will not result in reversed flow and there is no need for one-way valves.

Purification of the system is effected by a cold trap.

The three metal-water exchangers (1 per circuit) are one stage with alternate mixed flow. The only terminal exchangers are the steam generators; but there are three auxiliary circuits to dissipate the heat transferred by the sodium to the water when the normal steam system cannot be used. The sodium in the pumps and the steam generator casing is covered with argon which is at a maximum pressure of 0.85 bars. This gas allows the sodium to expand. The piping and the intermediate exchanger are preheated by induction, and the rest of the secondary system is preheated by resistors.

The piping and the steam generators are of ferritic steel containing 2.1/4% Cr - 1% Mo, which is a good material for holding water, steam and sodium up to 450°C. (Above this temperature sodium dissolves some of the carbon and the strength of the steel drops by 20%).

References : 7, 14, 126

Figure III-9 : Secondary cooling system

Table III-5 : Secondary system

III-8 : Steam system

Comparative table IV : Secondary systems.

4. PFFBR

There are three secondary cooling circuits, in which sodium is used. The intermediate exchanger input and output temperatures of the secondary sodium are 298 and 493°C. The total volume and mass flows are 13,740 m^3/hr and 11,280 t/hr respectively. The pressure loss in the system is 32.3 m of sodium.

There are three pumps in the secondary system (i.e., 1 per circuit). They are centrifugal mechanical ones, with vertical shafts and single suction.

One purification system is used for the three secondary circuits.

The three metal-water exchangers are of the vertical, one-stage type.

In addition, each circuit has an expansion tank connected to the inlet pipe to the intermediate exchanger tube system.

The secondary blanket gas system (argon) is identical to the primary gas system, but simpler, since the circuits are insulated and there is no gas zone on the secondary side of the intermediate exchanger.

Secondary sodium from the intermediate exchanger enters the steam generator casing near the top, crossing two 400 mm diameter thresholds. It then flows above and around the tubes until it reaches the bottom of the casing and leaves the terminal exchanger by a 500 mm diameter threshold.

The piping, pumps and steam generators are made of steel containing 2.1/4% Cr and 1% Mo.

Reference : 18

Figure IV-1 : Layout of the primary and secondary Na systems

IV-5 : Layout of the secondary gas system

Table IV-2 : Secondary system

Comparative table IV : Secondary systems.

5. LAMPRE I

There is no secondary cooling system, since the primary sodium is cooled by air.

6. DFR

NaK flows through each of the twelve secondary circuits (each secondary circuit is connected to two primary circuits). The exchanger input and output temperatures of the secondary NaK are 175 and 325°C.

The total mass and volume flows are 1400 t/hr and 1610 m^3/hr respectively, and the pressure loss is 1.8 bars. There are two electromagnetic pumps per circuit (i.e., 24 in all). They are set up in parallel on the cold return branch of each circuit.

Two cold traps, identical to those in the primary system, are set up in a by-pass at the top of each circuit.

There is an expansion tank connected in series to the two cold traps.

There are twelve metal-water exchangers in all; their tubes are immersed in copper to prevent contact between the liquid metal and the water.

In addition the secondary circuits have four thermal siphon circuits, each with a heat transfer capacity of 0.45 MW (th).

In the event of an emergency shutdown, the piping and tank are heated by resistor heaters. These heaters are alternately connected to two independent electric circuits.

The secondary system piping is made of 316 stainless steel.

Reference : 24

Figure VI-1 : General layout of the plant

VI-12 : Layout of the systems

Table VI-3 : Secondary circuits and steam generator

Comparative table IV : Secondary systems.

7. RAPSODIE

There are two secondary cooling circuits, in which sodium is used.

The intermediate exchanger input and output temperatures of the secondary sodium are 220 and 310°C for the first rate and 420 and 510°C for the second rate.

The total volume flow per circuit is 380 m^3/hr. The pressure loss is 1.5 bars.

Each secondary circuit has a centrifugal mechanical pump, an expansion tank, a cold trap and blockage indicator which are both on a branch circuit to the main piping (they are supplied by an auxiliary electromagnetic pump), and lastly a sodium-air terminal exchanger.

Argon is used as the blanket gas. The piping connecting the leakproof chamber (i.e., the intermediate exchanger) to the thermal system housing (in which the two secondary circuits are housed) is situated in underground galleries. The part of the sodium piping inside the chamber has a double casing with leak detectors as in the primary system.

Electric resistors are used for preheating.

The circuits are of type 316 low carbon austenitic steel.

References : 28 and private communication

Figure VII-2 : Layout of the circuits

Table VII-2 : Secondary circuits

Comparative table IV : Secondary systems.

8. BR 5

There are two secondary cooling circuits in which NaK is used. In one of these circuits the heat is dissipated through an air exchanger, and in the other by a steam generator.

The experimental loop has a secondary, organic liquid cooled, circuit (polyphenyl is used).

The intermediate exchanger input and output temperatures of the secondary NaK are 300 and 430°C.

The NaK leaves the air exchanger and the steam generator at 300°C. The total mass and volume flows are 200 t/hr and 260 m^3/hr.

Each of the two secondary circuits has a centrifugal mechanical pump and a cold trap. All the secondary system apparatus is held in a single compartment.

References : 29, 66

Figure VIII-2 : Layout of the circuits

Table VIII-2 : Secondary system

Comparative table IV : Secondary cooling systems.

9. SEFOR

Sodium flows in the secondary system at a rate of 1020 m^3/hr.

On leaving the intermediate exchanger the sodium is cooled in a sodium-air exchanger, and then goes into the electromagnetic pump.

Argon is used as the blanket gas.

304 stainless steel is used.

The FCR reactors to be built after SEFOR will have steam generators made of either steel containing 2.1/4% Cr - 1% Mo, or steel with 5% Cr - ½% Mo - ½% Ti. (A decision will be made after research on carbon transfer at above 500°C).

Reference : 149

Figure IX-1 : Cooling system

Table IX-2 : Primary and secondary systems.

10. SRE

There is a main secondary circuit and an auxiliary secondary one. The coolant is sodium. The intermediate exchanger input and output temperatures of the secondary sodium are 227 and 482°C. (SRE is being altered, and temperatures of 368 and 630°C will be reached). The main circuit has a steam generator and an air cooler. The auxiliary circuit has an air cooler.

Pressure loss in the main circuit and the auxiliary circuit is 2.5 bars and 1.2 bars respectively.

The total mass flow is 220 t/hr (441 t/hr in modified SRE). There are two centrifugal mechanical pumps, a main one and an auxiliary one, and two expansion tanks. Two cold traps (one main, one auxiliary) on a by-pass are used to purify the system.

The steam generator is of the single stage type with double-walled tubes. A metal-air exchanger is also fitted on the secondary circuit. Valves in the main secondary circuit permit the sodium to be driven either towards the main metal-air exchanger, or towards the steam generator. When the metal-air exchanger is used, the input and output temperatures of the sodium are identical to the steam generator input and output temperatures.

The sodium is heated by electric resistor and by steam.

The piping is made of 304 stainless steel. The filling tank and the cold trap are made of carbon steel.

References : 36, 76

Figure X-2 : Layout of the circuits

Table X-3 : Secondary circuits and steam system

Comparative table IV : Secondary systems.

11. HNPF

There are three secondary cooling circuits, in which sodium is used.

The exchanger input and output temperatures of the secondary sodium are 292 and 480°C. The total mass flow is 3816 t/hr.

Each secondary circuit has an expansion tank, an adjustable-speed centrifugal pump, a bayonet-tube and casing type steam generator, and a regulator valve outside the screened cells containing the intermediate exchangers.

The secondary system is purified by an air-cooled cold trap on a by-pass.

The secondary sodium is pumped from the expansion tank through the steam generator and the intermediate exchanger, and returns to the expansion tank.

Helium is used as the blanket gas, at a pressure of 1.4 bars. The sodium in the secondary system can be heated electrically.

The piping is made of 304 stainless steel, and the cold trap and filling tank are of carbon steel. For the evaporators and superheaters, 304 and 321 stainless steels, steel containing 5% Cr - ½% Mo, and steel with 2.1/4% Cr - 1% Mo, are used.

References : 42, 68

Figure XI-2 : Layout of the circuits and the steam system

Table XI-3 : Secondary circuits and steam system

Comparative table IV : Secondary systems.

12. SGR - Current Technology

There are four secondary cooling circuits, in which sodium is used. The nominal intermediate exchanger input and output temperatures of the secondary sodium are 307 and 485°C.

The total mass flow is 13,280 t/hr.

Each secondary circuit has a centrifugal mechanical pump with a vertical shaft, butterfly valves (fitted to the sodium piping before the heater to allow the steam heating temperature to be checked, and to isolate the heating circuit in the

.../...

event of a shutdown), a control valve, an expansion tank, and expansion-band type joints. In addition, each of these circuits has a one-stage vertical steam generator, with casing and tube system; there is sodium in the casing and water and steam in the tube.

The secondary system also has two steam heaters of the one-stage type with casing and tube system; they are used to heat the steam coming out of the steam generator. This is then taken to the intermediate pressure body of the turbine, and then expanded for discharge.

The parts of the sodium circuits are covered with helium, and a nitrogen atmosphere is maintained in the tank connected to the heater and steam generator safety diaphragms.

The sodium circuits and piping are heated by electric resistor heaters. The steam generators are preheated by a hot water generator of the Lamont one-stage type, and heated with oil.

The piping between the intermediate exchanger and the steam generator is made of 304 stainless steel, and the sodium pipes between generator and the heater are of steel containing 2.1/4% Cr - 1% Mo.

Reference : 46

Figure XII-1 : Layout of the circuits

Table XII-2 : Secondary circuits and steam system.

13. SGR - Advanced Technology

The secondary cooling system is divided into three parallel circuits, in which sodium is used. The secondary sodium enters the intermediate exchanger at 316°C and leaves it at 621°C. The total mass flow is 5670 t/hr.

Each circuit has an electromagnetic pump with a spiral rotor, an expansion tank, a regulator valve between the intermediate exchanger and the pump, and a one-stage steam generator with steam and water on the tube side and sodium on the casing side. The generator tubes are single-walled.

There is a cold trap on a by-pass.

Nitrogen is used as the blanket gas; it is kept at a pressure of 1.4 bars.

Resistors are used to heat all the parts and piping, except for the steam generators which are to be heated by steam, and the sodium tank-waggon, for which steam-heated oil will be used. The steam required is provided by a steam generator running on fuel oil.

All the piping is of 304 stainless steel. The steam generators are of steel containing 2.1/4% Cr - 1% Mo.

Reference : 47

Figure XIII-1 : Heat-balance diagram

Table XIII-2 : Secondary circuits and steam system

Comparative table IV : Secondary systems.

III B SECONDARY PUMPS

1. EBR I

In the secondary system there is a centrifugal mechanical pump, with an oil sump, vertical shaft, and gas leakproof packing.

The bearings are situated above the free surface. To prevent their immersion, leaks are returned to an adjacent large capacity tank. A gas leakproof casing surmounts the whole motor. This casing is attached to the top of the tank by flanges, and the motor bearings work in inert gas. There is a labyrinth joint on the shaft at the top of the tank to restrict gas leaks in the event of the upper cover being opened or removed, and prevent entrainment of metal vapor from the lower tank in the direction of the motor compartment. When the pump is working, there is identical pressure in the upper and lower compartments, and there is no leakage of gas to the atmosphere. Cooling of the outer surface of the upper casing by means of a forced air flow ensures the cooling of the motor, controls, and bearings. Expansion joints, rendered leakproof on the outside, enable the pump delivery to leave via the lower tank. A joint makes the suction leakproof.

The shaft is 90 mm in diameter, with an overhang of 1 m. The critical and operating speeds are 2500 r.p.m. and 1750 r.p.m. respectively. The NaK flow is 113 m^3/hr with a manometric head of 1.7 bars and a temperature of 354°C. The shaft power is 10 kW.

All the parts coming into contact with NaK or its vapor are made of 304 stainless steel. (This applies, in particular, to the tank and the mountings of the pump, shaft, and wheel).

References : 62, 103

Figure I-6 : Mechanical pump.

2. EBR II

In the secondary system there is a linear induction AC electromegnetic pump. At full power (460 kW) this pump can drive 1475 m^3/hr of sodium at a delivery pressure of 3.7 bars. The flow can be adjusted down to almost zero flow (1.5 m^3/hr) by means of variable tension produced by an amplidyne generator unit. This type of pump was designed (at the same time as a mechanical pump) by General Electric for a flow of 1150 m^3/hr, a delivery pressure of 2.8 bars, a capacity of 220 kW (480 volts and 755 amperes) and a power factor of 0.37. By using condensers in parallel to correct the power factor, the current can be reduced to 376 amperes. At nominal flow the pump has a 43% yield. The operating temperature was set at 370°C, but the pump is capable of continuous operation at a slightly higher temperature. The class H windings operate at a lower temperature than that of the sodium, due to a thin thermal barrier and water cooling.

This pump has no detachable parts. No joints are used in the pump conduit. The electric windings and magnetic structure of the pump are in a second chamber filled with inert gas. This second chamber is closed by a toroidal joint. If there is a sodium leak from the first chamber, it comes into the second chamber which prevents any leakage of sodium to the

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ambient air. Under these conditions a reaction between the sodium and the cooling water is very unlikely, since a simultaneous leak from the thick-walled water pipe would be necessary for such a reaction to occur.

The winding temperature must be below 200°C. To obtain such a low temperature, a 33 m^3/hr water flow is required. The coil has six poles, setting up a drifting magnetic field with a synchronous linear speed of 18 m/s at 60 Hz.

The pump conduit has a cross-section of 26 mm by 695 mm; it is approximately 1025 mm long, and its wall is 1.5 mm thick. All parts of the conduit are of 347 stainless steel.

The thermal insulation acting as a barrier between the windings and the hot sodium in the conduit consists of alternate layers of plates and thin strips of stainless steel.

References : 8, 9, 110, 152.

3. <u>EFFBR</u>

In the secondary system there are three vertical centrifugal pumps. The suction and delivery connections are welded directly on to the piping. The lower bearing is situated above the wheel, and is lubricated with sodium. The upper pump bearing is a combination of a radial bearing and a thrust bearing. An oil system lubricates and cools the mechanical mountings and the upper bearing.

All the parts of the pump which come into contact with the sodium are made of steel containing 2.1/4% Cr - 1% Mo.

The pumps are driven by induction motors running on 4800 volts. The pump-motor coupling is magnetic; the sodium flow is regulated by action on the magnetic coupling.

As for the primary pumps, there is an auxiliary motor installed on each main motor.

References : 8, 12, 14, 126

Figure III-10 : Secondary Na pump

Table III-7 : Secondary pumps.

4. PFFBR

The three mechanical pumps are, like the primary pumps, single suction, vertical shaft mechanical ones, with leakproof mountings with inert gas.

The nominal flow per pump is 4462 m^3/hr for a manometric head of 32 m and a normal nominal operating temperature of 300°C. The yield of the pump is 80%.

The coiled rotor electric motors have a unitary capacity of 521 kW, and the pumping capacity (per pump) is 443 kW. The pumps work at 1170 r.p.m.

The speed can be varied from 50 to 100%.

The pumps are made of steel containing 2.1/4% Cr - 1% Mo.

Reference : 18

Figure IV-7 : Secondary sodium pump

Table IV-3 : Primary and secondary pumps. Reference performance and data.

5. LAMPRE I

There is no secondary pump.

6. DFR

There are 24 secondary pumps (two in parallel per circuit); they are identical to the primary pumps, i.e., flat linear induction electromagnetic ones.

Each pump delivers 63 t/hr NaK. There is 24% efficiency.

Reference : 24

Figure VI-3 : Electromagnetic pump

Table VI-2 : Primary pumps.

7. RAPSODIE

The two secondary pumps are, like the primary pumps, vertical centrifugal mechanical ones with axial delivery and lateral suction.

The nominal operating flow at 20 MW is 380 m^3/hr, at a delivery pressure of 1.5 bars.

Reference : Private communication

Table VII-2 : Secondary system.

8. BR 5

The two secondary pumps are identical to the primary pumps, i.e., free-level centrifugal ones with a suspended vertical shaft and the bearing and mountings in argon.

They are replaced by draining the system completely, as the NaK is not solid at the ambient temperature.

Reference : 109

Figure VIII-3 : Diagram of a pump.

9. SEFOR

The electromagnetic secondary is similar to the primary pump (a triphased AC linear one).

It gives a flow of 1140 m^3/hr at a pressure of 5 bars.

10. SRE

The two secondary pumps (one main, and one auxiliary) are similar to the primary pumps; the only difference is the lack of a protection cap, and consequent shortening of the casing and driving shaft.

The manometric pressure is 2.9 bars.

The capacity of the main secondary pump motor is 36 kW, and that of the auxiliary pump motor 3.5 kW.

The pumping capacity (per pump) is 25 kW. In the modified SRE the secondary pumps will, like the primary pumps, be replaced by free-surface hydrostatic centrifugal pumps with AC motors and eddy current couplings. The main secondary pump will be inside the expansion tank, at the high point of the secondary system.

The scheduled flow is 658 m^3/hr at a manometric head of 71 m of sodium with a 150 kW pumping capacity. The pump will work at 1800 r.p.m.

References : 73, 76, 82

Figure X-5 : Cross-section of the main secondary pump

Table X-3 : Secondary system.

11. HNPF

The three secondary pumps are almost identical to the primary pumps; the only difference is the absence of protection.

The pumps are in the steam generator housing.

Each pump delivers 1632 m^3/hr at a pressure of 3.7 bars.

The three secondary pumps were dismantled in June 1963; the shafts became stuck in the bearings as a result of a combination of the presence of foreign bodies, and uneven temperature distribution producing varying expansion. The sodium was filtered to remove the foreign bodies (introduced during construction) and a forced cooling system was installed to correct the uneven cooling of the pump casing. Since these alterations the pumps have operated correctly.

References : 68, 74, 111, 159, 161

Figure XI-3 : Primary pump

Table XI-3 : Secondary system.

III C TERMINAL EXCHANGERS

1. EBR I

a) Steam Generator

There is a single steam generator which is divided into three parts - economiser, reboiler and superheater - and has, in all, 31 exchangers about 3 m long.

The economiser is a device consisting of nine exchangers placed horizontally in series.

The reboiler is a forced flow reboiler of the liquid film type (so as to reduce the quantity of water). It consists of eighteen exchangers placed horizontally in parallel.

The superheater consists of four exchangers placed horizontally in series.

Each heat exchanger consists of an ordinary tube enclosed in casing; the NaK flow goes into the casing and the water or steam into the tube (in the opposite direction).

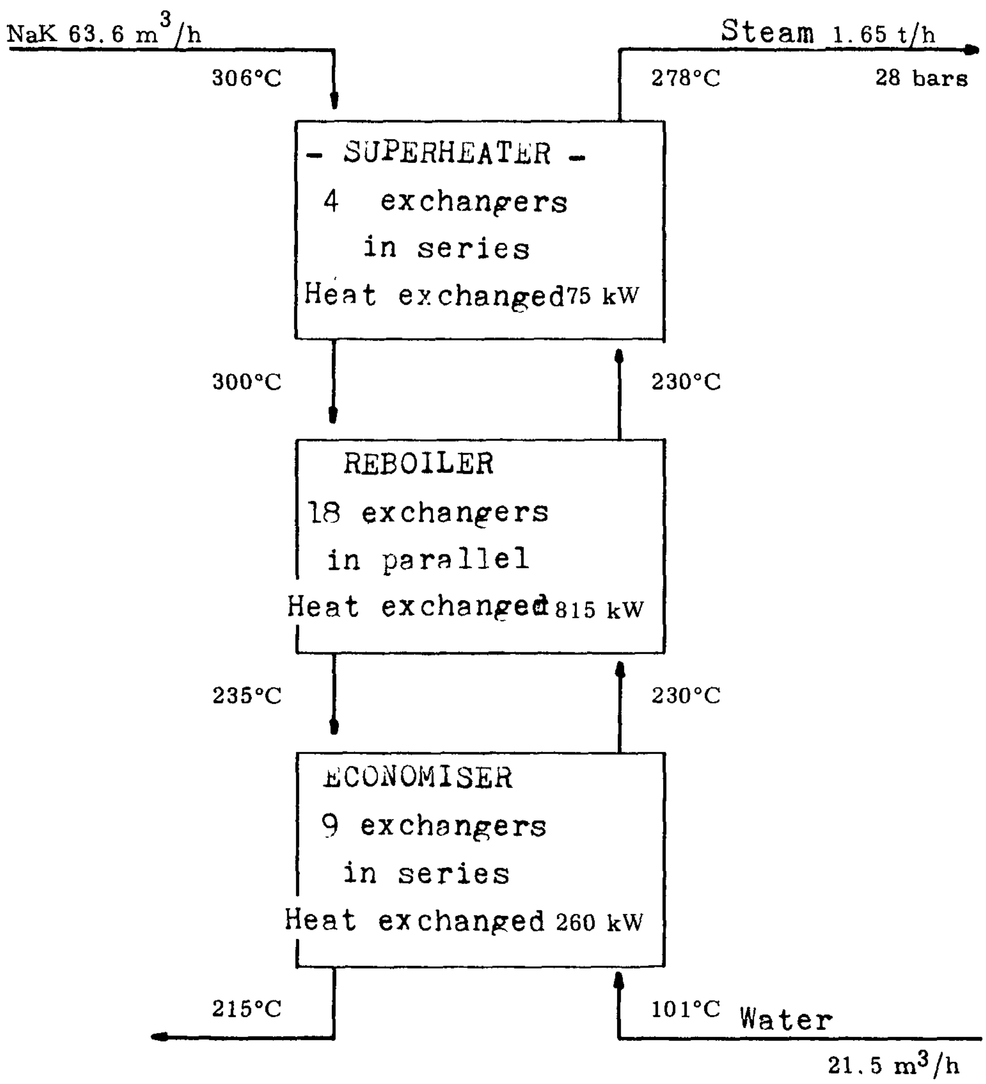
All the heat exchange tubes in the various parts have three layers (the inside and outside are of nickel, and the middle layer is copper). The total thickness of the tube wall is 8 mm, of which 4.8 mm is nickel.

The casing is of stainless steel.

The total inner area of the tubes is 4.2 m^2 in the economiser, 8.3 m^2 in the reboiler, and 1.85 m^2 in the superheater.

By means of a baffle, a film of water forms in the reboiler at the upper end of the inner tube. This film falls towards the bottom, where the excess water is collected as well as the steam produced which is then taken to the separator.

The steam produced in this way is used to drive a 300 kW AC turbo-generator. The plant has a net efficiency of 17%. If required, the steam produced can go straight to the condenser.



b) Air Cooler

In experiments where the reactor operates at low temperatures, the secondary NaK does not go into the steam generator, but into fin-tube air coolers.

References : 2, 60, 103, 115, 120

Figure I-1 : Layout of the systems

I-4 : Steam generator tube

I-7 : Layout of the steam system

I-8 : Photo of the steam generator

Table I-4 : Terminal exchanger

I-5 : Turbo-generator.

2. EBR II

The steam generator is of the natural recycling type. It has an evaporator section, a steam collector, and a superheater section.

The evaporator section consists of eight identical exchangers with casing and tube system, which are connected in parallel, on the tube side, to a horizontal steam collector in which conventional water separators are incorporated.

The dry saturated steam coming from the top of the steam container goes down through four identical vertical superheaters with casing and tube system, and then goes to the turbine.

The evaporators and superheaters use one-piece duplex tubes. No leak detection system or third annular fluid is used.

The duplex tubes of four evaporators are mechanically linked, while the tubes of the other four are connected by brazing.

The apparatus has double tubular plates at each end. The outer tube is welded onto the tubular plate of the sodium casing, and the inner tube to the steam tubular plate. The space between the tubular plates communicates directly with the atmosphere. There are no welds in the parts separating the sodium from the water or steam.

In the fabrication of the superheaters, difficulties were encountered with welds on the sodium side tubes (the superheater tubes have a smaller diameter and thinner walls than the evaporator tubes).

Two extra evaporators, adapted for use as superheaters, will be used temporarily. The characteristics of the evaporator and the superheater are identical, and analyses show that reasonable superheating efficiency can be obtained with a slightly modified evaporator. The modification consists of a tube of outer diameter 20 mm in the evaporator tubes; this allows the speed of the steam in the 3.1 mm annular section to be increased.

The use of two modified evaporators will allow a steam temperature of approximately 438°C to be produced with 45 MW (th).

The water content in the last part of the turbine will increase slightly.

The thermal efficiency of the plant is 28%.

In the event of a sodium-water reaction, two diaphragms placed in series break when the pressure reaches 7 bars. The diaphragms are situated between the tube taking the sodium from the superheater to the evaporator, and a 4.5 m^3 discharge tank. The tank communicates with the atmosphere through two tubes closed by diaphragms which break at a pressure of 2 bars.

The evaporators and superheaters are made of steel containing 2.1/4% Cr - 1% Mo.

References : 8, 9, 70, 115, 152

Figure II-1 : Layout of the circuits

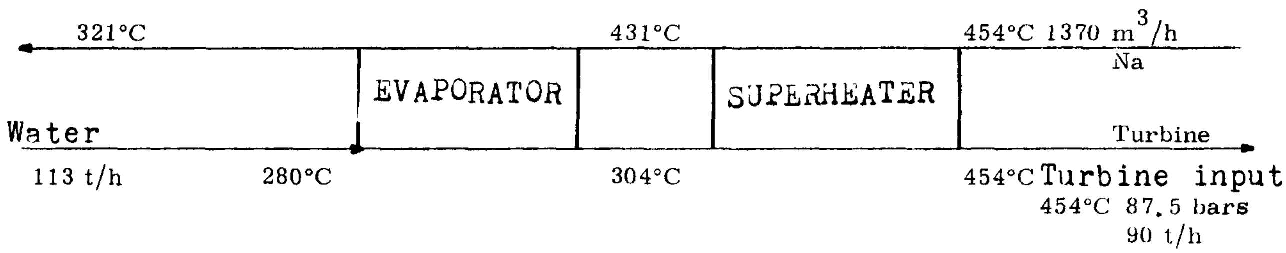
II-7 : Steam generator

II-11: Details of the superheater and evaporator

Table II-1 : Reactor capacity

II-3 : Cooling circuits and steam system.

E.B.R. II



3. EFFBR

There are three steam generators. They are vertical one-stage generators with alternate reflux-type flow. Sodium flows in the casing and steam inside the tubes. These tubes, of which there are 1200 arranged in a tube system, have single walls. Their outer diameter is 16 mm, they are 1.06 mm thick and 23.7 mm long, and the total tube surface exposed to the sodium is 1000 m2.

Each steam generator has a heater, an evaporator, and a superheater; which are all enclosed in one casing.

The following measures have been taken to prevent leakage. All joints are in the gas zone above the sodium (reduction of thermal shocks). The wall between the sodium and the water is of ferritic steel containing 2.1/4% Cr - 1% Mo, which shows good resistance to corrosion and thermal stress. All the parts were tested. The tube system can be removed for inspection and maintenance of the outside of the tubes.

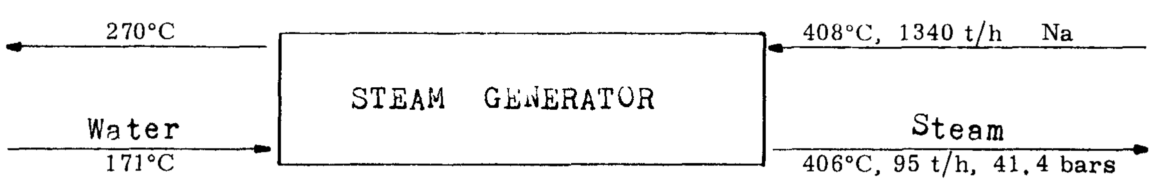
To restrict the effects of a sodium-water reaction, the generator has a large volume of gas in its central area. There is a safety diaphragm (which breaks at a pressure of 3.5 bars) in the upper part of the apparatus; if this breaks, the reaction products enter a centrifugal separator which retains the solid particles and sends the gas into the atmosphere. This is what occurred in December 1962, after a tube fracture caused by vibrations; there was no damage. Devices have been installed to reduce vibration at the sodium input level.

The sodium enters through 300 mm connections in the casing near the top of the steam generator. It flows once through the casing and leaves through the opening at the bottom.

The supply water enters an annular collector near the top of the generator, goes down through the 1200 tubes in the center of the casing, and then rises through horizontal uranium tubes to a steam collector in the upper part of the casing. The steam feeds a turbine.

The steam generator is made of slightly alloyed (2.1/4% Cr - 1% Mo) ferritic steel. The cost price of the generator is low.

References		:	51, 71, 104, 115, 126
Figure	III-11	:	Steam generator : nominal characteristics
	III-12	:	Diagram of the steam system
Table	III-1	:	Capacity of the reactor
	III-8	:	Capacity of the steam system



4. PFFBR

The three steam generators (one-stage vertical ones with single-walled tubes) are similar to those in EFFBR. They differ, however, in several ways, namely :

1. the PFFBR generator tubes are longer (26 m) than those in EFFBR (23 m) to provide the required heat transfer surface (this total heat transfer surface capacity is 2055 m^2, 1506 m^2 of which is effective surface).

2. the speed of the steam, which is 18 m/s in EFFBR, rises to 33.2 m/s in PFFBR, which produces an increase in the heat transfer coefficient in every section.

Each steam generator has a diameter of 2.47 m and an overall height of close to 10.6 m.

The heat transferred by each steam generator is 259 MW (as against 100 MW in EFFBR).

The secondary sodium enters the steam generator casing at 493°C near the top through two 400 mm diameter openings. It flows around the tubes down to the bottom of the casing and leaves the generator at 298°C after passing through a 500 mm diameter opening.

The supply water enters on the tube side of the generator via the collector, at a nominal temperature of 195°C. The water is taken to the central section, which is baffled on the sodium side to minimise heat transfer to the water. The water then rises in the opposite direction to the sodium, and leaves the generator as superheated steam at 466°C, a pressure of 100 bars and a rate of 377 t/h.

The net electric capacity is 283 MW, and the thermal efficiency 36.7%.

The zone above the sodium is filled with argon, which reduces thermal shock. This zone is also a protection against sodium-water reactions.

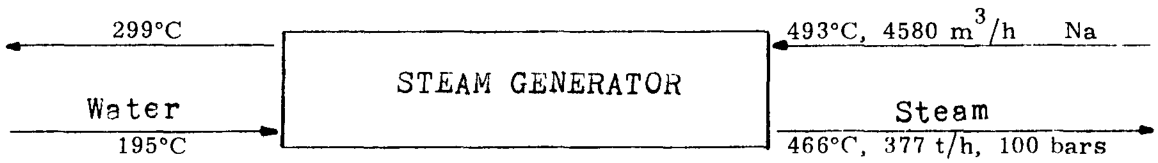
The steam generator tubes are made entirely of steel (2.1/4% Cr - 1% Mo).

References : 18, 51

Figure IV-1 : Diagram of the circuits and steam system

IV-9 : Steam generator

Table IV-5 : Steam generators : nominal characteristics.



5. LAMPRE I

The air exchanger (which is in the primary system) consists of fin tubes which transfer the heat from the sodium to the air; the air is, in turn, discharged via a stack outside the building. The flow of air through the exchanger is regulated by the sodium temperature at the exchanger outlet. The temperature is measured by means of a thermocouple connected to a servo-potentiometer. This potentiometer controls a pneumatic system which adjusts the position of a register on the ventilator inlet.

References : 19, 94.

6. DFR

The twelve secondary circuits have twelve steam generators (one per circuit). To prevent excessive stress, the tubular plate on these exchangers was done away with, thereby producing an apparatus using butt-welding only and having the minimum number of necks and high stress zones.

To produce such an apparatus, it was necessary to design exchangers where the NaK and the water ran in separate tubes, connected by a body with good thermal conductibility. In the first designs for terminal exchangers along these lines, the stainless steel tubes were set in a mass of aluminum moulded around them. At a later design stage, it was decided to use copper, as a good connection between aluminum and steel could not be guaranteed. The part adopted consisted of copper plates 3.2 mm thick, assembled in a unit 2.4 m long, and brazed on to the 18 mm stainless steel tubes.

Each steam generator, with a capacity of 6 MW, has a set of these parts. There are twenty parts in each row, and thirteen rows vertically.

The NaK flows in parallel from the bottom to the top, while on the steam-water side the sections of the economiser, evaporator and superheater are connected.

As this type of steam generator is very expensive, it was decided to start up initially at half the required thermal capacity, thereby permitting employment of either the same system, or a more economical one, in any future extension.

At present two steam generators, each with a 3 MW thermal capacity (and each, therefore, with 10 copper plate parts in rows, instead of 20), are placed together in a common recess. Hence there are six recesses holding all the generators.

The sides, top and base of these recesses consist of stainless steel blocks 75 mm thick, insulated with mineral wool.

Each recess is equipped with electric heaters to keep the temperature at 150°C in the event of a reactor shutdown.

The thermal efficiency of the plant is 20%.

The equipment is made of 316 stainless steel and copper.

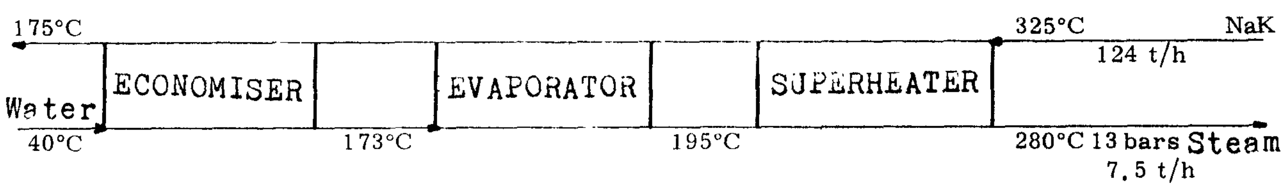
References : 24, 26

Figure VI-8 : Steam generator

VI-9 : Detail of the sodium-water exchangers

Table VI-3 : Secondary system and steam generator

VI-4 : Steam plant



7. RAPSODIE

Each of the two secondary cooling circuits has an air exchanger consisting of a horizontal tube system containing the secondary sodium placed in a flue with a forced air flow.

The sodium flows inside the tubes, and the air outside.

The arrangement of the tube system is as follows : 224 tubes in parallel are connected to an inlet collector and an outlet collector; they pass four times through the flue. They are arranged so as to form sixteen sheets of 56 tubes in line. The tubes are arranged in rectangular pitch. These are tubes with rolled in fins. The 56 tubes in a sheet are connected on one hand to the 28 sub-collectors of the main inlet collector, and on the other hand to the 28 sub-collectors of the main outlet collector.

The diameter of the tubes is 21.4/25.4 mm; the finned length per tube, is 2.15 m; the outer diameter of the fins is 40.6 mm, they are 1 mm thick, and their pitch is 100 mm. The total exchange surface is 1145 m^2.

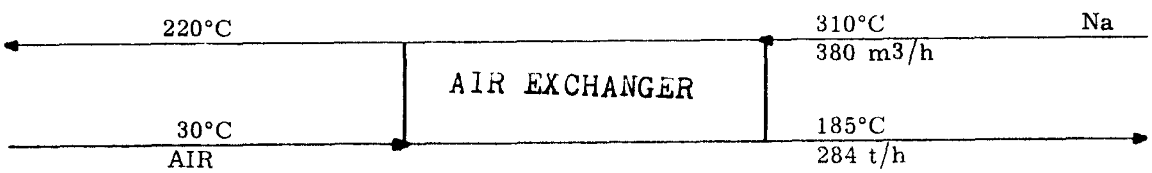
The fan is helicoidal. The operating speed is varied by adjusting the fan guide bladings. For a maximum air flow of 284,000 kg/hr, the total delivery pressure is 250 mm of water, and the input power 260 eV.

The air exchanger input and output temperatures of the secondary sodium are 310 and 220°C respectively.

The air enters at 30°C and leaves at 185°C. The air pressure loss is 0.020 bars, and that of the secondary sodium 0.20 bars. The exchangers are of 316 stainless steel.

Reference : Private communication

Table VII-2: Secondary system.



8. BR 5

One of the secondary cooling circuits is equipped with a steam generator, and the other with an air exchanger.

a) Steam generator

It is of the type with double-walled tubes and casing. To prevent accidental contact between the NaK and the water, the NaK and water tube systems are in a ring filled with mercury. The mercury levels and pressure are measured to detect any leakages of NaK or water. The steam generator input and output temperatures of the secondary NaK are 430 and 300°C.

The steam produced is at a pressure of 16 bars, 400°C, and a rate of 5 t/hr. It is condensed in a water-flow condenser (flow : 70 m^3/hr).

b) Air exchanger

Heat is dissipated by a flow of ambient air (40,000 m^3/hr) from a fan.

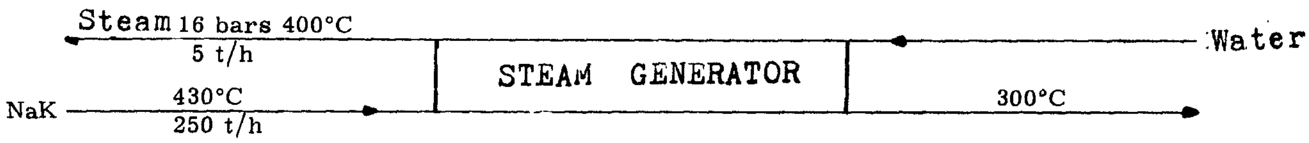
The air exchanger input and output temperatures of the secondary NaK are 430 and 300°C.

In the event of a reactor shutdown, the 24 m high stack permits dissipation of the residual heat by natural convection.

References : 66, 72

Figure VIII-2 : Diagram of the circuits and steam system

Table VIII-2 : Secondary system.



9. SEFOR

The air exchanger is of the forced draught type with finned heat exchange surfaces. The tubes are of 304 stainless steel. Three fans equipped with two-speed motors allow the temperature to be controlled over a wide reactor power range.

The heat exchange surface is based on a temperature difference of 250°C.

During initial operation the exchanger input temperature of the sodium will be 382°C, but it will be possible to raise it later to 510°C.

304 stainless steel is used.

Reference : 149

10. SRE

The secondary circuits have a steam generator, with main and auxiliary air exchangers.

The steam generator is horizontal, U-shaped, with single flow and double walls; there is mercury in the annular section between the inner tube containing water and the outer, sodium-heated, tube. The greatest outer diameter of the tube is 17 mm; the casing has a diameter of 475 mm, and is 24 m long.

The sodium enters the generator at 482°C and leaves it at 227°C. The supply water, at 140°C, enters the preheating section which is at the bottom. It rises through the evaporator and leaves the superheater at 440°C, a pressure of 41 bars, and a rate of 27 t/hr. (The net thermal efficiency is 38.5%).

304 stainless steel is used (whereas generators are often made of ferritic steel).

The steam generator planned for the modified SRE is likely to have a capacity of 30 MW (th).

The maximum generator input temperature of the sodium would then be 625°C, and the condition of the primary sodium would be adjusted to give steam at 566°C and 41 bars. Since this steam is clearly too hot to go through the 7500 kW turbo-alternator (temperature 440°C, pressure 41 bars), it is necessary to provide de-superheating installations in the steam plant.

Another kind of steam generator has also been tried on SRE. It is of the natural flow type, and has two evaporators producing saturated steam at 41 bars, a steam container and a superheater.

The two evaporators and the superheater consist of vertical casings filled with coils stacked one on top of another. The evaporator casing has a diameter of approximately 1.5 m, is 2.4 m high, and holds 48 coils. These coils are double-walled, with mercury in the annular section; the inner tube is of 347 stainless steel, and the outer tube of carbon steel. In the evaporator the sodium flows inside the coils, and the steam is produced on the casing side. The water comes in at the base of the casing and the superheated steam leaves via the top, going to the steam container and then the superheater. The construction of the latter is identical to that of the evaporator, but the steam flows in the tubes, and the sodium on the casing side; the outer and inner tubes of the coils are both of 347 stainless steel.

This generator system has operated without significant incident at up to two-thirds of the maximum capacity of the reactor.

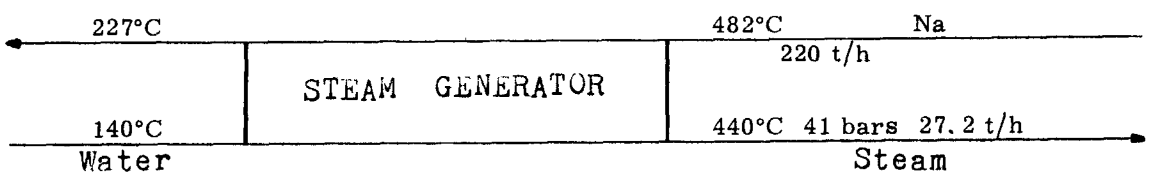
The air exchangers are U-shaped tube systems situated in protection housings above fans driven by electric motors. The tubes are similar to those in the intermediate exchangers; but 410 stainless steel fins of diameter 51 mm are mounted on them, eight fins to every 25 mm of tube. All the tubes are connected in parallel on one side, and connected to the collectors.

The air flow is perpendicular to the sodium flow. The main air exchanger has 204 U-shaped tubes 8 m long, giving a heat surface of 2104 m^2. At normal power, the heat transfer coefficient is estimated at 47 W/m^2.°C for air input and output temperatures of 38 and 136°C. Under the tube systems are two 3.36 m diameter ventilators, each driven by a 37 kW adjustable speed electric motor.

The air-cooled auxiliary exchanger, of similar design, has 30 U-tubes 2.43 m long, with a single 1.53 m diameter fan driven by a 3.7 kW adjustable speed electric motor.

Since the steam generators have been sufficient to dissipate the heat, there has been no call to date to use the air exchangers at any considerable level of power. However, the 45 MW capacity scheduled for the modified SRE will exceed the thermal capacity of the steam generator; consequently, when such power is reached, the air exchanger will operate in parallel with the steam generator.

References	:	36, 73, 76, 115, 157
Figure X-9	:	Steam generator
X-10	:	Natural flow evaporator
Table X-1	:	Reactor capacity
X-2	:	Secondary circuits and steam system
X-4	:	Comparison of present and modified SRE.



11. HNPF

There is a steam generator in each of the three secondary circuits.

Each generator consists on the one hand of an evaporator and a superheater (of the tubes-and-casing type) and, on the other, of a water separator.

The evaporator and superheater are each equipped with double-walled bayonet tubes (680 in the evaporator, 560 in the superheater). The purpose of these tubes is to maintain a double barrier between the sodium and the steam or water. The zone between the two tubes acts as an intermediate chamber, and is used in the leak detection system. The central supply tubes taking the flow towards the bayonet tubes are also double-walled; the annular zone between the tubes is filled with inert gas. The bayonet tubes, consisting of four concentric tubes, make the cost price of this generator very high.

The evaporator is of the boiler type; in the boiler casing the water is kept at a slightly higher level than that of the highest tube.

The construction of the superheater is similar to that of the evaporator but, on the casing side disc-shaped baffles are used to improve the coefficient of heat transfer to the steam.

The water separator is outside the casing. Its purpose is to eliminate the moisture preserved in the steam, thereby ensuring a supply of dry steam to the superheater.

Helium is used as the third fluid, and enables any leak in the steam generators to be detected. The normal helium pressure is about 21 bars. In the event of a leak on the sodium side, the helium pressure falls to that of the sodium (less than 7 bars). In the event of a leak on the steam side, the helium pressure rises to that of the steam 59 bars). (When a leak is announced, an immediate shutdown is not necessary, as an ordinary leak does not affect operation of the reactor.)

The only difficulty encountered with this reactor was a problem of steam purity; this decreased when the evaporation rate increased, and it was a question of the water level in the evaporator. The problem was settled by adjusting the water level as a function of the evaporation rate.

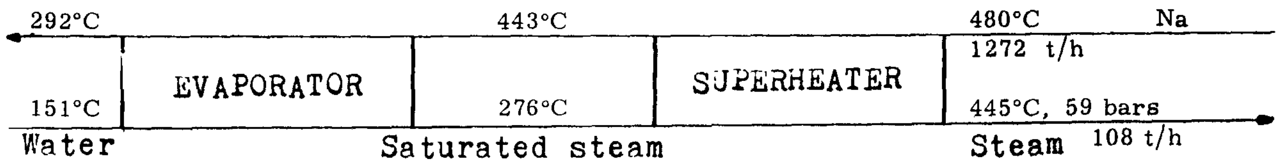
304 and 321 stainless steel and 2.1/4% Cr, 1% Mo ferritic steel are used for the evaporator.

For the superheater, 304 and 321 stainless steel and 5 Cr, ½ Mo and 2.1/4 Cr, 1 Mo ferritic steel are used (5 Cr, ½ Mo steel is used for the parts coming into contact with sodium at above 450°C.)

References : 68, 115, 159, 161

Figure XI-7 : Steam generators

Table XI-3 : Secondary circuits and steam system.



IV. MISCELLANEOUS

IV A PURIFICATION SYSTEMS

1. EBR I

In the primary system, as in the secondary system, a small part of the pumped coolant is by-passed and goes through a cold trap and a filter which retain the oxide particles; the filter is of sintered stainless steel.

Reference : 120

2. EBR II

1. The primary purification system consists of a cold trap, two fouling indicators and two vacuum samplers. It operates continuously, flow being ensured by an electromagnetic pump.

The cold trap consists of a 1.8 m^3 tank, filled with 304 stainless steel wool. An economiser exchanger was incorporated in the main sodium flow.

The operating temperature of 177°C is maintained by a secondary sodium flow.

Some parts of the cold trap are situated below the sodium level in the primary vessel. To prevent leakage of the radioactive sodium, there is an expansion tank at the highest point of the inlet pipe to the cold trap. Argon pressure is maintained so that, in static conditions, the sodium level is just below the delivery opening of the expansion tank. When the pump is running, the level rises enough to establish a flow. The supply of electricity to the pump is controlled by a sodium vapor detector situated at cold trap floor level; this is so that the current can be cut off, thereby closing the sodium inlet to the expansion tank, in the event of a sodium leak being detected. There is also an argon pipe to permit gas to be added, so that the sodium column can be broken in the event of an emergency shutdown. The cold trap delivery pipe discharges into the primary vessel blanket gas, .../...

ruling out any possibility of siphoning in the delivery pipe. Five remote-controlled valves are situated in the cold trap circuit.

There are fouling indicators on the cold trap inlet and outlet piping.

Two vacuum samplers allow sodium samples to be taken for chemical or X-ray analysis. Samples can be taken either at the inlet to the cold trap, or from the delivery pipe.

2. The secondary purification system treats a flow of 4.5 m^3/hr. The sodium is pumped into the storage tank and goes to the expansion tank, which keeps the level constant. The overflow returns to the storage tank.

References : 9, 152

Figure II-4 : Diagram of the primary purification system.

3. EFFBR

1. The primary purification system has a cold trap and a fouling indicator. Its object is to keep the oxide content below 30 ppm. The sodium is pumped into the storage tank and passes through either the trap or the indicator before being taken into the primary system. (The surplus sodium in the circuit goes through an overflow into the storage tank). Purification is therefore intermittent. There is also a device for taking sodium samples for chemical analysis.

Cold trap

The oxide-charged sodium comes from the casing side into the economiser, where it is cooled. It then rises through the central part of the trap, which is lined with stainless steel gauze where the oxides and hydrides precipitated will gather. On leaving the cold trap the sodium goes through the tube side of the economiser to be heated by the oxide-charged sodium. The trap is cooled by an NaK flow produced by two electromagnetic pumps (the NaK itself is cooled in an air exchanger).

Fouling indicator

It is cooled by the same NaK system as the cold trap. The openings have a diameter of 0.75 mm.

Hot trap

There is also a hot trap designed to remove the dissolved carbon.

Pumps

The two mechanical pumps producing the sodium flow in the purification system are in the storage tank. They can be removed easily.

Material

The system is made of 304 stainless steel.

2. The secondary purification system has a cold trap and four fouling indicators. Its operation is also intermittent.

Cold trap

The sodium goes firstly into an economiser and then to an air cooler with fan which brings the sodium temperature down to the point where the oxides start to precipitate. On leaving the cold trap the sodium passes through the economiser.

The air flow is regulated by a temperature controller; the air can also be preheated if necessary.

There is no intermediate NaK system as there is in the primary system.

The cold trap can only be operated on one of the three independent secondary circuits at any one time.

Fouling indicators

There is one of each of the three independent loops, and one on the cold trap circuit. The indicators are cooled by air, with the sodium flowing through a finned tube. Separate fans supply the air to each indicator.

Pumps

The flow is produced by the secondary circuit pump or by an electromagnetic pump which can give 22.7 m^3/hr at 12 bars.

Material

304 stainless steel is used.

References : 14, 126

Figure III-5 : Cold trap

III-6 : Fouling indicator

Table III-4 : Primary auxiliaries.

4. PFFBR

a) - The primary purification system, which has a cold trap, and economiser and a fouling indicator, is situated in the "reactor" housing.

Sodium from the delivery of one of the circuit pumps is taken through the cold trap circuit and then returned to the inlet to the same circuit pump. The cold trap reduces the oxide and hydride content of the sodium to about 50 ppm.

b) - In the secondary system there is one purification unit for all three circuits.

Reference : 18

Figure IV-2 : Layout of the systems.

5. LAMPRE

The purification system has a cold trap, three hot traps and a fouling indicator.

Cold trap

The cold trap and the fouling indicator are set up in the lateral branch of the drainage tank. The sodium flows firstly through the primary cooling system, and then returns to the drainage tank via the cold trap (the main circuit can in this way be cold-trapped without the cold trap being connected to the circuit itself). While the reactor is running, a volve enables the cold trap and the primary system drainage tank to be cut off.

Hot traps

The three hot traps are set up in parallel on a 25 mm circuit bypassing the primary system. There is one heating controller per hot trap. Only one hot trap is operated at any one time. To prevent a bypass flow through the two unheated traps, the sodium is allowed to congeal there. To absorb oxygen, zirconium sheets (foil) are used, and the sodium is heated to 700°C. The hot trap circuit is equipped with an electromagnetic pump and a flowmeter. The hot traps should reduce the oxide content to 1 or 2 ppm. The capacity of the hot traps is estimated to be 10 times that required, and the flow in the bypass circuit represents approximately 5% of the total flow (i.e., 1.15 m^3/hr).

Fouling indicator

This enables the oxide content to be determined up to 15 ppm.

Reference : 19

Figure V-1 : Layout of the circuits.

6. DFR

The primary purification system has 24 shunted circuits consisting of 15 cold traps, 5 hot traps, and two electric resistivity measuring devices, to which a corrosion measurement device and a sampler were later added. (It had originally been planned to have one cold trap per circuit, and hence 24 in all, but in order for the oxygen content of the NaK to be brought down to less than 5 ppm, it was necessary for nine of the cold traps to be replaced by five hot traps.)

Two cold traps are set up in a bypass at the top of each secondary circuit. The secondary cold traps are similar to the primary ones.

a) Cold traps

In the cold trap circuits the sodium flows from the pump outlet to the cold trap, and returns to the main circuit, at the reactor inlet, via the expansion tank.

The NaK (flowing at 1.3 m^3/hr) enters the cold trap at 200°C, is cooled to 115°C by means of an economiser, and passes through a tank containing stainless steel RASCHIG rings at a rate of 0.48 m^3/hr (the remaining NaK goes straight out of the cold trap). After staying five minutes in this

.../...

tank, the cold NaK enters the casing side of the economiser, which it leaves at 195°C. To ensure the 0.48 m^3/hr flow through the tank, an opening was made in the top of the central tube; its measurements were determined on a prototype cold trap placed on a separate loop. Cooling is effected by bypassing the cooling air from the lateral protection.

b) Hot traps

The NaK flow through the hot trap is 3.4 t/hr (i.e., 6% of the flow of the loop to which it is connected). The hot trap consists of a main tank with safety casing, containing an economiser, zirconium sheets, tubular heaters and a heater. The tank is 6.7 m high and its diameter is 380 mm.

In the lower part there is an economiser with casing and tube system, in which the NaK is heated from 200 to 580°C. The coolant goes through the heater tube where it is finally brought to about 600°C; it then flows through a tank containing zirconium sheets which absorb the oxygen. These sheets are rolled in strips 76 mm wide and 0.125 mm thick and placed in alternate flat and corrugated layers on stainless steel coils 203 mm in diameter. There are twenty such coils in each hot trap, which gives a total exposed surface of approximately 372 m^2. After the NaK has left the tank containing the zirconium sheets, and before it leaves the cold trap, it is cooled to 220°C by means of the economiser.

The NaK flow is measured by a flowmeter in the branch circuit, while a thermocouple measures the temperature of the NaK entering the tank holding the zirconium sheets. To keep a fixed temperature in the heater, this thermocouple automatically controls an induction voltage regulator providing the heater with power.

A thermocouple in the heating elements prevents these parts from overheating.

c) Corrosion measurement apparatus

This apparatus, which is set up in a tank designed for a hot trap, determines the oxide content by measurement of the corrosion of a niobium cylinder (comparison of NaK flows at 600°C through a niobium cylinder and a stainless steel one).

d) Sampler

This is set up on the site of a hot trap. 100 cm^3 of NaK can be taken in a nickel tube. The NaK is analysed by distillation.

e) Purification systems

As a result of numerous technical difficulties arising from inadequate purification of the systems, an unprotected cold trap circuit was set up among the existing ones. This circuit has a fouling indicator to measure the impurity content on entering and leaving the trap. This temporary circuit replaced the fifteen cold traps from June 1960 until June 1962.

As a long-term measure, a similar, protected installation was built. This plant, in which various types of cold trap are tested, has rhometers and fouling indicators to measure the impurity content. It has been in operation since June 1962.

In the PFR power reactor it is planned to make the purification system independent of the main systems.

References : 24, 26, 79, 84, 114

Figure VI-5 : Hot trap

VI-6 : Diagram of a corrosion indicator

VI-10 : Cold trap

VI-11 : Permanent cold trap circuit.

7. RAPSODIE

In the primary purification system there are two cold traps in parallel. They are supplied by a small DC electromagnetic pump immersed in the overflow expansion tank. There are also two fouling indicators. The purification system was designed so as to be completely independent of the cooling system. A place was left free for hot traps, if required.

For each secondary circuit there is a cold trap and a fouling indicator, branched on the main circuit. The secondary cold traps are smaller than the primary ones (flow : 1 m^3/hr); they are cooled by atmospheric air (4 t/hr).

Cold trap

This is a cylindrical vessel with a vertical axis, closed at the ends by elliptical plates. This vessel has :

- an inner zone filled with stainless steel wool, through which the sodium flows from the bottom upwards.
- an annular zone filled with stainless steel wool, through which the sodium flows from the top downwards.
- an annular zone where there is a cooling coil (nitrogen under pressure). The coil itself is a 40/44 mm tube, spirally wound with quadruple pitch, with an average diameter of 574 mm.

The cold trap is completely enclosed in cladding to allow it to be heated. All the parts of the apparatus which come into contact with the sodium are of 316 stainless steel. There is an economiser exchanger on the cold trap circuit.

The input and output temperatures of the sodium are 160 and 130°C respectively; the sodium flow is 4 t/hr. For the nitrogen the temperatures are 40 and 100°C, and the flow is 2.6 t/hr at a pressure of 5 bars.

Fouling indicators

The fouling indicator unit consists of :

- an economiser exchanger formed by two concentric U-tubes of diameter 12/14 and 21/25.
- the indicator itself, consisting of a fouling collar at the cold point of a bayonet exchanger, cooled by a forced nitrogen flow.

The fouling collar is a ring enclosing the 12/14 tube; it is 2 mm thick, and the Na can pass through 12 grooves of 1 mm side.

References : 28 and private communication

Figure VII-6 : Diagram of the primary purification system

VII-7 : Cold trap.

8. <u>BR 5</u>

To purify the sodium there is a cold trap for each primary and secondary circuit.

In the cold trap the sodium is cooled by boiling toluene at 130°C, which is in turn cooled by steam. The sodium remains in the cold trap for about 10 minutes.

The cold traps are shunt assembled; the flow through them is 0.5% of the total flow.

The oxide content is determined by fouling indicators.

The primary system was initially filled with distilled sodium; this method made it possible not to exceed an oxide content of 30 ppm after start-up (this fully satisfies the operating requirements of the reactor).

In the course of operation, it has been necessary several times to replace the cold traps. The first replacement was effected after the primary circuits had been drained completely; later replacements in the primary system were made by partial drainage and solidification of the remaining sodium. In addition the primary cold traps have been transferred to a different chamber from the rest of the primary system, which enables them to be dismantled without shutting the reactor down. Oxide content at the time of repair work has never exceeded 70 ppm.

Reference : 72.

9. <u>SEFOR</u>

10. SRE

The primary purification system has two cold traps, two hot traps, and fouling indicators. The secondary system has two cold traps, and fouling indicators.

Cold traps

Tetraline was originally used to cool the sodium. It was done away with throughout SRE after a leak which contaminated the sodium and the fuel in the reactor. It was replaced with nitrogen in the primary system, and air in the secondary system.

The primary cold traps and the main secondary trap are similar to those in the HNPF. They are removable, and the primary traps are in a separate protection gallery.

The sodium goes down through the annular zone filled with stainless steel wool, rises in a central tube and flows through an economiser before leaving the trap. The input and output temperatures are 260 and 197°C, with a temperature of 143°C at the bottom of the trap. The flow is 3 m^3/hr. The concentration obtained is 10 ppm.

Ventilators provide the reflux gas flow.

For the nitrogen the input and output temperatures are 65 and 150°C with a flow of 2550 m^3/hr. (Power exchanged : 64 kW).

The auxiliary secondary trap was originally situated under the expansion tank; it never worked (length-diameter ratio too small; connection to tank too wide). The new trap consists simply of a tube 0.60 m long and 5 cm in diameter fixed vertically below a right angle elbow in the circuit. The trap is cooled by air, using natural convection. The temperature at the bottom of the trap is 120°C for a sodium flow at 260°C. The oxygen concentration is brought down to 5½ ppm.

Hot traps

The two hot traps are also situated in the protection gallery outside the reactor housing.

The hot traps originally consisted of a detachable assembly containing the zirconium; leakproofing was ensured by a solid joint. Experience showed that this type was not easily removable because of the possibility of radioactive contamination, and that special equipment was required.

In the new hot traps the assembly is no longer detachable, and the solid joint has been done away with; the whole unit is removed in one piece. These traps contain sheets of 304 stainless steel, which withdraw the carbon from the sodium. 2 kg of carbon can be extracted from a 200 kg load. 90% of the carbon quantity moves into the steel in 100 hours. 410 stainless steel, whose carbon withdrawal capacity is one-third greater, is to be used in the larger traps.

Fouling indicator

This consists of an economiser and a sodium-gas cooler, a fouling valve with a wall opening, a thermocouple and a permanent magnet flowmeter. Nitrogen is used to cool the sodium in the primary system, and air in the secondary system. The fouling opening is set up on a 25 mm Y-shaped valve body. The standard valve disc is replaced by a disc of 304 stainless steel. The face of the disc has a number of holes; the number depends on the pressure loss obtained through the fouling indicator. The sides of the disc (downwards flow to the base) are also perforated, allowing a small flow through the openings when the valve is in the closed position.

.../...

The advantage of this disc arrangement is to facilitate cleaning.

References : 31, 37, 85, 172

Figure X-1 : Tetraline-cooled cold trap

X-2 : Layout of the systems

X-4 : Zirconium cold trap

X-6 : Fouling indicator

X-11 : New cold trap

X-12 : New hot trap.

11. HNPF

The apparatus for purifying the primary sodium consists of two cold traps, a carbon trap with a sodium sampler, and fouling indicators. A cold trap and fouling indicators are provided for the secondary sodium.

Cold traps

The removable cold trap assembly is entirely at one level to make it possible to construct the trap without expansion joints for the casing. The two cold traps are situated in separate concrete galleries, so that one of the units is accessible when the other is running. The sodium is cooled in the trap by nitrogen flowing through a sealed casing. The use of nitrogen makes it necessary to weld fins on to the outer surface of the sodium tank. These fins are strips of carbon steel 4 mm thick and 2.5 m long.

On entering the trap the sodium is discharged on to the economiser coil, which cools it. It then goes into the screen section, where it is further cooled by a nitrogen flow in the cooling casing. The oxide precipitation occurs here. In this section the flow is baffled to prevent bypassing, which necessitates uniform cooling of the whole flow. After passing through the screens, the sodium is considered clean. It is then at 120°C.

It should be noted that a sodium buffer zone is used to reduce the heat transfer rate at the bottom of the trap, thereby permitting stricter temperature control. The purified sodium enters the 125 mm return tube and rises to the economiser coil. This rising flow produces heating which enables the sodium to be brought back to the main piping system without a junction to prevent thermal stress being necessary.

The heat in the cold trap is dissipated by the nitrogen by means of heat transfer across the finned section to the nitrogen. The nitrogen enters this section at the bottom of the cold trap, rises through the finned section and is then discharged into the piping at the top of the trap. The hot nitrogen delivered in this way flows back in a closed nitrogen cooling circuit.

Operation of the trap can be made fully automatic by connecting the lower thermocouple to a temperature-recording controller which regulates the nitrogen flow. The controller is then adjusted so as to keep the sodium temperature constant at 120°C at the opening of the 125 mm return tube. The controller can also be regulated so as to give a constant nitrogen flow and a controlled sodium flow. Previous difficulties with sodium regulator valves would seem to show that controlling the nitrogen flow is the simplest and most advantageous method. The cold trap can remove up to 90 kg of sodium oxide, which makes it possible to clean a system containing 430 tons of sodium; this quantity represents about twice the volume of the saturated system at 232°C.

Carbon trap

The carbon trap makes it possible to remove carbon from the sodium. The sodium is heated to 650°C and then taken over stainless steel sheets situated in the carbon trap. At this high temperature the carbon passes from the sodium onto the stainless steel, so that the sheets are carburised and the carbon removed from the sodium. To cool the sodium it is then passed through an economiser in which the carbon-free sodium transfers its heat to the sodium entering the carbon trap.

Sampler

The sampling device situated at the inlet to the carbon trap enables small quantities of sodium to be taken from the system for analysis. The device is dosed periodically to determine the extent of carburisation.

Fouling indicator

The fouling indicator used in HNPF consists of the same elements as are used in SRE, namely :

- an economiser. This is an ordinary double-tube exchanger. The inner tube is a 50 mm pipe.
- a nitrogen-sodium exchanger. This element was fabricated from a 620 mm long section of tubing with lengthwise fins, 50 mm in diameter.
- a fouling valve of the perforated type
- an electromagnetic flowmeter. It is situated on a 25 mm pipe before the economiser inlet.

On the other hand, and contrary to the indicator adopted for SRE, the one used in HNPF can operate automatically and continuously, which enables the temperature to be recorded every two hours.

References : 68, 86, 87, 88

Figure XI-4 : Cold trap

XI-5 : Fouling indicator

IV B MEASUREMENT TECHNIQUES

1. EBR I

Conventional apparatus is used for measurement.

All readings are shown or recorded in the control room.

a) Flow measurement

Primary system. When the flowmeter at the outlet of the supply tank shows too small a flow while the reactor is on power, there is immediately an automatic emergency shutdown.

When the flow at the pump outlet is too small, there is an automatic emergency shutdown if no correction is made within two minutes.

Secondary system. Too small an NaK flow simply sets off an alarm.

b) Level measurement

This is coupled, in every tank, with alarm systems.

c) Pressure measurement

At the pump outlets.

Reference : 120.

2. EBR II

a) Flow measurement

Primary system. Five permanent magnet electromagnetic flowmeters are situated in the primary system. The main flowmeter is on the pipe leaving the reactor. Measurement of the total coolant flow from the reactor is shown continuously and recorded in the control room.

The flow indicator is equipped with an adjustable safety circuit-breaker which can be used in the event of an emergency shutdown.

There are four other flowmeters, two on the high pressure collector inlets and two on the low pressure collector inlets.

These flow rates are also shown and recorded in the control room.

Five conventional diaphragm flowmeters, set up on the circuits, are used in emergency and to calibrate the electromagnetic flowmeters.

Primary vessel. There is an electromagnetic flowmeter in the cold branch of each of the two shutdown coolant devices. The flow rates are shown in the control room.

Secondary system. There is an electromagnetic flowmeter on the pump delivery pipe. The sodium flow is continuously shown and recorded in the control room. The indicator is equipped with contacts which can be adjusted to minimum and maximum flow so as to give the alarm signals. A flowmeter with aperture, which can be read in the reactor housing, is used for calibration and as a stand-by meter in the event of the other flowmeters breaking down. The purification system flow is measured continuously and shown in the control room. The alarm is given when there is a small flow.

b) Sodium level measurement

In the primary vessel. The primary vessel has two vessel detectors. The sodium level measured by one of these detectors is shown continuously and recorded in the control room. The other detector only gives indications. The two instruments can set off an alarm when the sodium reaches the maximum and minimum levels.

In the secondary system. There are two level detectors, one in the expansion tank at the pump inlet and the other in the storage tank. The two levels are shown continuously in the control room. The two detectors set off an alarm when the sodium reaches the maximum and minimum levels.

c) Pressure measurement

In the primary system. Pressure is measured at eight points in the primary system, namely : the two main pump outlets, two points on the main pump piping just below the pump connections, both collector inlets, the collector outlet and the inlet to the intermediate exchanger.

Pressure is measured by means of pressure pick-offs with pneumatic recopiers. All the pressure readings are shown in the control room. The three collector pressures are recorded continuously. The recorders enable an alarm to be set off at high and low pressures.

In the primary vessel. A pressure pick-off with a pneumatic recopier is set up in the primary vessel inert gas blanket. The indicator is equipped with adjustable high and low pressure contacts for alarm signals, and an adjustable high pressure contact for shutdown and alarm.

In the secondary system. Pressure is measured at nine points of the secondary system. Readings and alarm are given locally and in the control room for inlet, delivery and differential pump pressure measurement, and for blanket gas pressure measurements.

Recordings, readings and alarm are given in the control room only for the intermediate exchanger inlet and outlet, the superheater inlet and the evaporator inlet and outlet. The pressure in the sodium purification system is shown locally; the alarm can be given in the control room.

References : 9, 152

Figure II-8 : Layout of the systems shown positions of the measurement and control apparatus.

3. EFFBR

a) Flow measurement

There are permanent magnet electromagnetic flowmeters. In addition to measuring and comparing the flow in the primary and secondary system, they determine the flow in the blanket inlet piping and show (by reversal of the flow) incorrect operation of the one-way valves of any of the sodium pumps. Flow signals are also used in the safety system, either to shut the reactor down or to prevent it operating with an insufficient flow.

b) Sodium level measurement

For continuous measurement of the sodium level in the reactor vessel and the primary cooling system, immersed pick-offs of the high temperature pneumatic recopier type are used. For measurement of the blanket gas pressure there are similar detectors in the gas zones above the sodium.

Systems of conventional float detectors are planned where replacement is possible. Also planned is the use of an auxiliary level indicator of the inductance type in the reactor vessel. Moved by hand in a shoe, this probe enables the sodium level to be determined by noting the point at which there is a sudden change in inductance.

The probe is used to calibrate the level detectors before the reactor is put into operation.

c) Pressure measurement

If the medium is radioactive and the fluid is liquid sodium or NaK (or contains their vapor), pressure is measured either by an NaK-filled pressure pick-off or by a low pressure pick-off with a pneumatic recopier. The high temperature pressure pick-off, filled with NaK, is to be used for pressures of above 0.35 bars. The NaK provides insulation between the sodium and the atmosphere and gives a very quick response.

Conventional pressure transmitters are used for measuring pressures not mentioned above.

References	: 8, 14, 126
Figure III-4	: Electromagnetic flowmeter
III-13	: Pressure pick-off with pneumatic recopier
III-14	: NaK-filled pressure pick-off
III-15	: Positioning of the instrumentation.

4. PFFBR

The measurement techniques planned for this reactor are similar to those of EFFBR.

5. LAMPRE

a) Flow measurement

Flow is measured by three electromagnetic flowmeters. Two of these are situated on the two pump pipes, while the third is on the piping between the tank and the expansion vessel.

The third flowmeter was supplied and calibrated by Atomics International.

b) Sodium level measurement

There are level detectors in the expansion tank upsteam from the exchanger, and in the storage tank. They are of the adjustable magnetic resistance type.

c) Pressure measurement

There are pressure telemeters in the expansion tank, at the pump inlets and outlets, and in the storage tank.

Reference : 19

Figure V-2 : Layout of the system showing positions of the measurement apparatus.

6. DFR

a) Flow measurement

Flow in the circuits is measured by the DC generator principle. A horseshoe-type permanent magnet is set directly on the piping, and situated so that the axis of the pipe is at right angles to the magnetic field and equi-distant from the two poles.

The flow of liquid metal through the pipe cuts the lines of force at right angles, producing an e.m.f. measured by two electrodes welded to the piping; the lines connecting the electrodes are at right angles both to the pipe axis and the axis of the magnetic flux.

The stainless steel pipe weakens the flowmeter signal, but does not produce any significant effect; the e.m.f. produced is consequently proportional to the speed of the fluid and the diameter of the tube. The magnet housing is made of brass; it is installed on the piping in such a way that the magnet is always accurately positioned.

The primary system flowmeters are inside the biological shielding, so the electrodes are extended by pins welded on to them. The pins and electrodes are made of stainless steel to prevent thermo-electric phenomena occurring.

The pins go through a protection cap divided into two sections, one of which can be removed to allow the magnet to be placed in its chamber.

In the primary system Calumax magnets with a 1000 gauss field intensity at a pole gap of 100 mm are used. All the magnets used are stabilised and can be removed and replaced.

The output voltage across the electrodes at full flow is 30 mV.

Three kinds of indicators are used and the voltage from each flowmeter is taken to the following points :

1. directly to the potentiometric indicator calibrated in lb/hr on a linear scale, which is situated on the summary panel in the control room.

2. to a set of four magnetic amplifiers which add the flows together, and then to the flow indicators and recorders in the control room.

3. to a second set of magnetic amplifiers which add the flows together and send them either to the alarm system in the control room, or to the multiple outlet circuit where the reading is combined with a value derived from the temperature difference to give an indication of the thermal power in the core and blanket.

The accuracy of the flow measurement is greater than 5%.

Each of the flowmeters was calibrated on an out-of-pile circuit, using a Venturi meter.

b) <u>Sodium level measurement</u>

Four of the expansion tanks are equipped with level indicators. They use a float and movements of the liquid are passed on by a cable to an electric transmitter situated at the top of the expansion tank tube, at floor level.

The level is also measured continuously by a mutual inductance indicator held in a shoe steeped in the liquid metal.

c) Pressure measurement

Blanket gas system. Instruments for measuring the blanket gas pressure are situated at the top of six of the expansion tank tubes, above the reactor floor.

This pressure is measured by Bourdon and capsule gages. These gages are filled with NaK and connected to the reactor by means of corrugated stainless steel diaphragms, the edge being welded between stainless steel flanges. The system's advantages are firstly allowing the indicator instrument to operate at a low ambient temperature, and secondly reducing leak hazards by what is in fact double casing.

References : 24, 95, 97, 153, 154

Figure VI-4 : Main primary circuit flowmeter.

7. RAPSODIE

a) Flow measurement

Primary system. There are electromagnetic flowmeters with a pair of electrodes welded on to the piping. Two main flowmeters between the pump delivery and the junction measure the sodium flow in each primary circuit. One flowmeter has a permanent magnet, and the other has an electro-magnet. There are ten other flowmeters on various pipes in the plant. Some of them are equipped with preheating cladding. Calibration is effected separately on sodium test benches.

Secondary system. There are five permanent magnet flowmeters in each secondary circuit.

b) Sodium level measurement

The sodium level is measured by using either continuous level indicators, or discontinuous ones, according to the case. The continuous level indicators

.../...

(fifteen in the primary system) have a sensitive element consisting of three vertical stainless steel tubes welded at the lower end onto a box inside which there is a temperature effect compensation resistor.

Each indicator is supplied at a stabilised continuous potential difference.

The discontinuous level indicators (about sixty in the primary system) consist of a stainless steel tube placed vertically in a tank where accurate measurement of the liquid metal level is required. Inside there is a silvered copper wire brazed to the lower part of the stainless steel tubes.

Reference : 28

Figure VII-4 : Continuous level indicator

VII-5 : Discontinuous level indicator

8. BR 5

9. SEFOR

10. SRE

a) Flow measurement

Seventeen electromagnetic flowmeters (of diameters ranging between 25 and 150 mm) are used for all the cooling circuits. Potentiometric recorders and indicators were adopted to eliminate the errors introduced by line voltage drops.

Accurate measurement was made of the magnetic field in each flowmeter to establish the calibration curves.

All the flowmeters of diameter not more than 50 mm were removed after installation, to check the calibration curves. The magnetic field was measured with a precision instrument. Careless handling of the magnets during installation produced field variations of up to 25%.

b) Sodium level measurement

Three types of apparatus with electromagnetic coils are used to determine the sodium level in the tanks, namely the long or continuous-type probe, short alarm coils, and precision or control coils.

The long or continuous-type probes, using constant current, operate up to 650°C. Since impedance is a function of the sodium level, the voltage is directly proportional to the level. Calibration curves were drawn for various sodium temperatures.

The short alarm coils consist of two coils in a bridge. One coil compensates the temperature effect, while the other is the sensitive coil. An abnormal sodium level changes the impedance of the detector coil, thereby unbalancing the bridge.

The precision coils are supplied with a 1000 Hz frequency current. In continuous operation the probe head can stand up to a temperature of 204°C, and in discontinuous operation to temperatures up to 650°C. Accuracy is ± 1.5 mm in the range from ambient temperature to 650°C.

c) Pressure measurement

Coolant system. In the primary system pressure is measured by pick-offs using differential transformers.

In the secondary system pressure pick-offs with pneumatic recopiers are used.

Electric transmissions were adopted for the primary system to eliminate the flow of filtered air in radioactive zones.

Blanket gas circuit. The pressure transmitters used in the inert gas systems consist of valves activating a precision potentiometer in one branch of a bridge assembly. When the valves are displaced, the bridge is unbalanced and there is a measurement reading proportionate to the pressure. Devices consisting of a diaphragm and a micro-switch are installed in the helium and nitrogen circuits. In the event of abnormal pressure in these circuits, the switches set off an alarm in the control room.

Reference : 76.

11. HNPF

a) Flow measurement

There are permanent magnet electromagnetic flowmeters, of Alnico S. A thermocouple measures the temperature of a polar face of one magnet. The field of the large control flowmeters (diameters between 150 and 350 mm) is calibrated periodically by moving away a measurement coil. The initial calibration curves can be corrected in proportion to the field variations.

A study was made of six types of flowmeter (the types were : permanent magnet, AC and DC electromagnetic, Venturi, Pitot tube and ultrasonic flowmeters) to determine the best solution. The permanent magnet flowmeter was finally adopted. Drawbacks : sensitivity to temperature, variations with respect to time, tube moistening problems, heavy. Advantages : simplicity, negligible pressure losses, no possibility of leaks, wide measurement range (not affected by flow conditions), linear law, low cost price, rapid response, toleration of high temperatures (700°C).

The DC electromagnetic flowmeter is similar, but not so simple, more expensive, and does not stand such high temperatures; however, time and temperature variations can be reduced by regulating the current.

The AC electromagnetic flowmeter is similar, but a little more complex.

The ultrasonic flowmeters have a temperature limit of 200°C for the time being.

A variant of the Pitot tube flowmeter was examined (gas flow system to prevent fouling of the Pitot tubes); its cost is high.

Lastly a Venturi high temperature pressure transmitter unit (filled with NaK) was examined. Advantages : lower cost than the other flowmeters except for the permanent magnet one, precision, smaller size, toleration of high temperatures. Drawbacks : greater pressure losses, non-linear response, penetration of the cladding making leaks possible, slower response, affected by flow conditions (Reynolds number...).

Under present conditions the permanent magnet flowmeter has been adopted; later, development of the electromagnetic and Venturi flowmeters is planned.

b) Sodium level measurement

Either a continuous reading induction coil probe, or one or more induction coil alarm points, are used to measure the sodium level in each tank. The induction coil element consists of a constantan wire with fiberglass insulation in the shape of a coil. The coils are situated on a support rod and insulated from the stainless steel outer protection tube by a fiberglass sleeve.

c) Pressure measurement

The pressure measurement instruments consist of sensitive NaK-filled elements with diaphragms, NaK-filled capillary transmission tubes, electronic transmitters, alarm relays, and indication and recording receivers. The sensitive element is a sealed NaK-filled cell with a 0.635 mm thick inconel diaphragm. It can operate within a 50-750°C temperature range and transmit pressure signals through a diaphragm and a capillary tube to an electronic transmitter where the pressure is converted into 1-5 mA signals actuating indicators, recorders and alarms.

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V B - CLASSEMENT DES REFERENCES

AVANT-PROPOS.

Ce chapitre intitulé "Classement des Références" est divisé en autant de parties que l'ensemble du rapport lui-même.

Dans chacune de ces parties, on trouvera, à la suite du nom des différents réacteurs étudiés, un ou plusieurs numéros suivis dans certains cas de la mention (p. - p.). Ces numéros correspondent aux références bibliographiques signalées au chapitre précédent.

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TABLE I-1

CAPACITY OF REACTOR EBR I

Thermal capacity	1200 kW
Net electric capacity	200 kW
Overall electric capacity	200 kW
Turbo-alternator capacity	300 kW
Steam characteristics on entering the turbine :	
- absolute pressure	27 bars
- absolute temperature	277°C
Net thermal yield of the plant	17%
Flow to the turbine	1.65 t/hr
Total quantity of steam produced	1.65 t/hr

TABLE I-2

EBR I COOLING SYSTEM

1. Primary cooling system

Coolant	NaK
Inlet temperature	228°C
Outlet temperature	316°C
Reactor input pressure	0.9 bars
Reactor pressure loss	0.7 bars
Average speed in the core	2.1 m/s
Total flow in the core	55 t/hr
Number of circuits	1
Type of pumps	DC electromagnetic + 1 centrifugal auxiliary
Number of pumps per circuit	1 in operation + 1 aux.
Pumping capacity per pump :	
- electromagnetic pump	18 kW
- centrifugal pump	10 kW
Flow per pump calculated as	90 m^3/hr
Manometric head at nominal flow	2.1 bars
Blanket gas	argon
Materials in contact with the coolant	stainless steel
Purification	Stainless steel sintered filters; cold trap
Safety in the event of the primary cooling system stopping	On shutdown, natural convection with auxiliary air exchanger

TABLE I-2 (continued)

II. Secondary cooling system

Coolant	NaK
Exchanger input temperature	215°C
Exchanger output temperature	306°C
Exchanger input pressure	1.4 bars
Exchanger pressure loss	0.35 bars
Flow	55 t/hr
Number of circuits	1
Type of pump	centrifugal
Number of pumps per circuit	1
Pumping capacity, per pump	10 kW
Manometric heat	1.7 bars
Materials in contact with coolant	Stainless steel and nickel
Purification	Stainless steel sintered filters; cold trap
Instrumentation and preheating system methods	90 kW electric immersion heaters in the secondary loop

TABLE I-3

EBR I INTERMEDIATE EXCHANGER

Number	1
Total length	4.6 m
Outer casing diameter	0.43 m
Type of flow	Casing and tube of two-way type
Number of tubes	102
Type of tubes	External diameter 19 mm, hairpin-shaped
Material of tube	Nickel A
External surface area of tubes	45.85 m^2
Heat exchanged	1.15 MW
Average logarithmic deviation	11°C
Average heat transfer coefficient	2270 $W/m^2.°C$
Primary NaK : input	316°C
Secondary NaK : input	215°C
output	306°C

TABLE I-4

EBR I TERMINAL EXCHANGER

1. Heat exchanger tube used in the superheater, reboiler and economiser :

- actual length	2.9 m
- external diameter	65 mm
- internal diameter	50.8 mm

2. Superheater :

- number of heat exchangers	4
- arrangement	In series, with reflux flow
- total internal surface area of the tubes	1.85 m^2
- diameter of casing	127 mm
- surface area of the straight section of the liquid flow in the casing	94 cm^2
- NaK speed	1.90 m/s
- average steam speed	18 m/s
- heat transfer coefficient (steam side)	850 $W/m^2.^oC$

3. Economiser :

- number of heat exchangers	9
- arrangement	In series with reflux flow
- total internal surface area of the tubes	4.2 m^2
- diameter of casing	127 mm
- surface area of the straight section of the liquid flow in the casing	94 cm^2
- NaK speed	1.9 m/s
- water speed in the annular zone surrounding the baffle - external diameter 45 mm	1.04 m/s
- heat transfer coefficient (water side)	1770 $W/m^2.^oC$

TABLE I-4 (continued)

4. Reboiler :

- number of heat exchangers	18
- arrangement	in parallel, with reflux flow
- total internal surface area of the tubes	8.3 m^2
- surface area of the straight section of the liquid flow in the casing, for each tube	12.8 cm^2
- diameter of casing	76 mm
- NaK speed	0.77 m/s
- water flow	13 times the steam flow
- heat transfer coefficient (steam side)	3980 $W/m^2.^oC$

TABLE I-5

EBR I TURBOGENERATOR

Data on the normal operation of the turbogenerator :

Capacity of generator	375 kVa
Nominal pressure	26.5 bars net
Nominal temperature	270°C
Vacuum condenser	0.05 bars
Coolant water temperature	
- input	18°C
- output	24°C
Temperature of the exhaust steam	26.7°C
Temperature of the condensed water	21.1°C
Power	165 kW
Power factor	0.88

TABLE II-1

CAPACITY OF REACTOR EBR II

Thermal capacity	62.5 MW
Net electric capacity	16.5 MW
Capacity of turbogenerator	20 MW
Steam characteristics on entering the turbine	
- absolute pressure	87.4 bars
- absolute temperature	454°C

TABLE II-1 (continued)

Net thermal yield of the plant	26.4%
Steam flow to the turbine	90 t/hr
Total steam produced	113 t/hr

TABLE II-2

EBR II PRIMARY SYSTEM

Number of circuits	1 (with 2 pumps in parallel)
Fluid	Na
Total volume of Na	340 m^3
Material	304 stainless steel
Channels : diameter of the pipes :	
- at core inlet	261 mm
- at blanket inlet	154 mm
- at reactor outlet	356 mm
Pressure loss across the reactor	2.8 bars
Heat transfer in the core :	
- heat transfer surface area :	
- per element	0.45 m^2
- in all	21 m^2
Heat flux density :	
- maximum	323 W/cm^2
- average	230 W/cm^2
Coolant flow surface area :	
- per fuel element	0.0012 m^2
- in all	0.05 m^2
Speed in the core :	
- maximum	7.9 m/s
- minimum	5.5 m/s
Operating pressure	4.2 bars
Flow : volume	1860 m^3/hr
mass	1600 t/hr
Temperature : reactor inlet	371°C
reactor outlet	482°C
Pumps :	
- number	2 main, 1 auxiliary
- type : main	mechanical
auxiliary	DC electromagnetic
Supply	2 480 V AC electric motors

TABLE II-2 (continued)

Pumping capacity, per main pump	255 kW
Manometric heat at nominal flow	4.2 bars
Flow (per main pump)	940 m^3/hr
Flowmeters :	
- number	5
- type	Permanent magnet electromagnetic
Valves	No valves in primary system
Coolant system safety	114 m^3/hr battery-operated auxiliary pump
Purification system	1 cold trap
Preheating	Electric immersion heaters
Blanket gas	Argon

TABLE II-3

EBR II SECONDARY SYSTEM

Number of circuits	1
Fluid	Na
Materials	304 stainless steel 2.1/4% Cr - 1% Mo ferritic steel
Temperature :	
- intermediate exchanger input	321°C
- intermediate exchanger output	454°C
Pumps :	
- number of pumps per circuit	1
- type	flat linear induction EM
- pumping capacity	460 kW
- manometric head	3.7 bars
Flow :	
- volume	1370 m^3/hr
- mass	1170 t/hr
Pressure :	
- exchanger input	4.3 bars
- total pressure loss	3.1 bars
- pressure loss in exchanger	0.5 bars

TABLE II-3 (continued)

STEAM SYSTEM

Description of the steam generator	Natural flow, separate superheater, steam container and evaporator; materials : 2.1/4% Cr - 1% Mo steel
Number	1
Output temperature	454°C
Output pressure	87.5 bars
Steam flow	113 t/hr
Condenser pressure	38 mm
Number of supply water heaters	4

TABLE III-1

CAPACITY OF REACTOR EFFBR

Thermal capacity of reactor	200 MW	174 core 26 blanket
Overall electric capacity	65.9 MW	
Net electric capacity	60.9 MW	
Turbogenerator capacity	157 MW	
Steam characteristics on entering the turbine :		
- absolute pressure	39.7 bars	
- absolute temperature	404°C	
Net thermal yield of the plant	30.5%	
Steam flow to the turbine	285 t/hr	
Total steam produced	285 t/hr	

STATE OF THE FLUIDS AT DIFFERENT POWER LEVELS

Capacity (MW th)	Primary Na temperatures (°C)	Secondary Na temperatures (°C)	Steam in the turbine: Pressure (bars)	Steam in the turbine: Temperature (°C)
200	288 - 427	270 - 408	39.7	404
300	288 - 427	260 - 399	40.7	395
430	316 - 482	271 - 482	59.7	416

TABLE III-2

EFFBR PRIMARY SYSTEM

Capacity	200 MW
Number of circuits	3
Fluid	Na
Channels : diameter of piping :	
- at the pump inlet	762 mm
- at the pump outlet	406 mm
- at the core inlet	356 mm
- at the reactor outlet	762 mm
- at the blanket inlet	152 mm
wall thickness	9.5 mm
Pressure loss :	
- core and axial blanket	3.16 bars
- total for the reactor	3.52 bars
- outside the reactor	0.24 bars
- total pressure loss	3.76 bars
Flow speeds :	
- core inlet	4.3 m/s
- blanket inlet	2.2 m/s
- pump inlet	1 m/s
- pump outlet	3.6 m/s
Na flow (per circuit) :	
- volume	1520 m^3/hr
- mass	1340 t/hr
Total volume of Na (at 177°C)	150 m^3
Na temperature :	
- reactor inlet	288°C
- reactor outlet	427°C
Heat transfer in the reactor	
- transfer surface :	
- in the core	143 m^2
- in the axial blanket	21 m^2
- in the radial blanket	737 m^2
- max. heat flux :	
- in the core	2000 kW/m^2
- in the axial blanket	228 kW/m^2
- in the radial blanket	685 kW/m^2
- coolant passage cross-section	0.185 m^2
- average transfer coefficient (Na-steel)	550 kW/m^2.°C

TABLE III-2 (continued)

Materials	304 stainless steel, stellite, zirconium, colmonoy
Blanket gas	Argon

TABLE III-3

EFFBR PRIMARY PUMPS

Number	3 (1 per circuit)
Type	Mechanical, centrifugal, vertical, with mechanical gas leakproof mountings
Reference data (per pump)	
- flow	2680 m^3/hr
- temperature (max)	540°C
- manometric head	7.6 bars
- yield	77%
- pumping capacity	486 kW
Main motors	
- number	3
- supply	4800 volts, triphased, 60 Hz, 900 r.p.m. adjustable between 35 and 100%
- capacity (per motor)	790 kW
Auxiliary motor (No.1 circuit)	
- number	1
- supply	125 volts (DC)
- capacity	2.25 kW
Auxiliary motors (circuits Nos. 2 & 3)	
- number	2
- supply	115 volts, triphased, 60 Hz
- capacity (per motor)	3.7 kW
Total flow produced by :	
- 2 pumps driven by auxiliary motors	454 m^3/hr
- 3 pumps driven by auxiliary motors	491 m^3/hr

TABLE III-4

EFFBR PRIMARY AUXILIARIES

Cold trap	
- flow	22.7 m^3/hr
- capacity	1893 liters
- pressure loss	0.77 bar
- outlet temperature	164 °C
- temperature drop (ref. data)	30 °C
- thermal power dissipated	235 kW
Cold trap economiser	
- type	U-shaped, with tube system and casing
Cold trap coolant	
- type	NaK
- flow	13.1 t/hr
- temperature deviation	61°C
Fouling indicator	
- maximum flow	200 kg/hr
- pressure loss	0.007 bars
Storage tanks	
- capacity per tank	56 m^3
- type of reheater	resistor
- heating time to 316°C (Na)	300 hr
- heating time to 149°C (gas)	10 hr
- maximum temperature	371°C
Na service piping	
- type of heating	Induction
- heating time	72 hr
Overflow pumps	
- type	immersed
- flow (per pump)	68 m^3/hr
- delivery pressure	22.8 m
Hot trap	
- Na flow	2.3 m^3/hr
- temperature	700°C
- capacity	5 kg carbon

TABLE III-5

EFFBR SECONDARY SYSTEM (Operation at 200 MW)

Number of circuits	3
Fluid	Na
Flow per circuit	1340 t/hr
- at the pump temperature	1520 m^3/hr
Materials	304 & 410 stainless steel, 2.1/4% Cr - 1% Mo ferritic steel, stellite, inconel
Temperatures :	
- intermediate exchanger inlet	270°C
- intermediate exchanger outlet	408°C
Pressure	
- intermediate exchanger inlet	0.90 bars
- intermediate exchanger outlet	0.76 bars
- steam generator inlet	0.35 bars
- pump inlet	0.28 bars
Total volume of Na	113 m^3
Total weight of Na	100 t
Piping system	
- material	2.1/4% Cr - 1% Mo low carbon steel
- reference pressure	12 bars
- reference temperature	482°C
- pipe dimensions	450/300 mm
- wall thickness	9.5 mm
- average fluid speed in the pipe	2.7 m/s
Total pressure loss	0.97 bars

TABLE III-6

EFFBR INTERMEDIATE EXCHANGERS

I. PERFORMANCE OF THE SYSTEM AT 200 MW

Number of units	3
Nature	Tube system and casing; free level; removable
Pressure loss - tube side	0.14 bars
Pressure loss - casing side	0.027 bars
Heat transfer surface	587 m^2

TABLE III-6 (continued)

Overall heat transfer coefficient	6200 W/m^2.^{o}C
Temperatures :	
- Primary Na	
- inlet	427^{o}C
- outlet	288^{o}C
- Secondary Na	
- inlet	270^{o}C
- outlet	408^{o}C

II. NOMINAL CHARACTERISTICS OF THE EXCHANGERS (scheduled to operate at 430 MW)

Heat transferred per unit	143.3 MW
Heat transfer surface	451 m^2
Overall heat transfer coefficient	5960 W/m^2.^{o}C
Fluid on the casing side	Primary Na
- flow on casing side	2400 t/hr
- inlet temperature	482^{o}C
- outlet temperature	316^{o}C
- pressure loss	0.075 bars
Fluid in the tubes	Secondary Na
- flow in the tubes	2400 t/hr
- inlet temperature	271^{o}C
- outlet temperature	438^{o}C
- pressure loss	0.33 bars
- number of tubes	1860
- external diameter	22 mm
- wall thickness	1.2 mm
- length	5.4 m
Dimensions of the exchangers	
- diameter	2.2 m
- length	9.4 m
- weight	58 t
Material	304 stainless steel

TABLE III-7

EFFBR SECONDARY PUMPS

Number	3
Type	Centrifugal
Reference data (per pump)	
- flow (per pump)	2950 m^3/hr
- temperature (max.)	540 ^{o}C

TABLE III-7 (continued)

- total manometric head	2.5 bars
- yield	82%
- pumping capacity	115 kW
Main motors	
- number	3
- supply	4800 volts, triphased
- speed	900 r.p.m., constant
- capacity (per motor)	260 kW
Auxiliary motors	See Table III-3
Flow provided by the auxiliary motors (per pump)	340 m^3/hr

TABLE III-8

CAPACITY OF THE EFFBR STEAM SYSTEM (at 200 MW)

1. Steam system equipment	
Number of units	3
Type	one-stage, reflux
Material	2.1/4% Cr - 1% Mo steel
Fluid in the tubes	Water and steam
- pressure loss	0.35 bars
Fluid in the casing	Sodium
- pressure loss	0.14 bars
2. Operating characteristics, per unit	
Steam production capacity	95 t/hr
Steam characteristics	
- pressure	41.4 bars
- temperature	406°C
Water input temperature	171°C
3. Data on the secondary Na (casing side)	
Flow	1340 t/hr
Temperature	
- input	408°C
- output	270°C

4. Heat exchange	Heat exchanged MW	Exchange surface m^2	Exchange coefficient $W/m^2.^oC$	Log. deviation ^oC
Water heating section	9.80	89	1760	63
Evaporation section				
Section 1 (quality 0.50%)	22.70	115	3440	57
Section 2 (quality 50-75%)	11.35	33	3580	95
Section 3 (quality 75-100%)	11.35	51	1875	119
Superheating section	11.46	712	546	30
Total	66.66	~1000		

TABLE IV-1

PFFBR PRIMARY SYSTEM

Thermal capacity of the reactor	775 MW
Overall electric capacity	300 MW
Net electric capacity	283 MW
Number of primary circuits	3
Fluid	Na
Flow per circuit	
- mass	3760 t/hr
- volume, at 343°C	4580 m^3/hr
Na speed in the core	4.1 m/s
Piping sizes and speeds in the system	
- reactor to inter.exch. : 500 mm	6.5 m/s
- exchanger to pump : 600 mm	4.5 m/s
- pump to reactor : 500 mm	6.5 m/s
- wall thickness : 9 mm	
Primary system temperature	566°C (reference data)
Operating temperature	
- reactor outlet towards exchanger (normal operation)	538°C
- exchangers to pump to reactor (d^o)	344°C
- shutdown and reloading	316°C

TABLE IV-1 (continued)

Primary system pressure	8.6 bars (reference data)
Operating pressure	
- reactor outlet towards pump	1.85 bars
- pump outlet towards reactor	7.2 bars
Pressure loss in the system	68 m Na
- in the exchanger	5.1 m Na
- piping, reactor outlet to exch.	4.8 m Na
- piping, exchanger to pump	2.4 m Na
- piping, pump outlet to reactor	5.32 m Na
- reactor inlet and loss at outlet	3.4 m Na
- fuel element	42.8 m Na
- reactor inlet loss	0.304 m Na
- one-way valve	3.35 m Na
Total volume of Na	127 m^3
Total weight of Na	104 t
Primary system material	304 stainless steel
Purification system	Cold trap, economiser, fouling indicator
Pumps	See Table IV-3

TABLE IV-2

PFFBR SECONDARY SYSTEM

Number of circuits		3
Fluid		Na
Na flow per circuit		3760 t/hr 4580 m^3/hr at 343°C
Piping; dimensions and speeds		
- exchangers to generator	: 500 mm	6.8 m/s
- exchanger to generator	: 400 mm	5.3 m/s
- generator to pump	: 500 mm	6.8 m/s
- pump to exchanger	: 500 mm	6.8 m/s
- wall thickness	: 9 mm	
Secondary system temperature		538°C (reference data)
Operating temperature (normal operation)		
- exch. outlet towards generator		493°C
- generator outlet via pump to exchanger		299°C
- shutdown conditions		316°C
- refuelling		310°C
Secondary system pressure		10.3 bars (reference data)

TABLE IV-2 (continued)

Maximum operating pressure	4.1 bars
Pipe, pump and steam gen.materials	2.1/4% Cr - 1% Mo steel
Intermediate exchanger material	304 stainless steel
Pressure loss in the secondary system	32.3 m Na
- piping loss (exchanger to branch)	6.3 m Na
- 400 mm piping to generator	1.1 m Na
- steam generator	8.4 m Na
- piping from generator to pump	1.6 m Na
- loss in tube side of exchanger	8.5 m Na
Total volume of Na	198 m^3
Total weight of Na	164 t
Pumps	See Table IV-3
Blanket gas	Argon
Intermediate exchangers	See Table IV-4
Steam generator	See Table IV-5

TABLE IV-3

NOMINAL CHARACTERISTICS OF THE PFFBR SODIUM PUMPS

	Primary	Secondary
Number of pumps in plant	3	3
Capacity per pump	4484 m^3/hr	4462 m^3/hr
Total head	67 m Na	32.3 m Na
Temperatures		
- nominal operation	343°C	299°C
- maximum (reference data)	566°C	538°C
- minimum	149°C	149°C
Pump suction pressure	0.9 bars	2.7 bars
Blanket gas		
- normal operation	1.3 bars	2.6 bars
- max. operation)reference data)	8.6 bars	10.3 bars
Pump yield	80%	80%
Pumping capacity, normal operation	923 kW	443 kW
- max. density at 149°C	968 kW	461 kW
Pump material	304 stainless steel	2.1/4% Cr - 1% Mo
Suction opening (internal diam.)	600 mm	525 mm
Delivery opening (internal diam.)	525 mm	525 mm

TABLE IV-3 (continued)

	Primary	Secondary
Speed	870 rpm	1170 rpm
Speed control, % field	50-100	50-100
Type	one-phase continuous op.	
Driving device	coiled rotor motor	
Capacity of the motor	1117 kW	521 kW
- yield of the motor	94%	93%
- power used by motor, theoretical conditions	985 kW	478 kW
Critical speed	2000	5000
Total weight of the motor, cap, tank and pump	54 t	22 t

TABLE IV-4

PFFBR INTERMEDIATE EXCHANGERS

PRIMARY SODIUM SIDE	
Sodium input temperature	538°C
Sodium output temperature	343°C
Sodium flow (per exchanger)	3760 t/hr
Pressure loss (per exchanger)	0.41 bars
Reference pressure	8.6 bars
Reference temperature	566°C
Diameter of casing	2.1 m
Total length of casing	8.2 m
SECONDARY SODIUM SIDE	
Sodium input temperature	299°C
Sodium output temperature	493°C
Sodium flow per exchanger	3760 t/hr
Reference pressure	10.3 bars
Pressure loss	0.48 bars
Reference temperature	538°C
REFERENCE DATA	
Heat transferred	259 MW
Tube dimensions	Ø 25 mm x 1.05 mm thick
Number of tubes	1200

TABLE IV-4 (continued)

Effective length of tube	9.3 m
Temperature deviation	44.5°C
Effective surface	808 m^2
Contact surface	889 m^2
Total surface	1064 m^2
Overall heat transfer coefficient	7220 $W/m^2.°C$
Diameter of casing	2.1 m
Total length of casing	8.2 m
Material	
- casing	304 stainless steel
- tubes	304 stainless steel
- forgings	304 stainless steel

TABLE IV-5

PFFBR STEAM GENERATORS (Nominal characteristics)

Reference temperature	
- casing	538°C
- tubes	538°C
Reference pressure	
- casing	10.3 bars
- tubes	106 bars
Steam characteristics	
- temperature	466°C
- pressure	100 bars
- flow per steam generator	377 t/hr
Supply water temperature	195°C
Sodium input temperature	493°C
Sodium output temperature	299°C
Na flow per steam generator	3760 t/hr
Pressure loss	
- casing	5.7 m Na
- tubes	2.1 bars
Data on the tubes	
- external diameter	15 mm
- minimum wall thickness	1.7 mm
- effective length	26 m
- number of tubes per steam gen.	1200
Effective heat transfer surface per generator	1506 m^2

TABLE IV-5 (continued)

Total heat transfer surface per generator	2055 m^2
Heat transferred per generator	259 MW

TABLE V-1

LAMPRE I COOLING SYSTEM

Capacity	1 MW (th)
Capacity of LAMPRE 2	20 MW
PRIMARY SYSTEM	
Coolant fluid	Na
Channels :	
- material	316 stainless steel
- number of circuits	1
- plate thickness	Double casing round the vessel
Temperature	
- reactor input	450°C
- reactor output	500 - 600°C
Fluid flow	Upwards
Heat transfer in the core :	
- average Na speed in the core	1.2 m/s
- heat exchange surface in the core	0.6 m^2
- heat transfer rate	165 W/cm^2
- average temperature in the core	600°C
- Δt in the core	113°C
- flow	Between 24 and 30 m^3/hr
Total volume of Na	0.74 m^3
Pumps	
- number	2
- type	AC electromagnetic
- nominal flow	22.6 m^3/hr
- pressure	1.4 bars
Cooling system purification system	
- hot traps : number	3 in parallel (on the circuits)
type	zirconium
temperature	700°C
flow	5%
- cold traps: number	1 (on drainage tank)
- shutdown safety	Natural cooling of the reactor vessel by ambient air

TABLE V-1 (continued)

Preheating	The system is the secondary circuit of a transformer
Blanket gas	Helium

SECONDARY SYSTEM

Intermediate exchangers : number	None (the primary Na is air-cooled)

TABLE VI-1

DFR : GENERAL POINTS - PRIMARY SYSTEM

A. GENERAL POINTS

Overall thermal capacity	72 MW
- core	60 MW
- blanket	12 MW
Overall electric capacity	15 MW
Own consumption produced by diesel-driven generator plants	3 MW
Fluid :	
- primary and secondary systems	70 - 30% NaK alloy
- thermo-siphon system	22 - 78% NaK alloy

B. PRIMARY SYSTEM

Number of circuits	
- core	20
- blanket	4
Thermal capacity of the core and blanket systems	3 MW
NaK speed in the core	
- average for the whole core	4.8 m/s
- maximum for the whole core	6.2 m/s
Average heat flux	
- in the core	2150 kW/m^2
- in the blanket	16 kW/m^2
Coolant pressure :	
- input	3.45 bars
- output	3.1 bars
Coolant temperature	
- input	200°C
- output	350°C

TABLE VI-1 (continued)

Mass flow through the core and 20 primary exchangers	1300 t/hr
NaK flow per circuit	65 t/hr
Constant diameter of piping	100 mm
Pressure loss outside the reactor	0.9 bars
Total volume of NaK at 300°C	61 m^3
Total weight of NaK at 300°C	51.3 t
Primary-secondary exchanger	
Number	24
Type	Non-removable co-axial U-tube
Input temperature	350°C
Output temperature	200°C
Heat exchange surface	35 m^2
Average temperature difference	20°C

TABLE VI-2

DFR PRIMARY PUMPS AND AUXILIARIES

Electromagnetic pumps	
Number	24
Type	Flat linear induction electromagnetic pumps
Flow	72 m^3/hr 65 t/hr
Pressure loss (core system)	1.65 bars
Voltage	410 volts
Capacity	14.7 kW
KVA (after power factor correction)	16.5 KVA
Pump yield at 410 V and 65 t/hr	24%
Minimum pressure at pump inlet	0.8 bars
Max. permissible temperature	240°C
Cold traps	
Number	15
Flow across the traps	425 kg/hr
Tank volume	0.056 m^3
Joint	12 mm diameter stainless steel rings

TABLE VI-2 (continued)

NaK residence	5 min.
Trap input temperature	200°C
Trap container temperature	100°C minimum
Trap output temperature	195°C
Hot traps	
Number	5
Type	Zirconium
Flow across the trap	3.4 t/hr
Oxide absorption material	0.125 mm thick Zr sheet
Surface in contact with NaK (per trap)	370 m^2
Trap input temperature	200°C
Temperature of NaK passing through Zr	600°C
Trap output temperature	220°C
Power used in electric heating	35 kW
Other parts	
Oxide corrosion measurement device	1, in hot trap tank
Oxide sampler	1, in cold trap tank
Resistivity measurement device	2, in cold trap tanks
Blanket gas system	
Gas	Nitrogen, later argon
Operating pressure	3.5 bars
Shutdown pressure	0.035 bars
Volume of system, buffer tanks included	67 m^3

TABLE VI-3

DFR SECONDARY SYSTEM AND STEAM GENERATOR

Number of circuits	12
Heat transfer per circuit	6 MW
Pumps : number	2 per circuit, 24 in all.
type	Removable stator EM
flow per pump	62 t/hr
total mass flow	1400 t/hr
Pressure loss in system	1.8 bars
Number of cold traps (similar to the primary ones) per circuit	2
Total weight of NaK	64 t

TABLE VI-3 (continued)

Primary-secondary heat exchanger	
Input temperature	175°C
Output temperature	325°C
Liquid metal/water exchangers (initially designed for a 60 MW steam generator)	
Number	12
Type	Tubes immersed in copper
Thermal capacity	6 MW
NaK flow	124 t/hr
Steam production per exchanger	7.5 t/hr
Heating section	
Water input temperature	40°C
Output temperature	173°C
Heat transfer surface	8 m^2
Evaporation section	
Water-steam pressure	14 bars
Water-steam temperature	195°C
Heat transfer surface	37 m^2
Superheater section	
Steam input temperature	195°C
Steam output temperature	280°C
Output pressure	13 bars
Heat transfer surface	7 m^2
Thermo-siphon system	
Number of circuits	4
Heat transfer per circuit, under thermo-siphon conditions	0.45 MW

TABLE VI-4

DFR STEAM PLANT

Condenser	
Number of condensers	12
Type	Tube and vertical casing to condense the steam produced or cool the pressurised water
Total surface	185 m^2
Maximum sea-water flow	600 t/hr
Supply pump	
Number of pumps	12
Type	6-stage centrifugal
Flow	11 t/hr
Suction pressure	0.035 bars
Delivery pressure	21 bars
Flow pump	
Number of pumps	12
Type	One-stage, immersed motor, centrifugal
Flow	68 t/hr
Head	18 m
Turbo-alternator	
Capacity	15 MW (e)
Steam pressure at inlet valve	10.5 bars
Steam temperature at inlet valve	270°C
Steam provided	76 t/hr
Sea-water pumps	
Number of pumps	4
Type	Vertical, centrifugal, diesel-driven
Flow	2350 t/hr
Manometric head	22.8 m
Capacity required	180 kW
Electric supply	
Number of independent diesel alternators supplying power to the 12 heat transfer units	12 in operation, 6 stand-by

TABLE VI-4 (continued)

Capacity	120 kW
Voltage	415 V
Number of diesel alternators supplying the auxiliary equipment	6
Capacity	220 kW
Voltage	415 V
Capacity of the network supply transformers connected in parallel	1000 KVA

TABLE VII-1

RAPSODIE PRIMARY SYSTEM

1st rate (250 - 340°C)

2nd rate (450 - 540°C)

Total capacity	20 MW
Number of circuits	2
Fluid	Na
Flow per circuit	375 m^3/hr
Reactor input temperature	250°C
Reactor output temperature	340°C
Total volume of sodium	Approx. 30 m^3
Volume in reactor	Approx. 15 m^3
Piping	316 stainless steel
Ø from reactor to pump	300/308 mm
Ø from pump to reactor	200/208 mm
Maximum speed in the reactor	6.3 m/s
Speed in the piping	1.5 m/s (Ø 300) 3.3 m/s (Ø 200)
Pressure loss in the reactor	2 bars
Pressure loss in the system	0.25 bars
<u>Intermediate exchangers</u>	
Type	Tube system
Stainless steel	316
Fluid in the tubes	Na
Fluid in the casing	Na
Na-Na temperature deviation	30°C
Number of tubes	888

TABLE VII-1 (continued)

Diameter of tubes	12/14 mm
Pitch of tube system	20 mm
Ø of casing	884/900 mm
Exchange length	2.15 m
Exchange surface	84 m^2
Weight of stainless steel	4500 kg
Primary pumps	
Number	2
Type	Vertical centrifugal
Utilisation temperature	250 or 450°C
Normal flow	375 m^3/hr
Nominal delivery pressure	2.25 bars
Yield	About 70%

TABLE VII-2

RAPSODIE SECONDARY SYSTEM

Capacity	20 MW
Number of circuits	2
Fluid	Na
- flow per circuit	380 m^3/hr
Temperature	
- interm. exch. input	220°C
- interm. exch. output	310°C
Volume of Na per circuit	8 m^3, approx.
Stainless steel piping	
- type	316
- diameter	200/208 mm
- speed	4.3 m/s
- pressure loss	1.5 bars approx.
Terminal exchangers	
Capacity per exchanger	10 MW
Type	Finned tubes
Fluid	
- in the tubes	Na
- outside the tubes	Air

TABLE VII-2 (continued)

Temperature	
- Na input	310°C
- Na output	220°C
- air input	30°C
- air output	185°C
Tubes	
- diameter	21/25 mm
- number	224
- exch. length per tube	2.15 m
- total exchange surface	1145 m^2
- air flow	227 t/hr
Pressure loss : air	0.020 bars
Na	0.20 bars
Weight of stainless steel	8000 kg
Secondary pumps	
Number	2
Type	Vertical centrifugal
Utilisation temperature	310 or 510°C
Nominal flow	380 m^3/hr
Nominal delivery pressure	1.5 bars
Yield	70% approx.

TABLE VIII-1

BR.5 PRIMARY SYSTEM

Thermal capacity :	
- core	5 MW
- uranium reflector	0.8 MW
- nickel reflector	0.13 MW
Material	Titanium-stabilised 18% Cr - 8% Ni stainless steel
Coolant fluid	Sodium (2.7 m^3)
Number of circuits	2, with one reactor inlet and one outlet
Heat transfer in the core	
- transfer surface	6.2 m^2
- maximum flux	1600 kW/m^2
- fuel element temperature	500°C
- transfer coefficient	235 kW/m^2.°C
- cross-section of coolant flow	150 cm^2
- sodium speed in the core	4.5 m/s
- total flow	240 m^3/hr

TABLE VIII-1 (continued)

Coolant temperature	
- reactor inlet	375°C
- reactor outlet	450°C
Average pressure	2.5 bars
Dissipation of residual heat	Stand-by pump and natural flow
Pumps : type	Free level vertical centrifugal, with suspended shaft, and bearing and mountings in argon. Pressure is greater in the motor chamber than in the pump
- number	2
Purification system	1 cold trap per circuit with toluene at 130°C
Blanket gas	Argon
Preheating system	Electric

TABLE VIII-2

BR.5 SECONDARY SYSTEMS

Coolant fluid	NaK
Number of circuits	2
Intermediate exchangers	
- number	2
- nature	U-tube system in fixed casing
- input temperature	300°C
- output temperature	430°C
Pumps	
- number	2
- type	similar to primary ones
First circuit	Air cooling 50% of capacity
Air flow	40,000 m^3/hr
Input temperature	5 to 20°C
Second circuit	Water cooling 50% of capacity
Steam generator	
- number	1
- type	Na and water tube system in mercury-filled ring

TABLE VIII-2 (continued)

- steam pressure	16 bars
- steam temperature	400°C
- flow	5 t/hr
Condenser	
- number	1
- cooling water flow	70 m^3/hr

TABLE VIII-3

BR.5 NATURAL FLOW STEADY STATE PARAMETERS

	State I	State II
Capacity	100 kW	240 kW
Sodium flow	2.85 m^3/hr	4.2 m^3/hr
Alloy flow	3.75 m^3/hr	5.9 m^3/hr
Na output temperature	322°C	390°C
Na input temperature	212°C	205°C
Temperature of air at temperature exchanger outlet	254°C	240°C

TABLE IX-1

CHARACTERISTICS OF SEFOR

Capacity of reactor	20 MW (th)
Size of core :	
- height	850 mm
- diameter	850 mm
Fuel	14% PuO_2
	86% UO_2
Fuel cladding	Stainless steel
Coolant fluid	Sodium
Composition of core :	
- fuel	50% (volumetric %)
- structure	24% "
- coolant	14% "
- moderator	12% "
Coolant fluid speed (mean fuel channel)	3.5 m/s
Doppler coefficient (av. fuel temp. 1320°K)	8.9 $10^{-6}/\Delta K$°/C
Critical mass (Pu 239)	277 kg
Neutron lifetime	5 10^{-7} sec.

TABLE IX-1 (continued)

Proportion of fission below 9 keV	22%
Change in reactivity produced by complete drainage of sodium from core	-0.75 ¢
Change in reactivity produced by total discharge of sodium from core	+0.03 ¢

TABLE IX-2

SEFOR PRIMARY AND SECONDARY SYSTEMS

Primary system	
Number of circuits	1 main one
Flow	1020 m^3/hr
Temperature	
- reactor input	370°C
- reactor output	440°C
Intermediate exchanger	
- type	Single-walled casing and tube system
- material	304 stainless steel
Pump	
- type	Adjustable-flow triphased AC electromagnetic pump
- nominal flow	1140 m^3/hr
- pressure difference	5 bars
Secondary system	
Number of circuits	1
Flow	1020 m^3/hr
Pump	Identical to primary pump
Terminal exchanger	
- type	Forced draught air exchanger with 3 fans
- material	304 stainless steel
Temperature	
- Na input	380°C

TABLE X-1

CAPACITY OF SRE

Thermal capacity	20 MW
Overall electric capacity	6 MW
Net electric capacity	5.7 MW
Turbogenerator capacity	7.5 MW
Steam characteristics at turbine inlet :	
- absolute pressure	41 bars
- absolute temperature	440°C
Net thermal efficiency of the plant	28.6%
Steam flow to turbine	27.2 t/hr
Total steam produced	27.2 t/hr

TABLE X-2

SRE PRIMARY SYSTEMS

Fluid	Na
Number of circuits	1 main and 1 auxiliary
Heat transfer in the core :	
Exchange surface : per element	5475 cm^2
: in all	21.9 m^2
Exchange coefficient	5850 $W/m^2.°C$
Speed	1 m/s
Mass flow	220 t/hr
Coolant temperature	
- inlet	260°C
- outlet	515°C
Coolant pressure	
- inlet	0.7 bars
- outlet	0.3 bars
Heat dissipation on shutdown	1 MWth auxiliary circuit
Pumps	
- number	1 per circuit
- type	Centrifugal with solid sodium joints
- pumping capacity per pump	9.5 kW
- Manometric head at nominal flow	0.96 bars
- Motor	Adjustable speed
- Flow at 1000 r.p.m.	240 m^3/hr
Blanket gas	Helium

TABLE X-2 (continued)

Material in contact with coolant	Zirconium and 304 steel
Purification systems	Hot and cold traps, fouling indicators
Preheating system	Electr. resist.
Valves	
- number	1
- type	with solid Na joint
Storage tank	
- number	1
- capacity	27 t
Piping	
- material	304 stainless steel
- size: in main circuit	161-168 mm
in aux. circuit	56-60 mm
Total pressure loss	
- main circuit	1.2 bars
- auxiliary circuit	0.5 bars

TABLE X-3

SRE SECONDARY AND STEAM SYSTEMS

Fluid	Na
Number of circuits	1 main and 1 auxiliary
Flow	320 t/hr
Temperature	
- exchanger input	227°C
- exchanger output	482°C
Pressure	
Exchanger inlet	1.85 bars
Total pressure loss :	
- main circuit	2.5 bars
- aux. circuit	1.2 bars
Intermediate exchangers	
- number	1 main and 1 auxiliary
- type	U-shaped with casing and reflux tube system
Main exchanger surface	107 m^2
Number of tubes in :	
- main exchanger	316
- auxiliary exchanger	28

TABLE X-3 (continued)

Pumps	
- number	1 main and 1 auxiliary
- type	centrifugal
- pumping capacity per pump	25 kW
- manometric head	2.9 bars
Material in contact with coolant	304 stainless steel
Purification	Cold traps
Preheating	Heating by electric resistor and steam
Storage tanks	
- number	1
- material	304 stainless steel
- capacity	9 t
Steam system	
Total number of steam generators	1
Type	Single-flow, with stainless steel double-walled U-tube (with Hg in the annular section)
Steam temperature	440°C
Steam pressure	41 bars
Steam flow	27 t/hr
Condenser pressure	50 mm Hg
Number of supply water heaters	2
Temperature of supply water going to steam generator	140°C

TABLE X-4

COMPARISON OF PRESENT AND MODIFIED SRE

	Present SRE	Modified SRE 1st objective	Modified SRE 2nd objective
Operating conditions			
reactor capacity	20 MW (th)	40 MW (th)	40 MW (th)
output temp.	515°C	538°C	649°C
input temp.	260°C	282°C	393°C
Steam generator			
input temp.	482°C	512°C	630°C
output temp.	227°C	256°C	368°C

TABLE X-4 (continued)

	Present SRE	Modified SRE 1st objective	Modified SRE 2nd objective
Capacity			
steam generator	20 MW (th)	25 MW (th)	25 MW (th)
air exchanger		15 MW (th)	15 MW (th)
Na flow			
primary	220 t/hr	442 t/hr	442 t/hr
steam generator	220 t/hr	281 t/hr	281 t/hr
air exchanger		160 t/hr	160 t/hr
Na speed in central channel	1.2 m/s	4.8 m/s	4.8 m/s
Apparatus			
pumps	Centrifugal, frozen shaft joints	Free surface, centrifugal	
tube size	150 mm	200 mm	200 mm
material	304 stainless steel	Expansion joints in the primary and secondary systems	
Na flow control			
primary	DC motor adjustable speed	AC motor with electro-magnetic coupling	
secondary	DC motor adjustable speed	Constant speed pump; regulation by eddy current brakes	
after emergency shutdown	Eddy current brakes	Eddy current brakes	

TABLE XI-1

CAPACITY OF HNPF

Net electric capacity	76 MW
Overall electric capacity	82 MW
Thermal capacity of the reactor	240 MW
Net thermal efficiency of plant	31.5%
Turbine characteristics of the steam	
- pressure	55 bars
- temperature	441°C
- flow	323 t/hr
Capacity of the turbine	100 MW
Electric generator	128,000 kVA 13,800 V

TABLE XI-2

HNPF PRIMARY COOLING SYSTEM

Fluid	Na
Number of circuits	3
Temperature	
- reactor input	321 °C
- reactor output	507 °C
Reactor input pressure	1.8 bars
- reactor pressure loss	1.4 bars
Total mass flow	3816 t/hr
Total volume flow	4626 m^3/hr
Flow per circuit	1542 m^3/hr
Pumps	
- number per circuit	1
- type	Adjustable speed, vertical, centrifugal
- pumping capacity per pump	254 kW
- manometric head at nominal flow	45 m
- nominal flow per pump	1632 m^3/hr
Heat transfer in the core :	
- Na speed in core (max.)	2.52 m/s
- heat transfer surface per element	3.2 m^2
- total heat transfer surface	480 m^2
- average heat flux	500 kW/m^2
- maximum heat flux	1200 kW/m^2
- coolant flow surface per element	47 cm^2
- total coolant flow surface	6400 cm^2
- heat transfer coefficient	31.5 kW/m^2.°C
- coolant pressure	1.4 bars
- heat dissipation on shutdown	By natural Na convection through the 3 primary circuits, each of which can deal with 4% of the full power of the reactor by natural convection.
Purification system	Cold trap
Cooling system safety	The reactor must never operate with less than 2 circuits
Material in contact with coolant	304 stainless steel
Preheating system	Electric
Blanket gas	Helium

TABLE XI-3

HNPF SECONDARY AND STEAM SYSTEMS

Fluid	Na
Number of circuits	3
Temperature	
- exchanger input	292°C
- exchanger output	480°C
Exchangers	
- number	3
- type	Vertical with tube system and casing
Pressure	
- exchanger input	3.7 bars
- pressure loss	
- casing side	0.4 bars
- tube side	0.08 bars
Total flow	3816 t/hr
Pumps	
- type	Adjustable speed, vertical, centrifugal
- number	1 per circuit
- pumping capacity per pump	225 kW
- manometric head	38 m
Material in contact with coolant	304 stainless steel 5 Cr - ½ Mo - Ti
Purification system	Cold traps
Preheating	Electric
STEAM SYSTEM	
Steam generator	Type with casing and bayonet tubes, with evaporator, separator and superheater
Total number of steam generators	3
Generator output temperature	445°C
Generator output pressure	59 bars
Steam flow (per circuit)	108 t/hr
HP turbine input temperature	441°C
HP turbine input pressure	55 bars
Condenser pressure	38 mm Hg
Number of supply water heaters	3 or 4

TABLE XI-3 (continued)

Temperature of supply water going to the steam generator	151°C
Exchange surface	
- in evaporator	342 m^2
- in superheater	200 m^2

TABLE XII-1

SGR PRIMARY SYSTEM (Current Technology)

Thermal capacity of reactor	835 MW	
Number of circuits	4	
Fluid	Na	
Reactor input temperature	330°C	
Reactor output temperature	507°C	
Total mass flow	13,280 t/hr	
Piping		
- material	304 stainless steel	
- diameters	61 and 56 cm	
Pumps		
- number	4	
- type	Vertical centrifugal	
- variation range	60-100%	
- flow	4100 m^3/hr	
- manometric head	50 m	
- motor	Triphased, 4160 V	
- capacity	700 kW	
Intermediate exchangers		
Type	Reflux type, with tubes and casing	
Number	8 (2 per circuit)	
	Primary	Secondary
Fluid	Tube side	Casing side
Flow	1660 t/hr	1660 t/hr
Input temperature	507°C	307°C
Output temperature	330°C	485°C
Reference pressure	10 bars	10 bars
Pressure loss	0.7 bars	0.7 bars
Transfer surface	600 m^2	
Material	304 stainless steel	

TABLE XII-2

SGR SECONDARY AND STEAM SYSTEMS (Current Technology)

Number of circuits	4
Fluid	Na
Temperature	
- steam generator input	485°C
- steam generator output	307°C
Total mass flow	13,280 t/hr
Blanket gas	Helium
Piping	304 stainless steel and 2.1/4% Cr - 1% Mo steel
Pumps	
- number	4
- type	Vertical centrifugal
- flow	4100 m^3/hr
- manometric head	71 m
- motor capacity	1080 kW
STEAM SYSTEM	
Number of steam superheaters	2
Input and output temperatures	252 - 455°C
Pressure	16 bars
Number of steam generators	4
Type	Single-flow, with sodium on the casing side and steam on the tube side
Steam conditions : pressure	86 bars
temperature	455°C
total flow	1120 t/hr
Number of supply water heaters	6, and 1 evaporator
Temperature of supply water	230°C
Condenser pressure	25 mm Hg
Overall electric capacity	328 MW
Net electric capacity	315 MW
Yield	37.8%

TABLE XIII-1

SGR PRIMARY SYSTEM (Advanced Technology)

Capacity of reactor	606 MWth	
Number of circuits	3	
Fluid	Na	
Reactor input temperature	343°C	
Reactor output temperature	649°C	
Total mass flow	5670 t/hr	
Pumps		
- number	9	
- type	Electromagnetic	
- stator	220 V and 15 cycle current triphased	
- temperature	340°C	
- manometric head	2.8 bars	
- flow	770 m^3/hr	
Storage tanks		
- number	4	
- volume	140 m^3	
Purification system	2 cold traps	
Preheating system	Heating, by resistors, to 177°C for all the piping except the steam generator and sodium tank	
Blanket gas	Nitrogen	

<u>Intermediate exchangers</u> : primary (casing), secondary (tube)

Number	3	
	<u>Primary</u>	<u>Secondary</u>
Flow	1890 t/hr	1890 t/hr
Input temperature	649°C	316°C
Output temperature	343°C	621°C
Operating pressure		3.5 bars
Reference temperature	691°C	691°C
Reference pressure	0.5 bars	7 bars
Maximum pressure loss	0.35 bars	1.4 bars

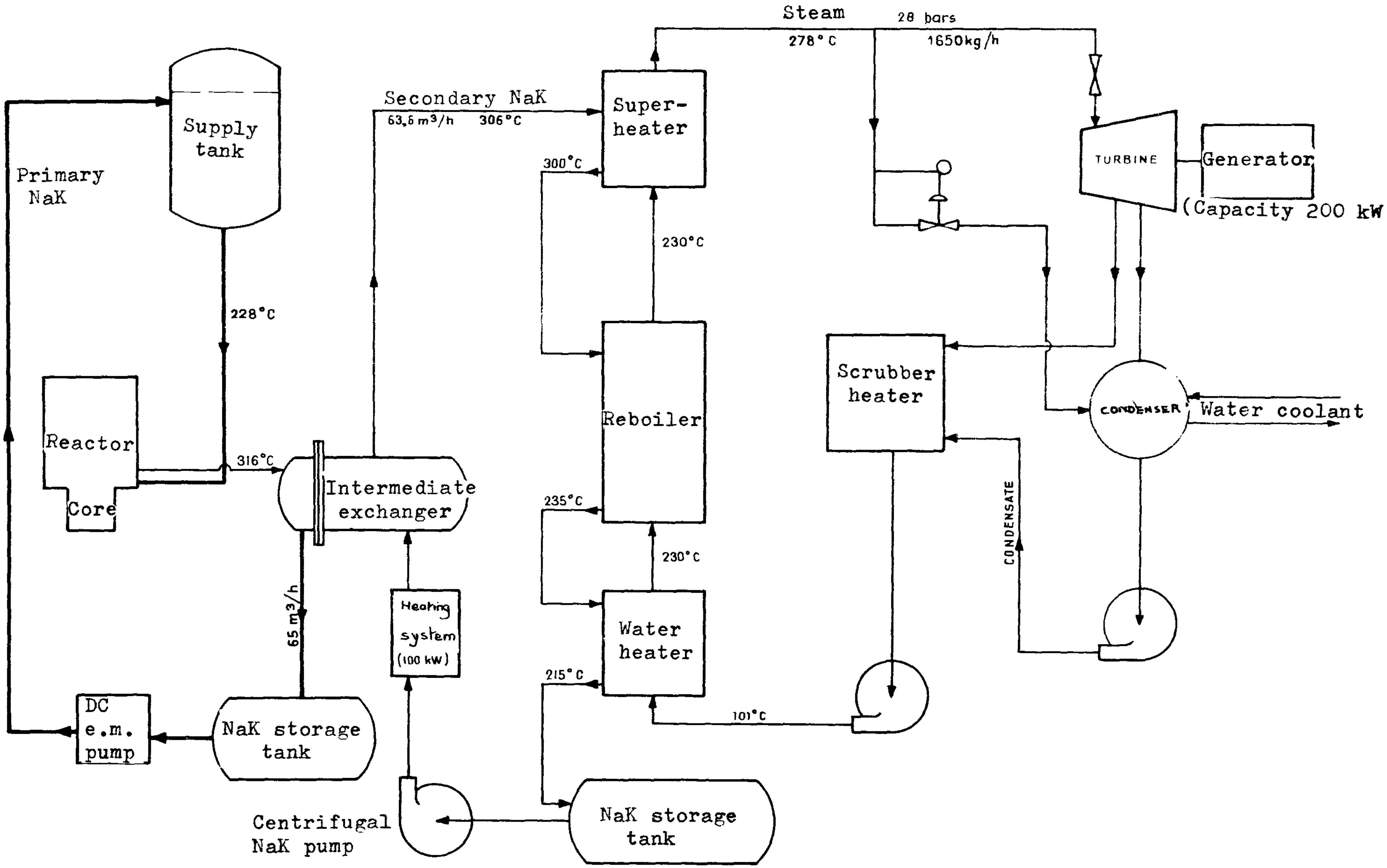
TABLE XIII-2

SGR SECONDARY AND STEAM SYSTEMS (Advanced Technology)

Number of circuits	3
Fluid	Na
Exchanger input temperature	316°C
Exchanger output temperature	621°C
Coolant flow	5670 t/hr
Piping	
- material	304 stainless steel
- wall thickness	6 mm
Valves	1 solid sodium joint regulator valve per circuit, between intermediate exchanger and pump
Storage tanks	
- number	2
- volume	140 m^3
Secondary pumps	
- type	Electromagnetic, with screw rotors
- number	3 (1 per circuit)
- maximum flow	2320 m^3/hr
- temperature	316°C
- manometric head	2.8 bars
STEAM SYSTEM	
Number of steam generators	3
Type	Single-flow, with steam and water on the tube side and Na on the casing side
Projected total steam flow	825 t/hr
Steam pressure	170 bars
Steam temperature	565°C
Number of supply water heaters	7 and 1 evaporator
Supply water temperature	282°C
Condenser return pressure	37 mm Hg
Overall electric capacity	270 MW
Net electric capacity	256 MW
Yield	42.3%

PART THREE : COMPARATIVE TABLES

List of Comparative Tables



EBR I – DIAGRAM OF THE SYSTEMS

Figure I 1

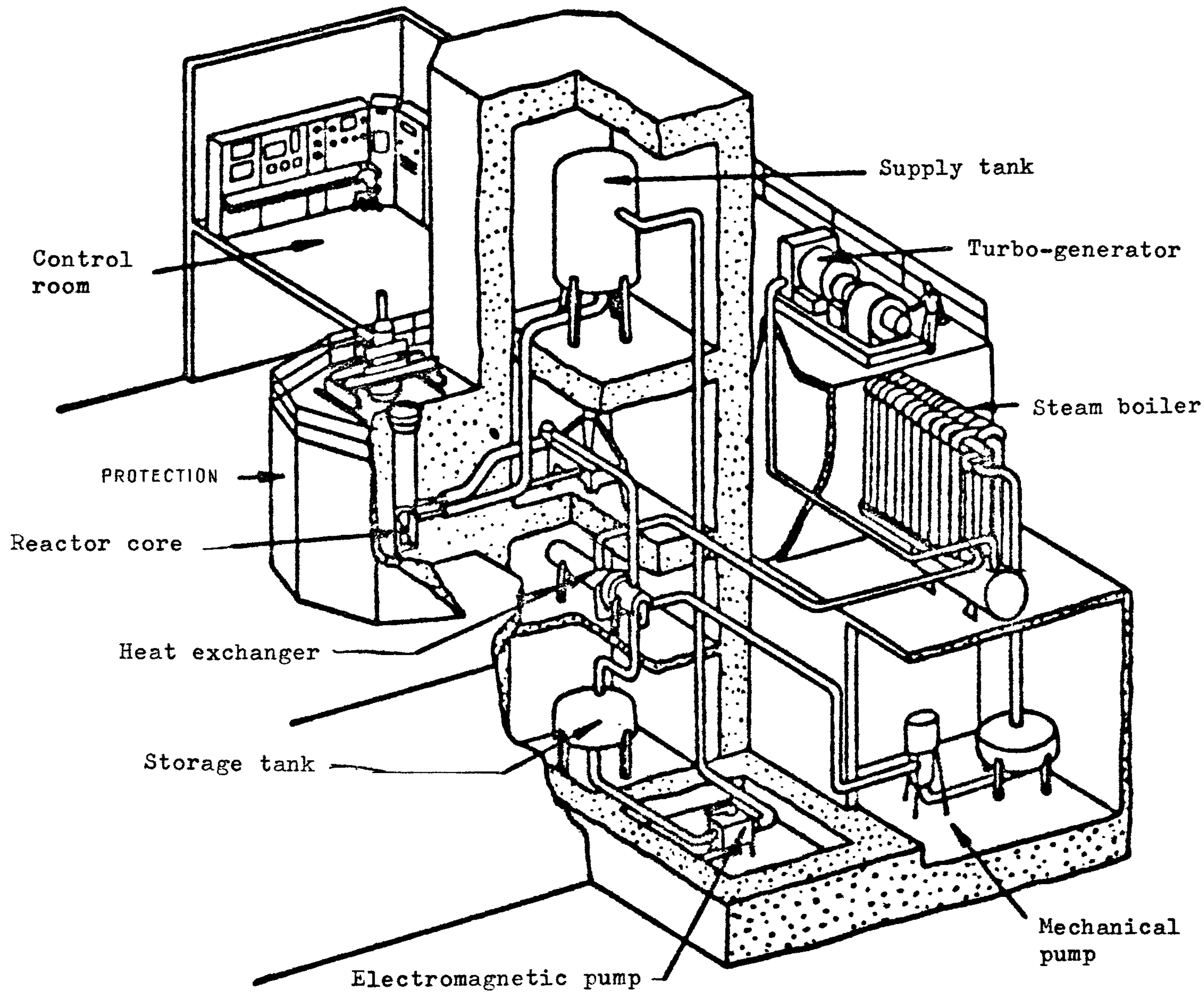
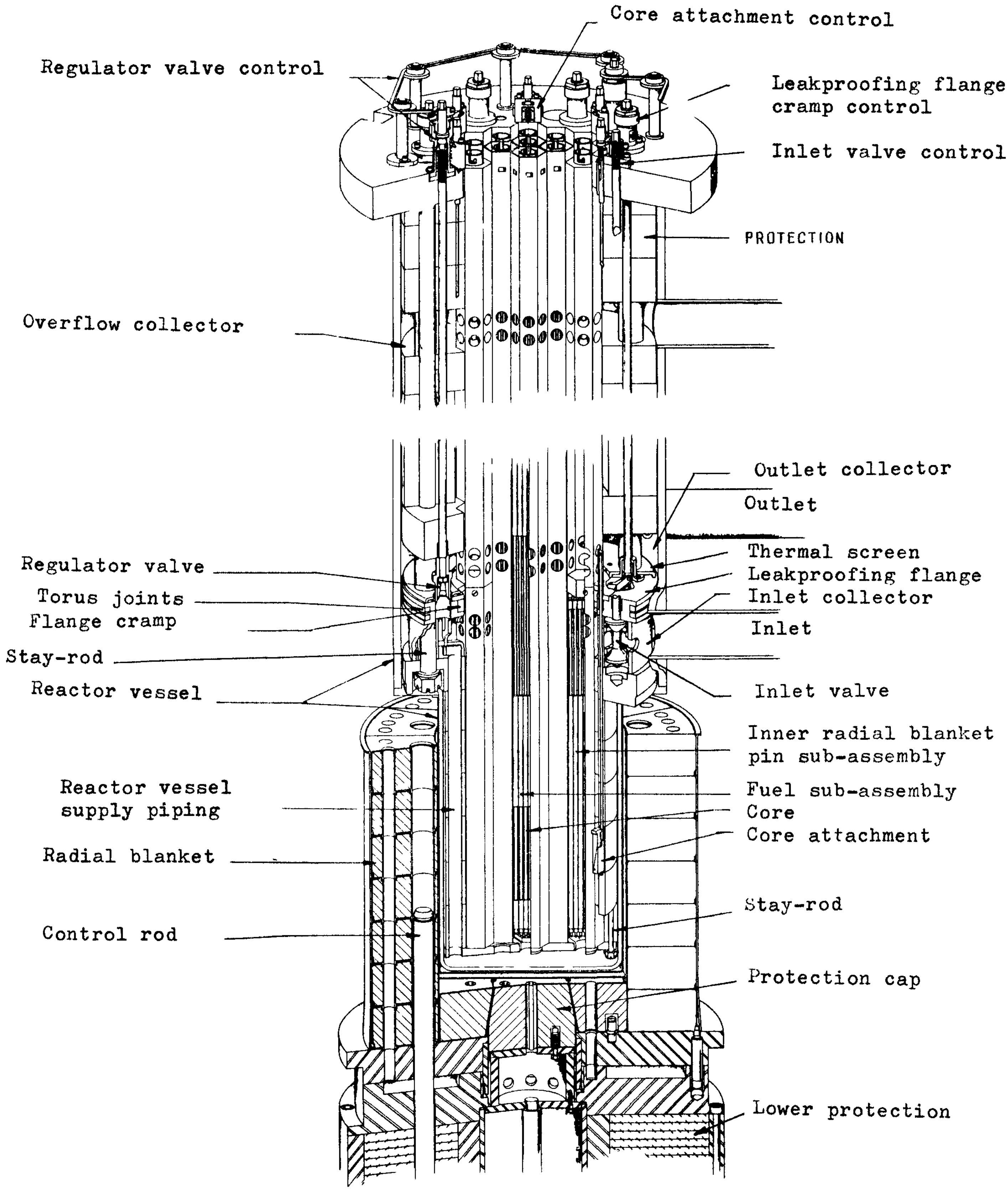


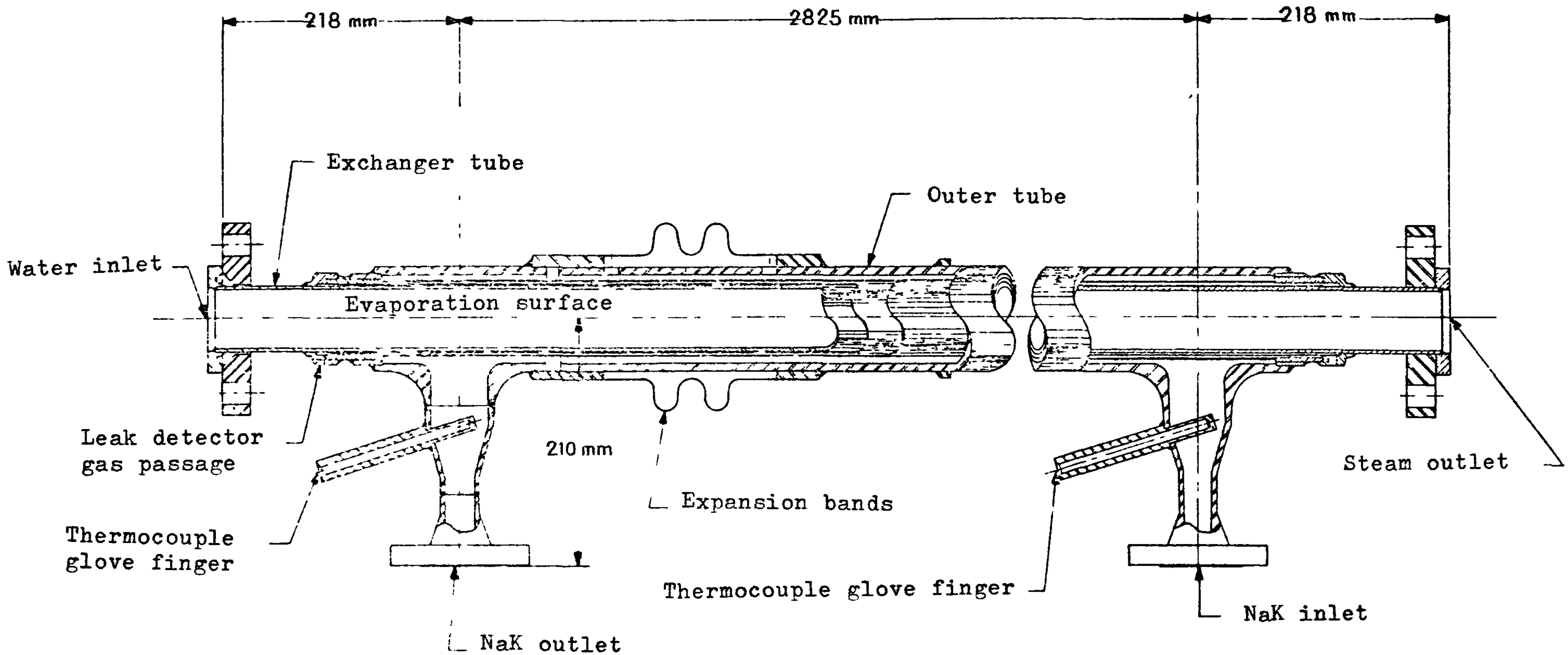
Figure I2

EBR I — GENERAL VIEW OF THE REACTOR



EBR I _ INNER VESSEL ASSEMBLY

Figure I 3



EBR I _ STEAM GENERATOR TUBE

Figure I4

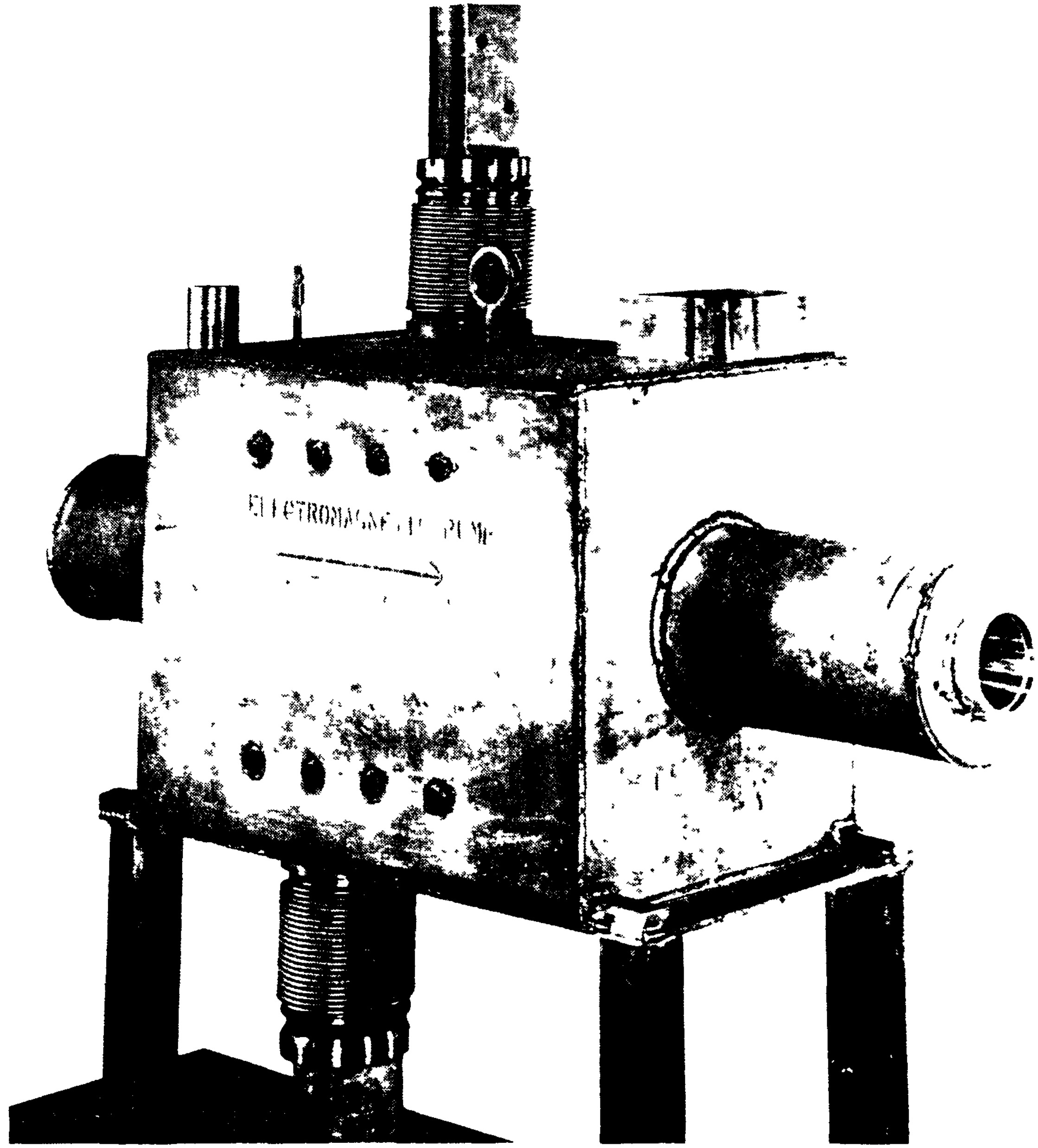
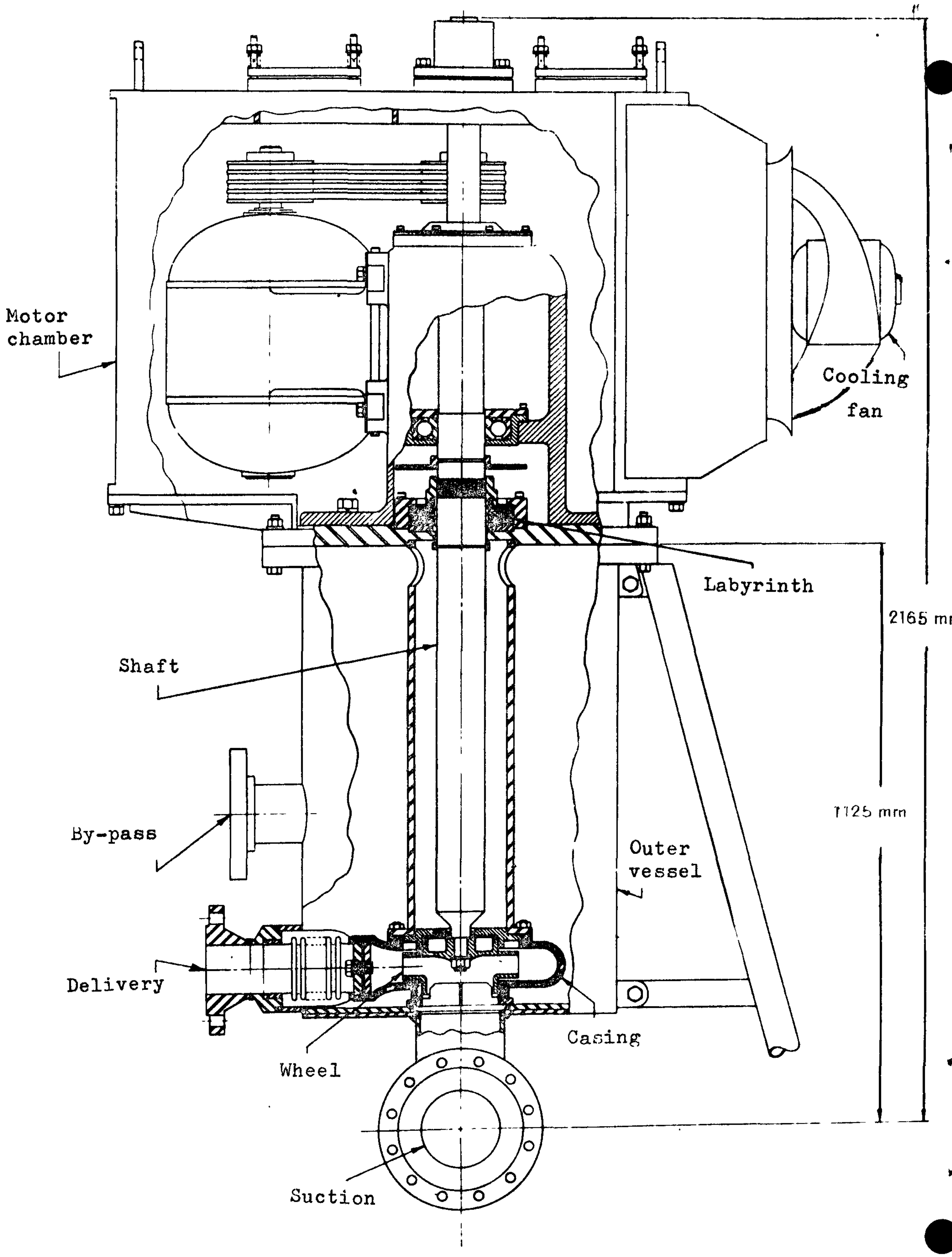


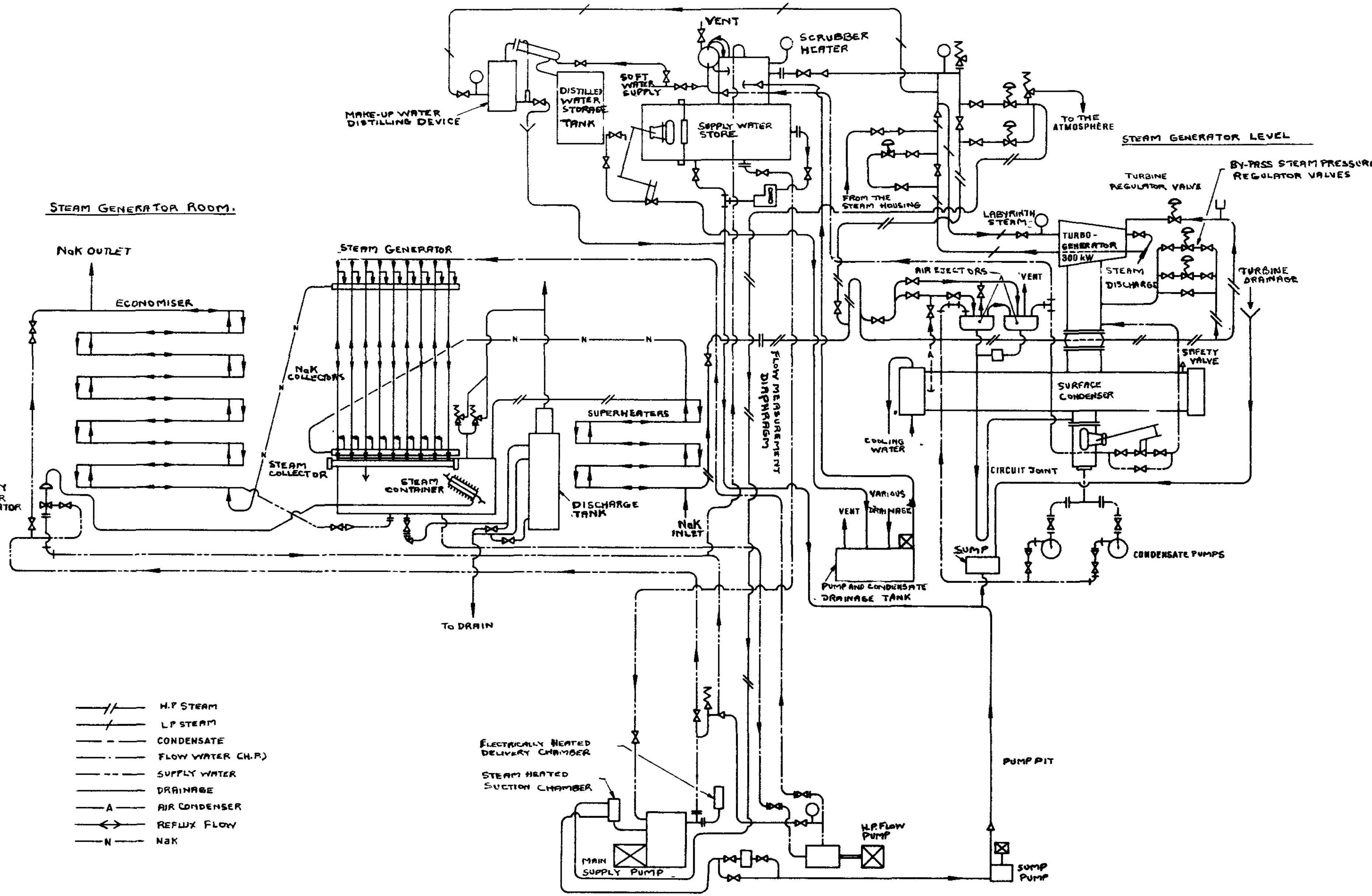
Figure I5

EBR I _ PRIMARY ELECTROMAGNETIC PUMP



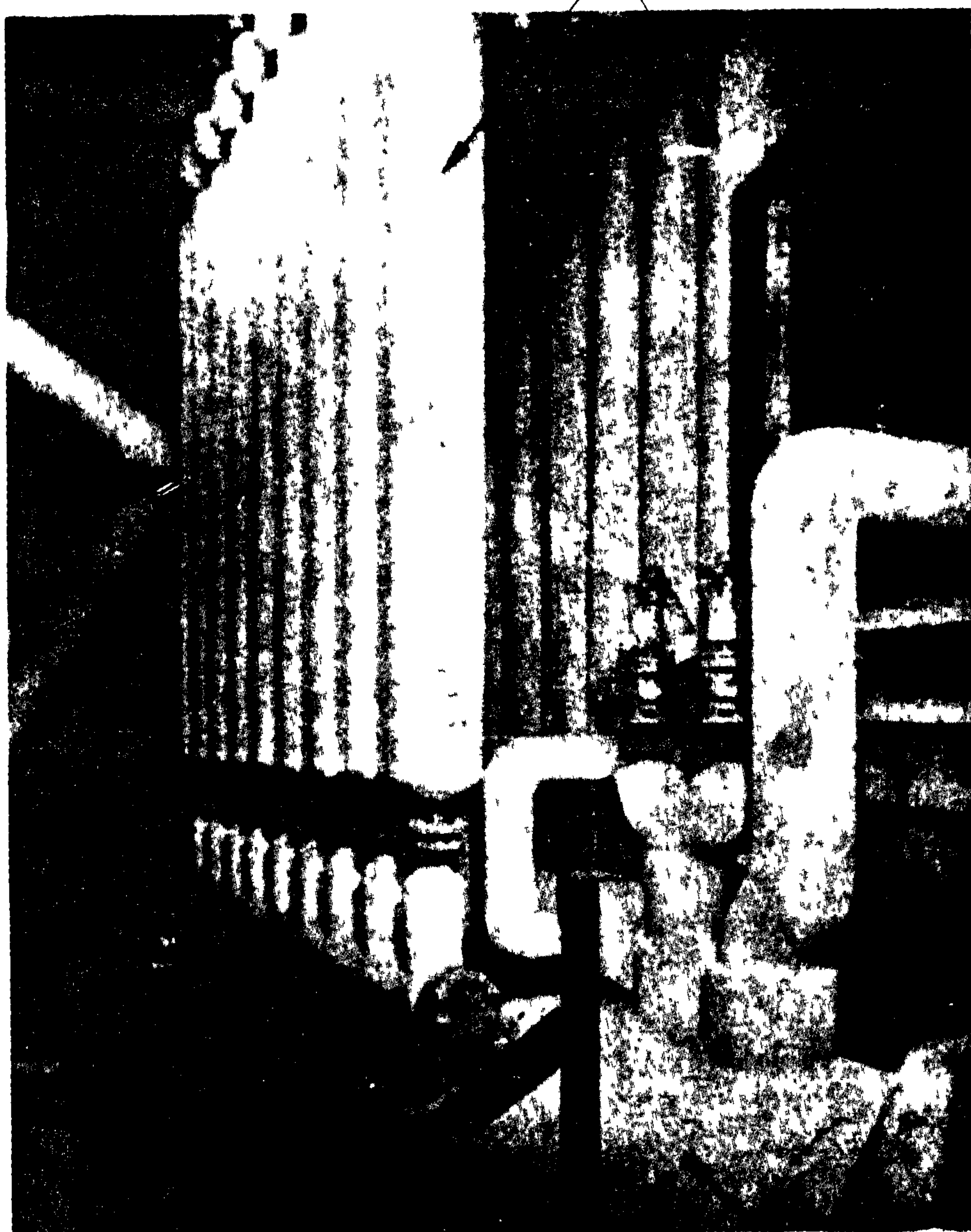
EBR I _ MECHANICAL PUMP WITH GAS LEAKPROOFING

Figure I6



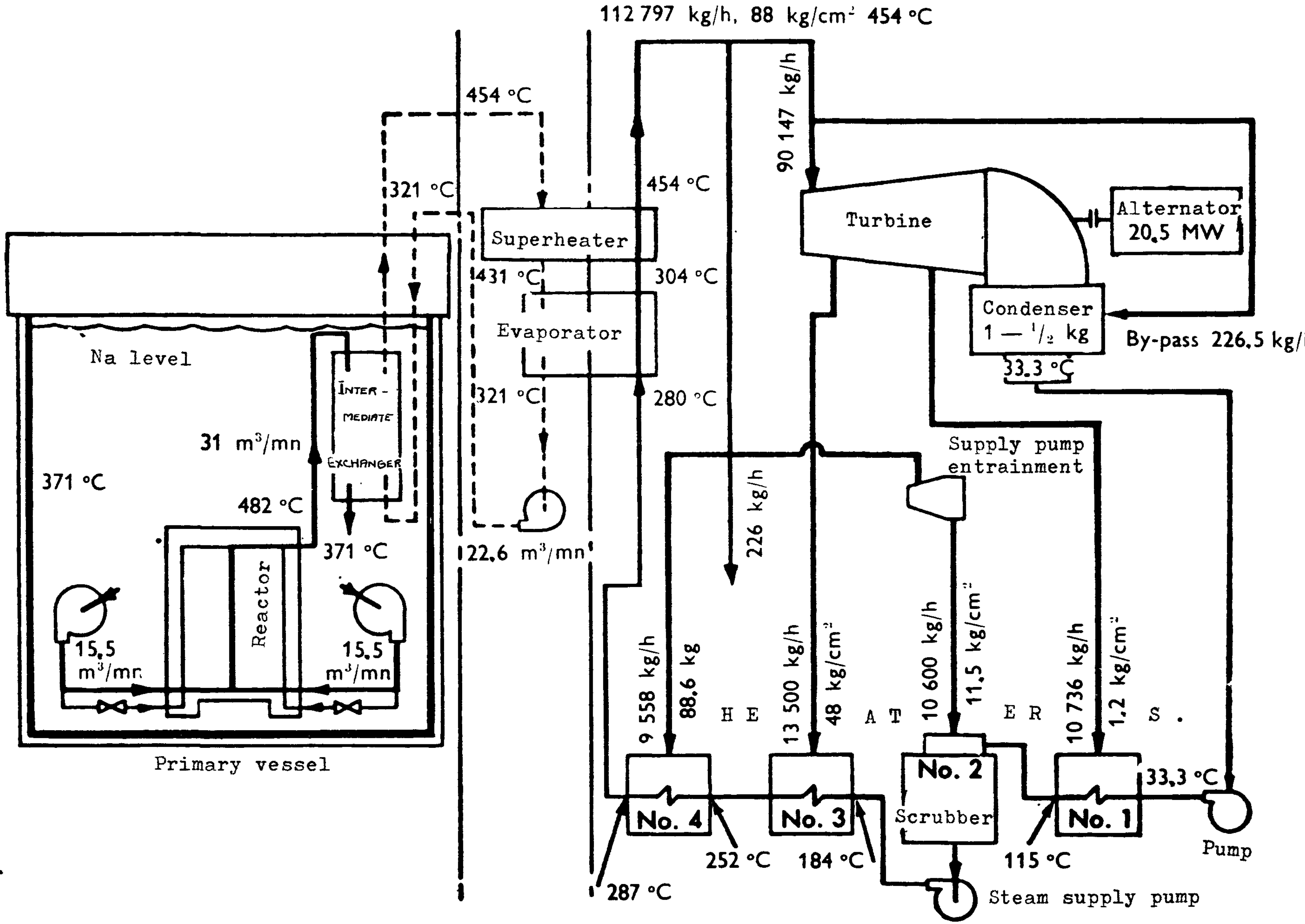
EBR I _ DIAGRAM OF THE STEAM SYSTEM

Figure I 7



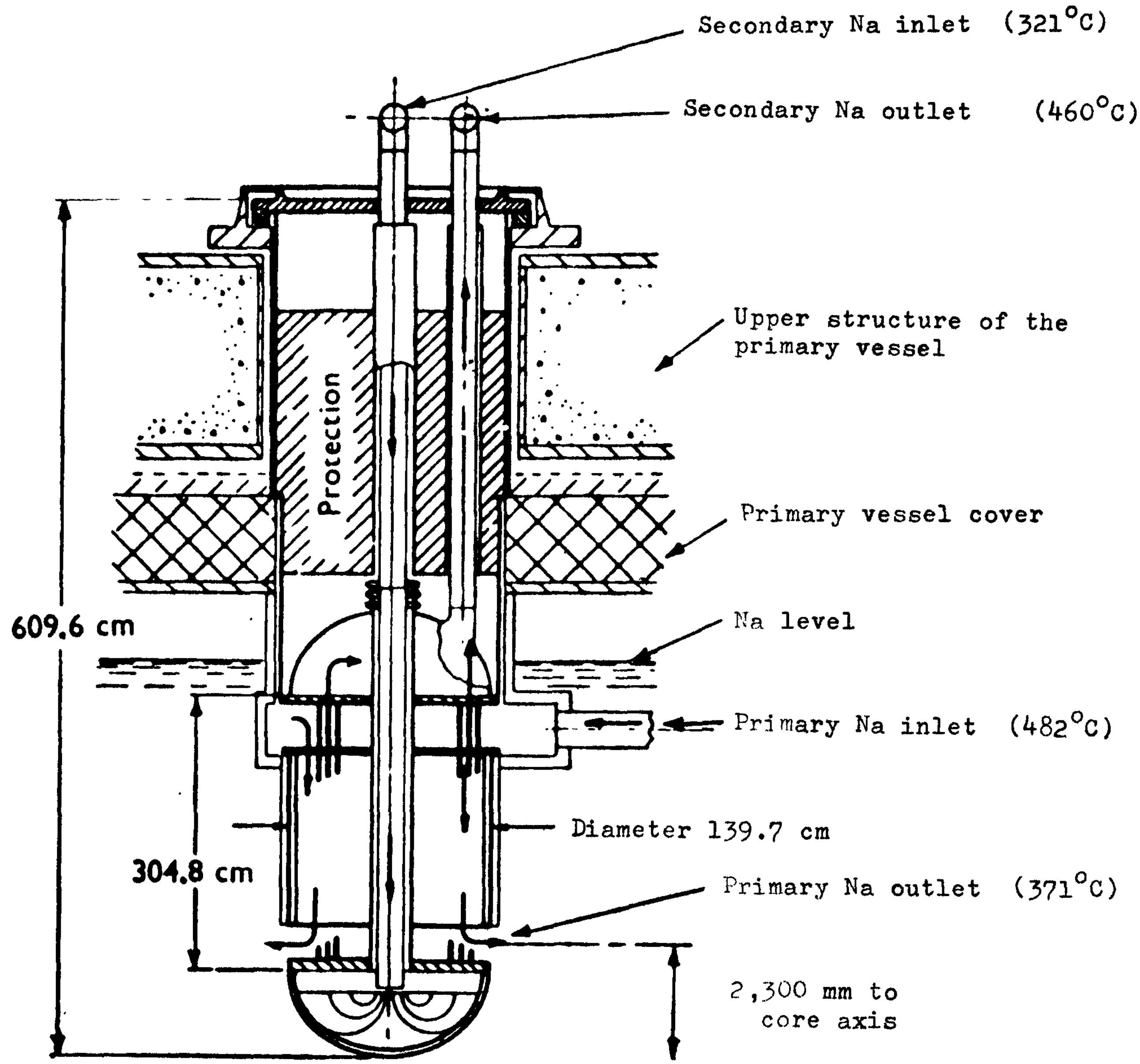
EBR I _ PHOTO OF THE STEAM GENERATOR

Figure 18



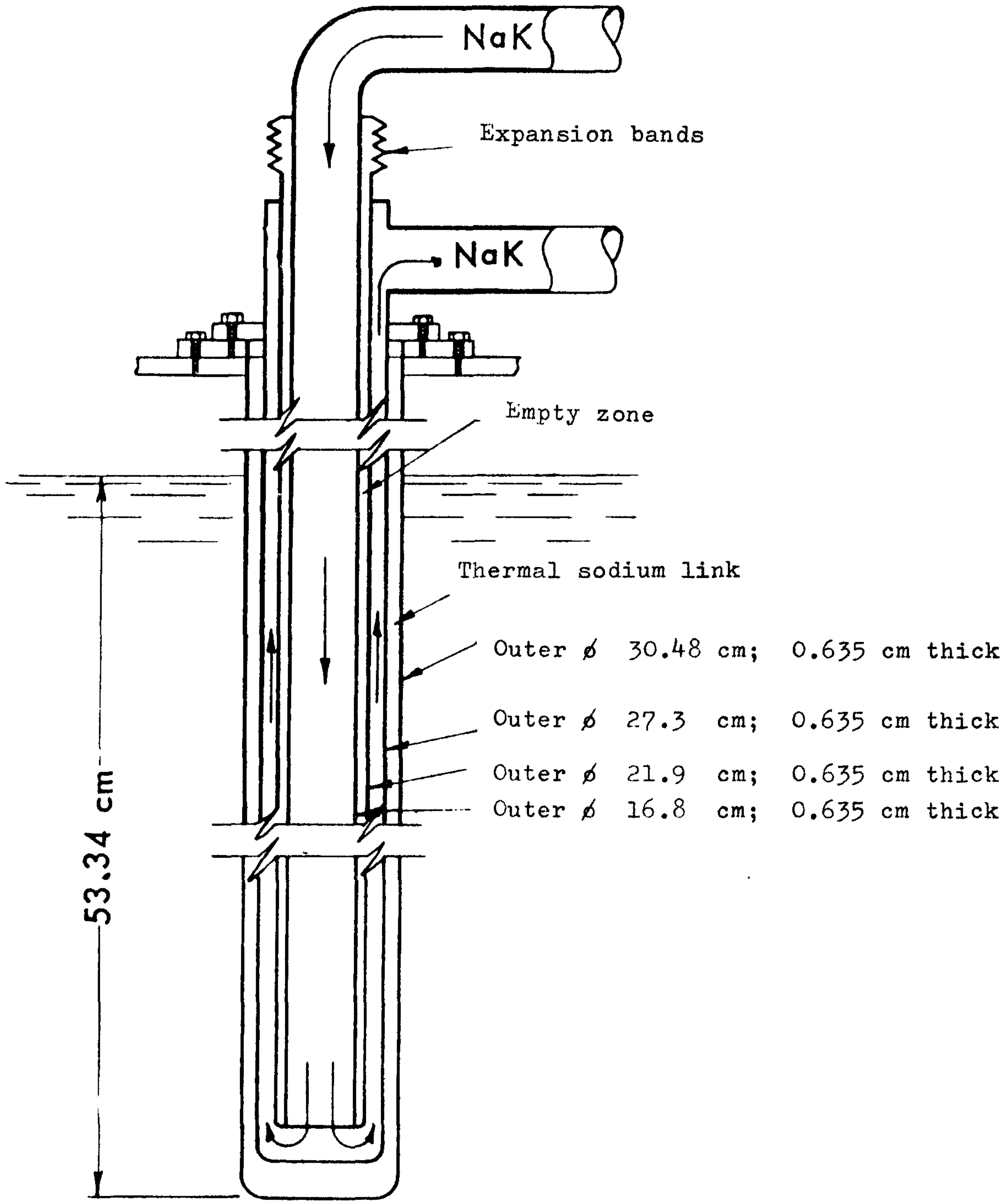
E B R II - DIAGRAM OF THE SYSTEMS

Figure II 1



E B R II - INTERMEDIATE EXCHANGER

Figure II 2



EBR.II _ SHUTDOWN COOLANT

Figure II 3

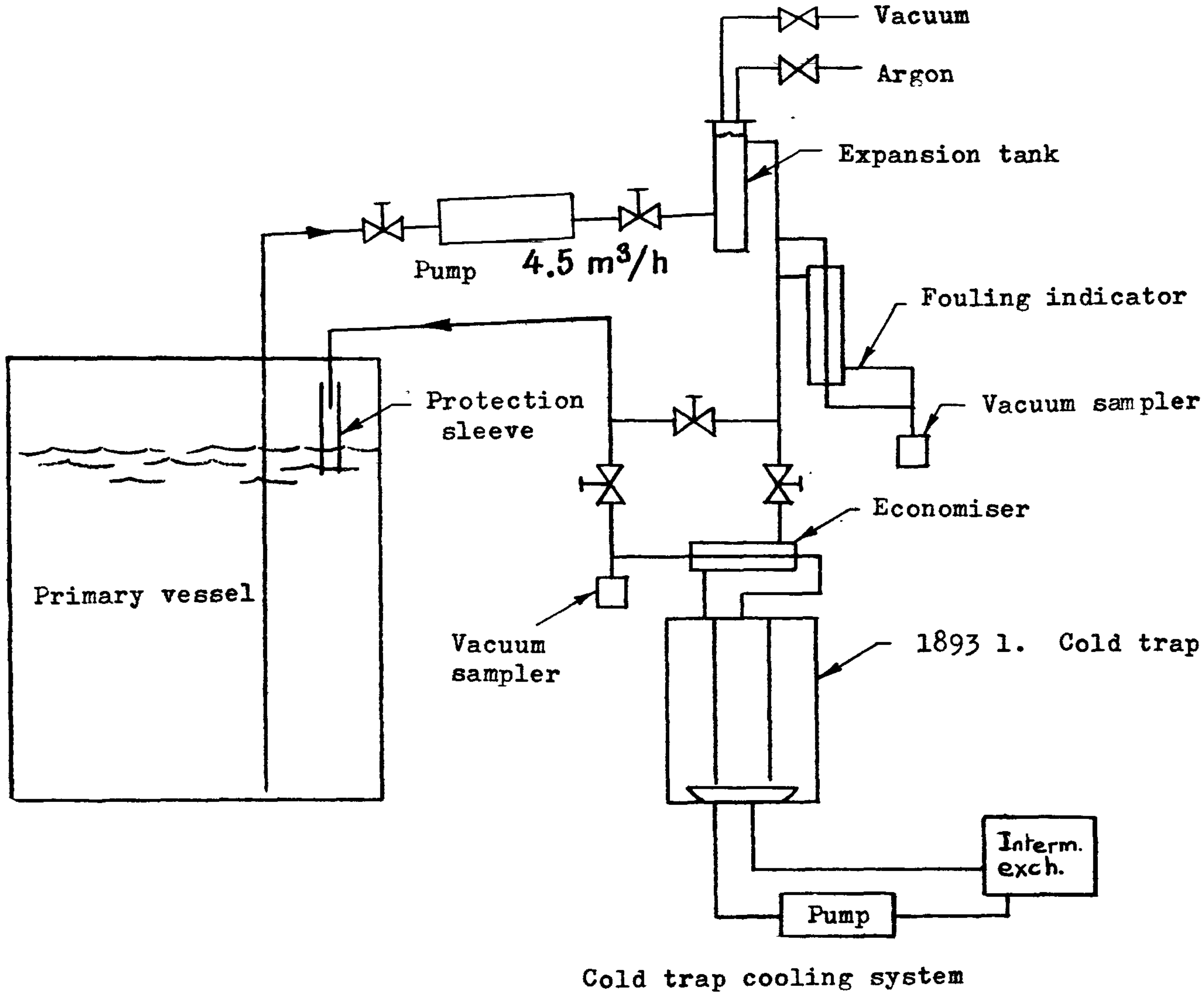


Figure II 4

EBR II - DIAGRAM OF THE PRIMARY PURIFICATION SYSTEM

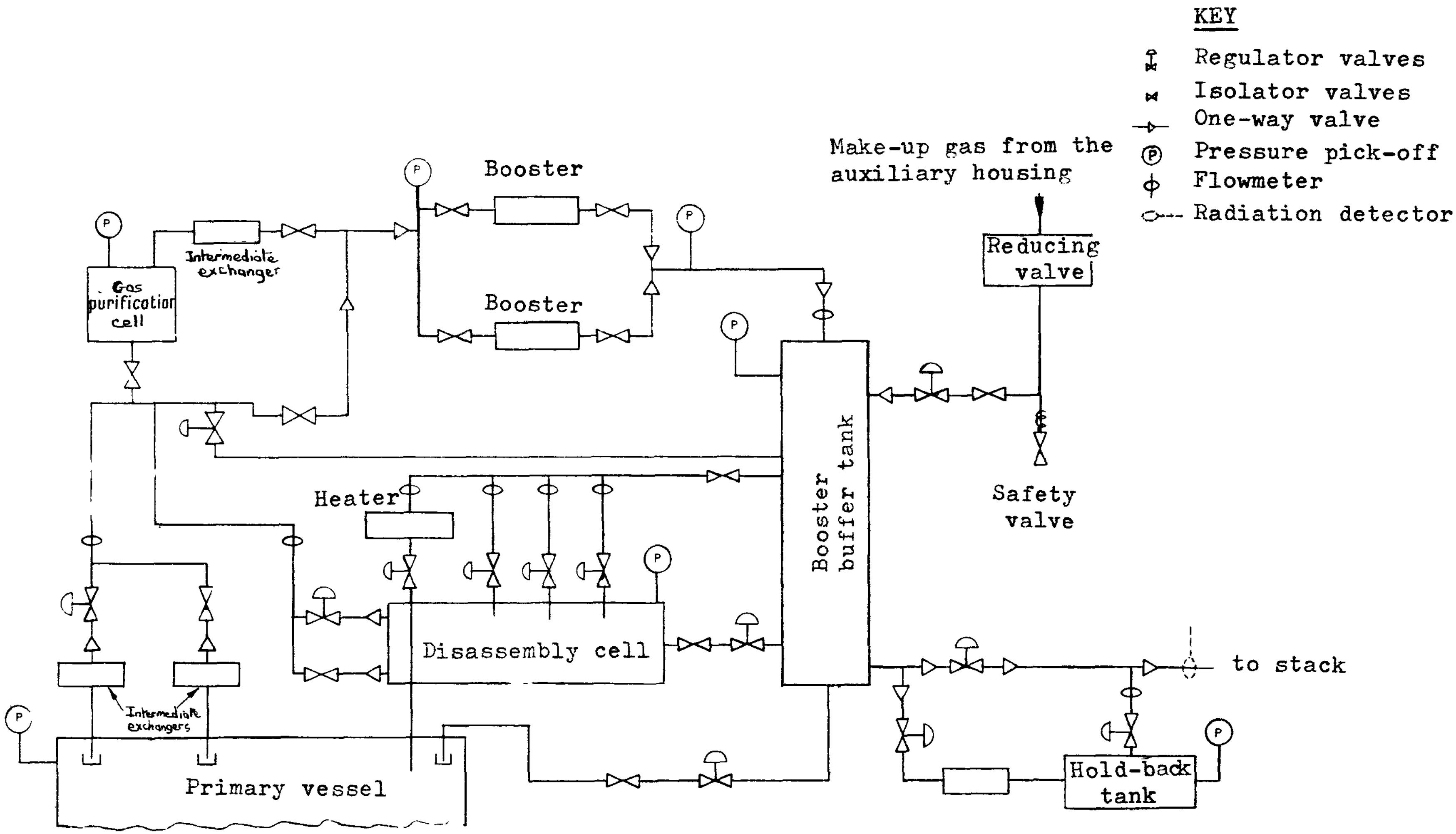
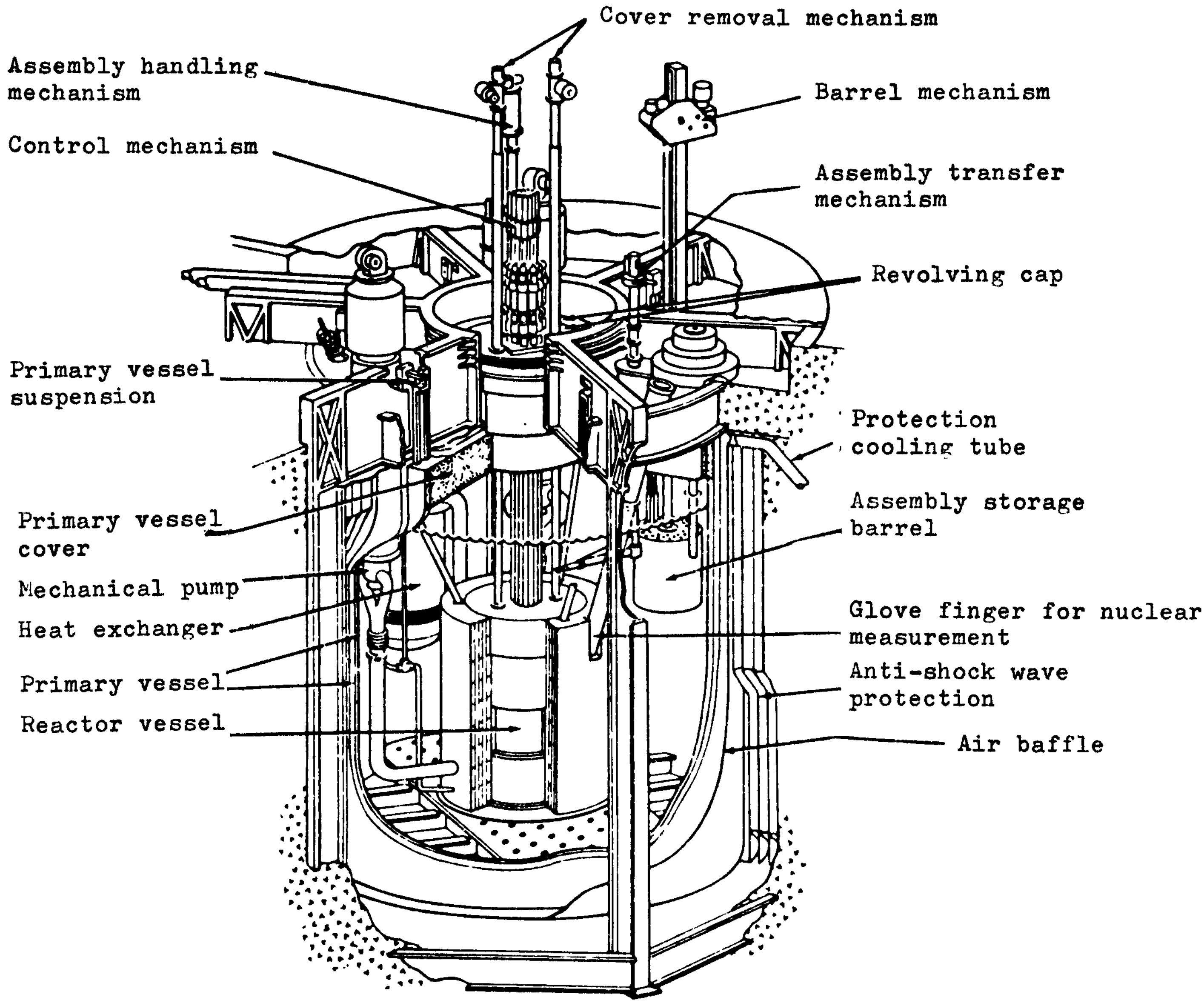


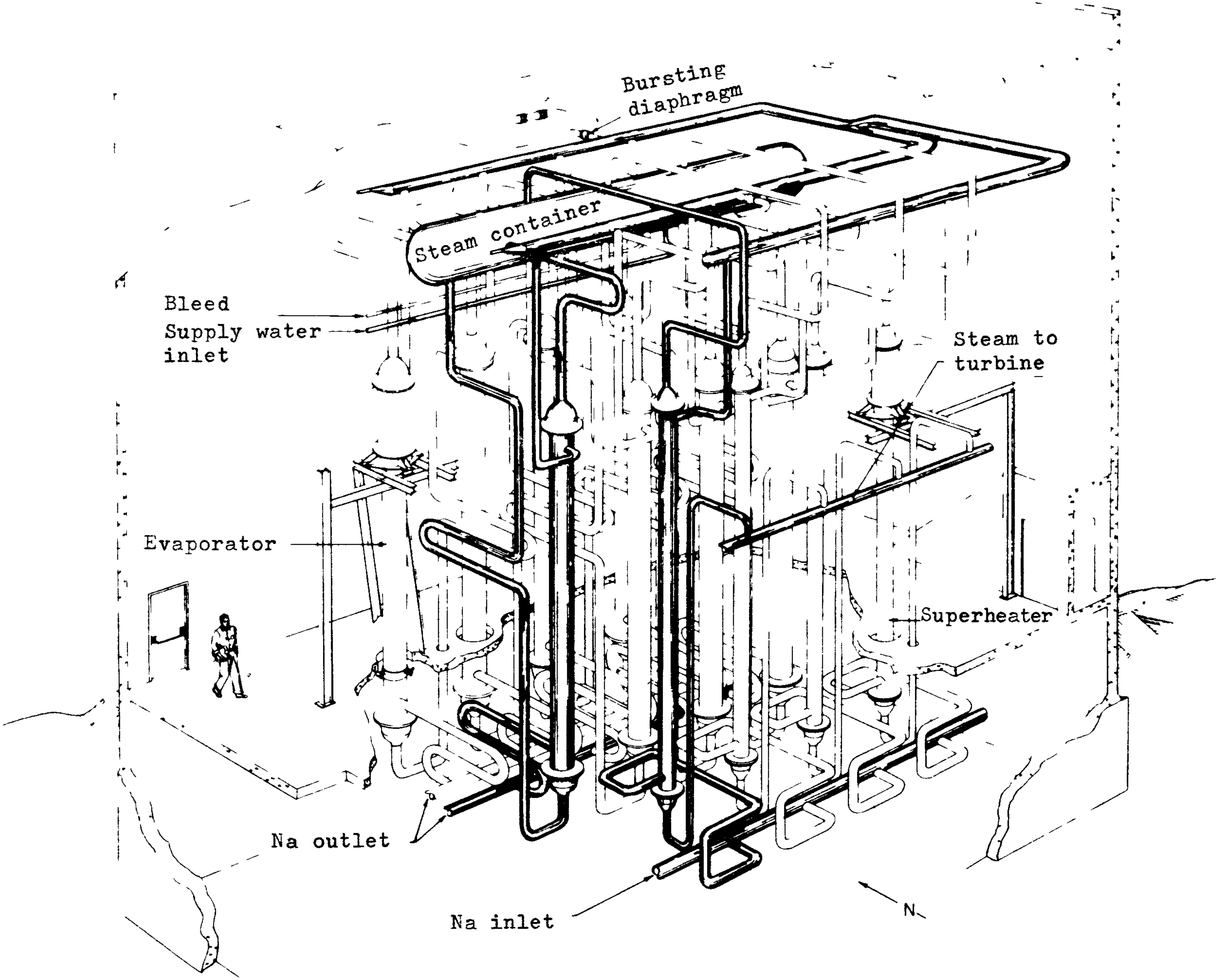
Figure II 5

EBR II - DIAGRAM OF THE PRIMARY ARGON SYSTEM



EBR II _ CROSS-SECTION OF THE PRIMARY SYSTEM

Figure II 6



EBR II — STEAM GENERATOR

Figure II 7

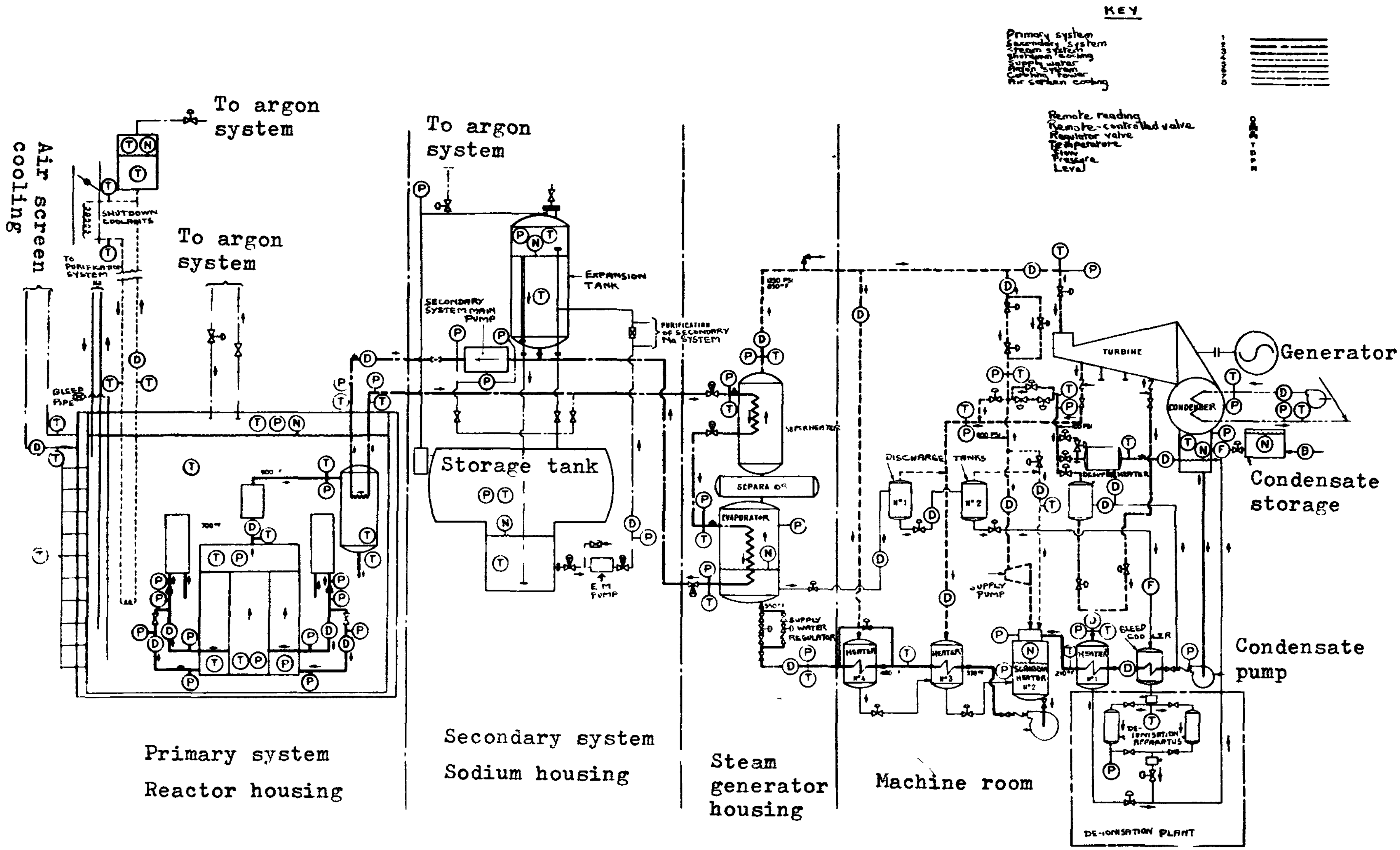


Figure II8

EBR 2 _ DIAGRAM OF THE SYSTEMS SHOWING POSITIONS OF THE MEASUREMENT AND CONTROL APPARATUS

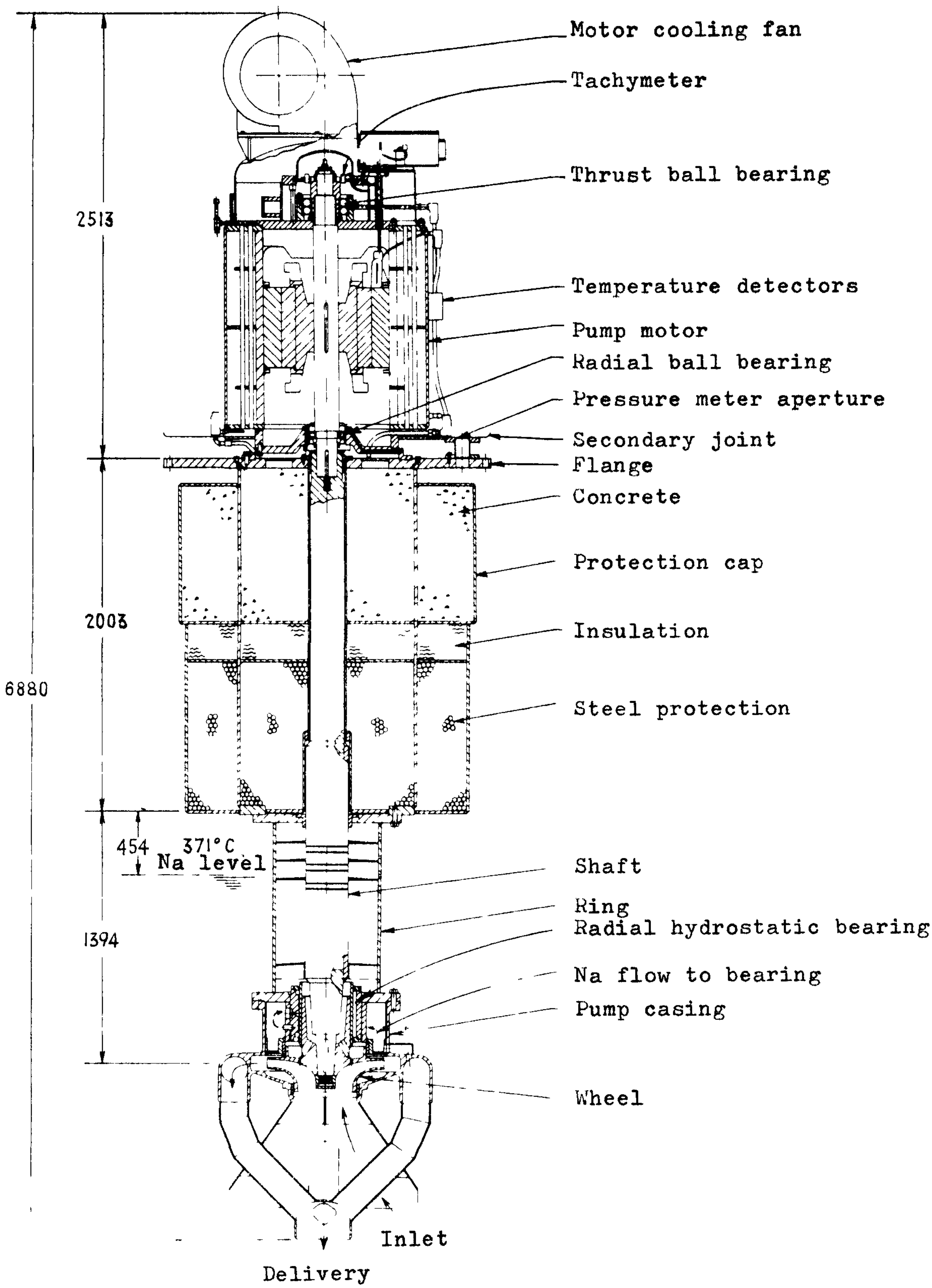
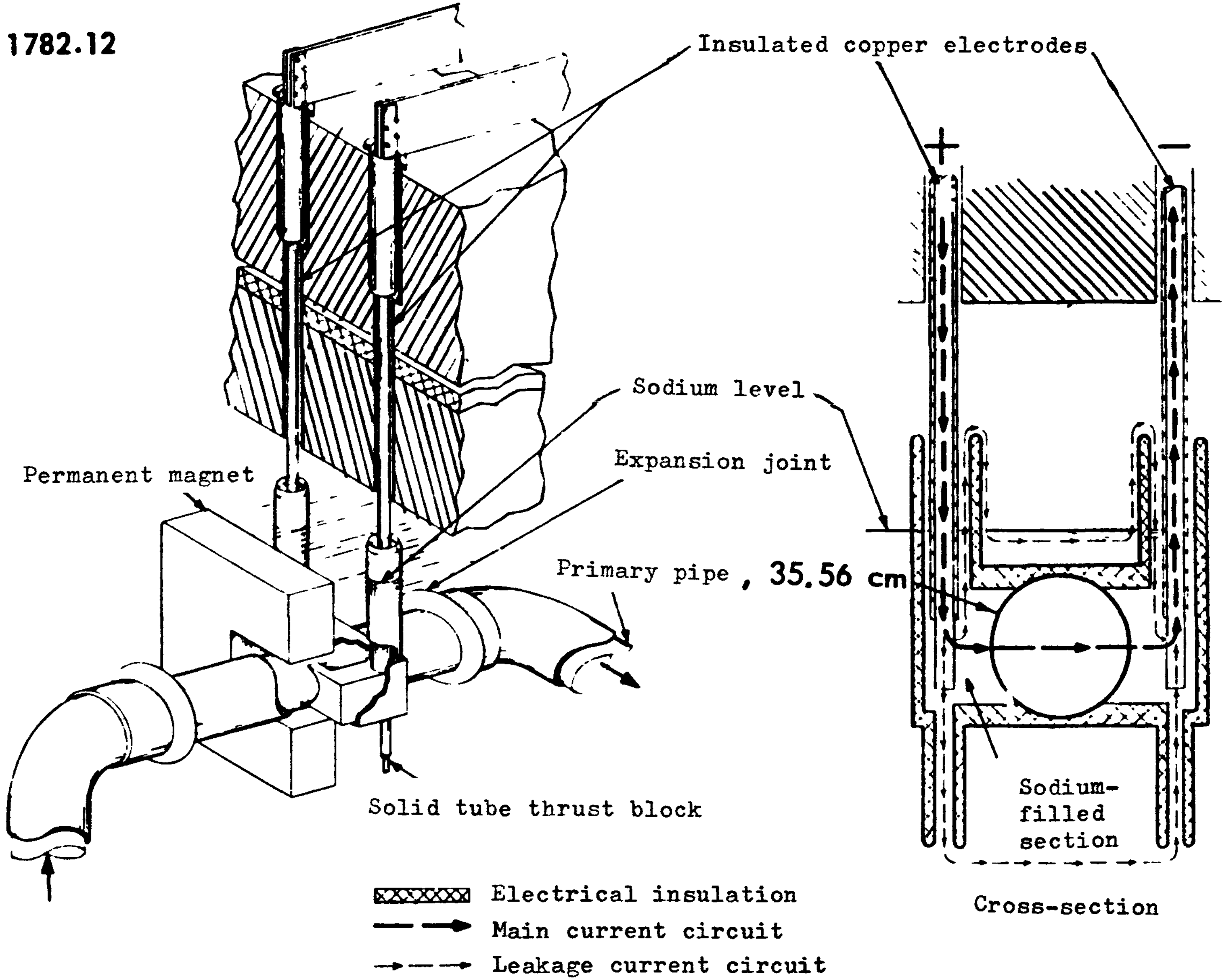


Fig. II. 9

EBR2 PRIMARY MECHANICAL PUMP

1782.12



EBR II _ ELECTROMAGNETIC PUMP

Figure II 10

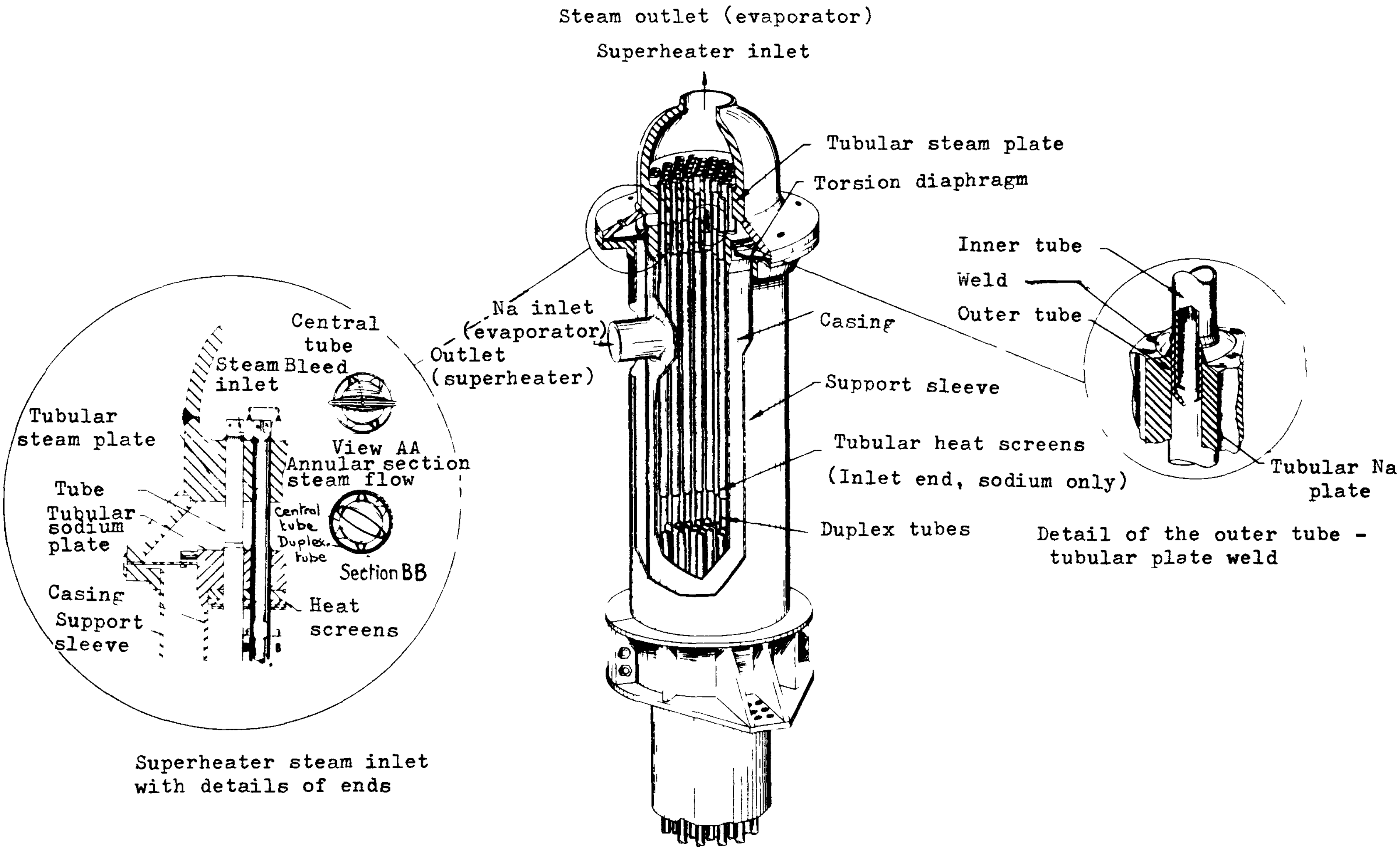
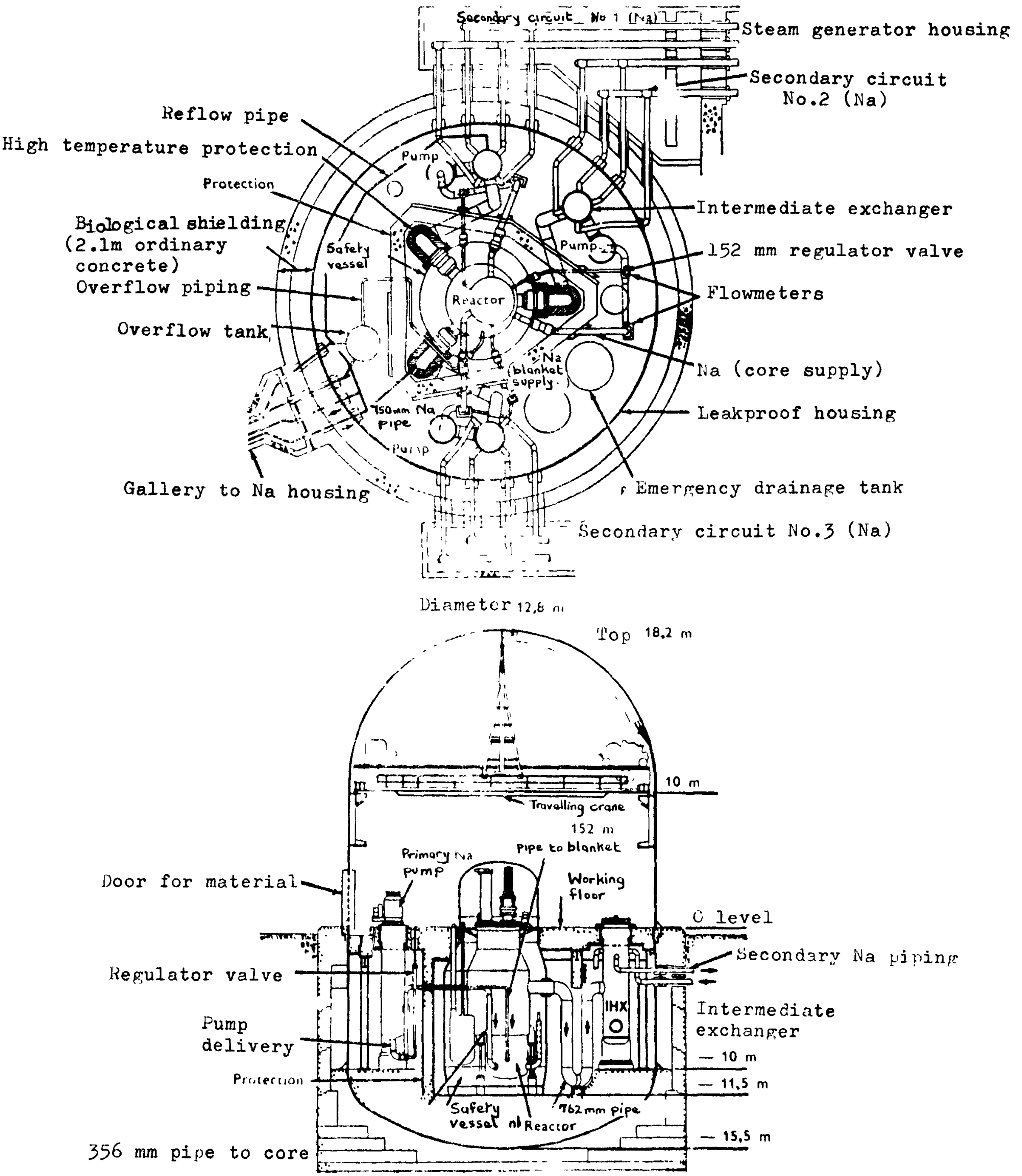


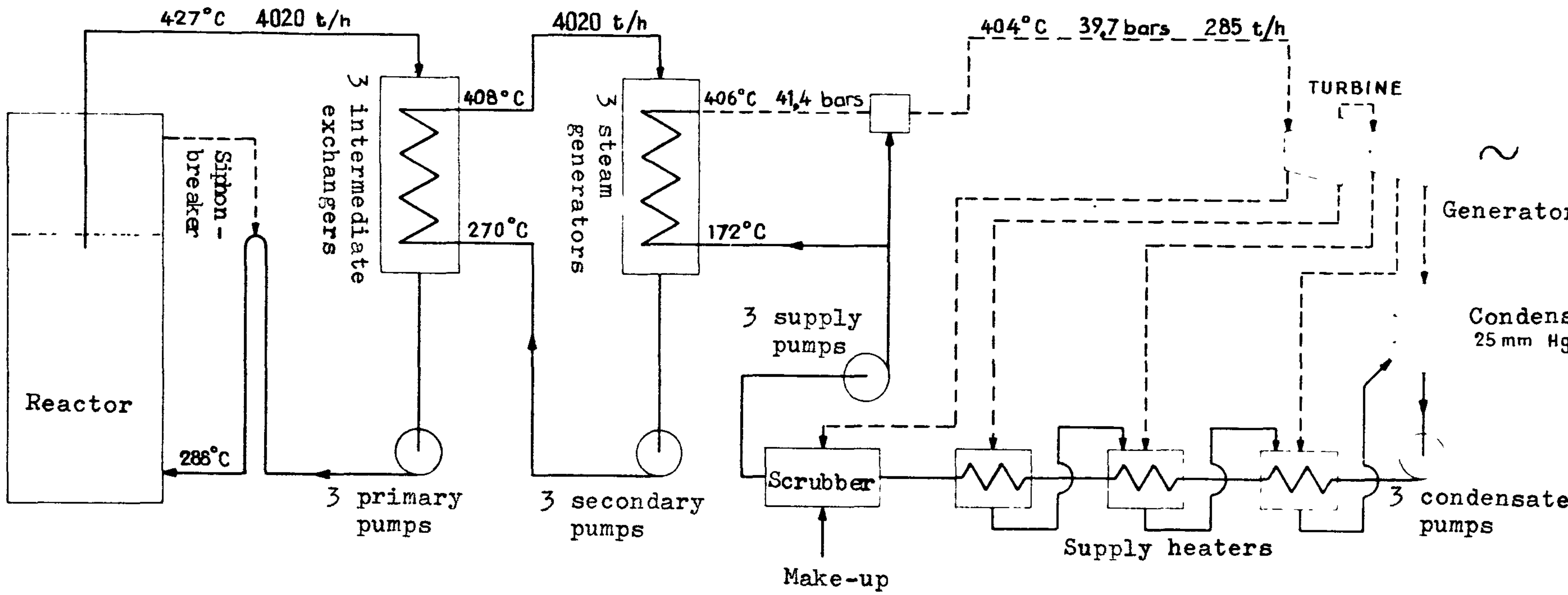
Fig. II 11

EBR II - DETAILS OF THE SUPERHEATER AND EVAPORATOR



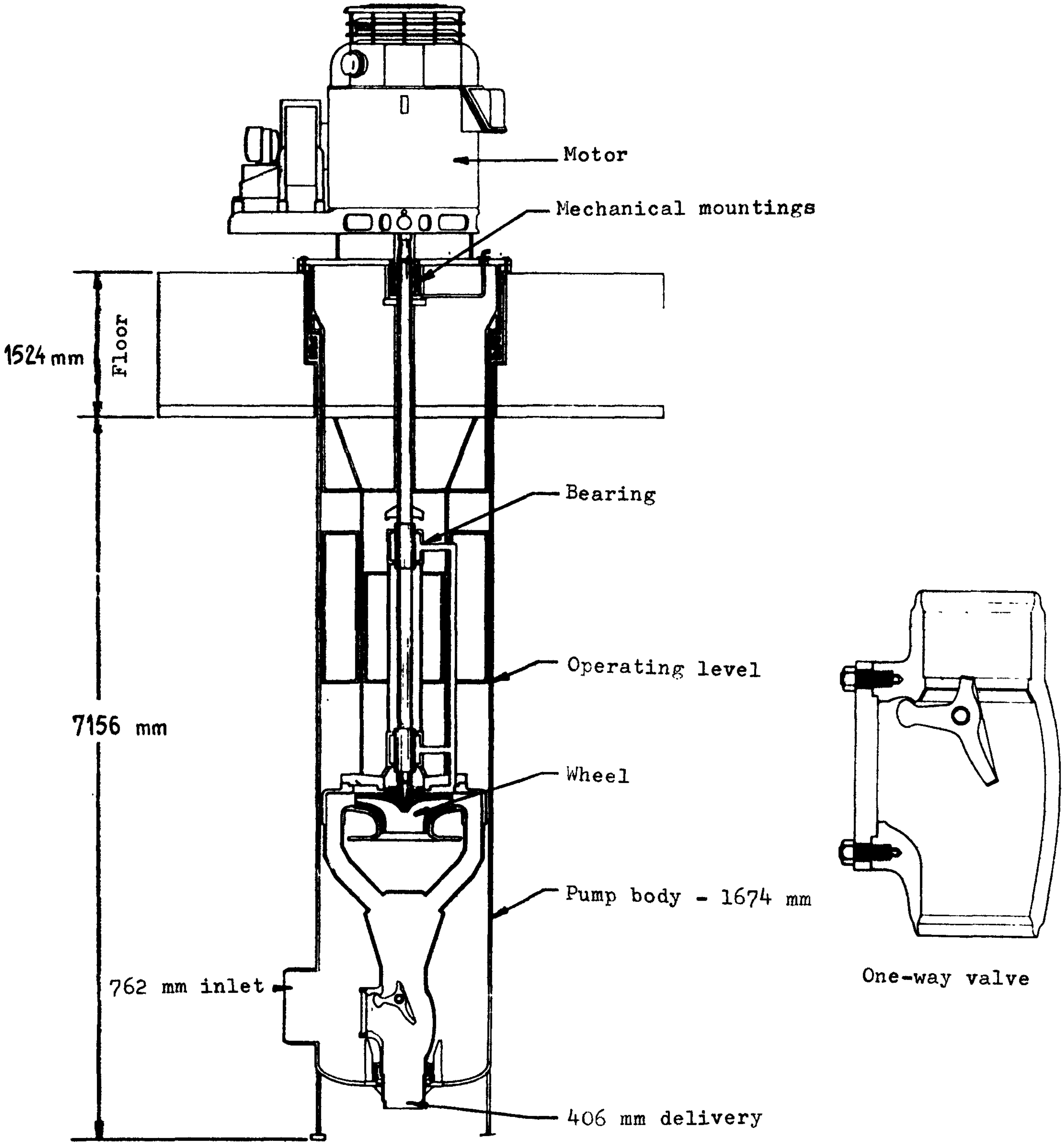
EFFBR — LEAKPROOF HOUSING WITH REACTOR AND PRIMARY SYSTEM

Figure III 1



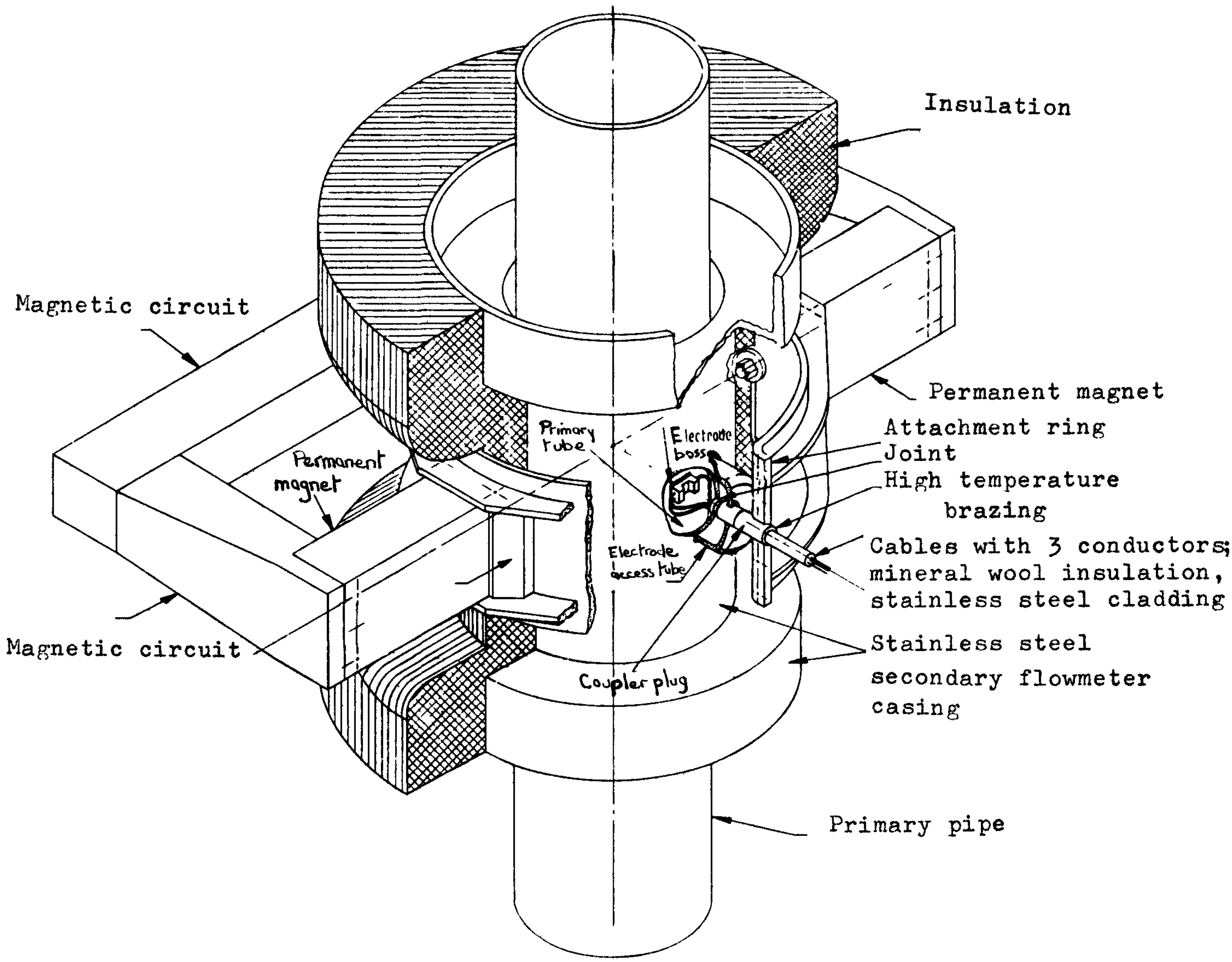
EFFBR _ DIAGRAM OF THE SYSTEMS

Figure III 2



EFFBR - PRIMARY SODIUM PUMP

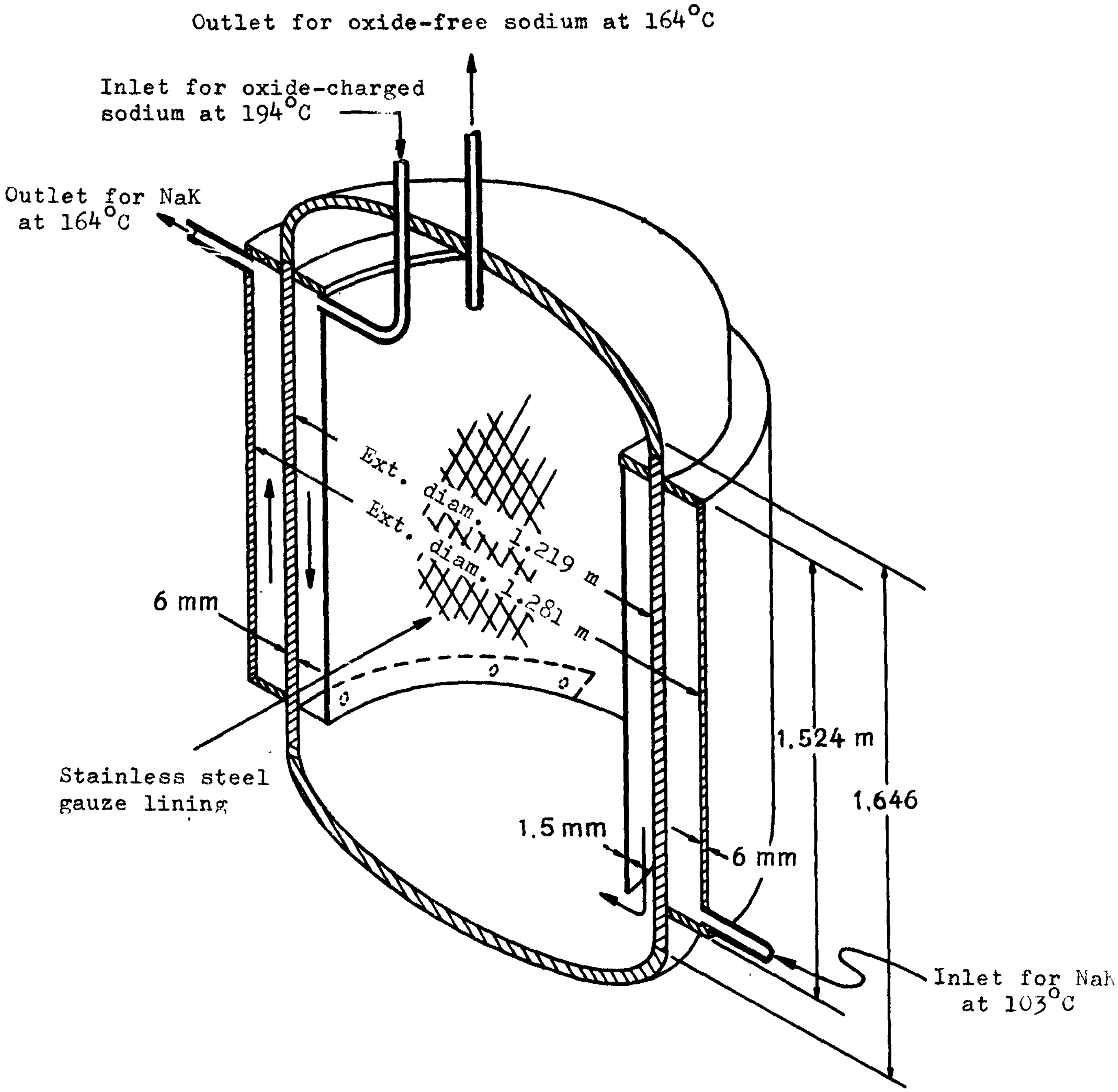
Figure III 3



EFFBR _ MAGNETIC FLOWMETER

Figure III 4

Material used : 304 stainless steel



EFFBR – COLD TRAP

Figure III 5

EFFBR - FOULING INDICATOR

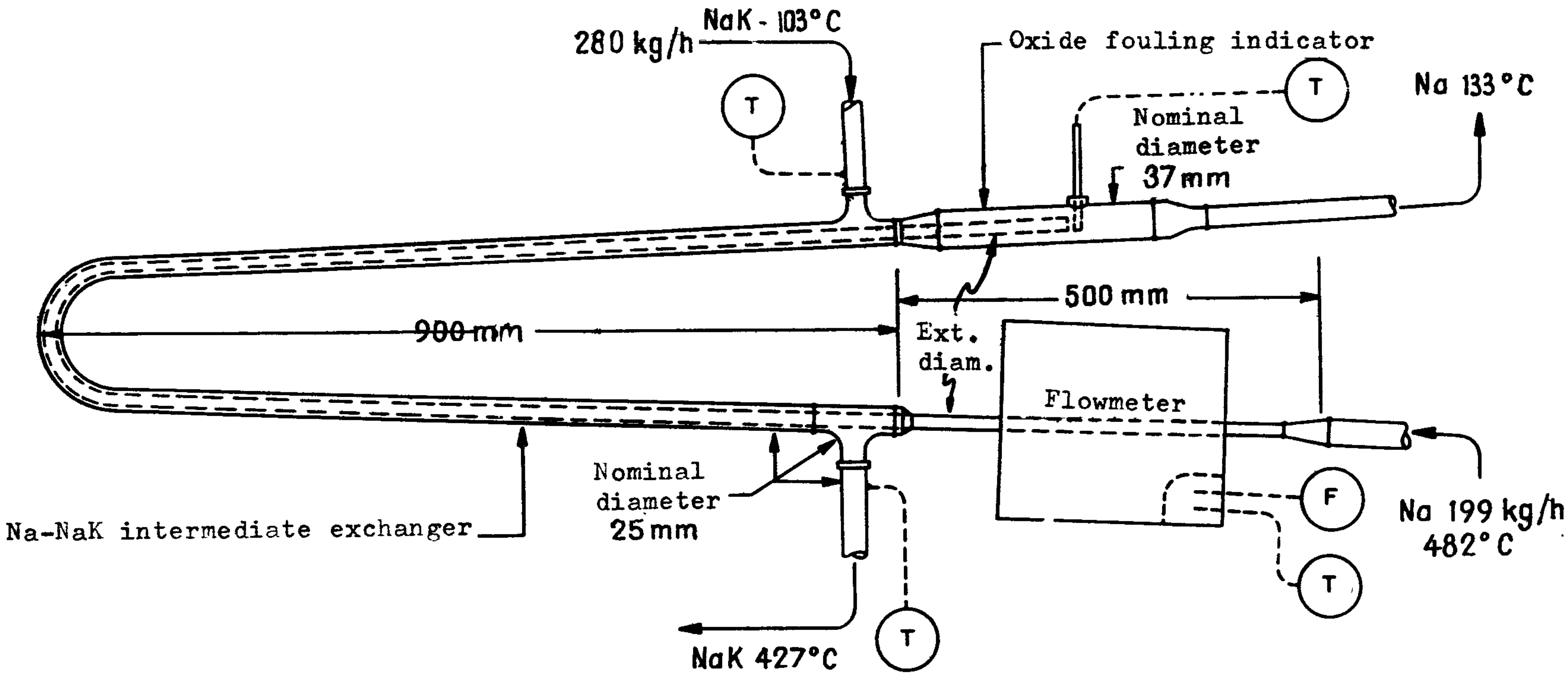


Figure III 6

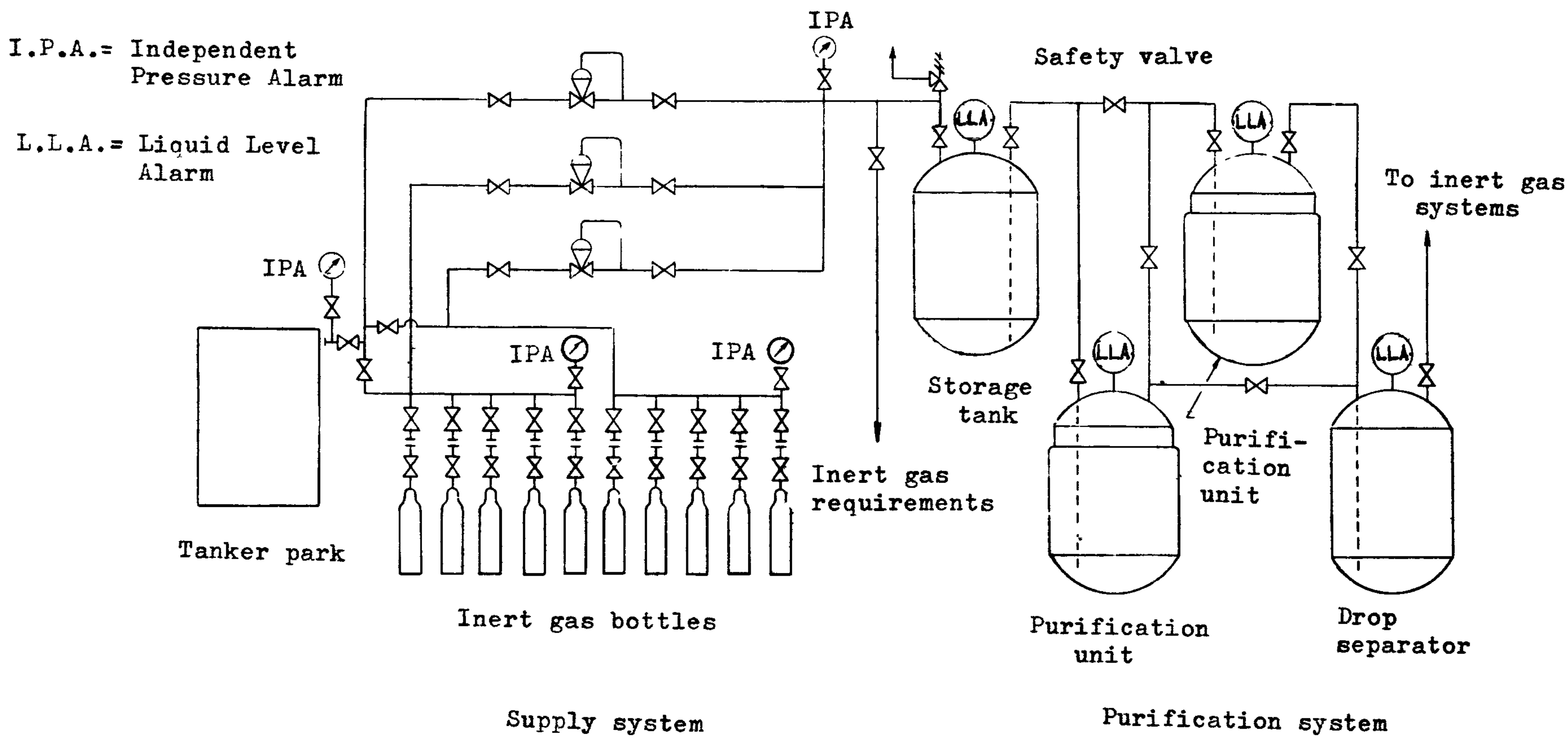


Figure III 7

EFFBR - INERT GAS SUPPLY SYSTEM

EFFBR - INTERMEDIATE EXCHANGER

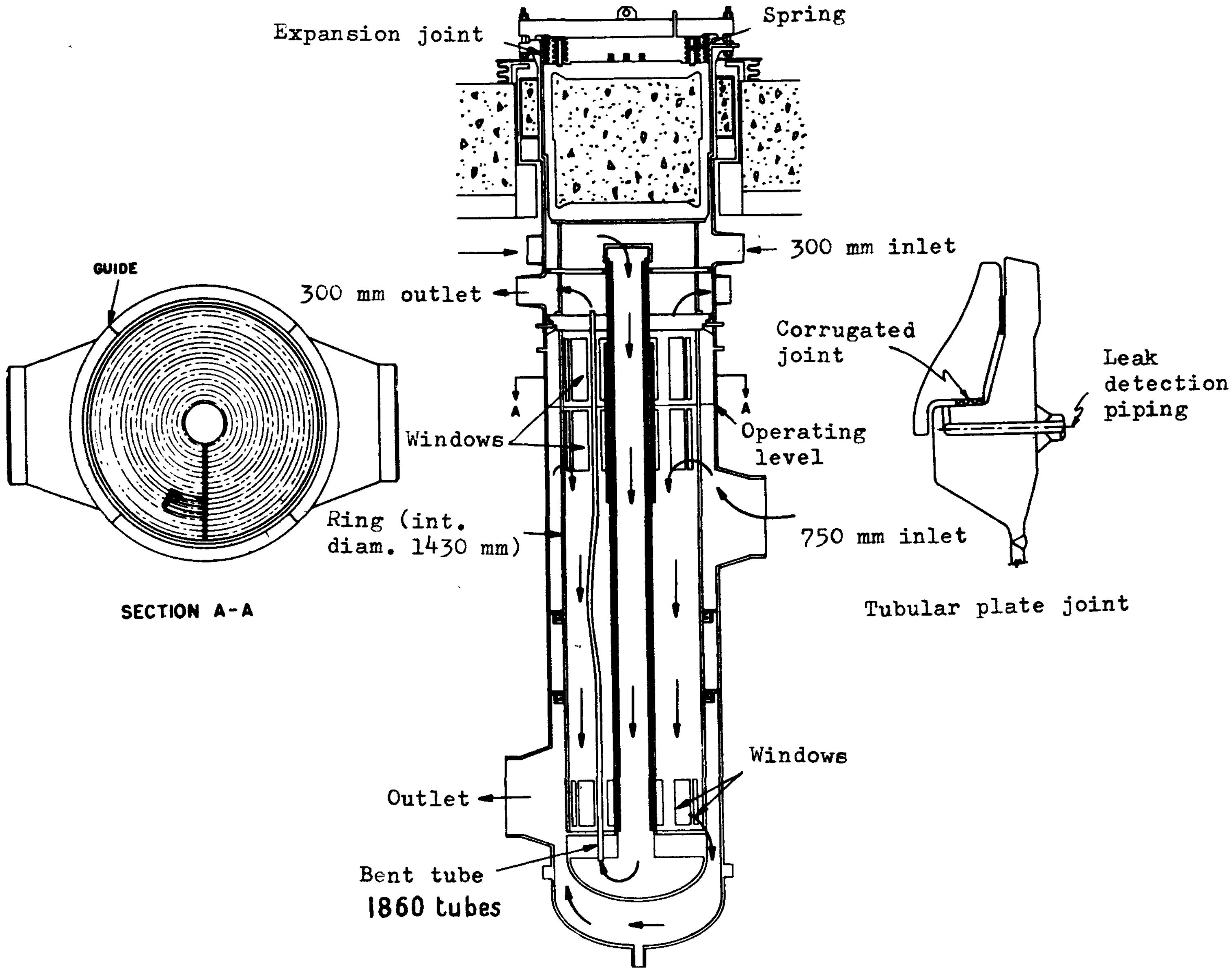
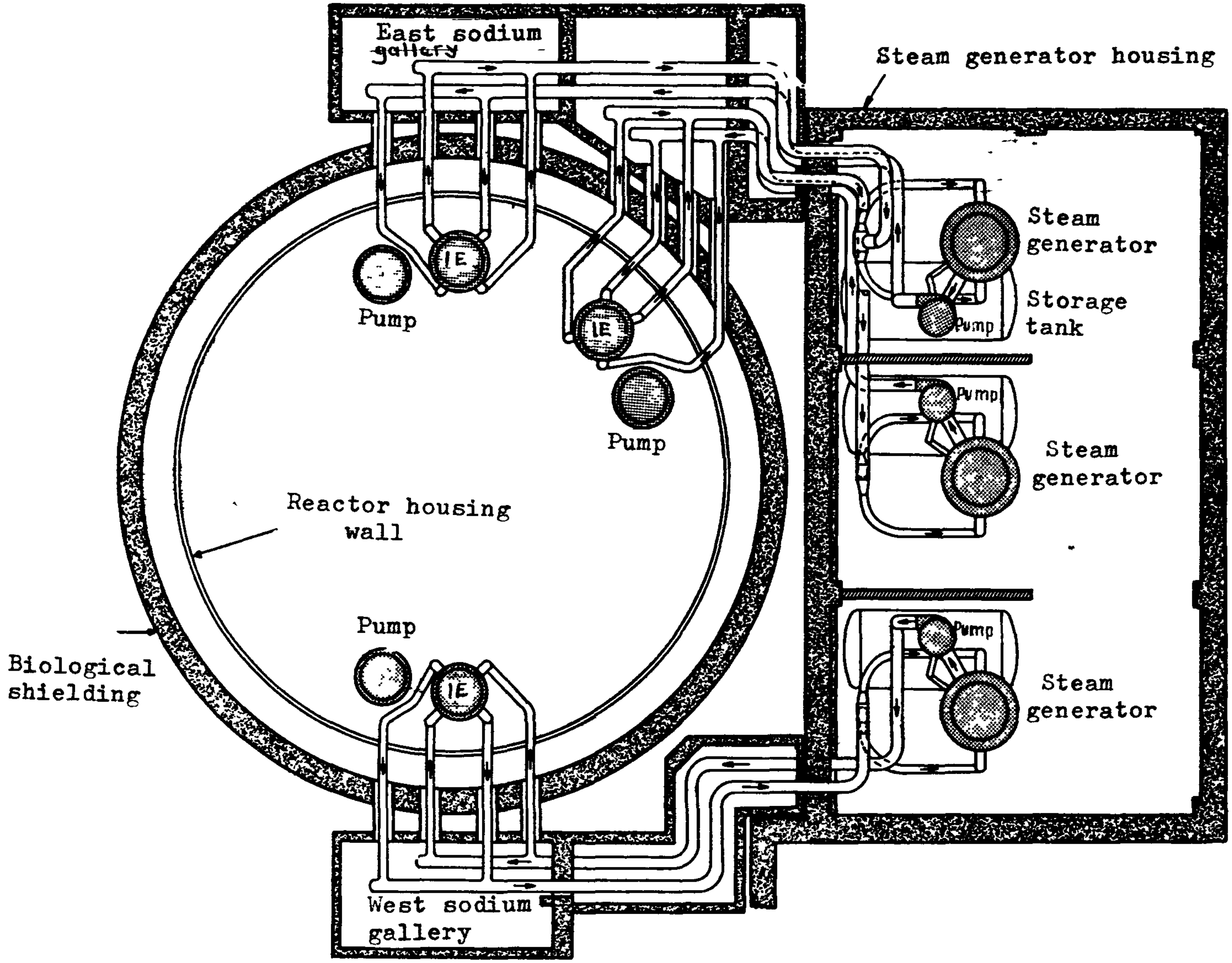
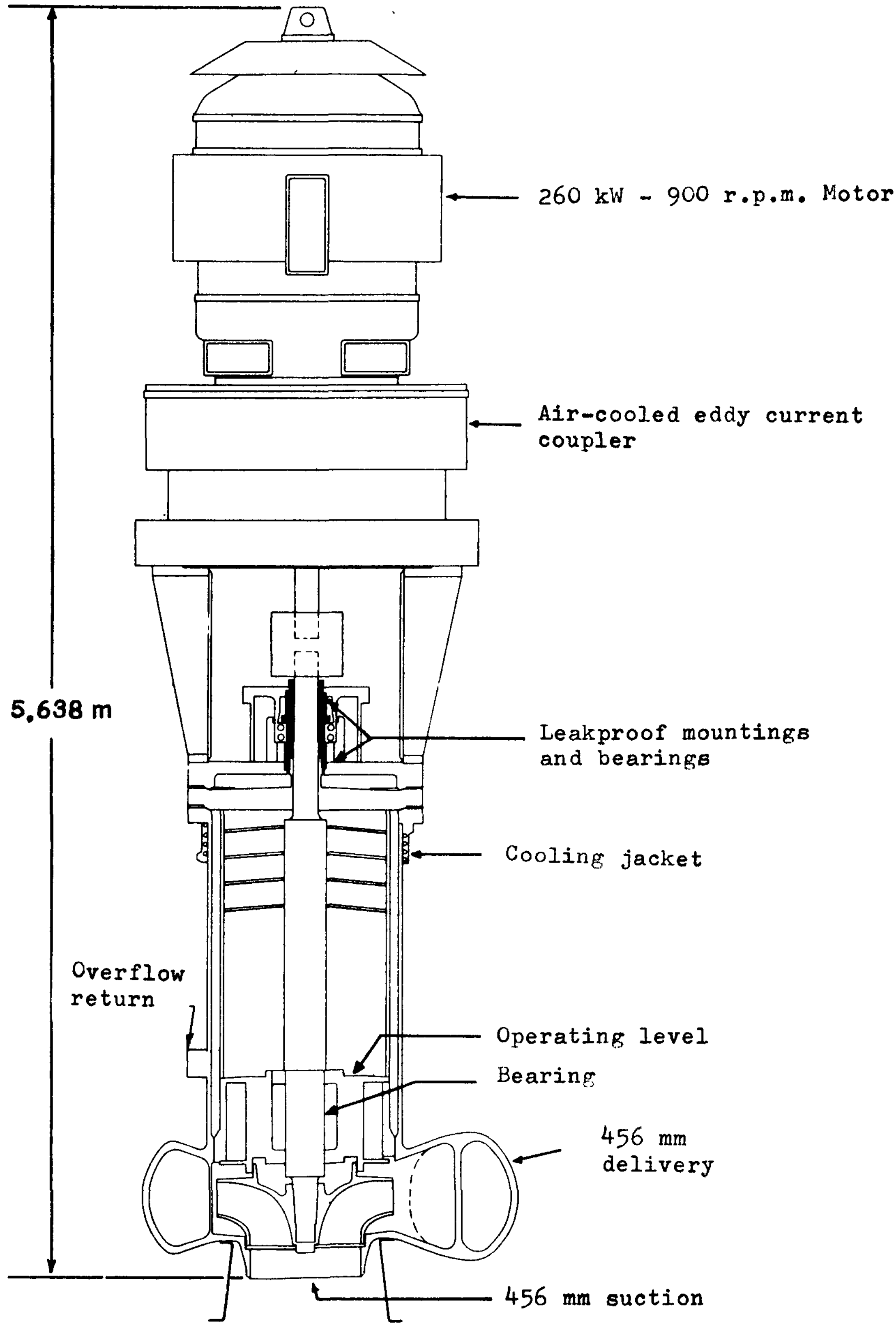


Figure III 8



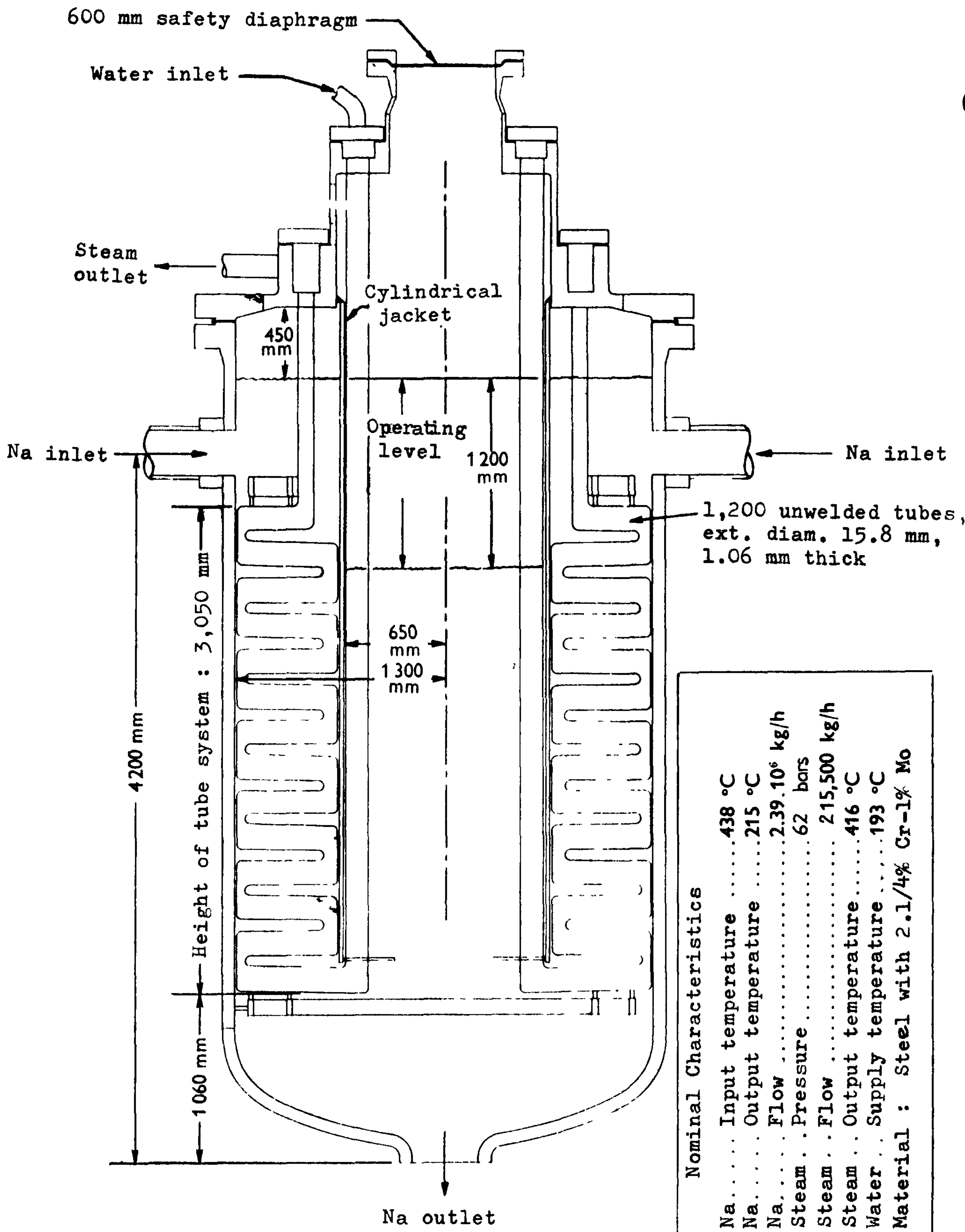
EFFBR – SECONDARY COOLING SYSTEM

Figure III 9



EFFBR _ SECONDARY SODIUM PUMP

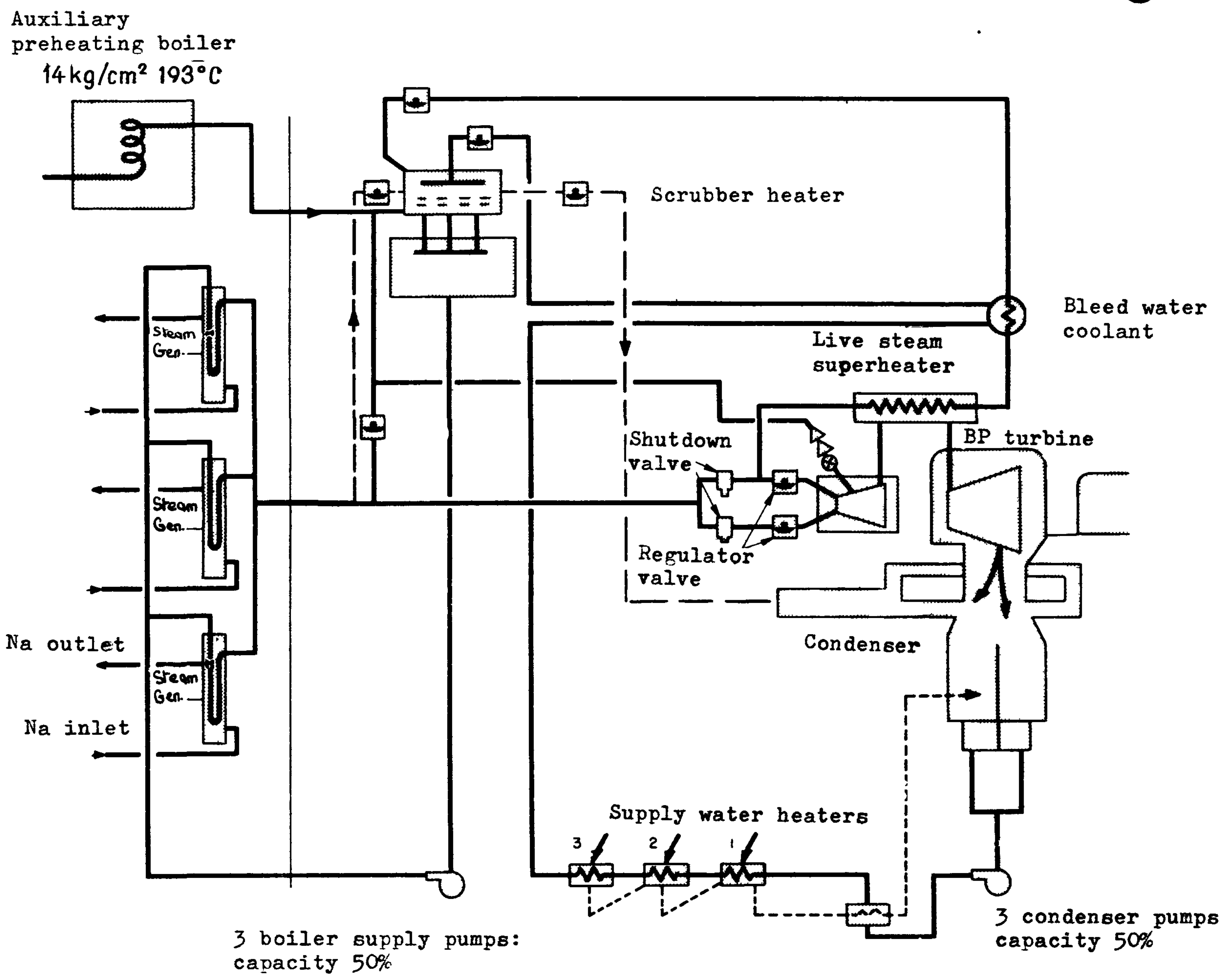
Figure III 10



Nominal Characteristics		
Na	Input temperature	438 °C
Na	Output temperature	215 °C
Na	Flow	$2.39.10^6$ kg/h
Steam	Pressure	62 bars
Steam	Flow	215,500 kg/h
Steam	Output temperature	416 °C
Water	Supply temperature	193 °C
Material :	Steel with 2.1/4% Cr-1% Mo	

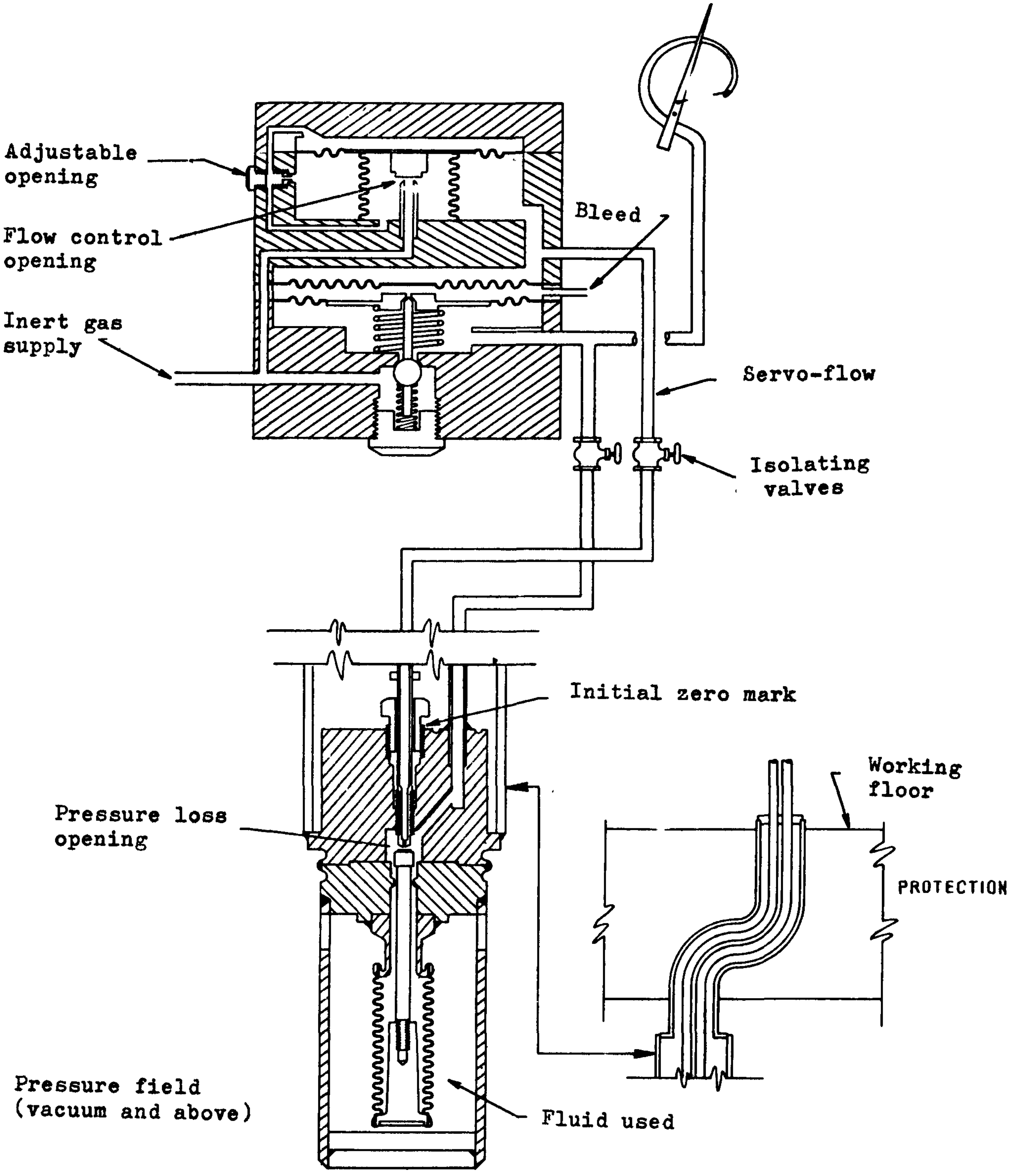
EFFBR – STEAM GENERATOR

Figure III 11



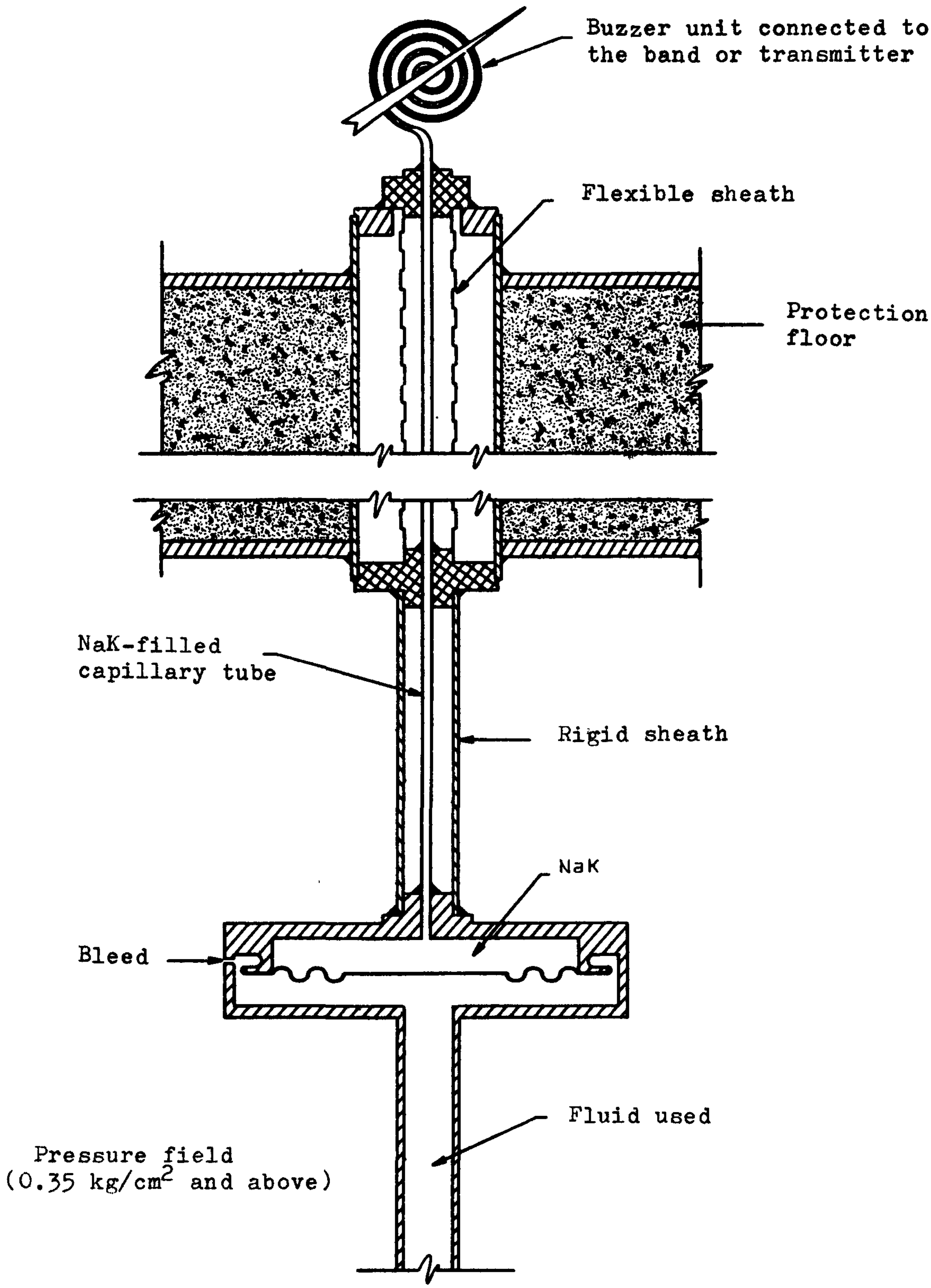
EFFBR - DIAGRAM OF THE STEAM SYSTEM

Figure III 12



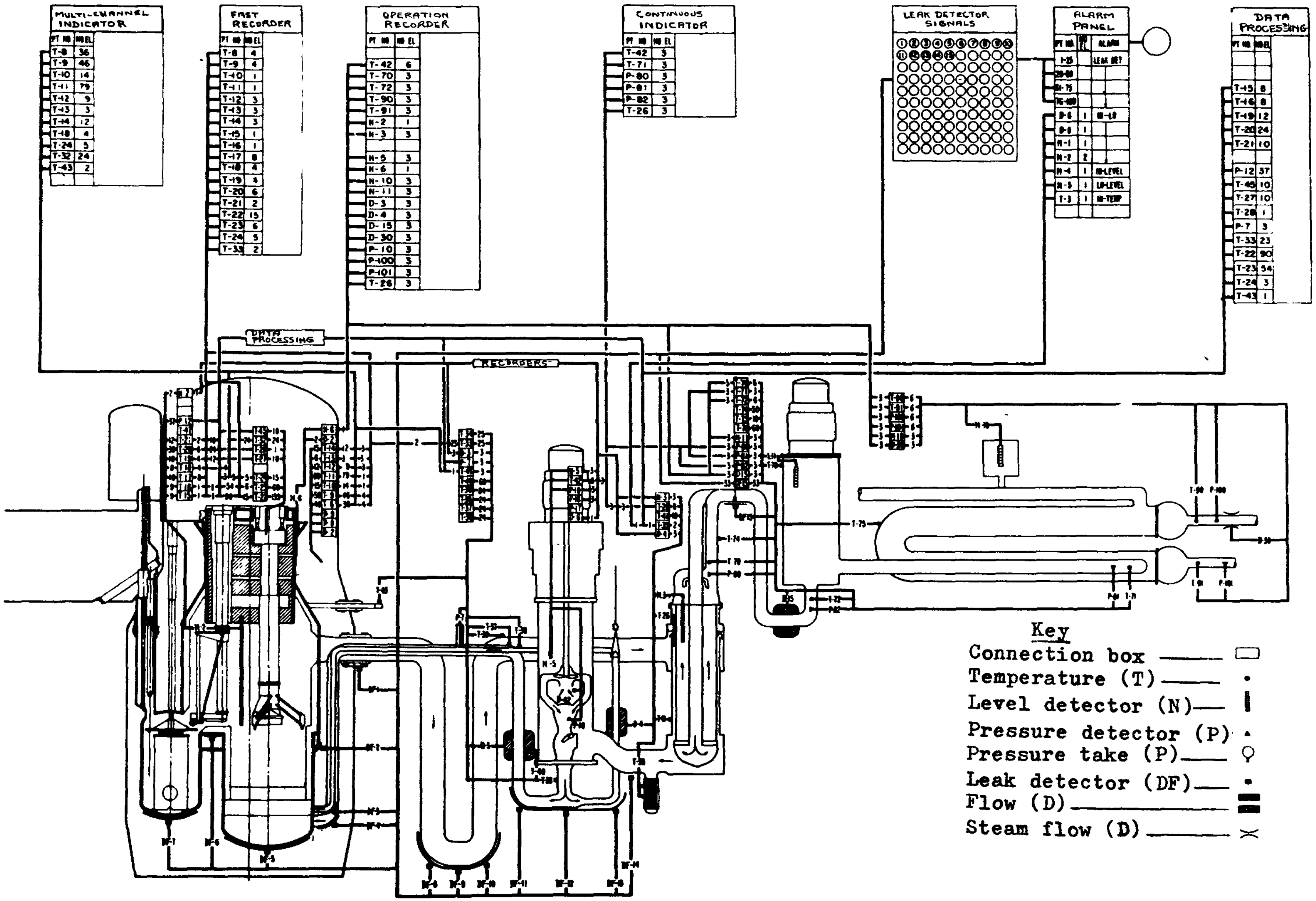
EFFBR – PRESSURE PICK-OFF WITH PNEUMATIC RECOPIER

Figure III 13



EFFBR – NaK-FILLED HIGH TEMPERATURE PRESSURE PICK-OFF

Figure III 14



EFFBR _ POSITIONS OF THE MEASUREMENT AND CONTROL APPARATUS

Figure III 15

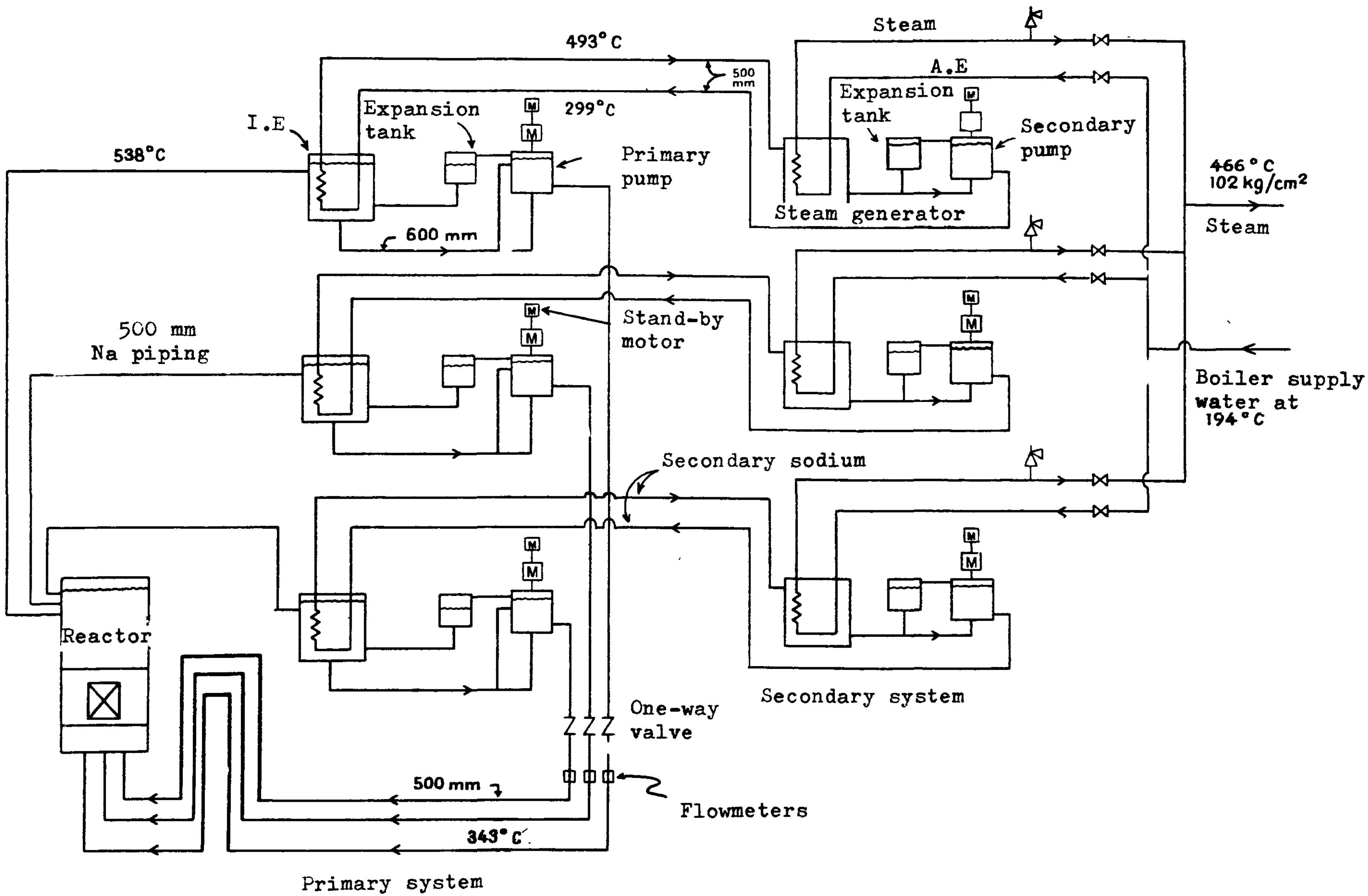
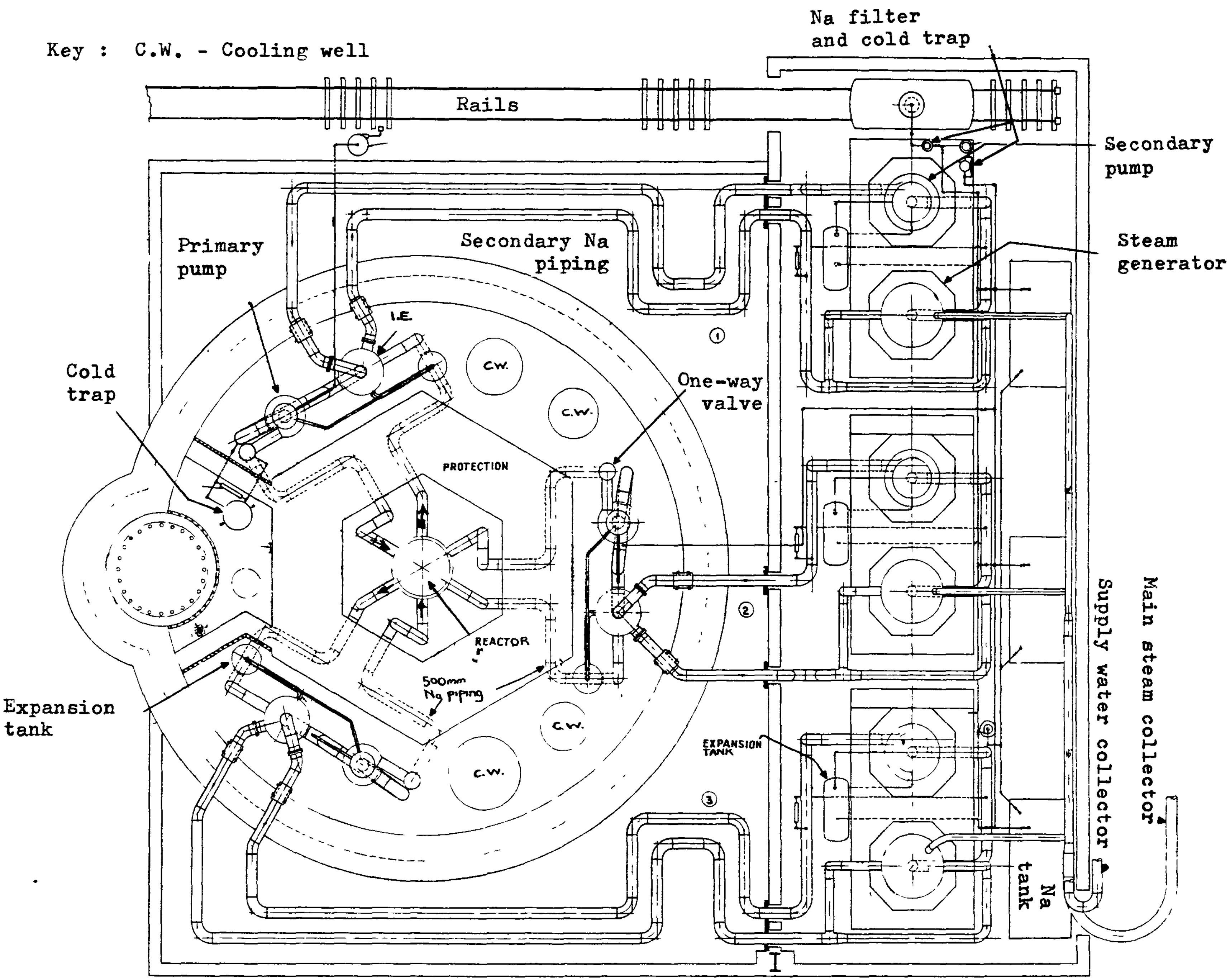


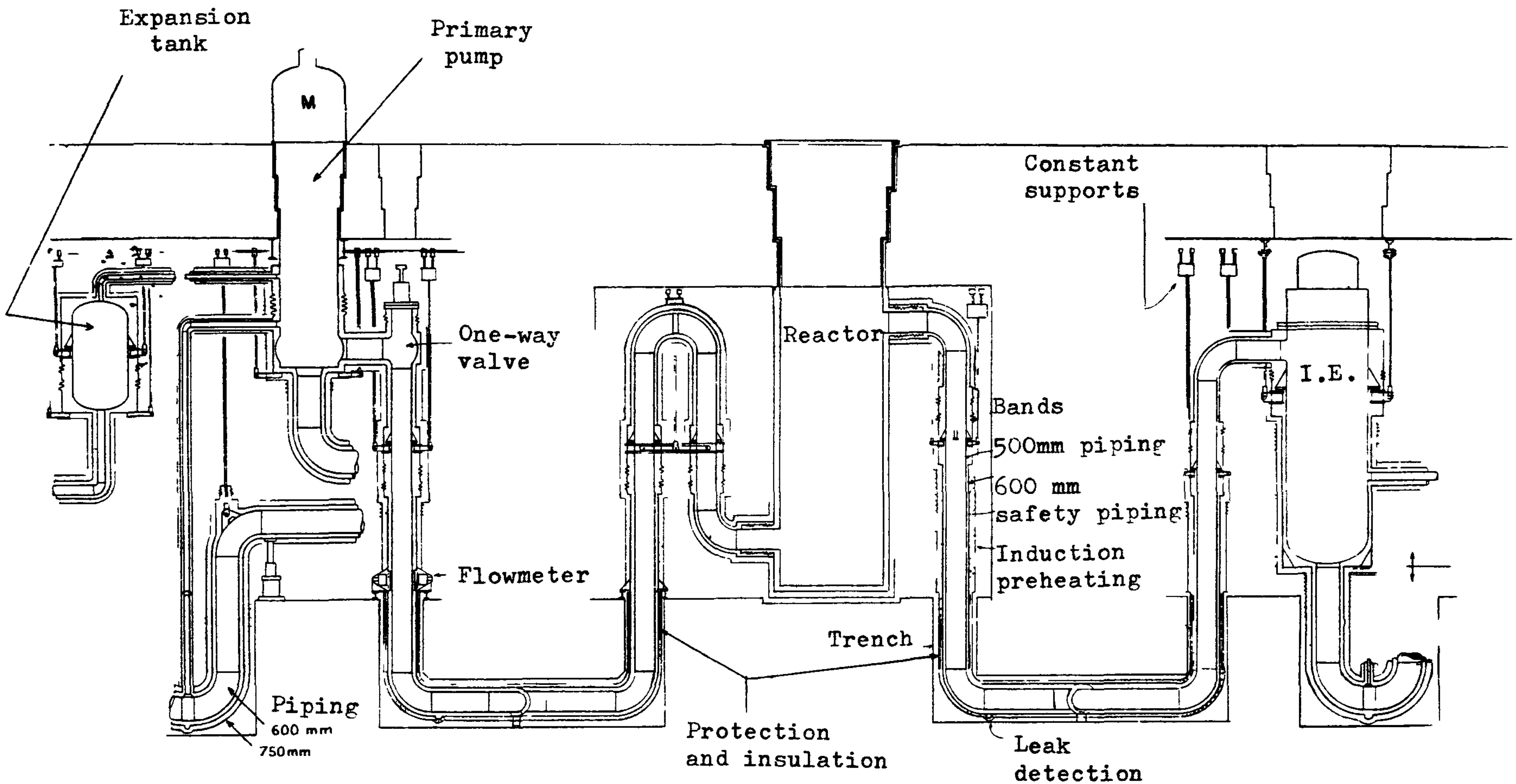
Figure IV 1

PFFBR_ DIAGRAM OF THE PRIMARY AND SECONDARY Na SYSTEMS



PFFBR – LAYOUT OF THE PRIMARY AND SECONDARY SYSTEMS

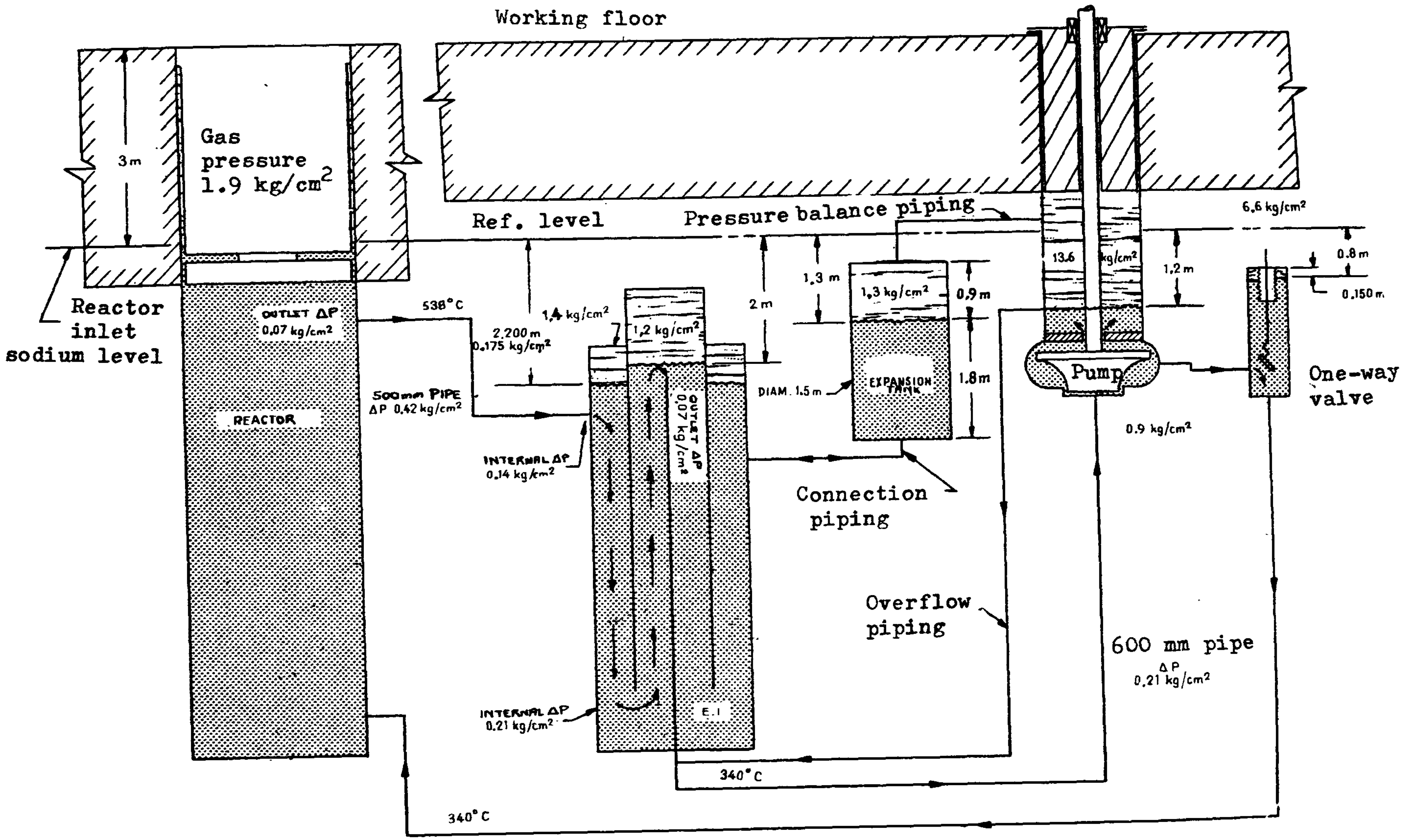
Figure IX 2



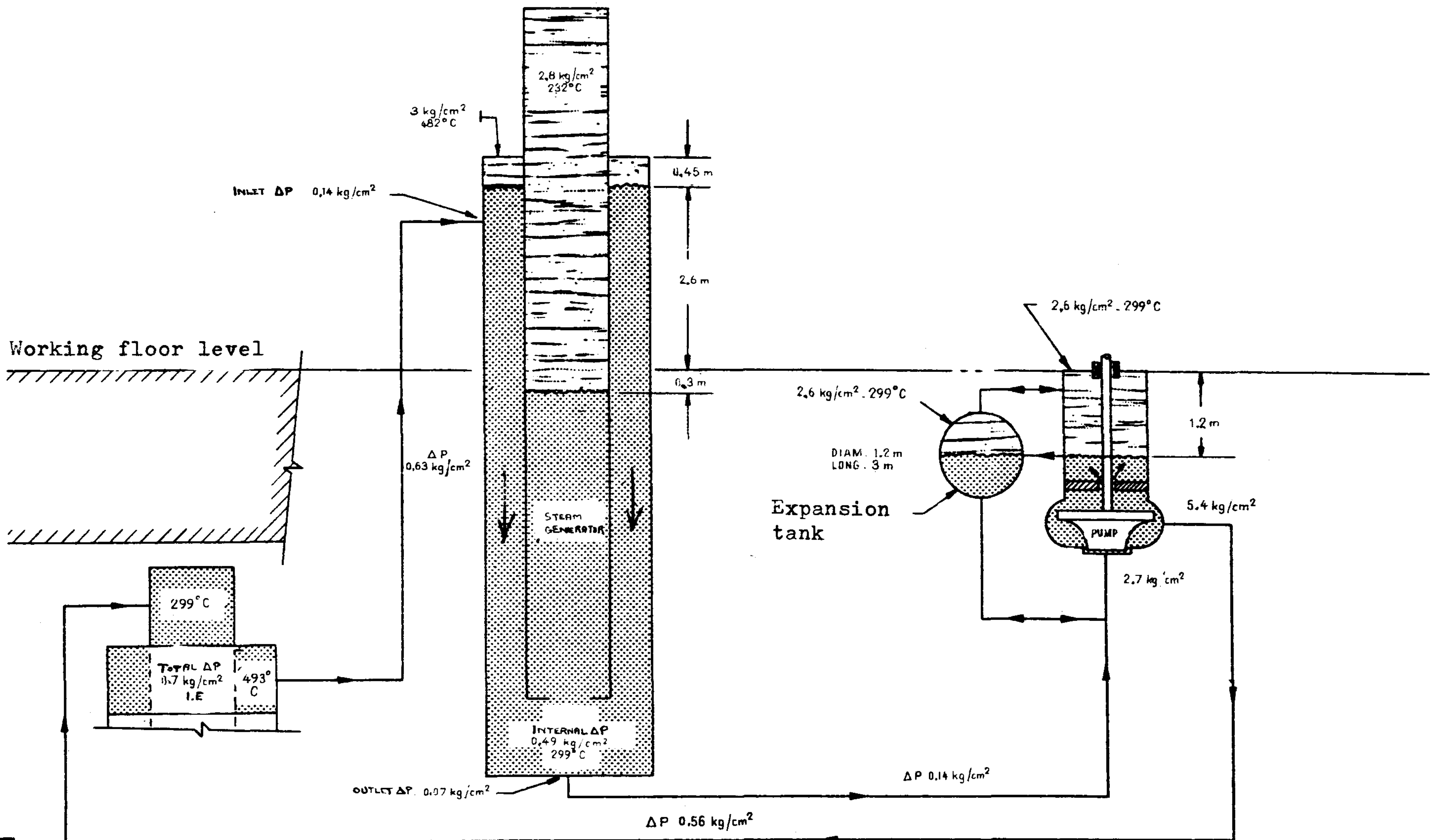
P F F B R _ PRIMARY PIPING AND TANK

Figure IV 3

Figure IV 4

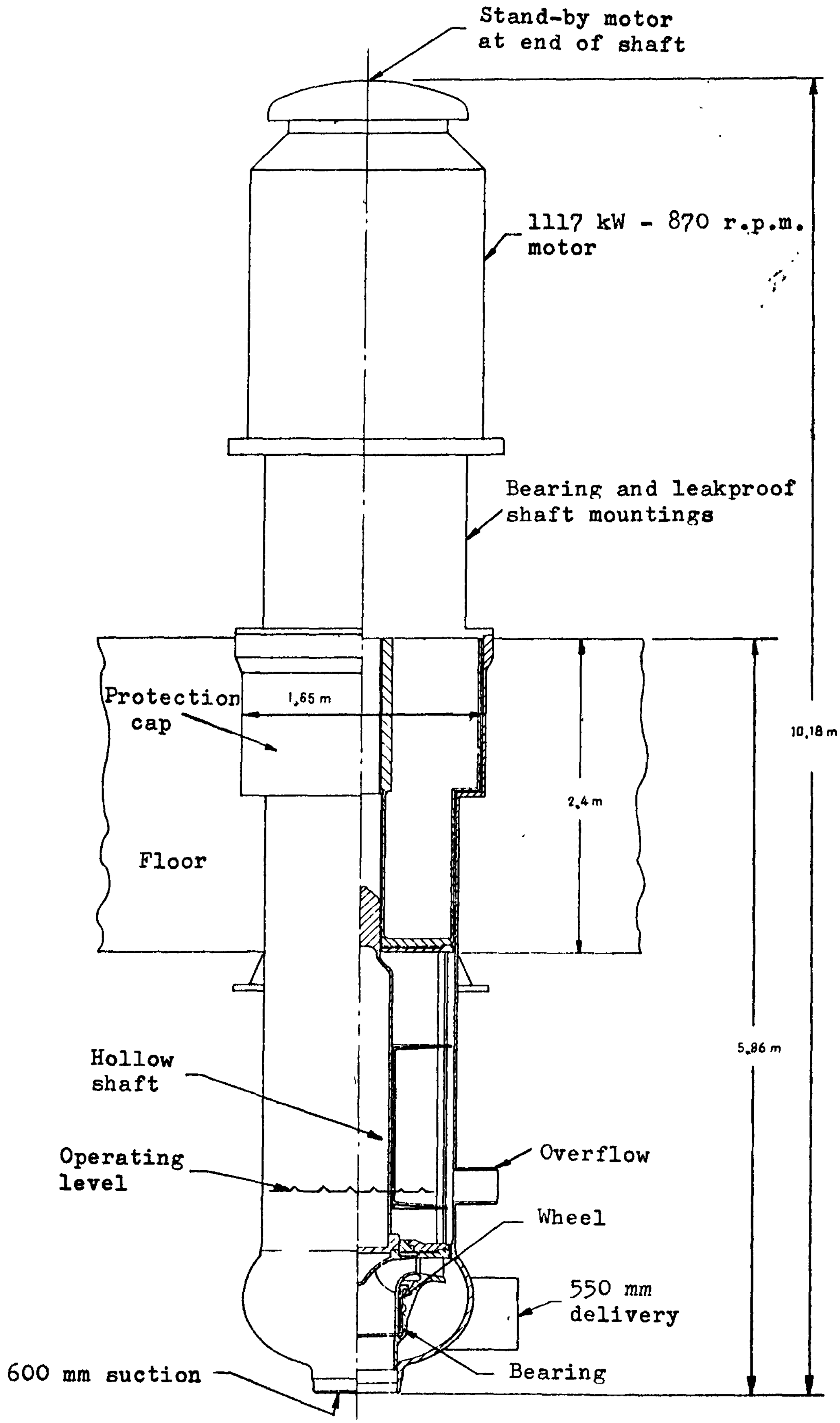


PFFBR _ DIAGRAM OF THE PRIMARY GAS SYSTEM



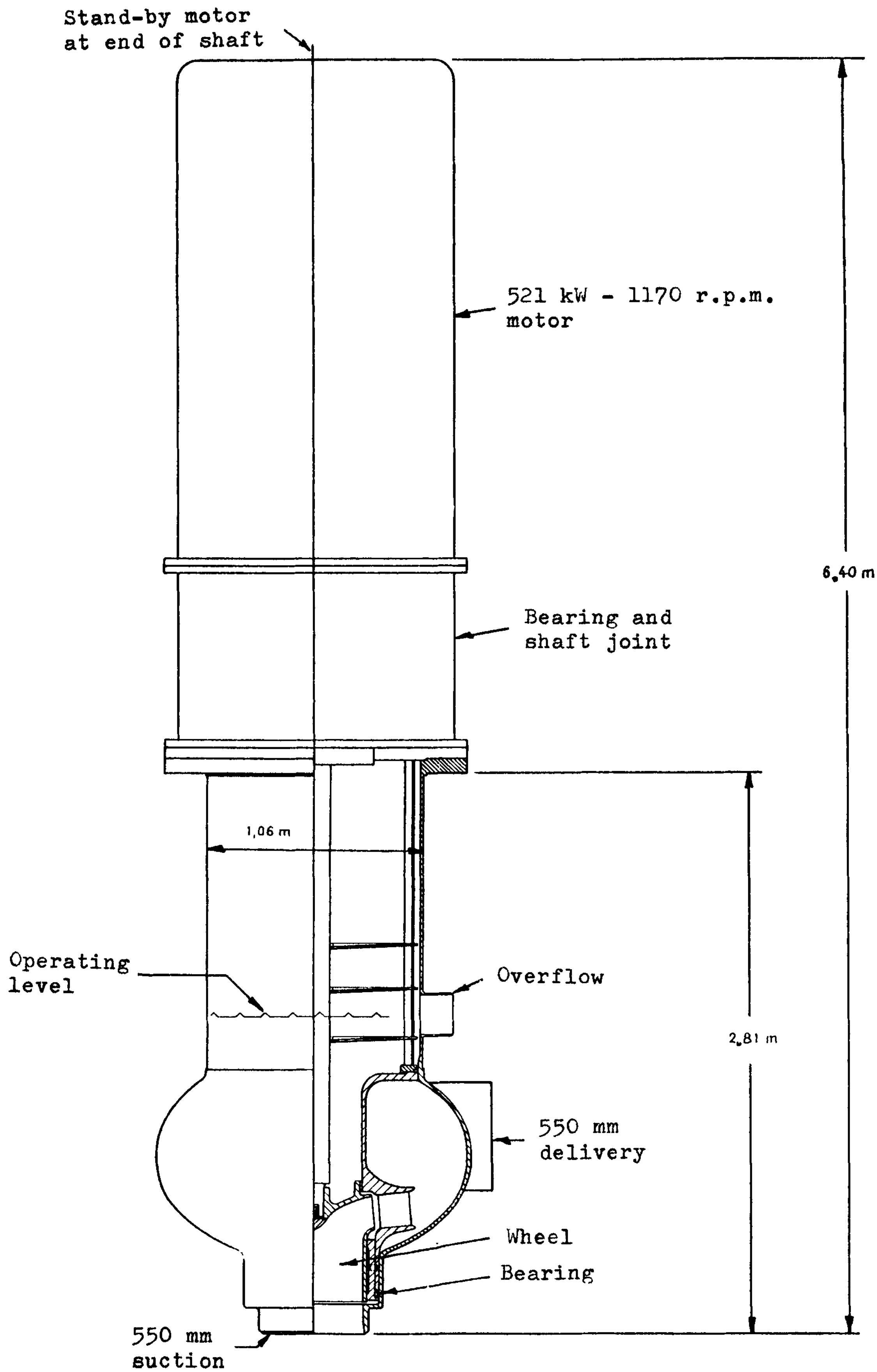
PFFBR – DIAGRAM OF THE SECONDARY GAS SYSTEM

Figure IV 5



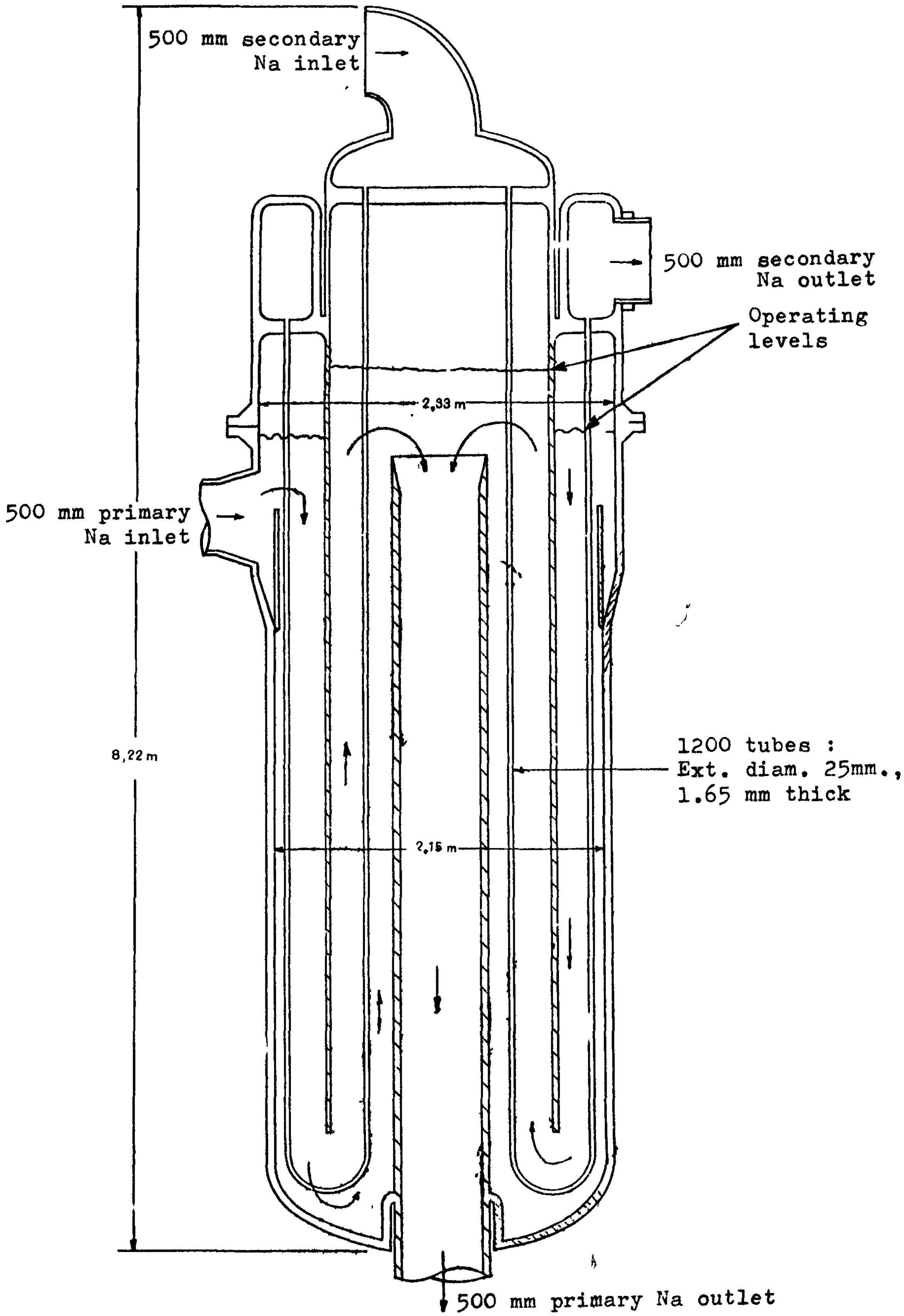
PFFBR - PRIMARY Na PUMP

Figure IV 6



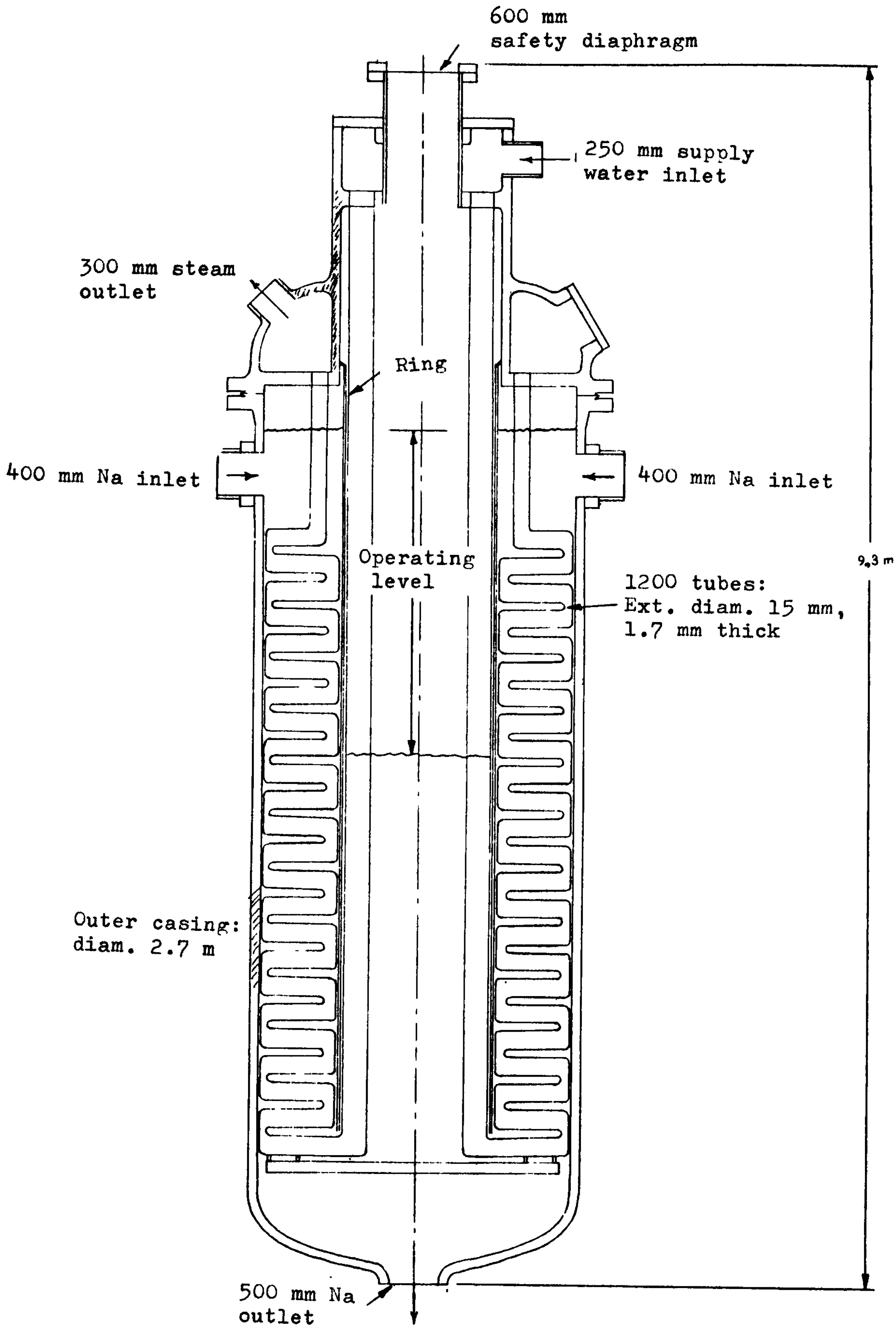
P F F B R _ SECONDARY Na PUMP

Figure IV 7



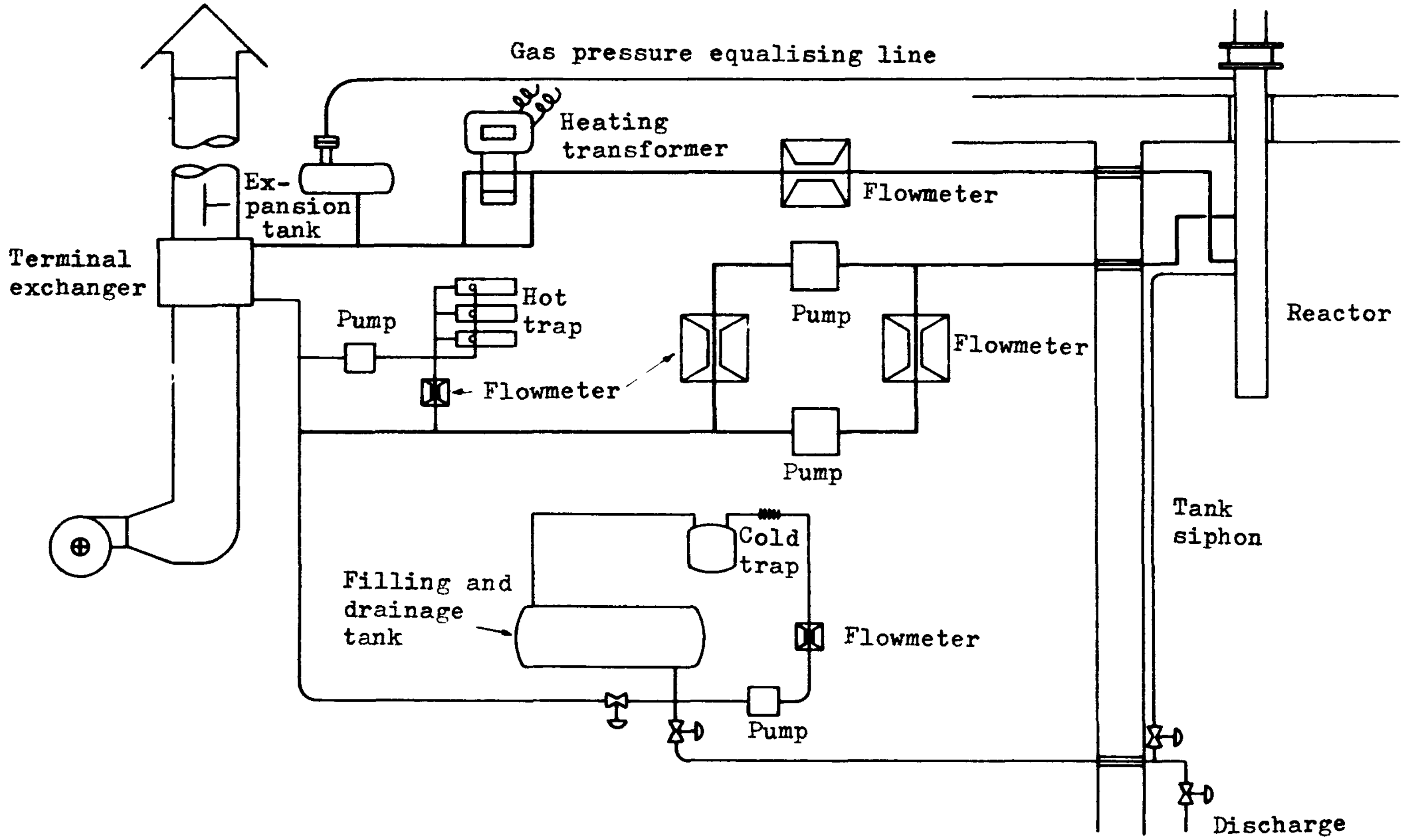
PFFBR – INTERMEDIATE EXCHANGER

Figure IVa



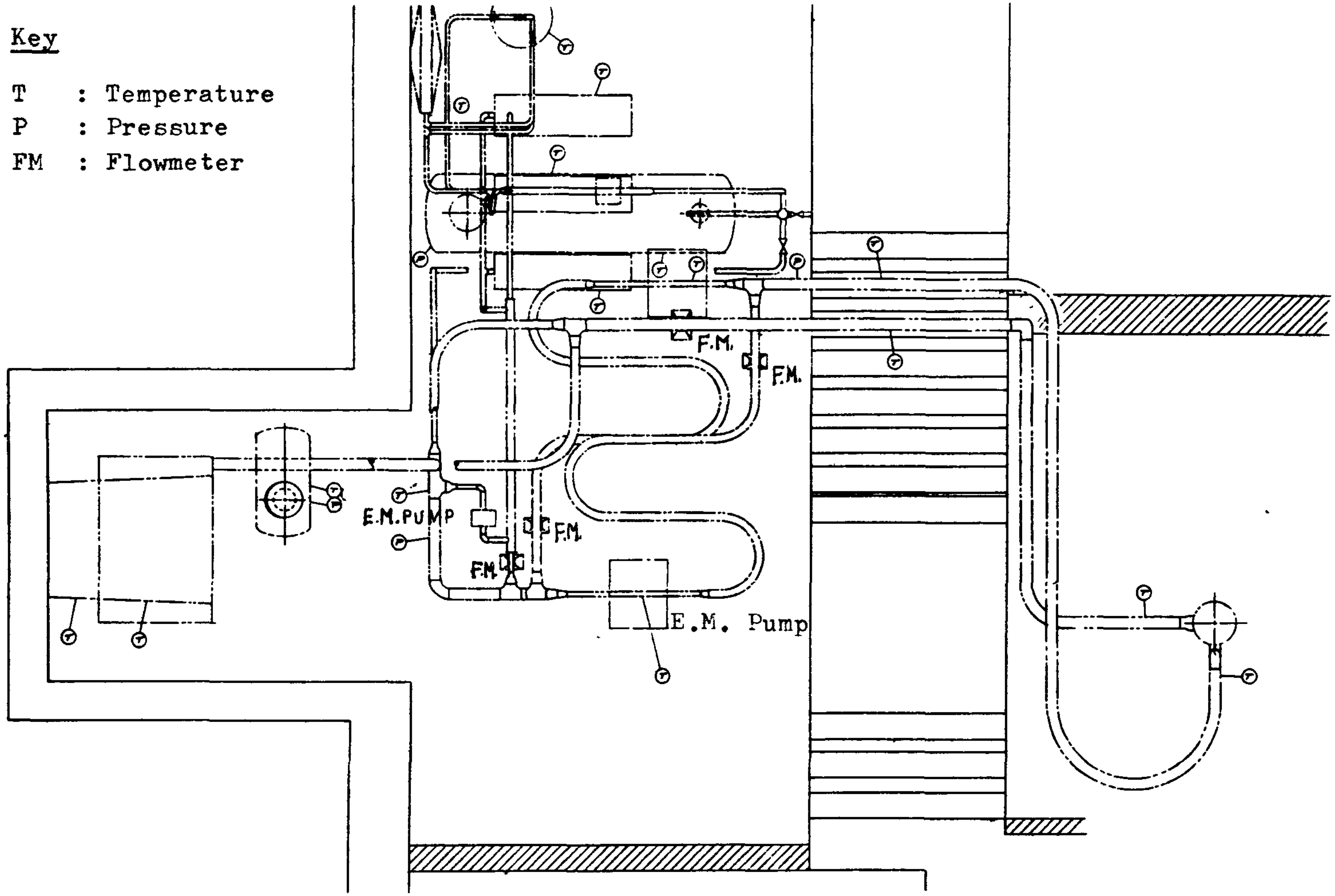
PFFBR _ STEAM GENERATOR (260 MW Th)

Figure IV 9



LAMPRE _ DIAGRAM OF THE SODIUM SYSTEM

Figure V 1



LAMPRE – LAYOUT OF THE SODIUM SYSTEM SHOWING POSITIONS OF THE MEASUREMENT AND CONTROL APPARATUS.

Figure V 2

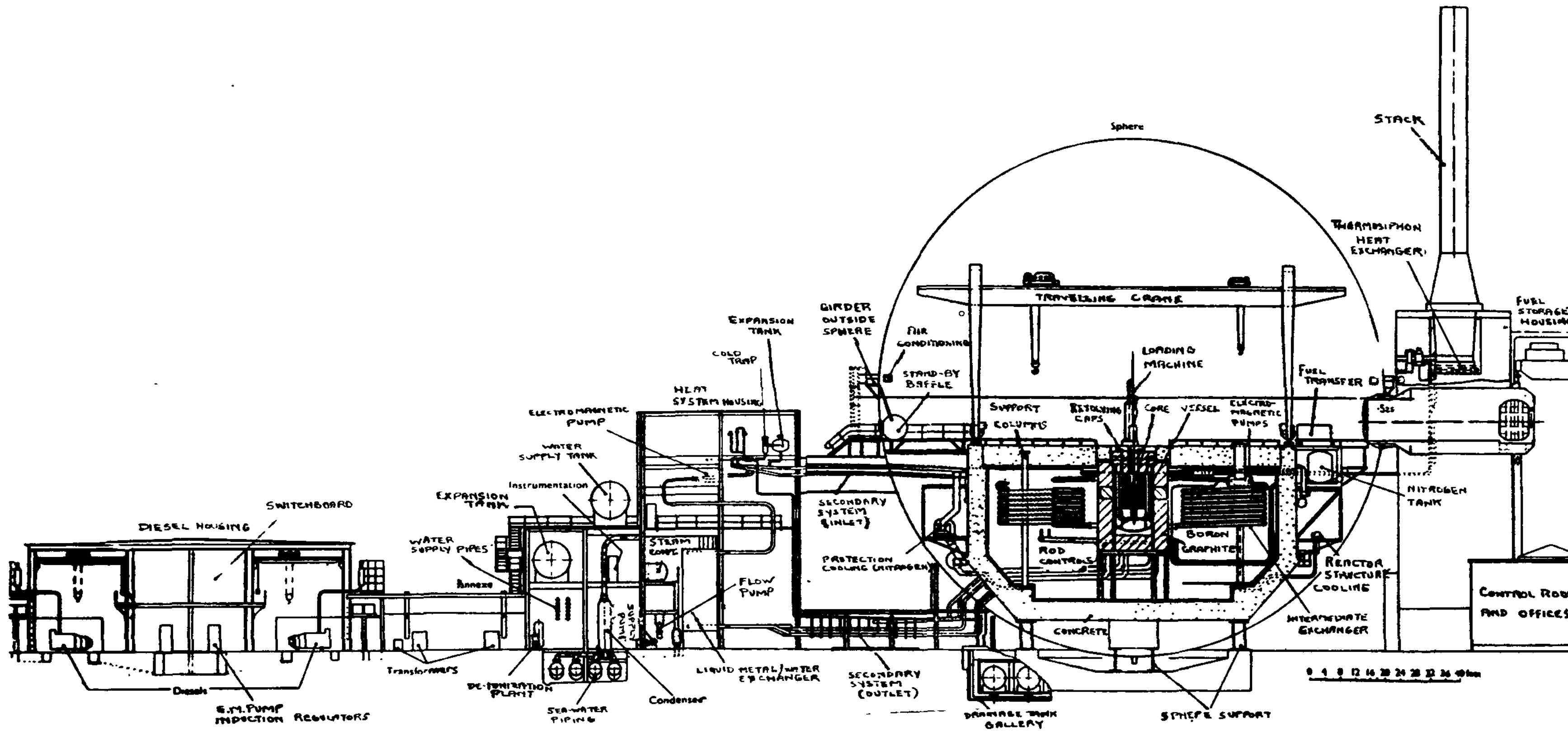
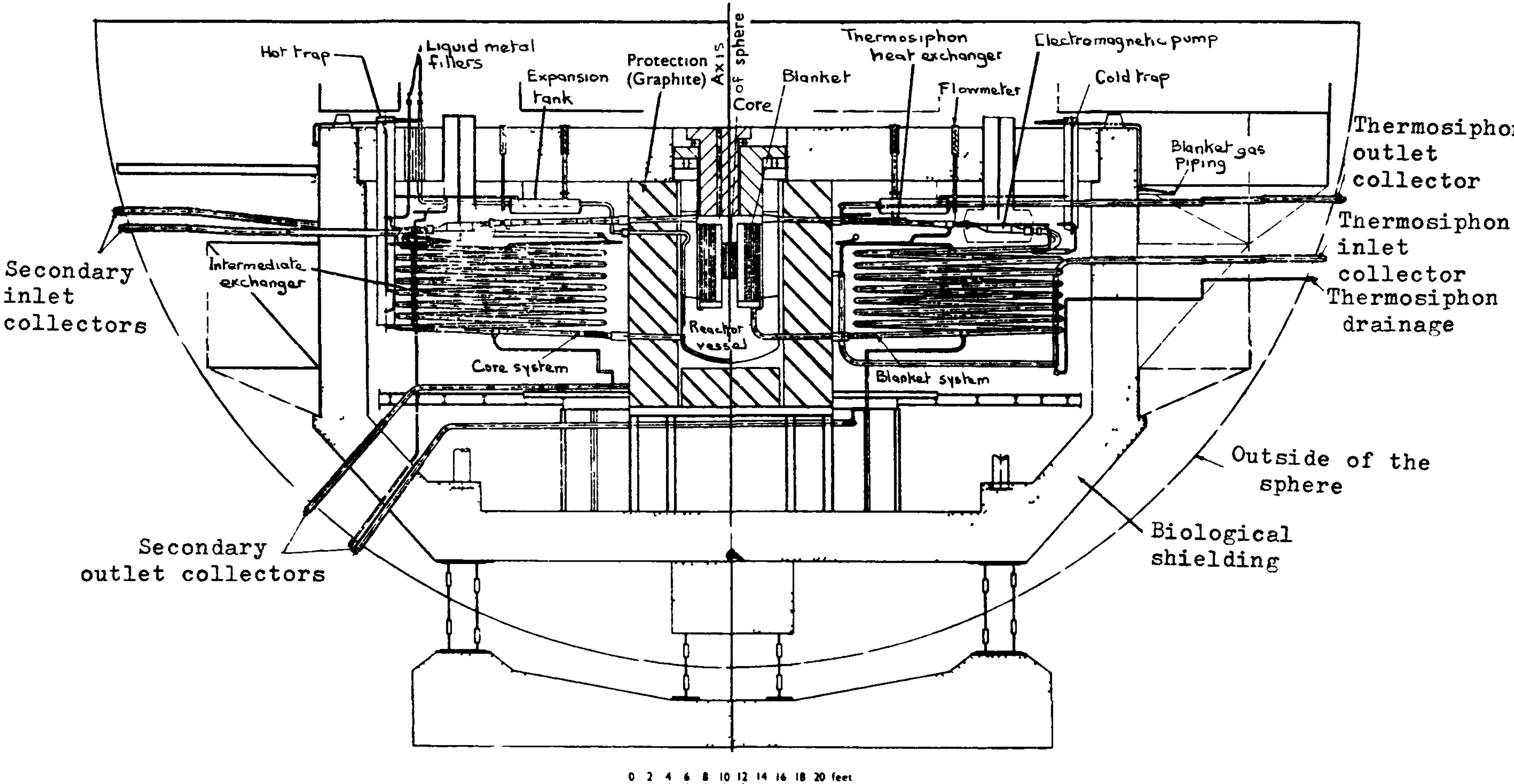


Fig. 33 - Dounreay Fast Reactor - Overall layout of the plant

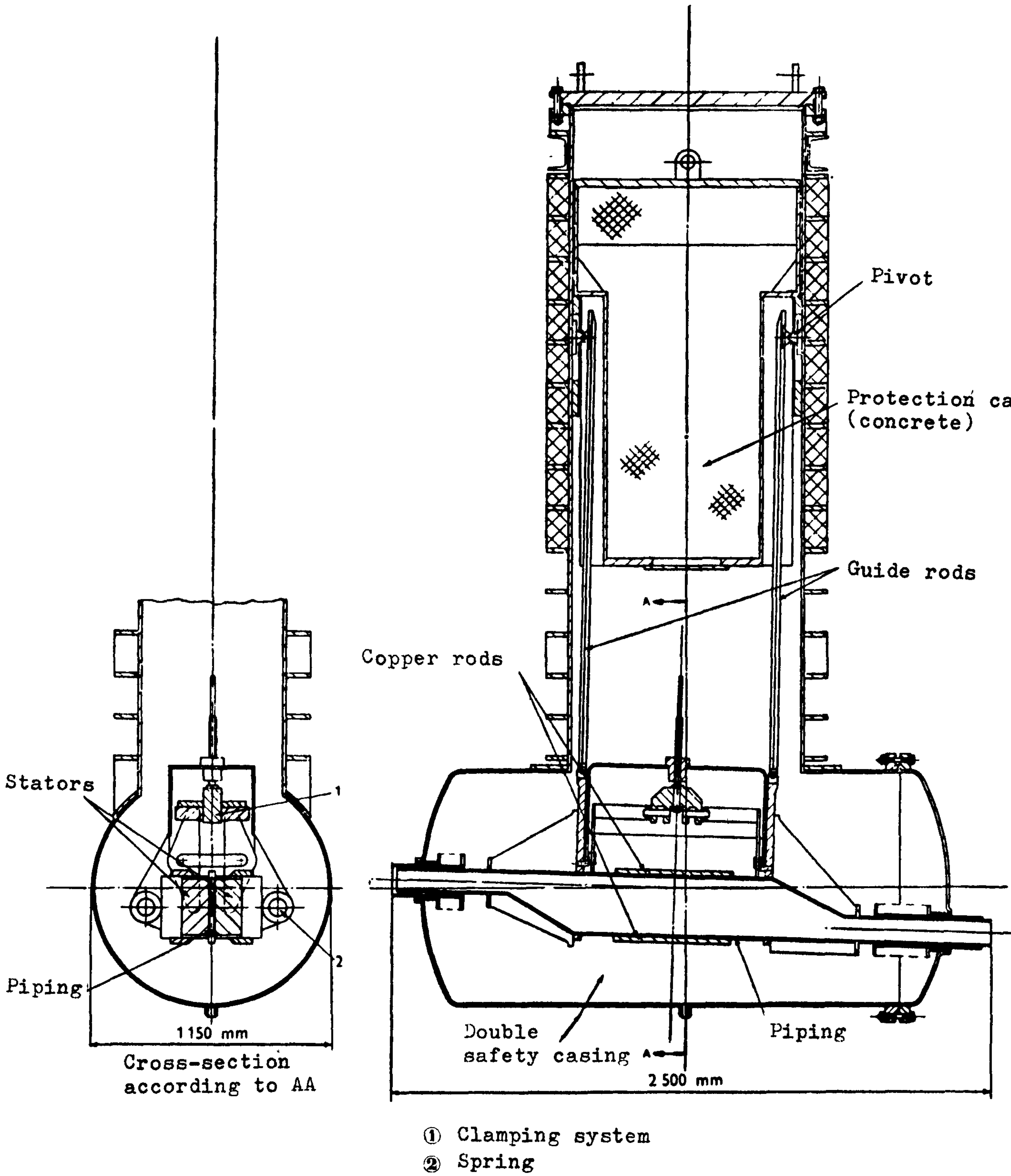
D F R - OVERALL LAYOUT OF THE PLANT

Figure VI 1



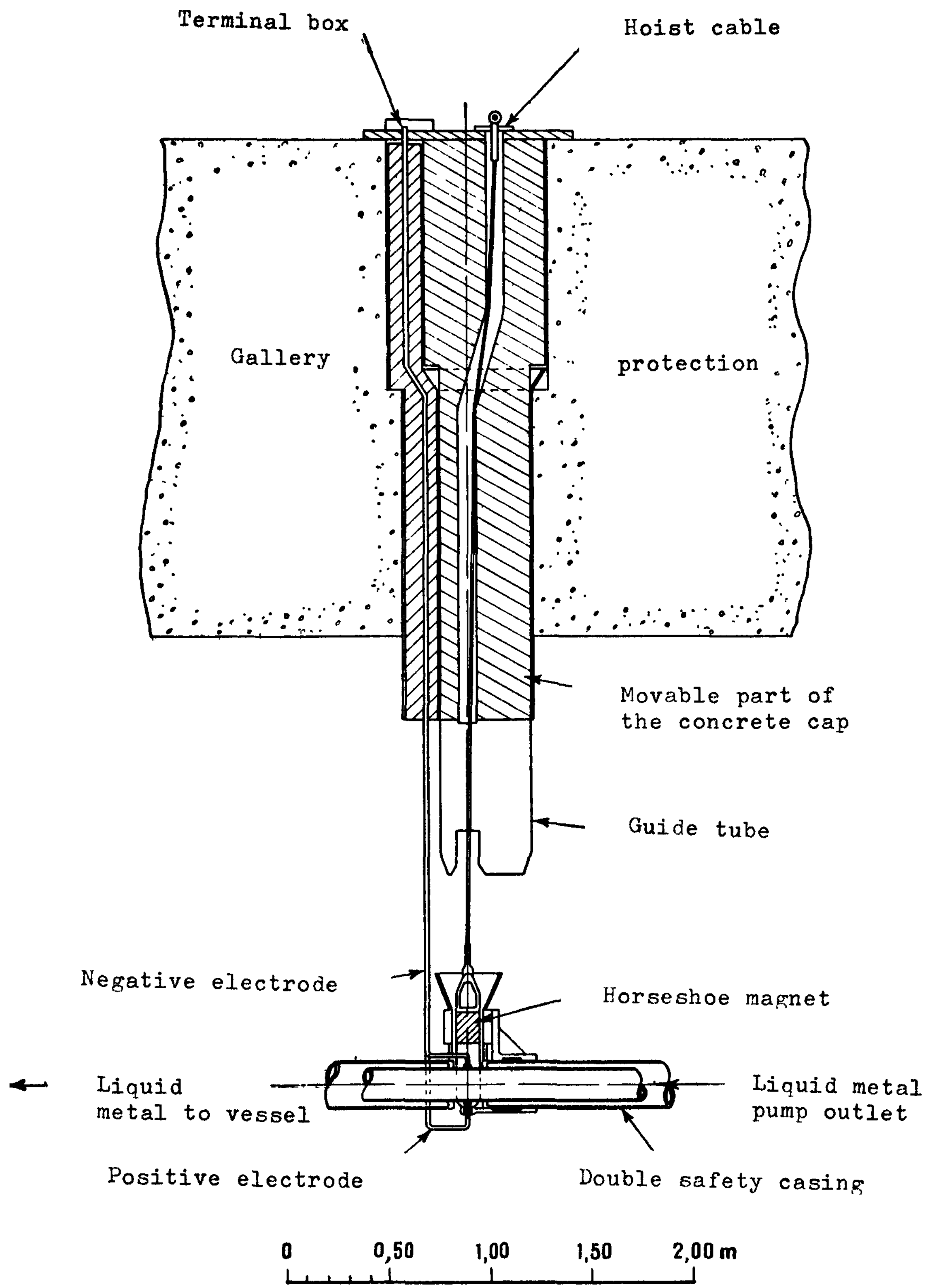
D F R – REACTOR AND PRIMARY SYSTEM

Figure VI 2



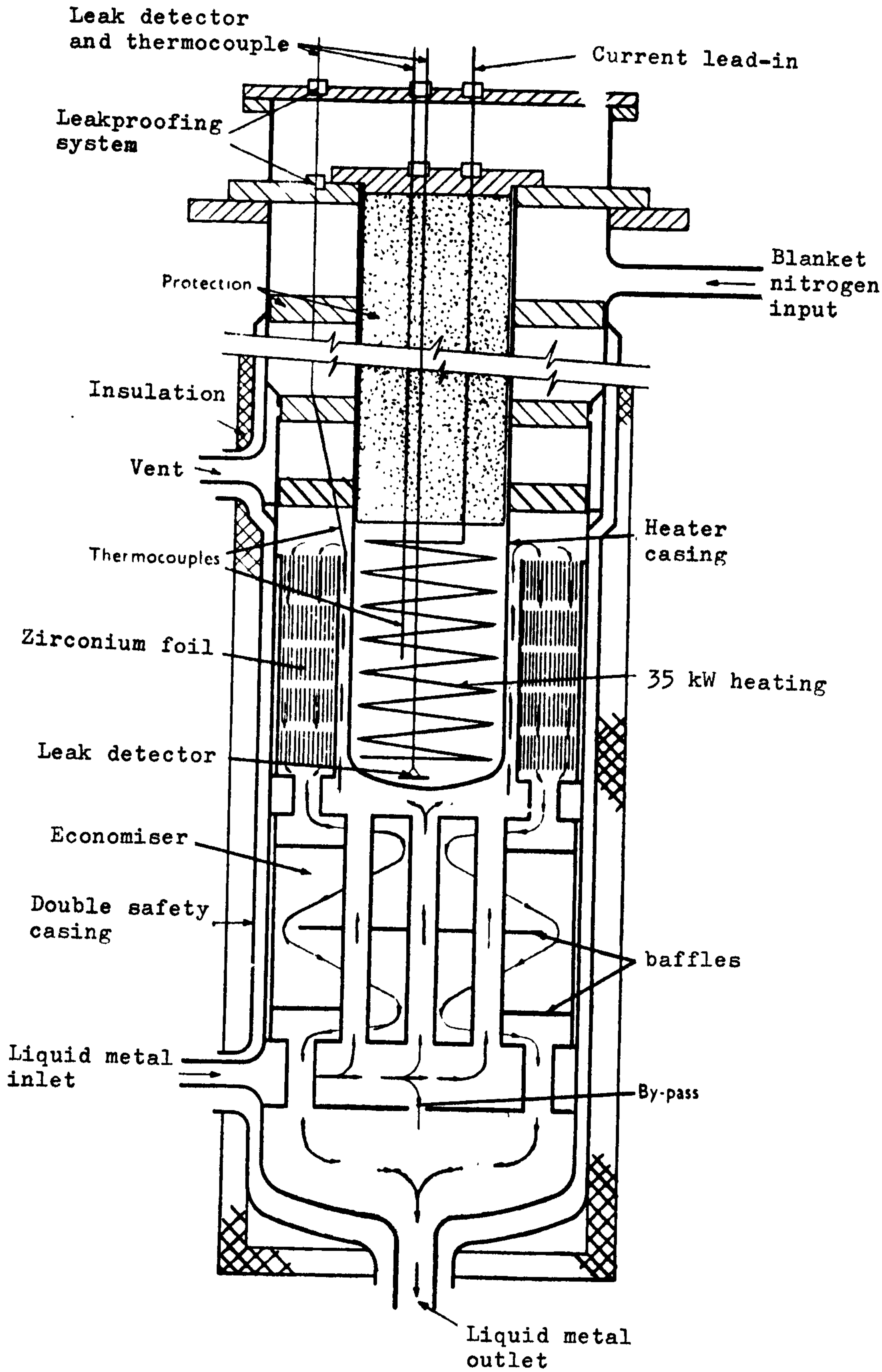
DFR _ PRIMARY SYSTEM ELECTROMAGNETIC PUMP

Figure VI 3



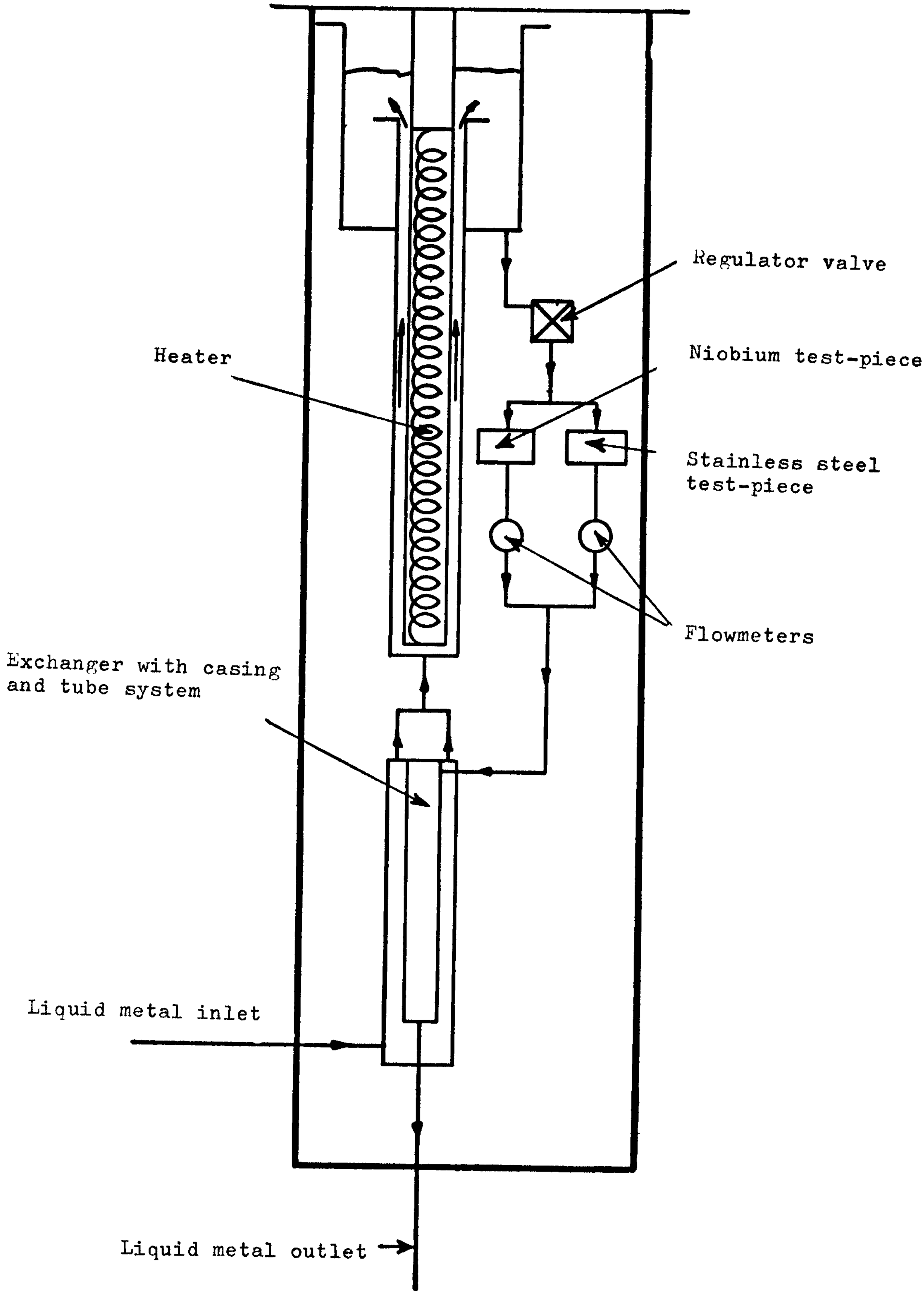
DFR - MAIN PRIMARY SYSTEM FLOWMETER

Figure VI 4



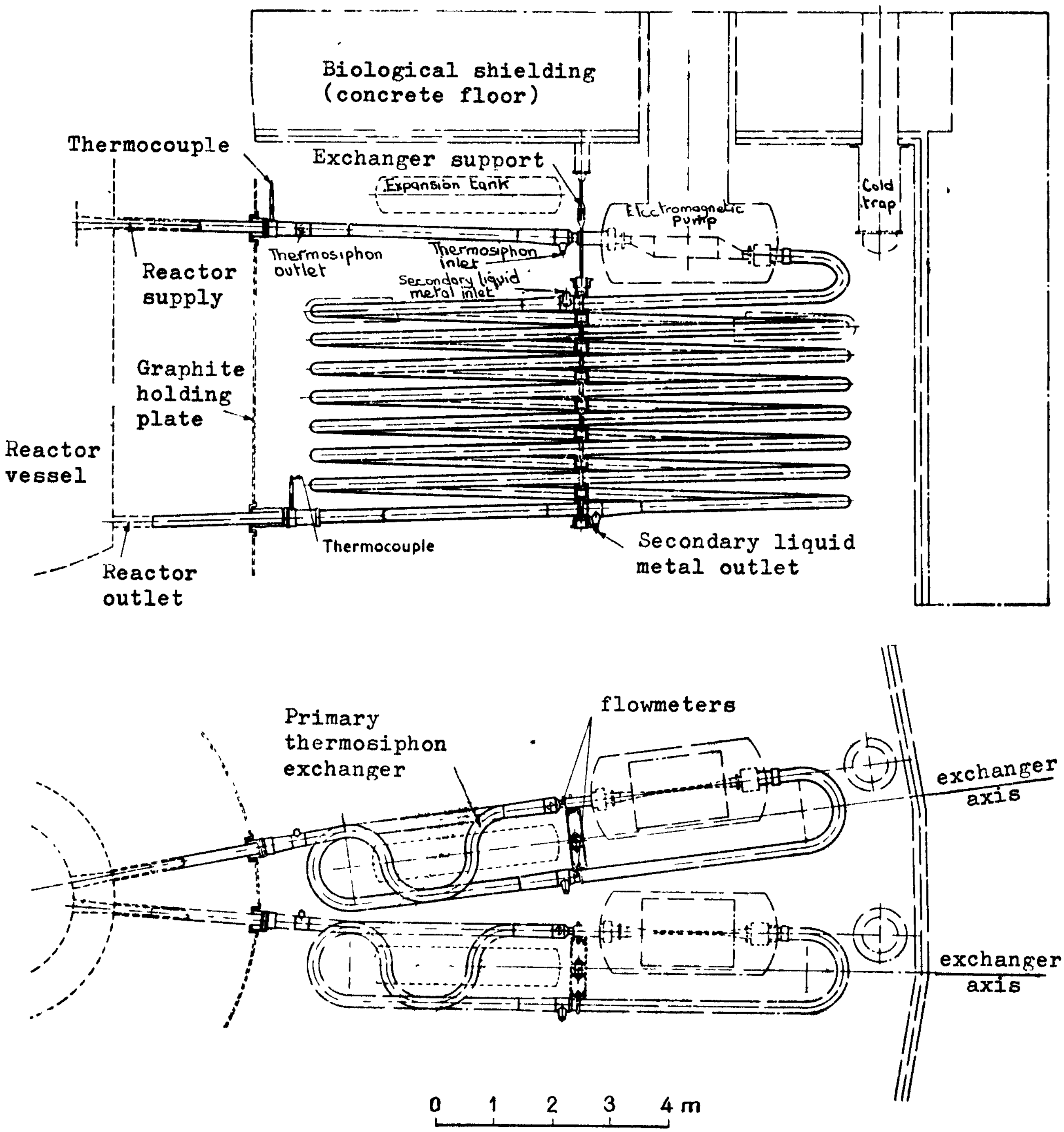
DFR - HOT. TRAP

Figure VI 5



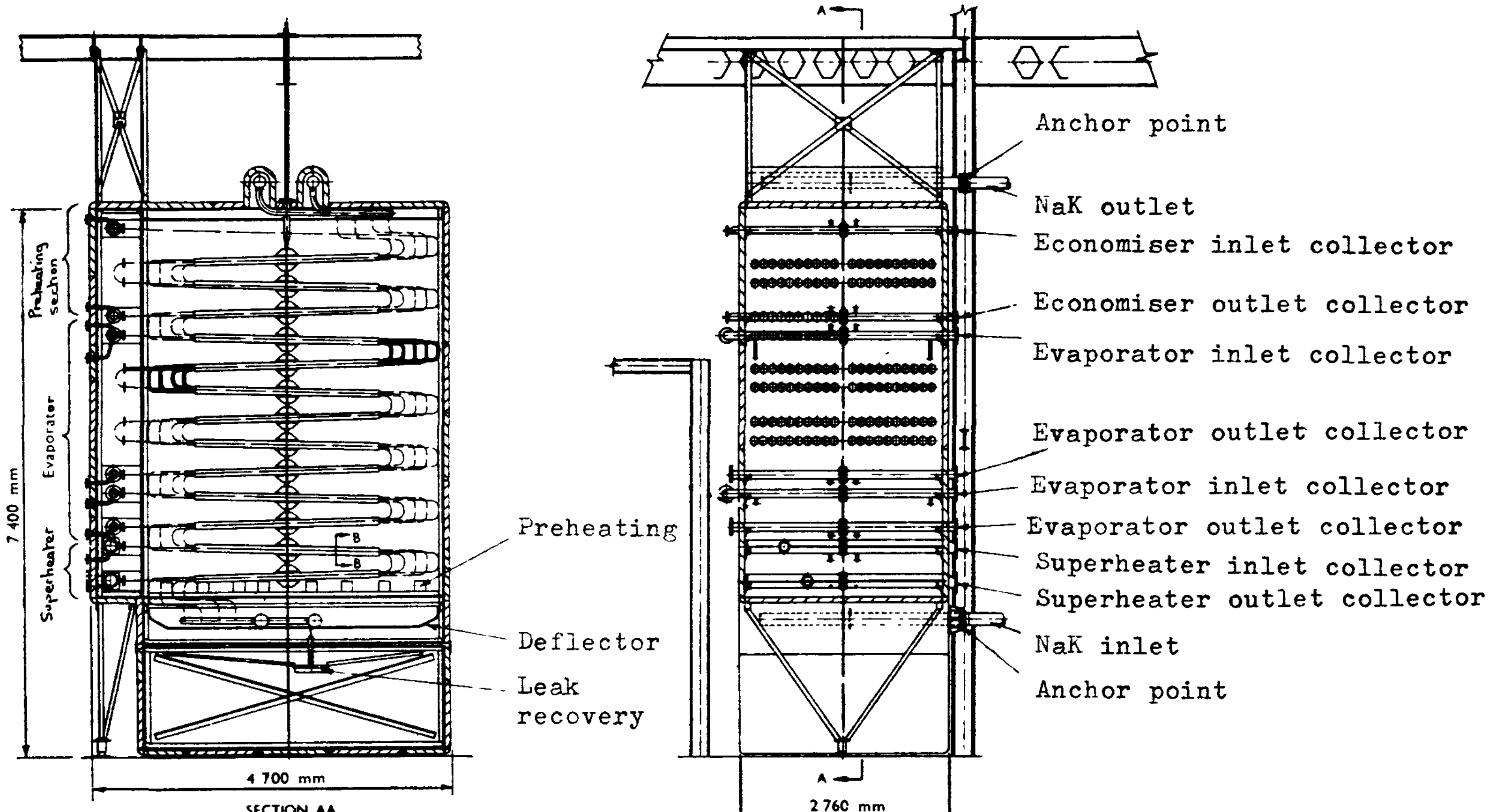
DFR – DIAGRAM OF A CORROSION INDICATOR

Figure VI 6

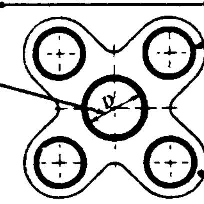


DFR - INTERMEDIATE EXCHANGERS

Figure VI 7

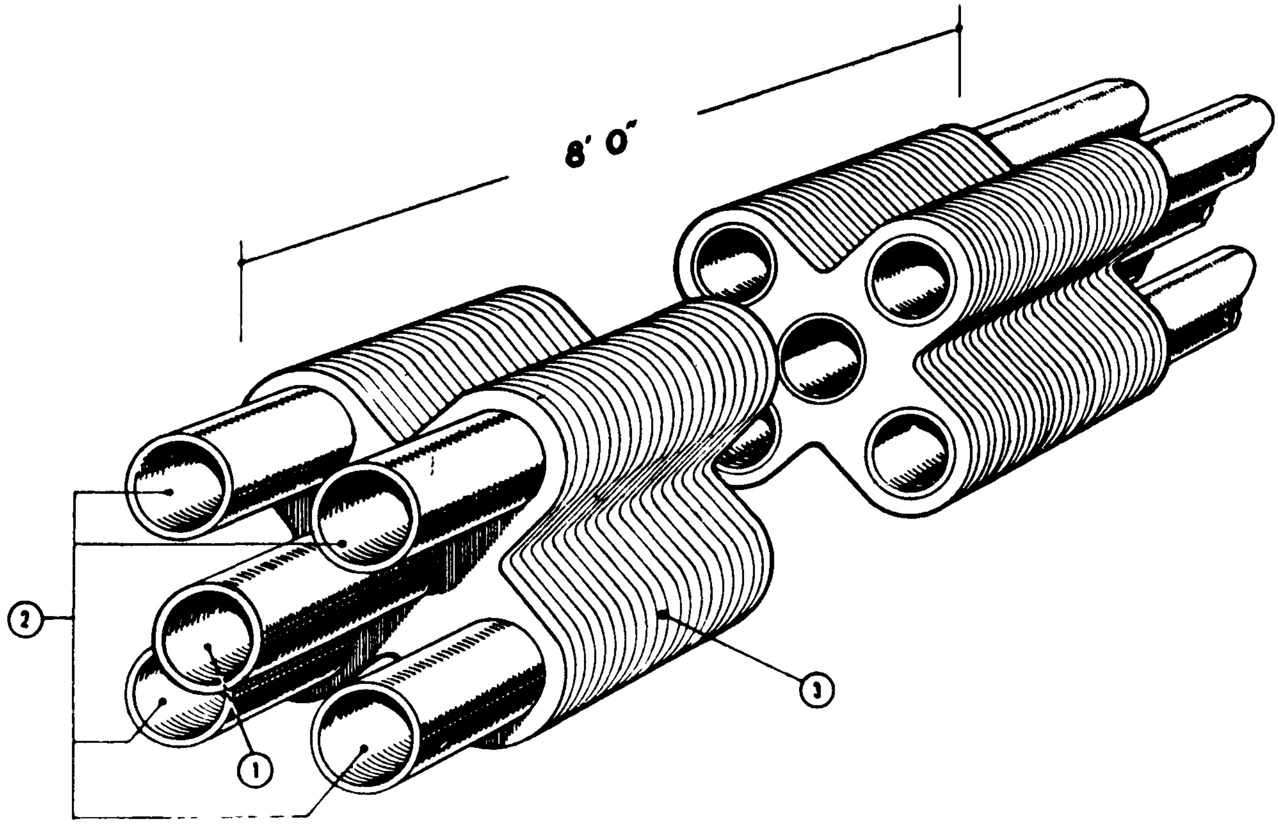


Water or steam tube	
Element	Dimension D
Heater	nominal diam. 12.5mm
Evaporator	nominal diam. 25 mm
Superheater	nominal diam. 19 mm



DFR – STEAM GENERATOR

Figure VI 8

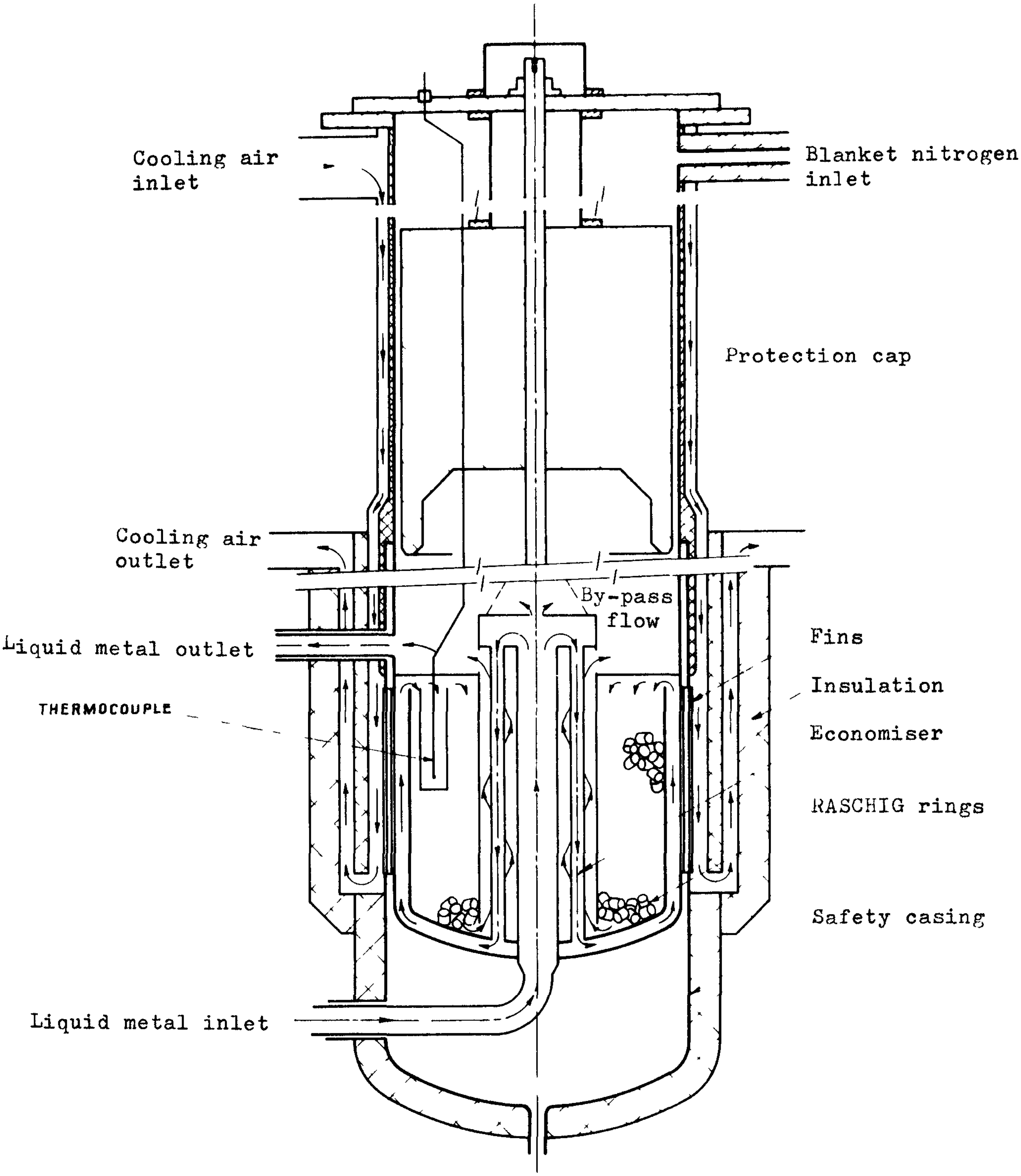


DFR

DETAIL OF THE SODIUM-WATER HEAT EXCHANGERS

1 - { Economiser pipe ϕ = 12.5 mm.
Evaporator ϕ = 25 mm. Superheater ϕ = 18.75 mm. }
2 - 4 liquid metal tubes ϕ = 18.75 mm.
3 - 3 mm-thick copper plate

Figure VI 9



DFR – PRIMARY SYSTEM COLD TRAP

Figure VI 10

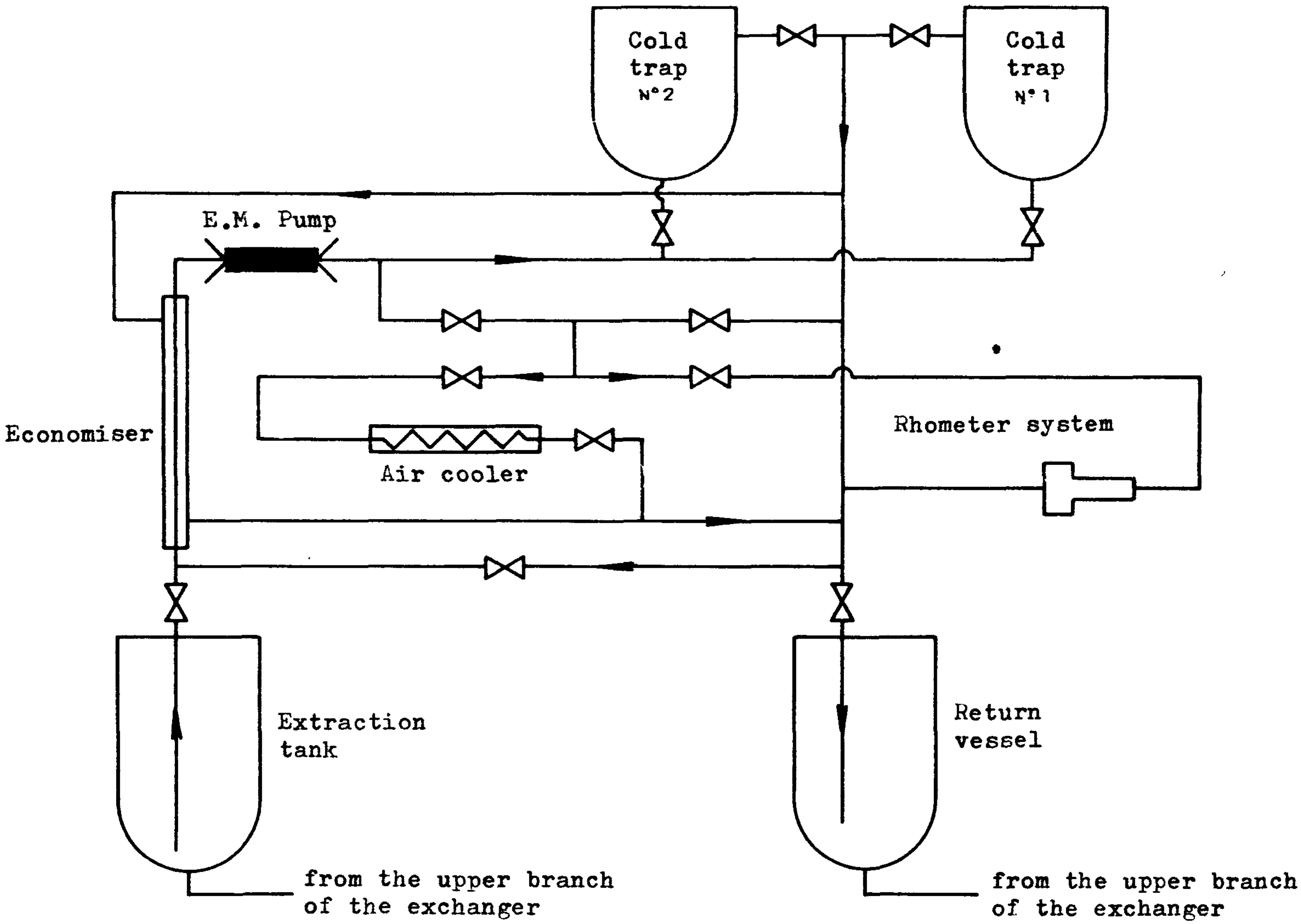
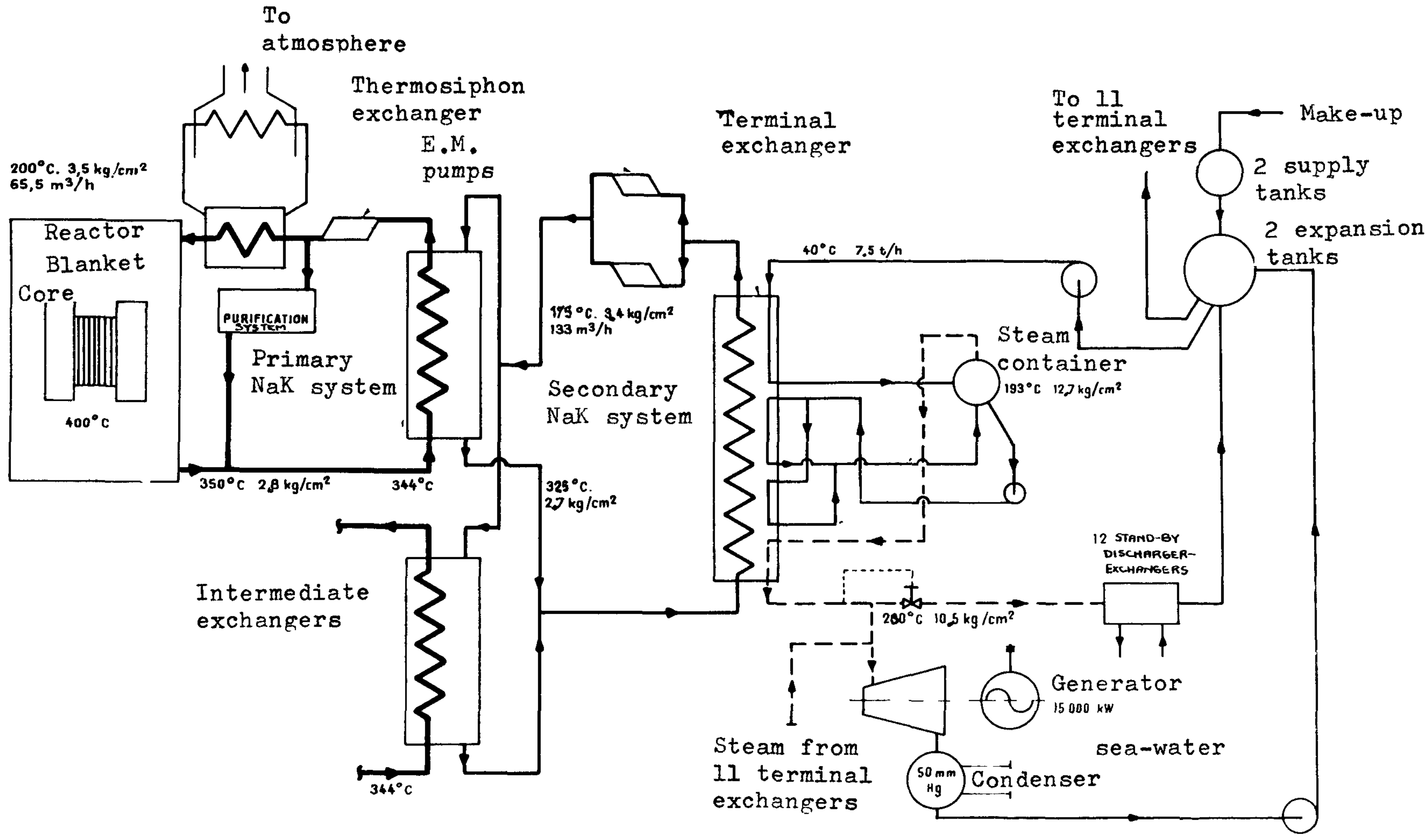


Figure VI 11

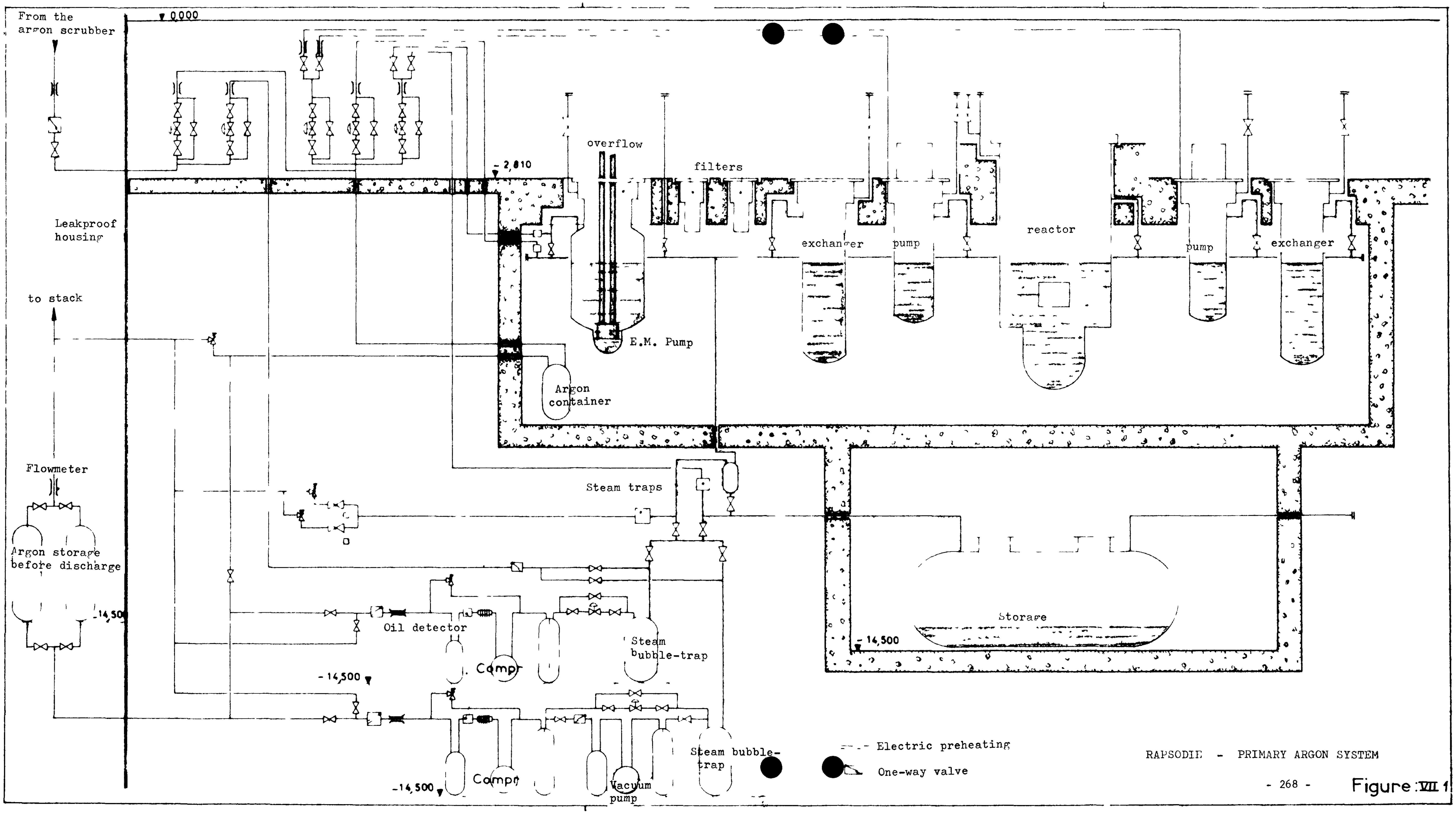
DFR _ PERMANENT COLD TRAP SYSTEM



24 Primary circuits (2 circuits shown)
12 Secondary circuits (1 circuit shown)

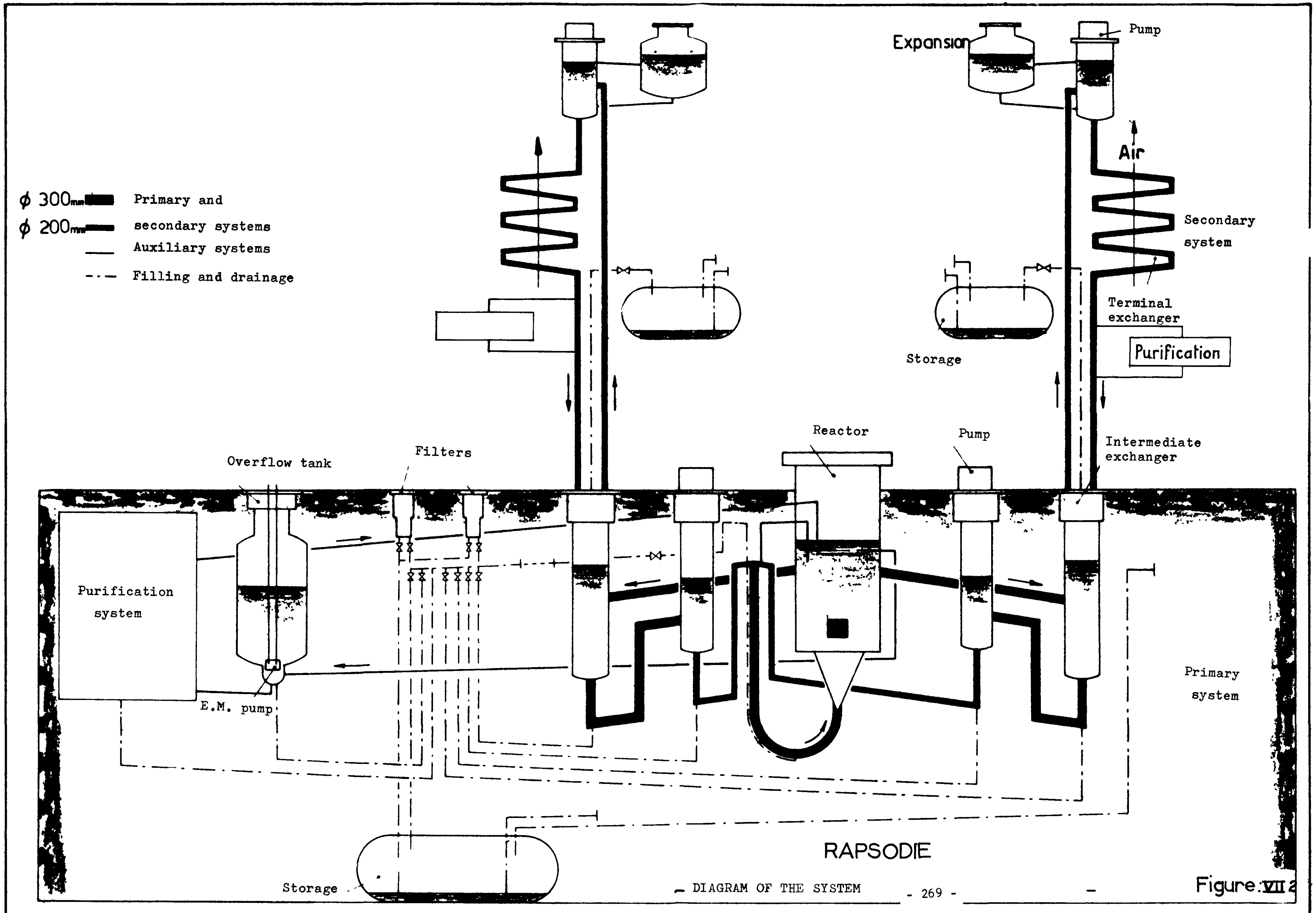
DFR - LAYOUT OF THE SYSTEMS

Figure VI 12



RAPSODIE - PRIMARY ARGON SYSTEM

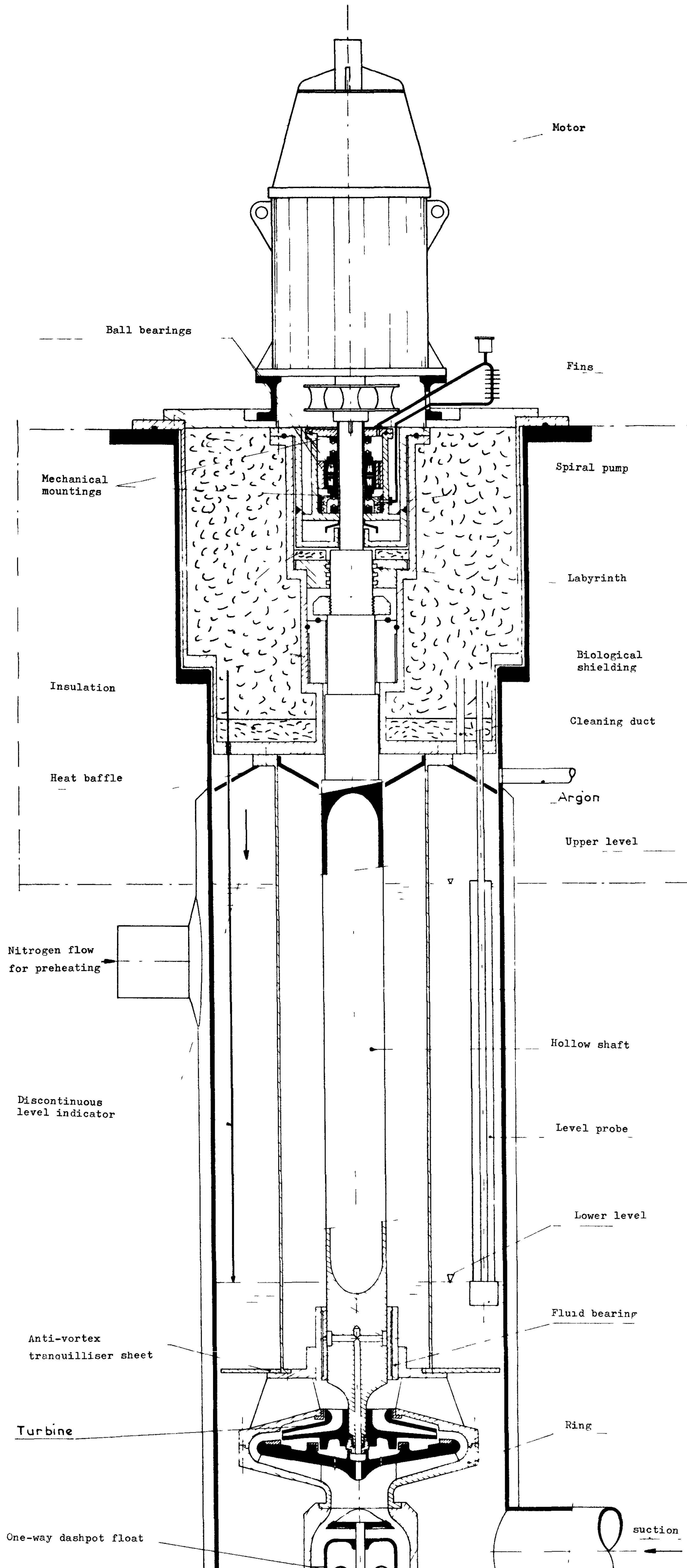
Figure VII 1



RAPSODIE

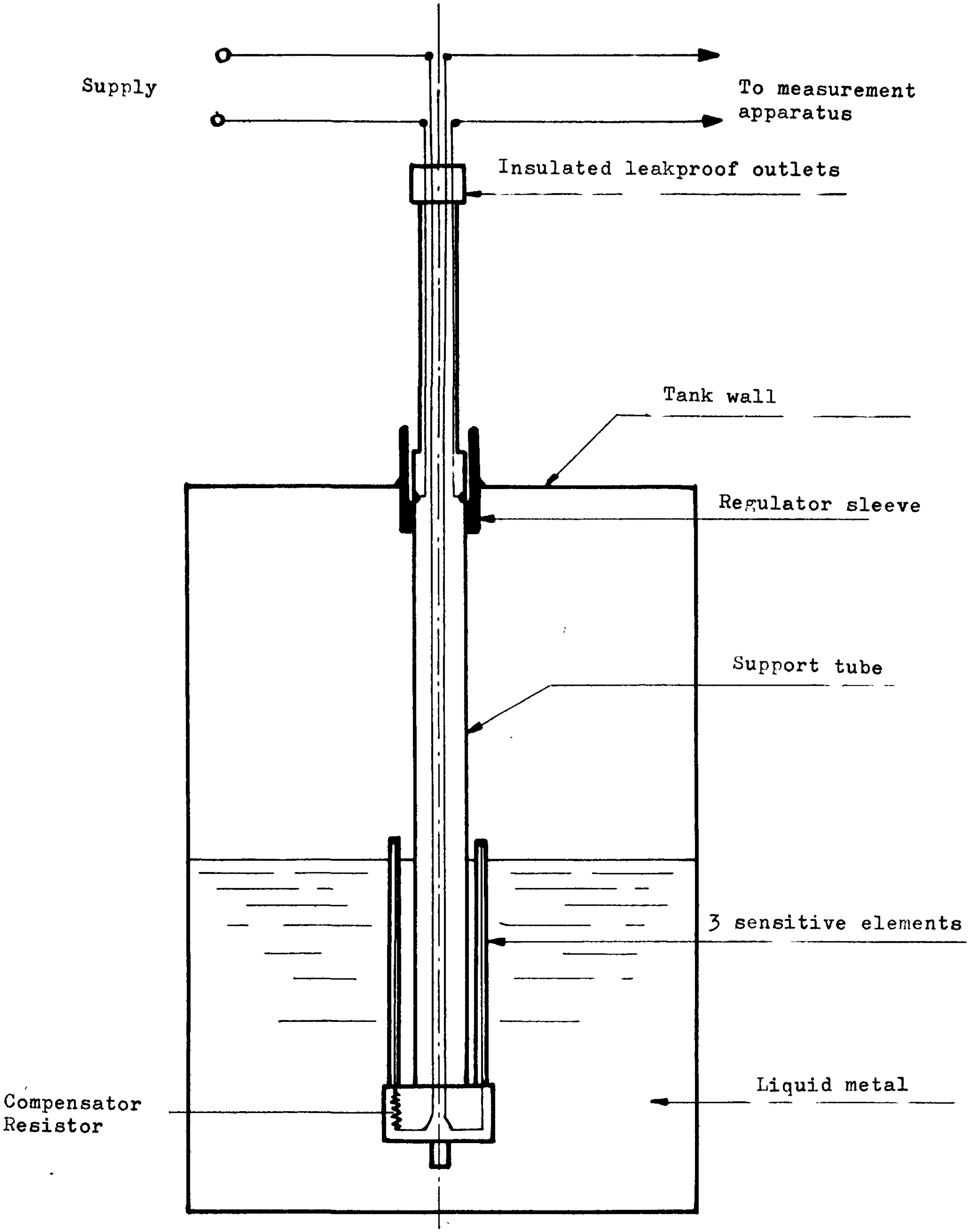
— DIAGRAM OF THE SYSTEM

Figure VII 2



PUMP P 350 m³/h 2,25 bars.

Figure VII 3



RAPSODIE

CONTINUOUS LEVEL PROBE

Figure VII 4

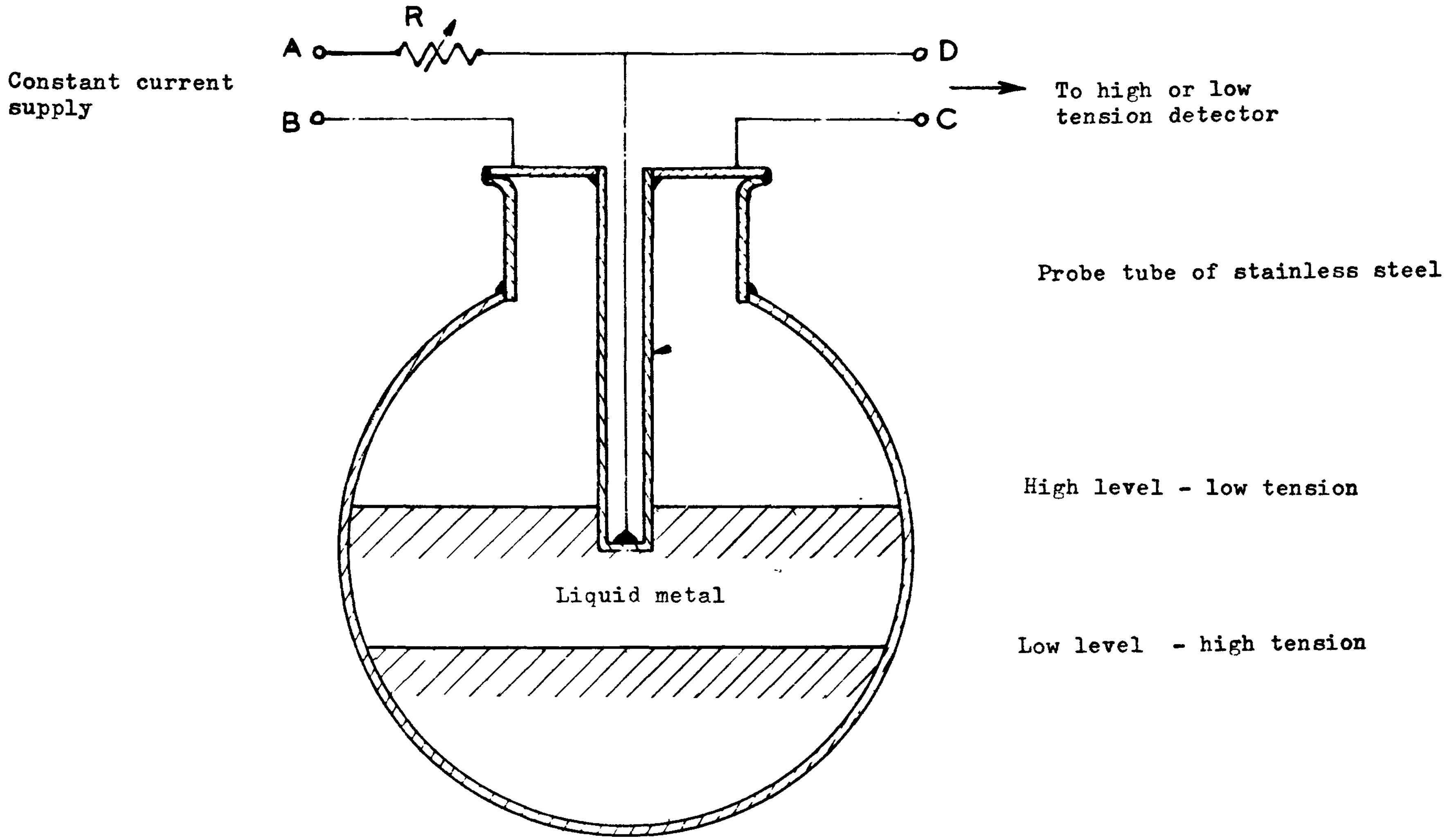
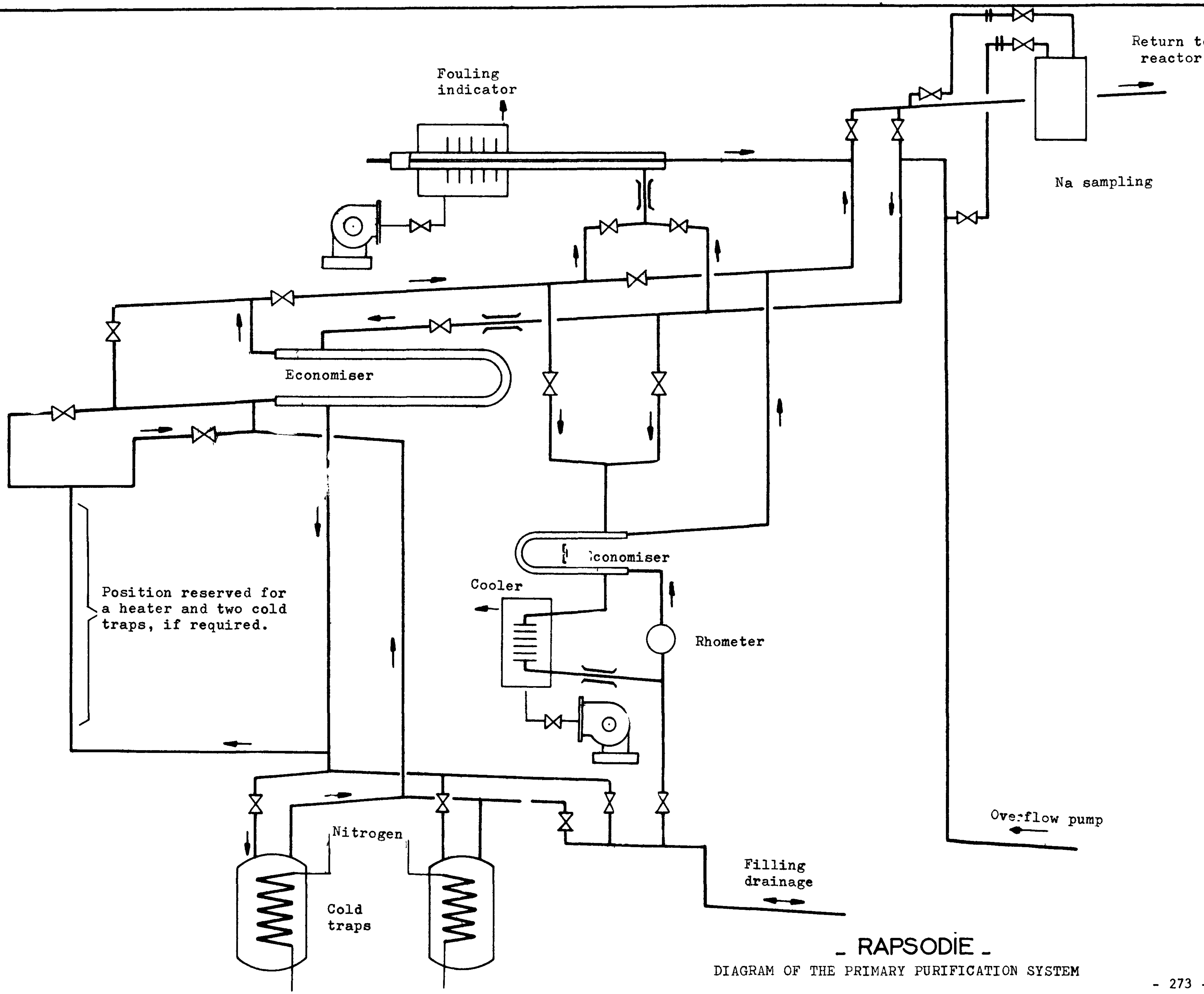


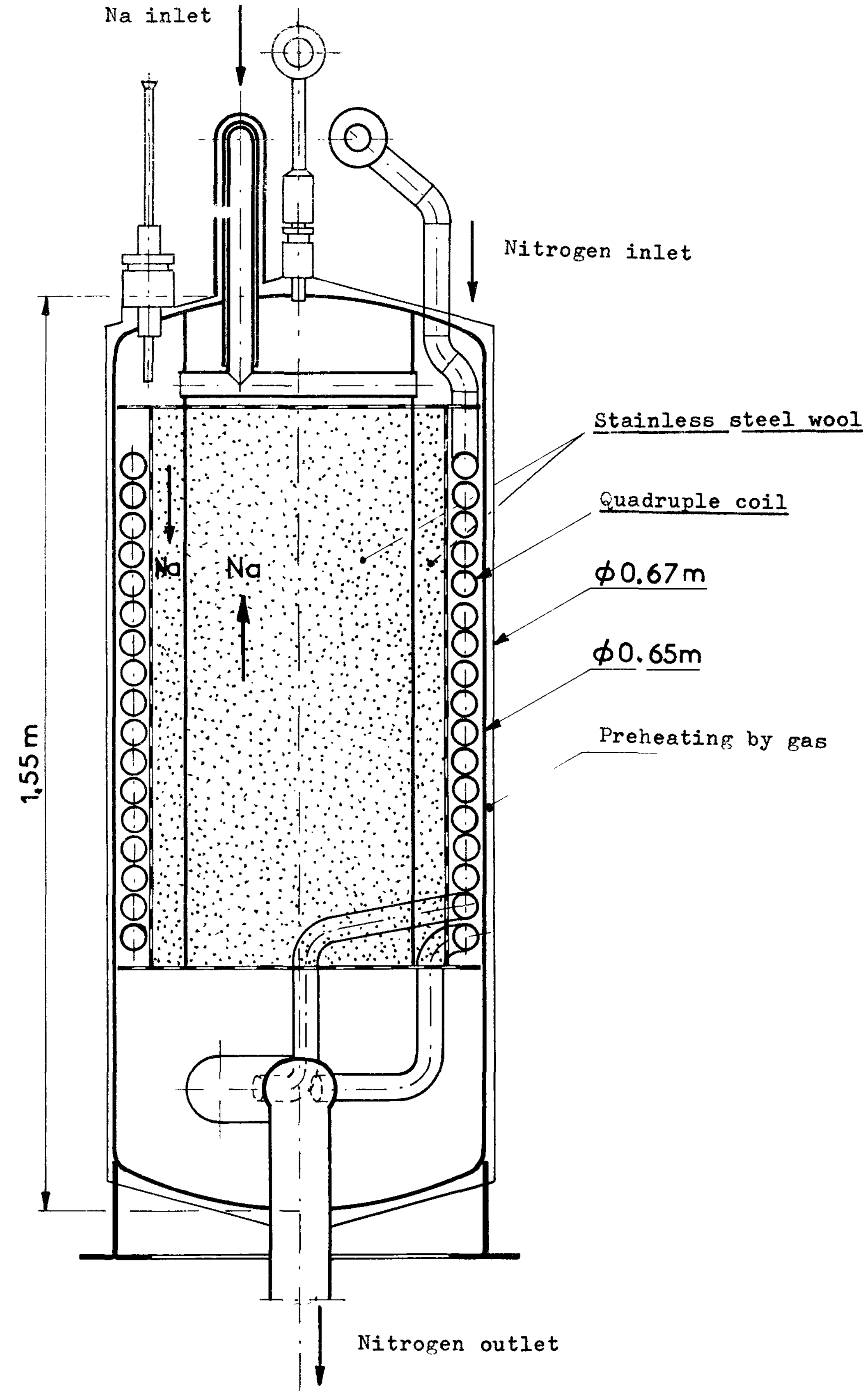
Figure XIII 5

RAPSODIE - PRINCIPLE OF A DISCONTINUOUS LEVEL PROBE



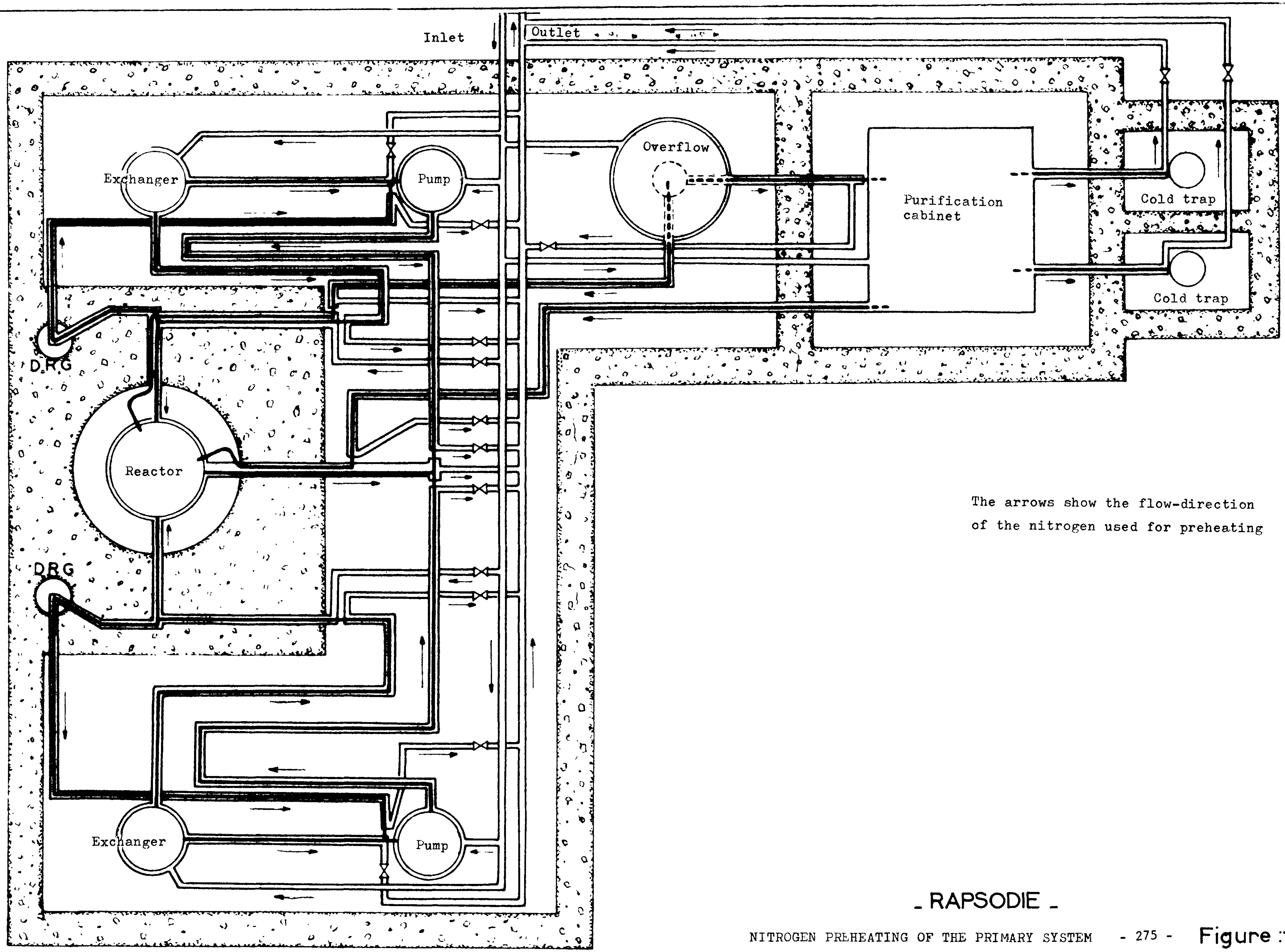
_ RAPSODIE _
DIAGRAM OF THE PRIMARY PURIFICATION SYSTEM

Figure: VII 6



RAPSODIE - COLD TRAP

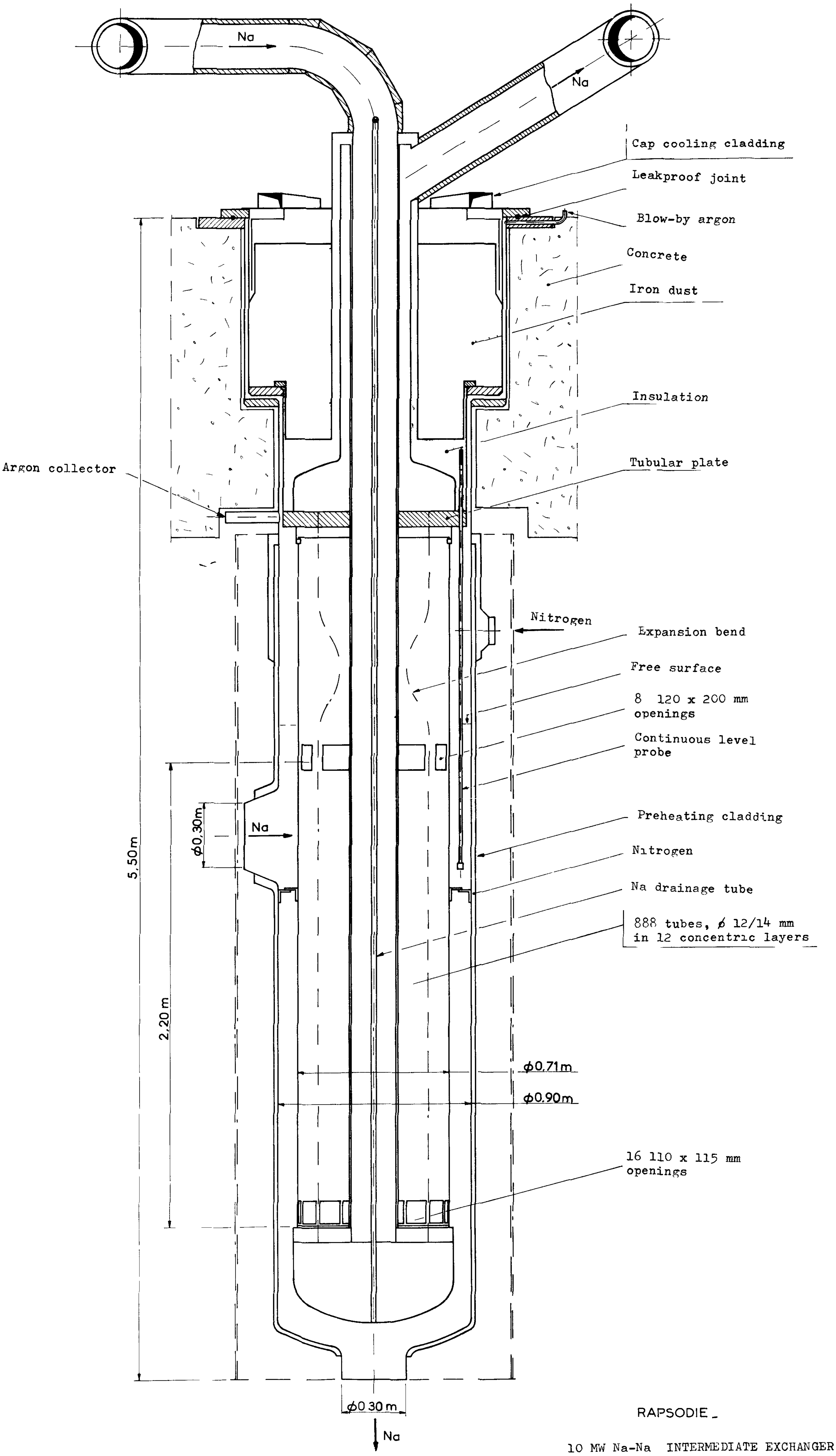
Figure VII 7



_ RAPSODIE _

NITROGEN PREHEATING OF THE PRIMARY SYSTEM

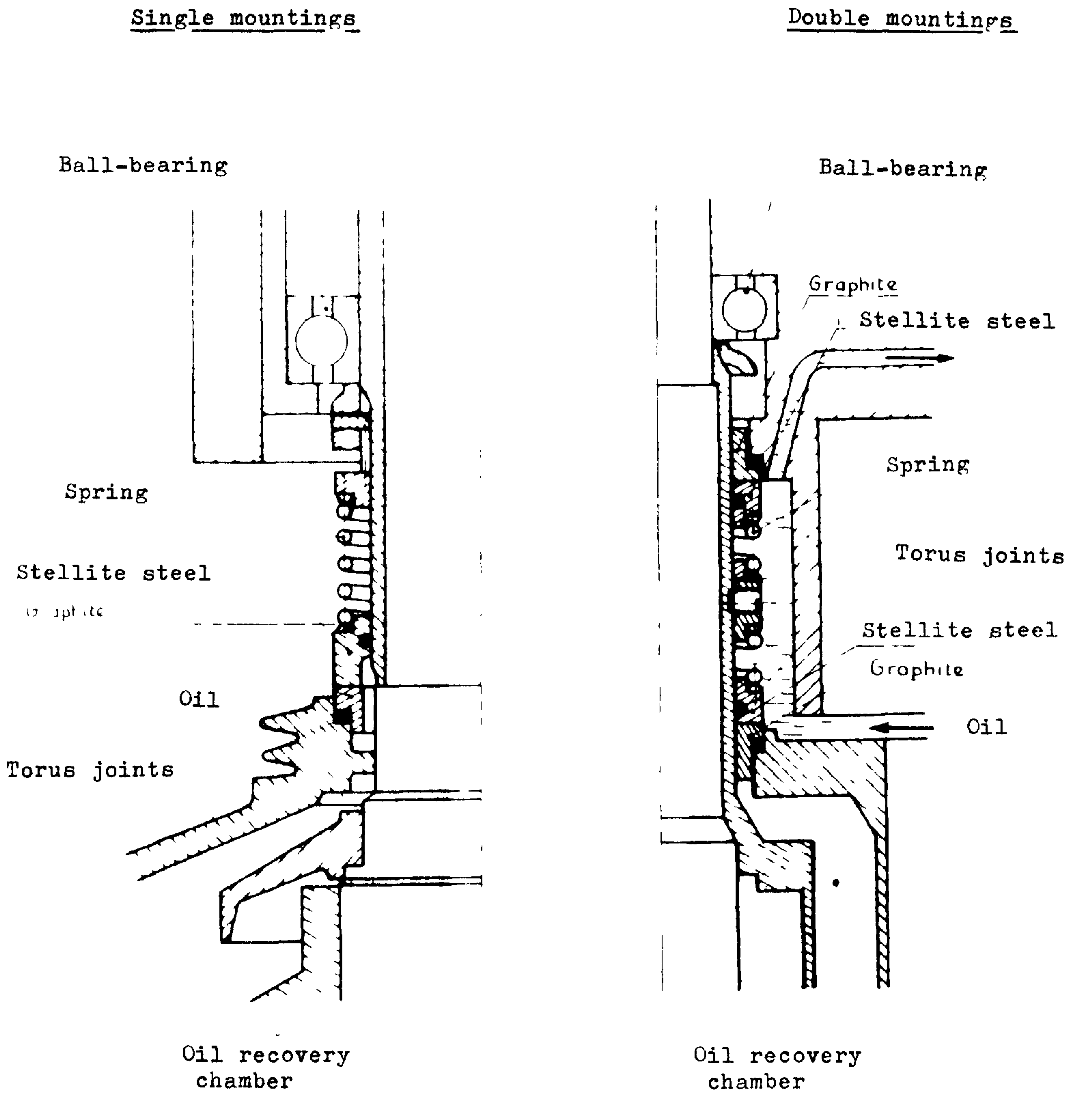
Figure : VII 8



RAPSODIE

10 MW Na-Na INTERMEDIATE EXCHANGER

Figure VII 9.



RAPSODIE _ MECHANICAL MOUNTINGS

Figure: VII 10

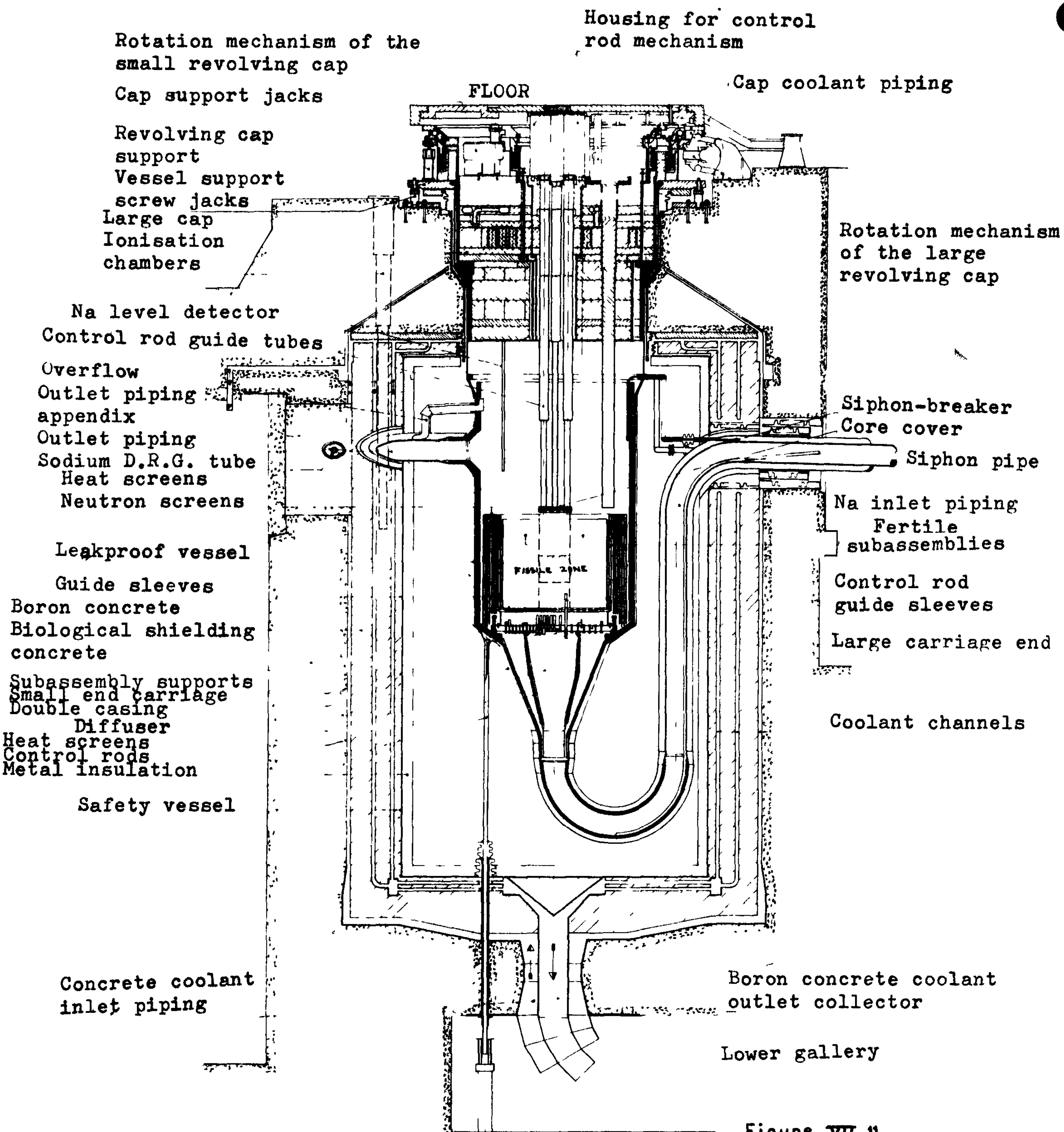
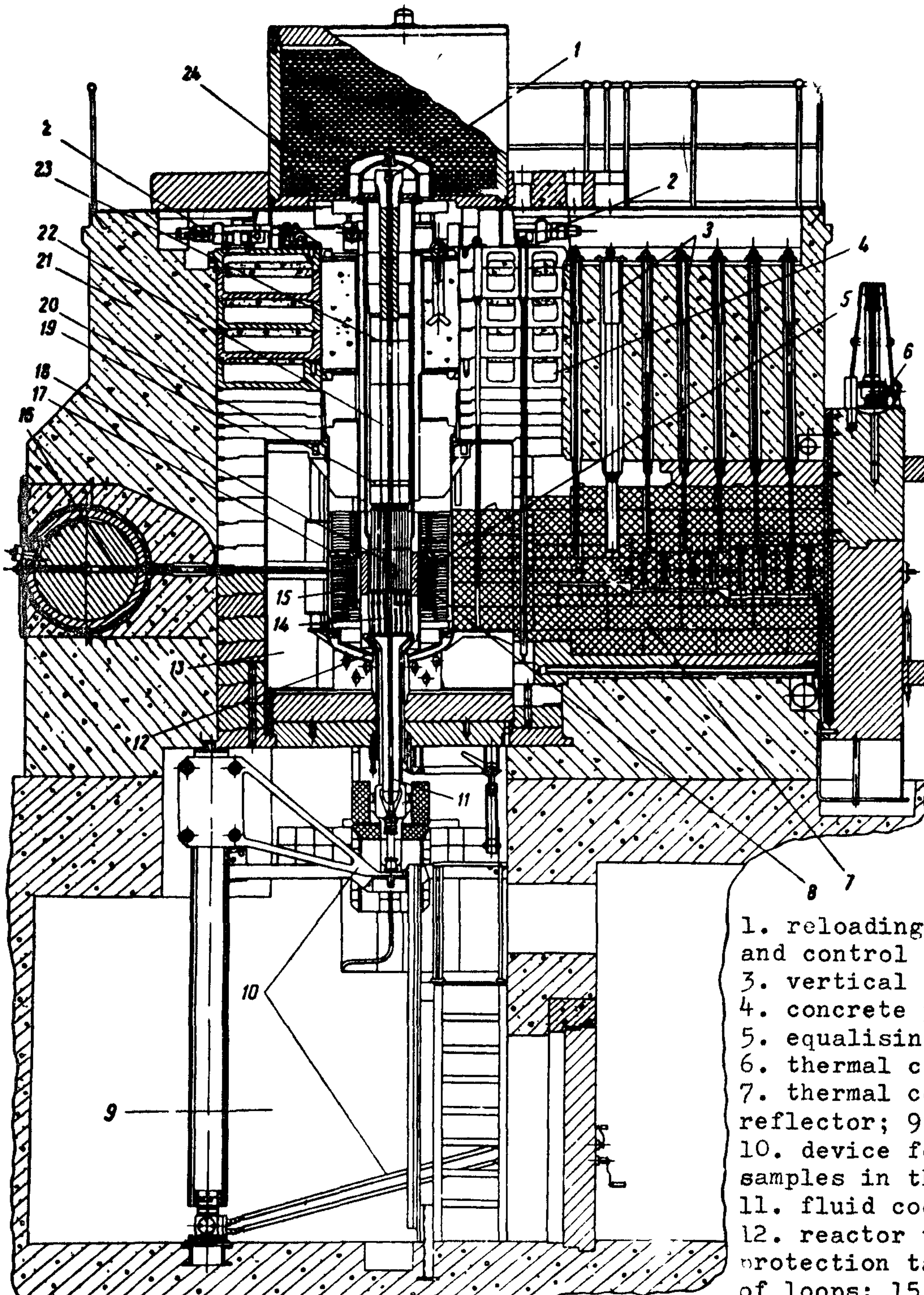


Figure VII 11

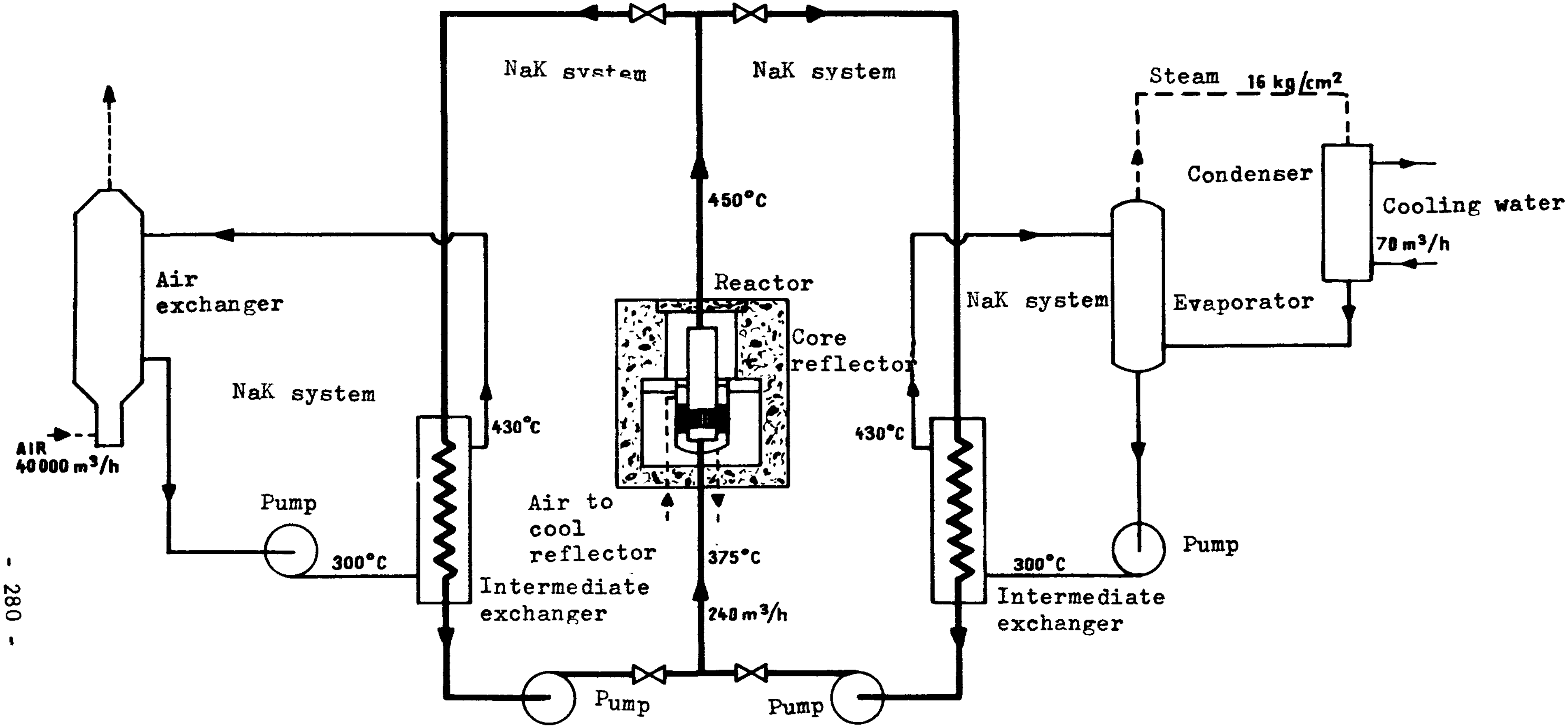
RAPSODIE - CROSS-SECTION OF THE REACTOR BLOCK



1. reloading device; 2. safety and control rod system hoists; 3. vertical experimental channels; 4. concrete protection; 5. equalising cylinder; 6. thermal column baffle; 7. thermal column; 8. movable reflector; 9. lower cell; 10. device for remove loading of samples in the experimental loop; 11. fluid coolant input; 12. reactor vessel; 13. water protection tank; 14. central channel of loops; 15. automatic control rod; 16. neutron tube system channel baffle; 17. permanent nickel cylinder; 18. active zone; 19. cast-iron protection; 20. cylinder containing the active zone; 21. concrete main protection; 22. rotating caps of the fuel assembly loading device; 23. fluid coolant level in the reactor vessel; 24. protection cover.

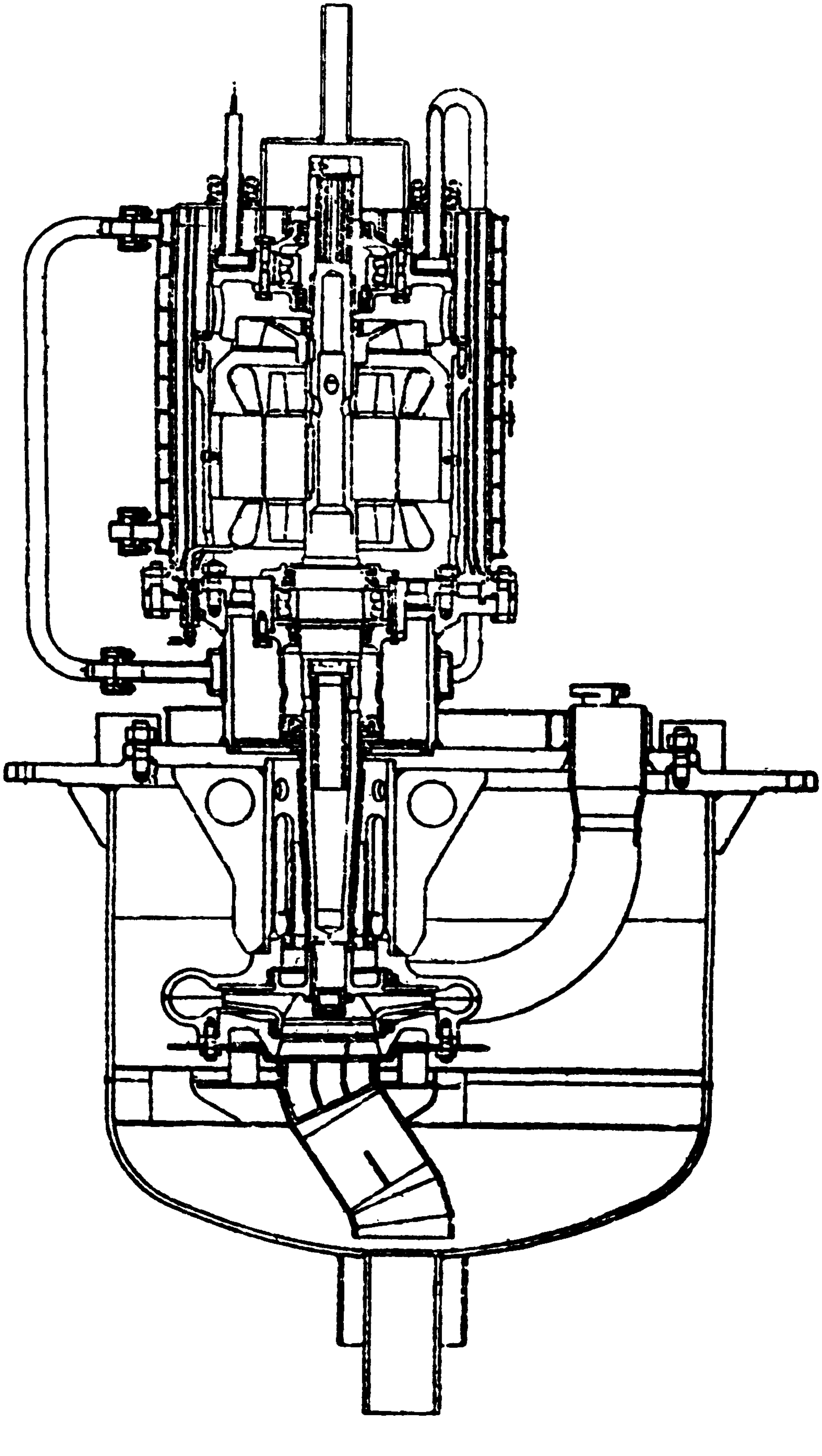
BR-5 LENGTHWISE CROSS-SECTION OF THE REACTOR

Figure VIII 1



BR 5 _ DIAGRAM OF THE SYSTEMS

Figure VIII 2

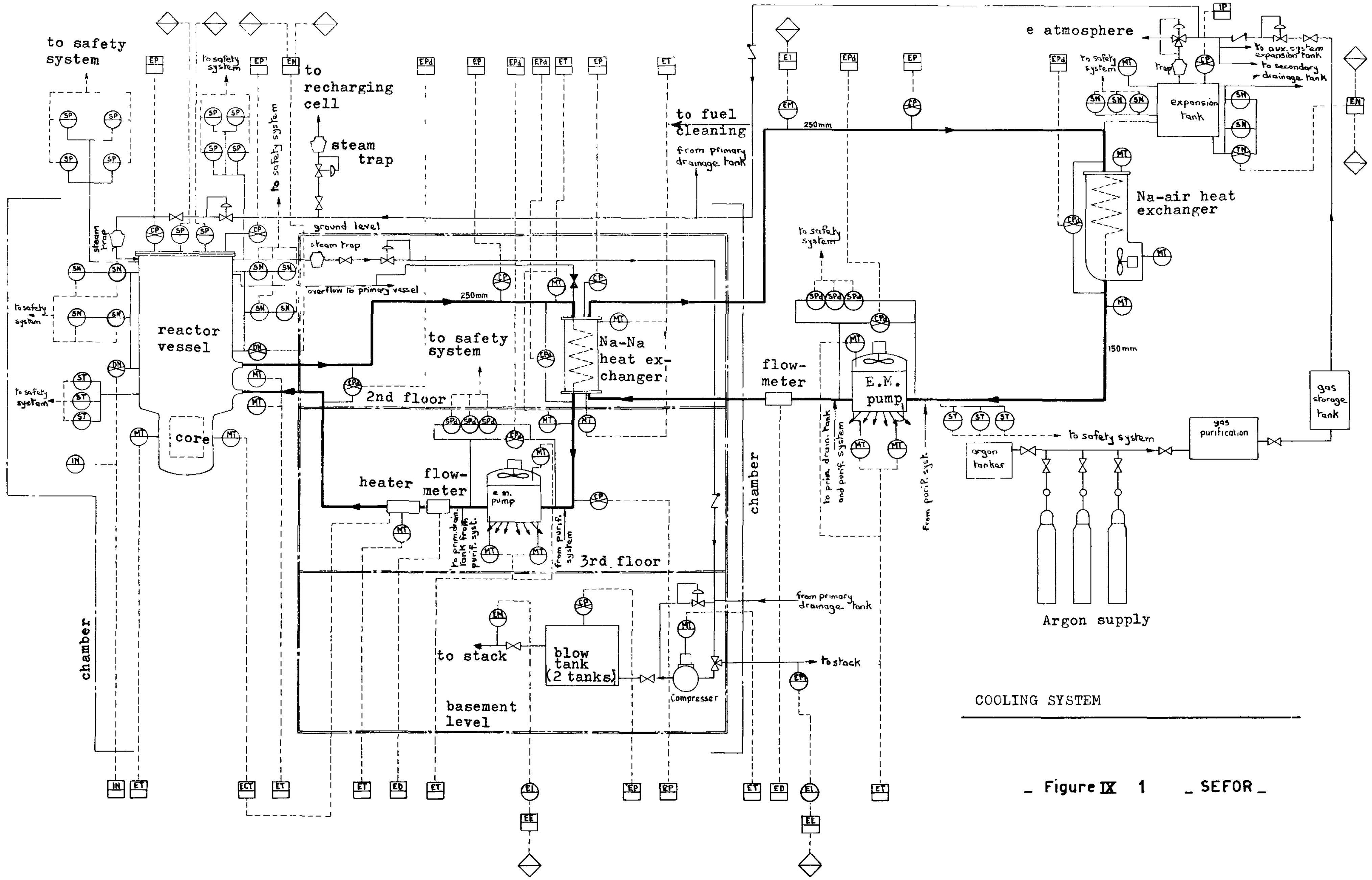


BR 5 _ MAIN PUMP

Figure VIII 3

K E Y

IN	Level indicator
ET	Temperature recorder
ECT	Comparative temperature recorder
ED	Flow recorder
CP	Pressure pick-off
MT	Temperature measurement
SN	Level signal
SP	Pressure signal
ST	Temperature signal
DN	Level detector
EPd	Differential pressure recorder
CPd	Differential pressure pick-off
SPd	Differential pressure signal

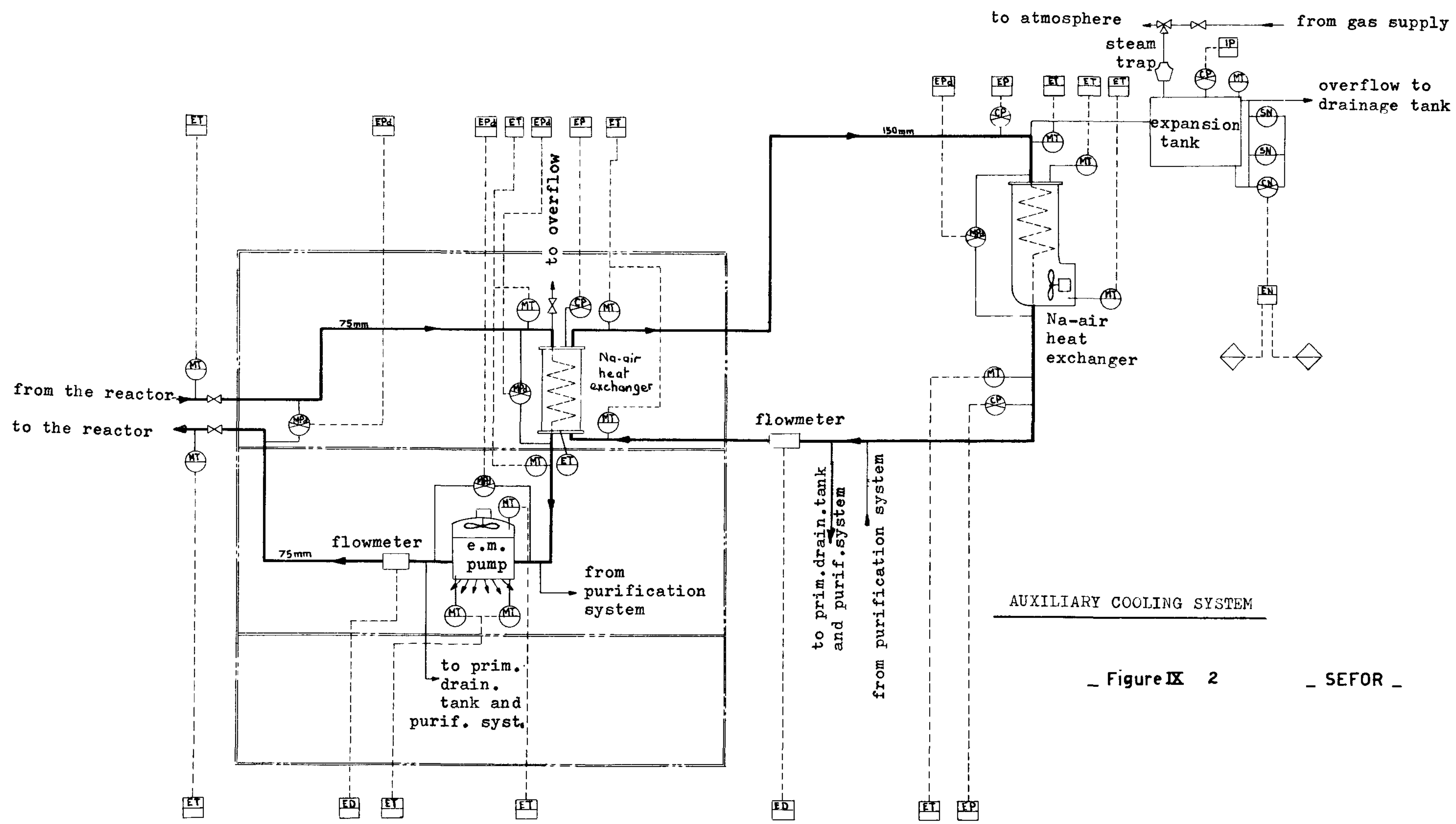


COOLING SYSTEM

_ Figure IX 1 _ SEFOR _

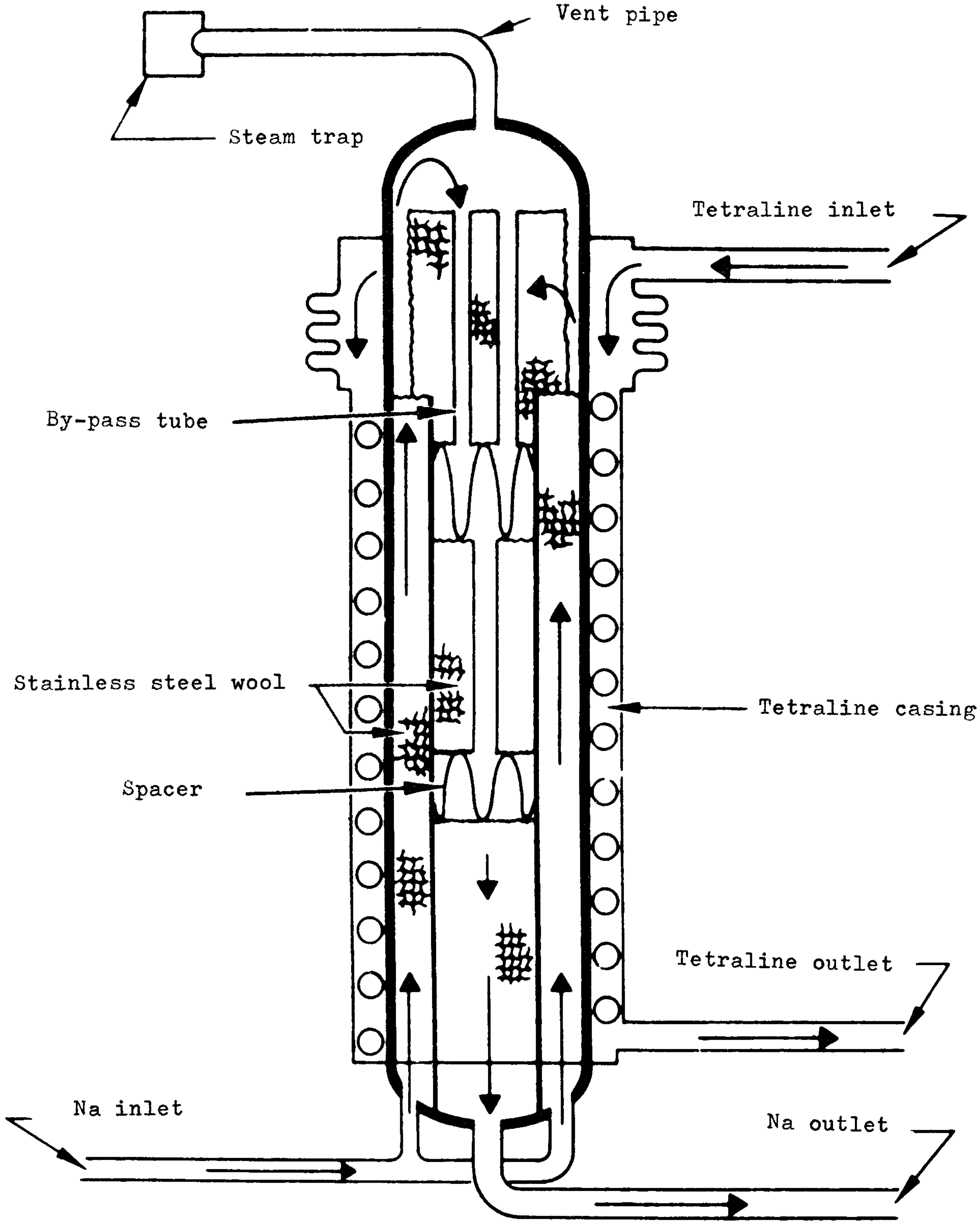
KEY

CP	Pressure pick-off
MT	Temperature measurement
MPd	Differential pressure measurement
ET	Temperature recorder
EPd	Differential pressure recorder
EP	Pressure recorder
SN	Level signal
CN	Level pick-off
EN	Level recorder



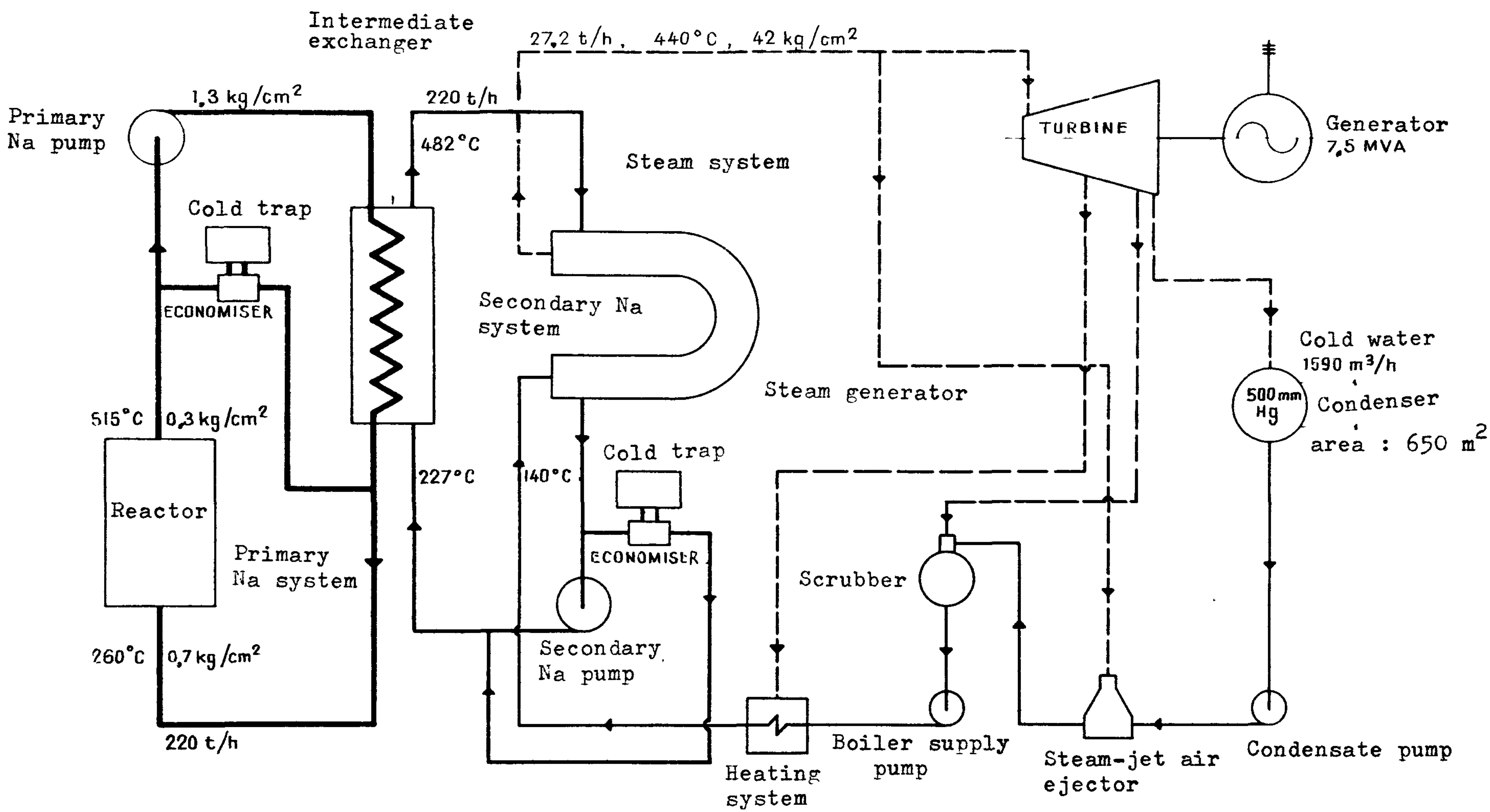
AUXILIARY COOLING SYSTEM

_ Figure IX 2 _SEFOR_



SRE – COLD TRAP WITH FORCED CONVECTION COOLING

Figure X 1



SRE – DIAGRAM OF THE SYSTEMS

Figure II 2

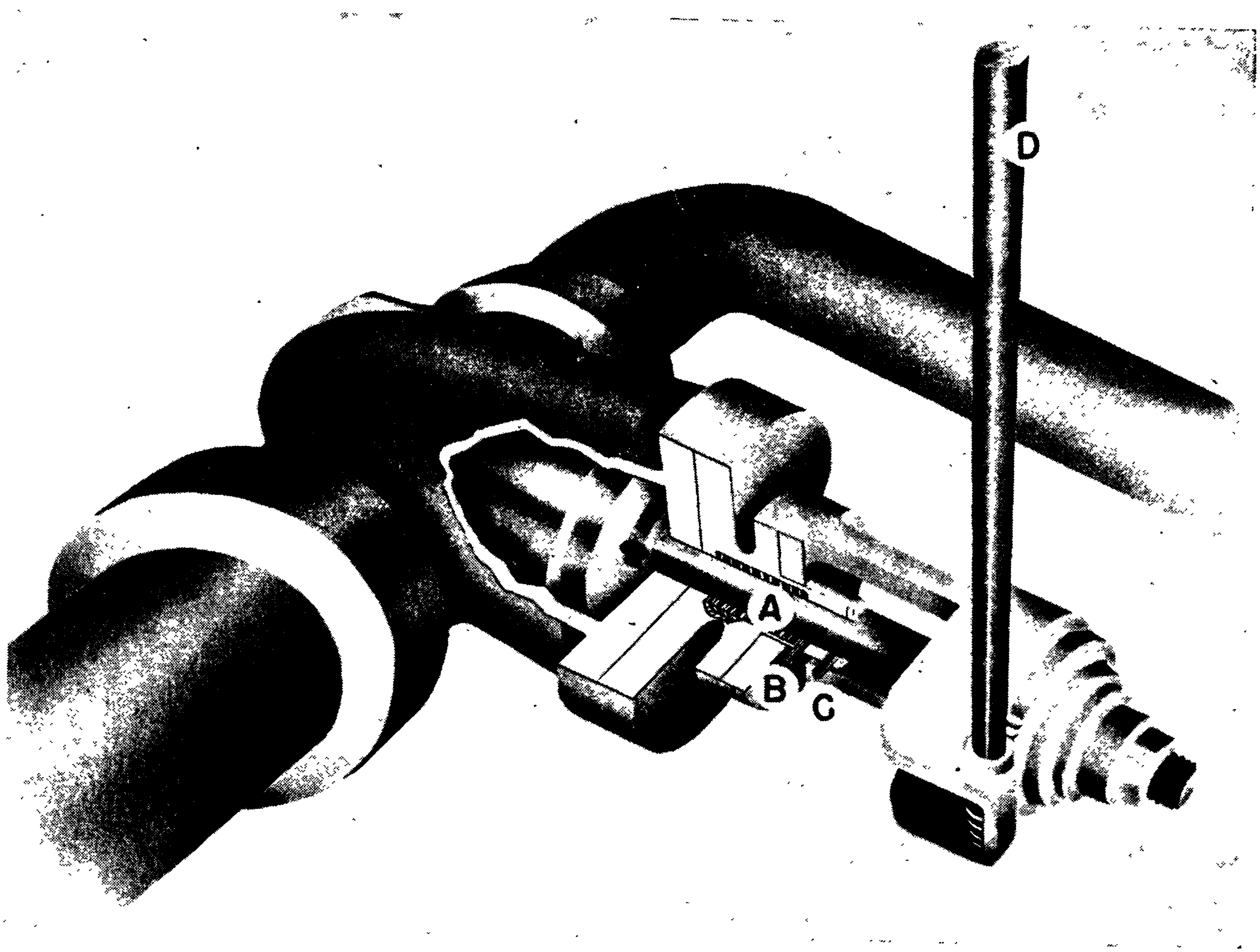
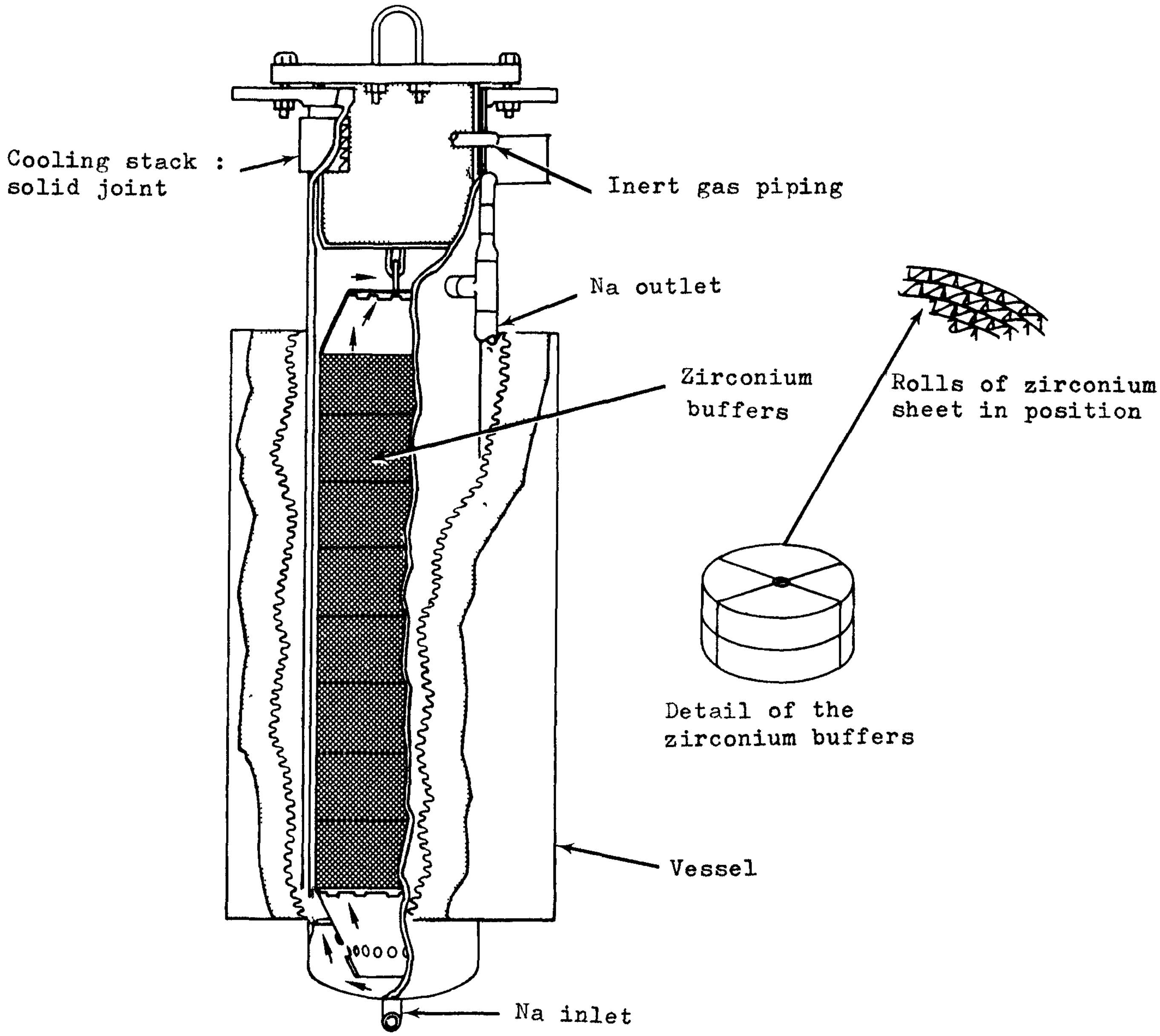


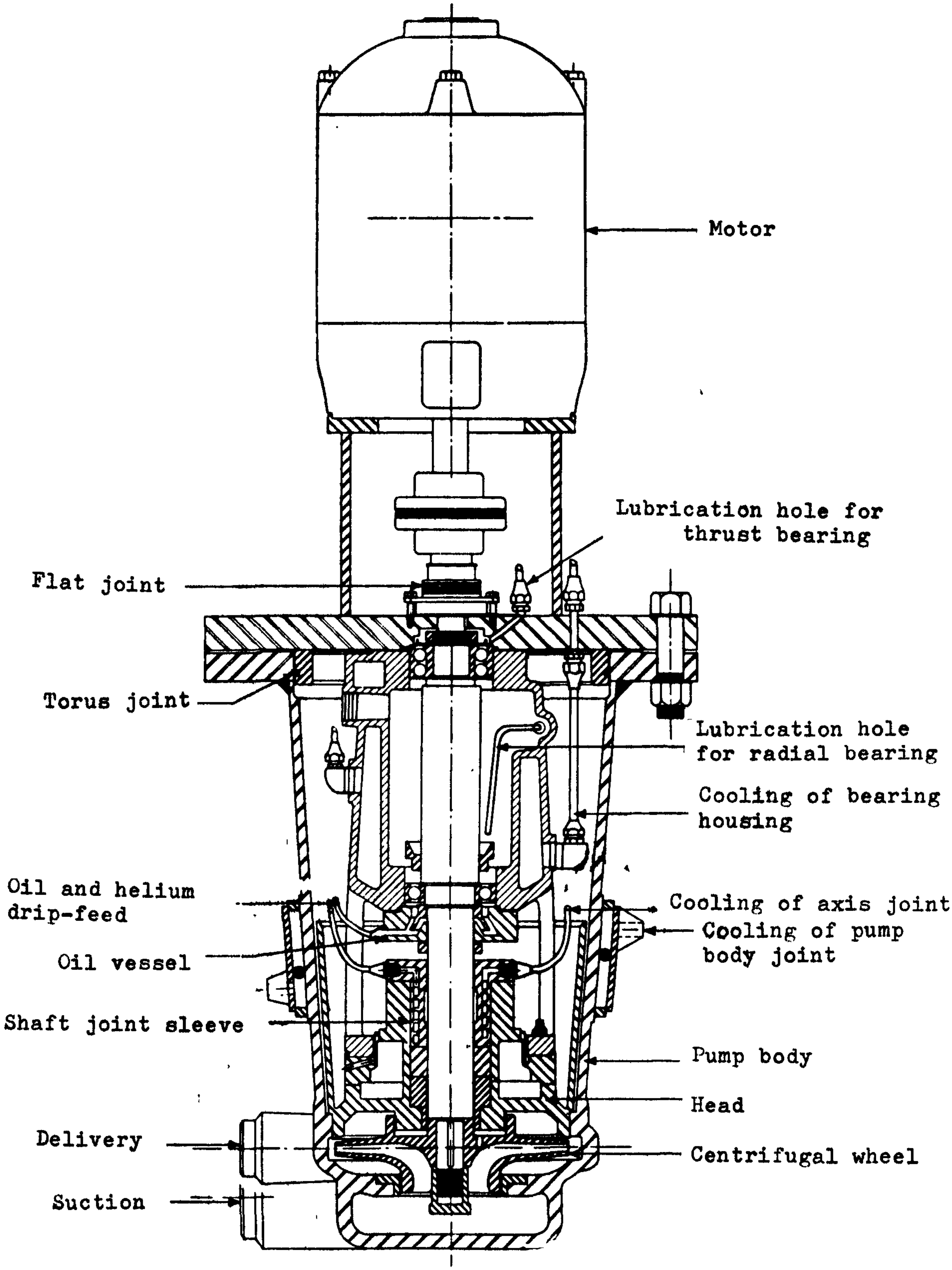
Figure X 3

SRE - ARRANGEMENT OF THE SOLID SODIUM JOINT VALVE



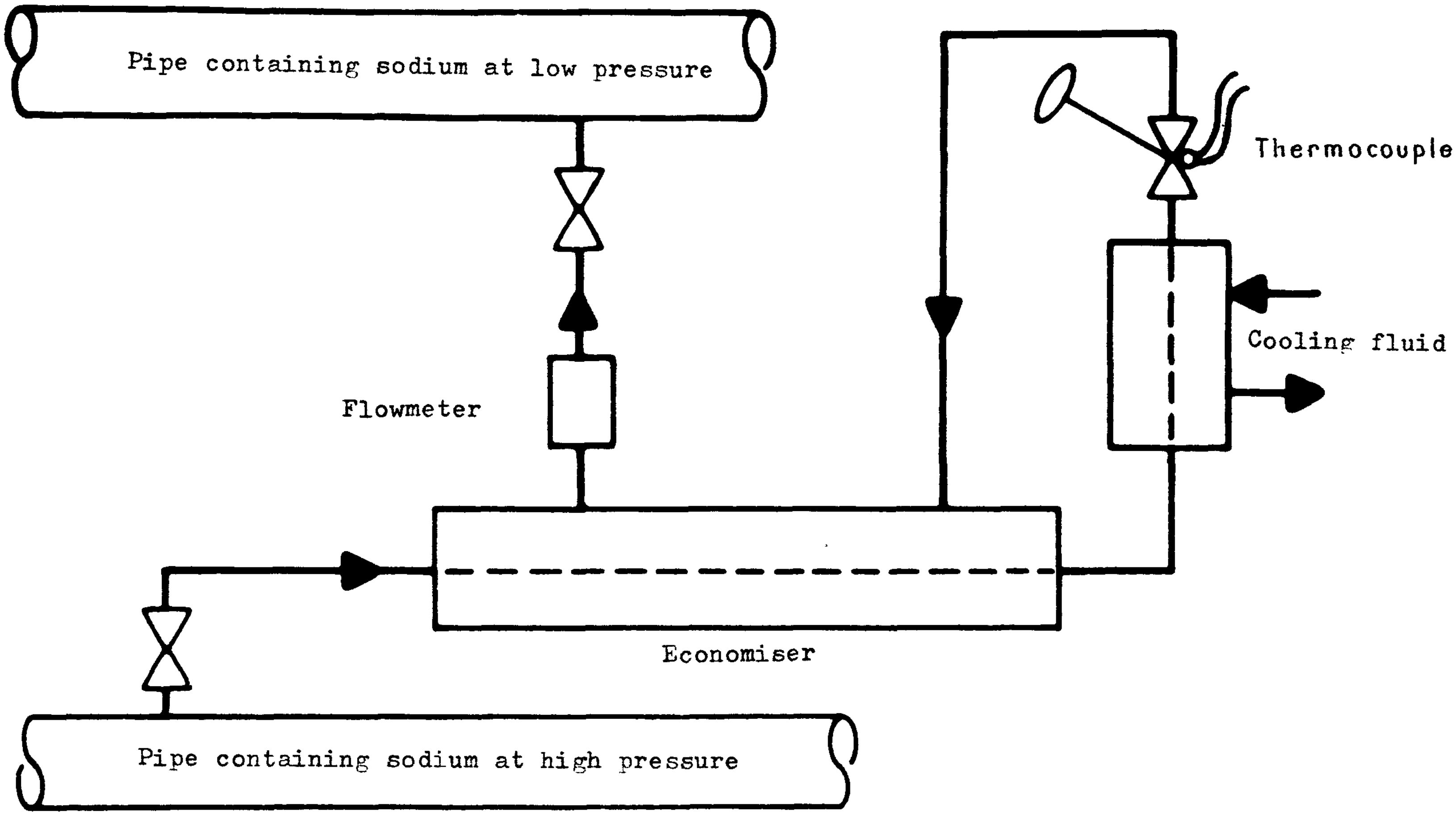
SRE - HOT TRAP

Figure X4



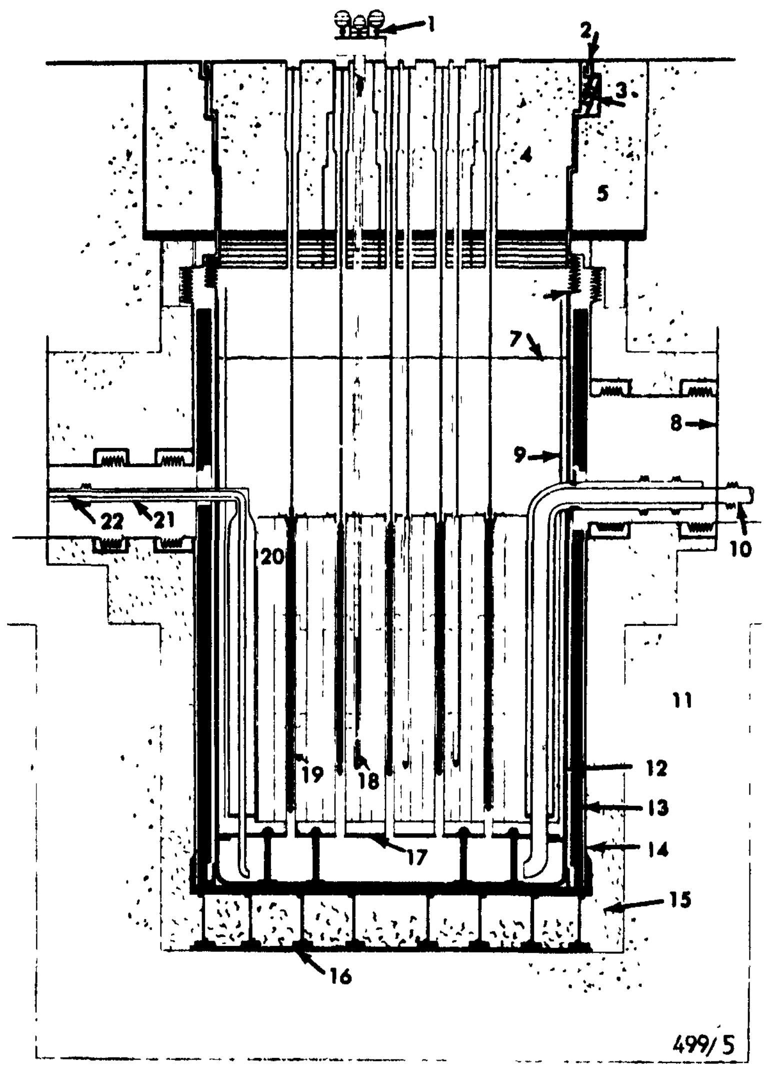
SRE - CROSS-SECTION OF THE MAIN SECONDARY SODIUM PUMP

Figure X5



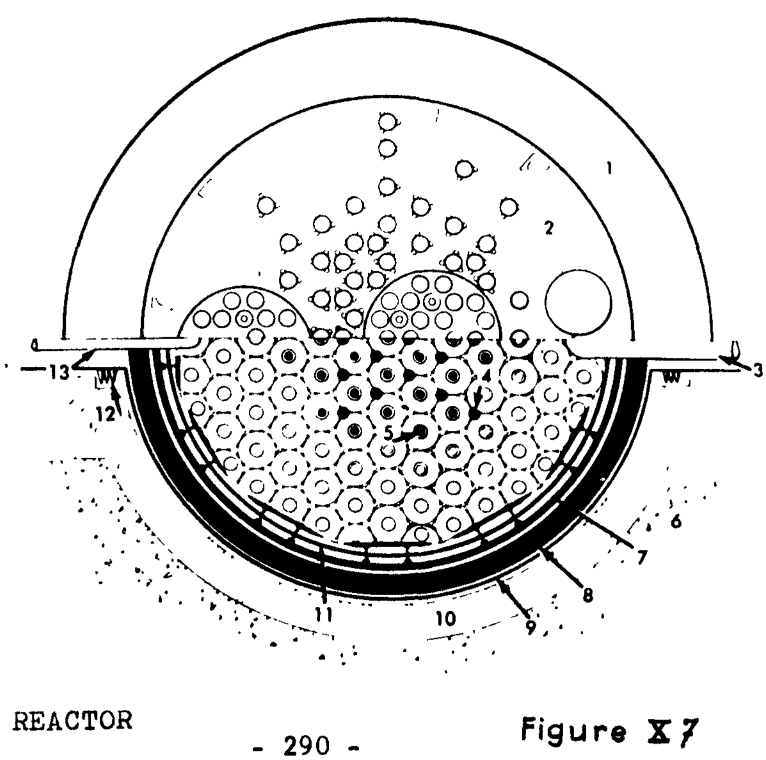
SRE – FOULING INDICATOR

Figure X6



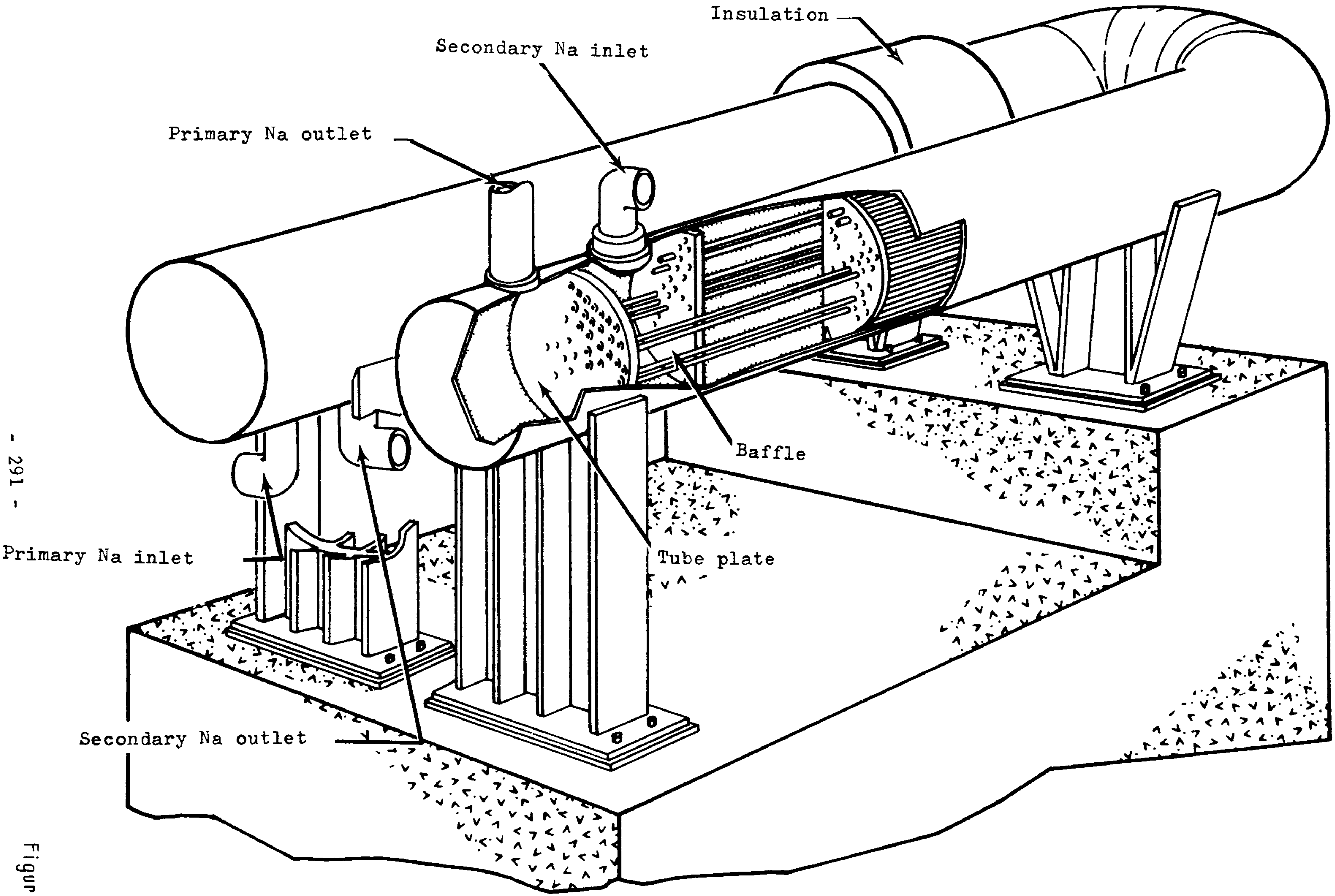
1. Regulator rod operating mechanism
2. Joint
3. Bearing
4. Revolving shield
5. Annular shield
6. Valves
7. Sodium level
8. Diaphragm
9. Inner lining
10. Main sodium inlet
11. Biological shield
12. Reactor vessel
13. Heat shield
14. Outer chamber
15. Insulation
16. Support plate
17. Grid
18. Regulator rod
19. Fuel element
20. Graphite box
21. Safety tube
22. Auxiliary sodium inlet

1. Annular shield
2. Revolving shield
3. Main sodium inlet
4. Regulator rod
5. Fuel element
6. Lateral biological shield
7. Reactor vessel
8. Heat shield
9. Outer chamber
10. Insulation
11. Inner lining
12. Valves
13. Auxiliary sodium inlet



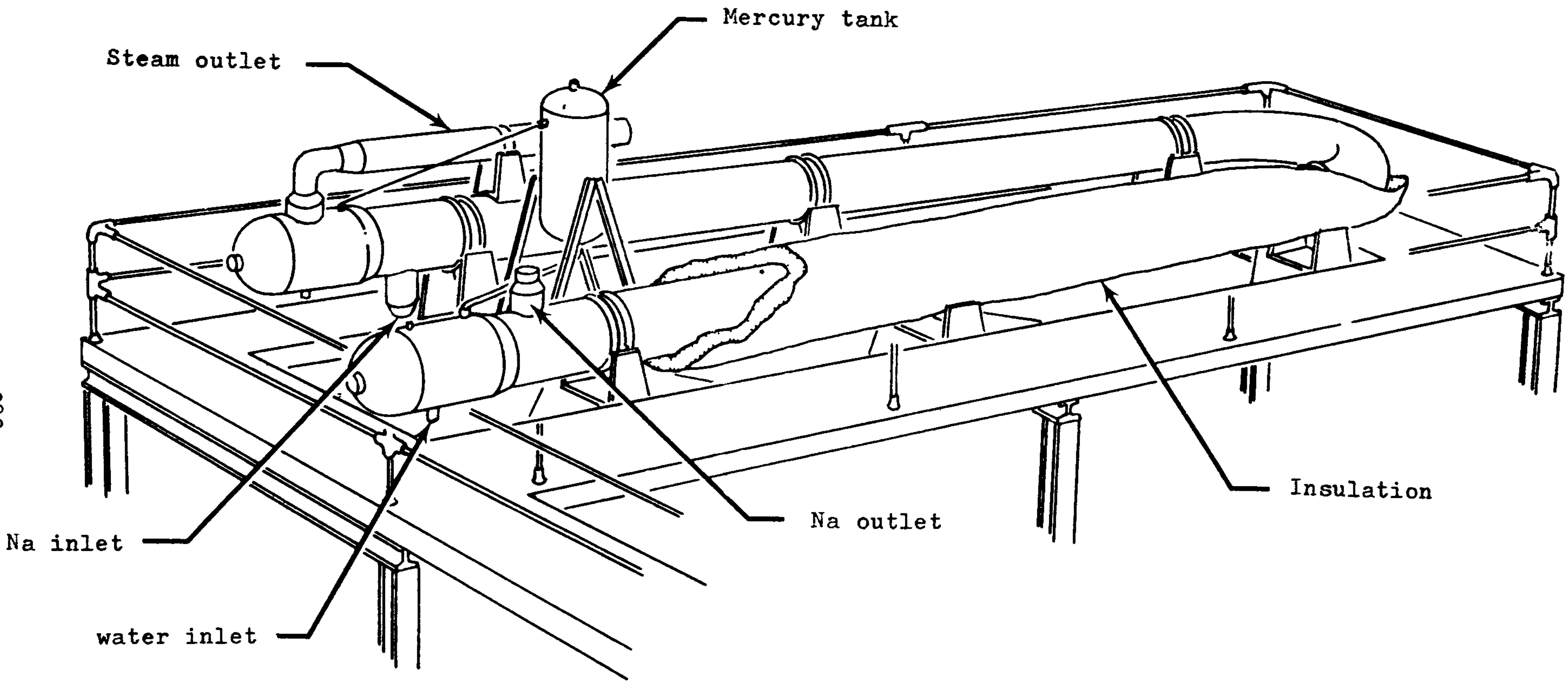
SRE – CROSS-SECTION OF THE REACTOR

Figure X 7



SRE — MAIN INTERMEDIATE EXCHANGER

Figure I 8



SRE _ STEAM GENERATOR

Figure X 9

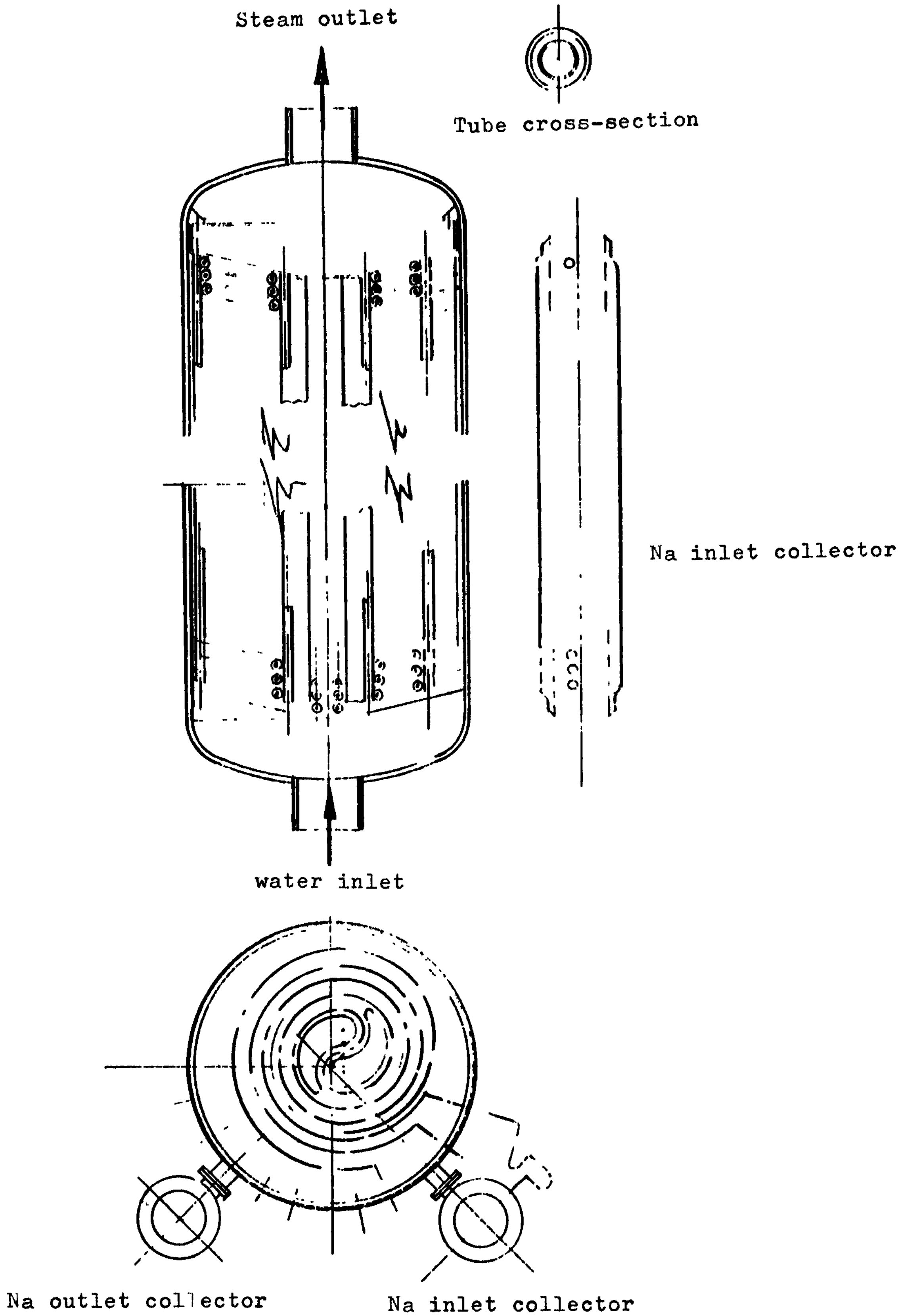


Fig: X 10 SRE NATURAL FLOW EVAPORATOR

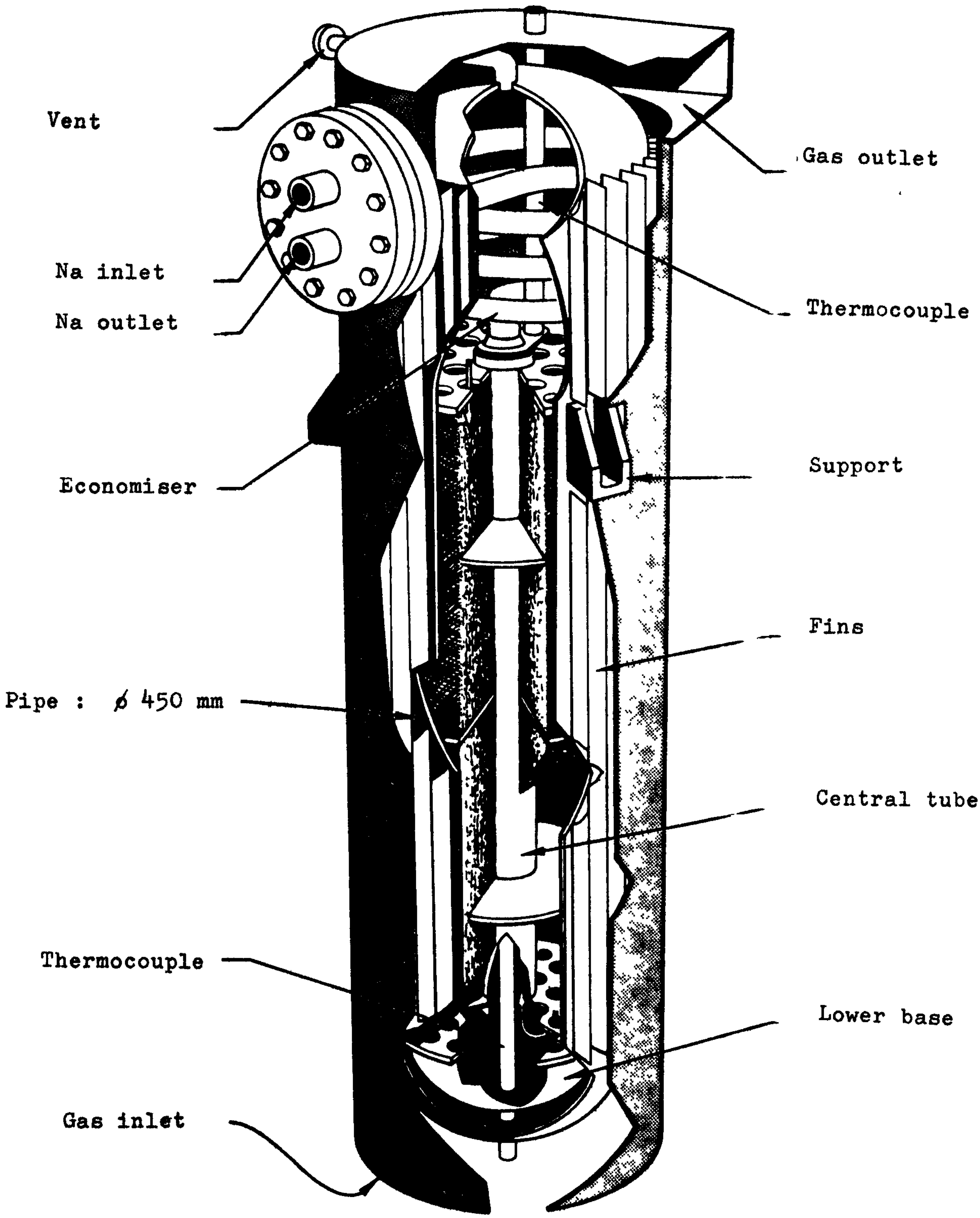


Figure : X . 11 . NEW COLD TRAP

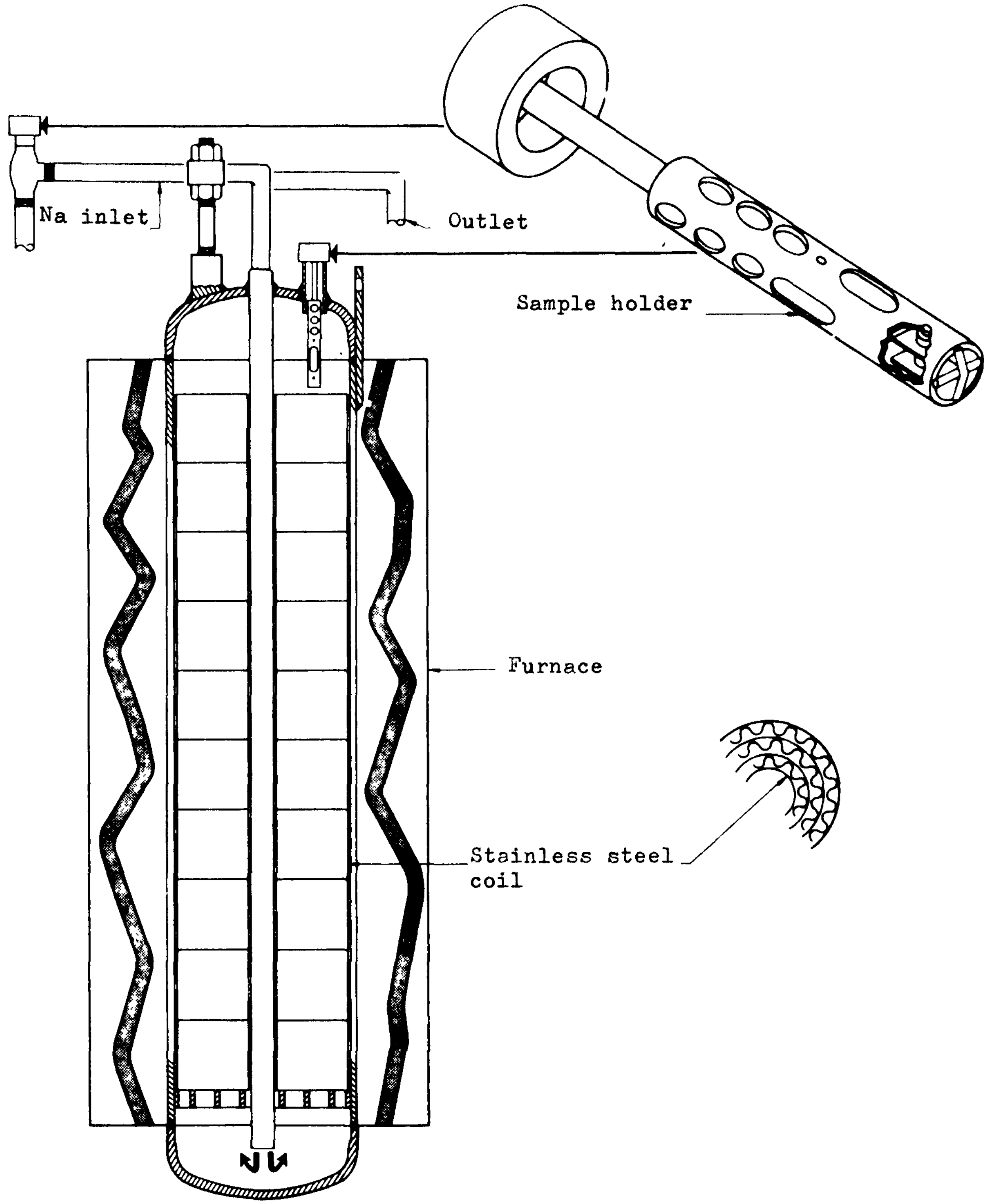
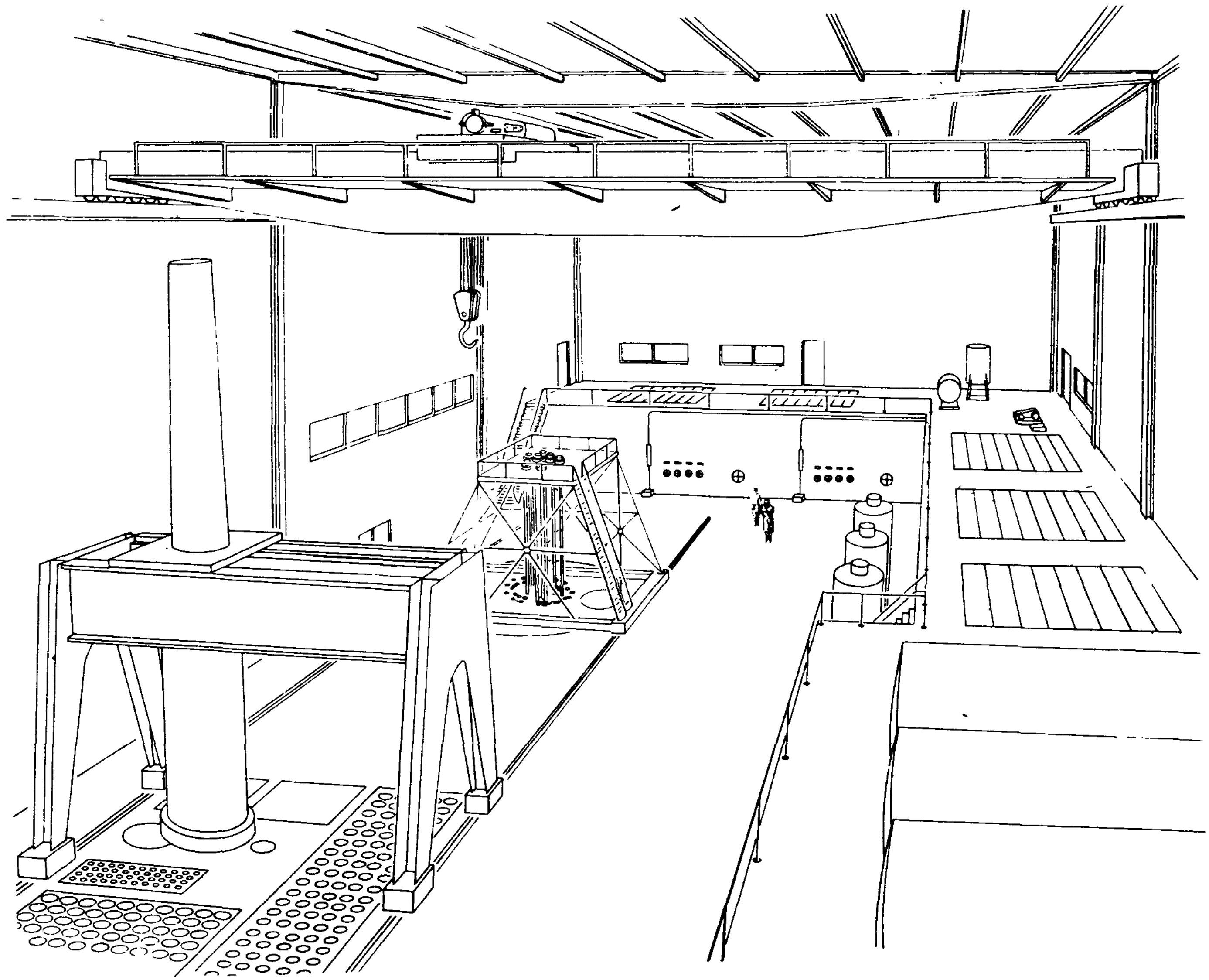


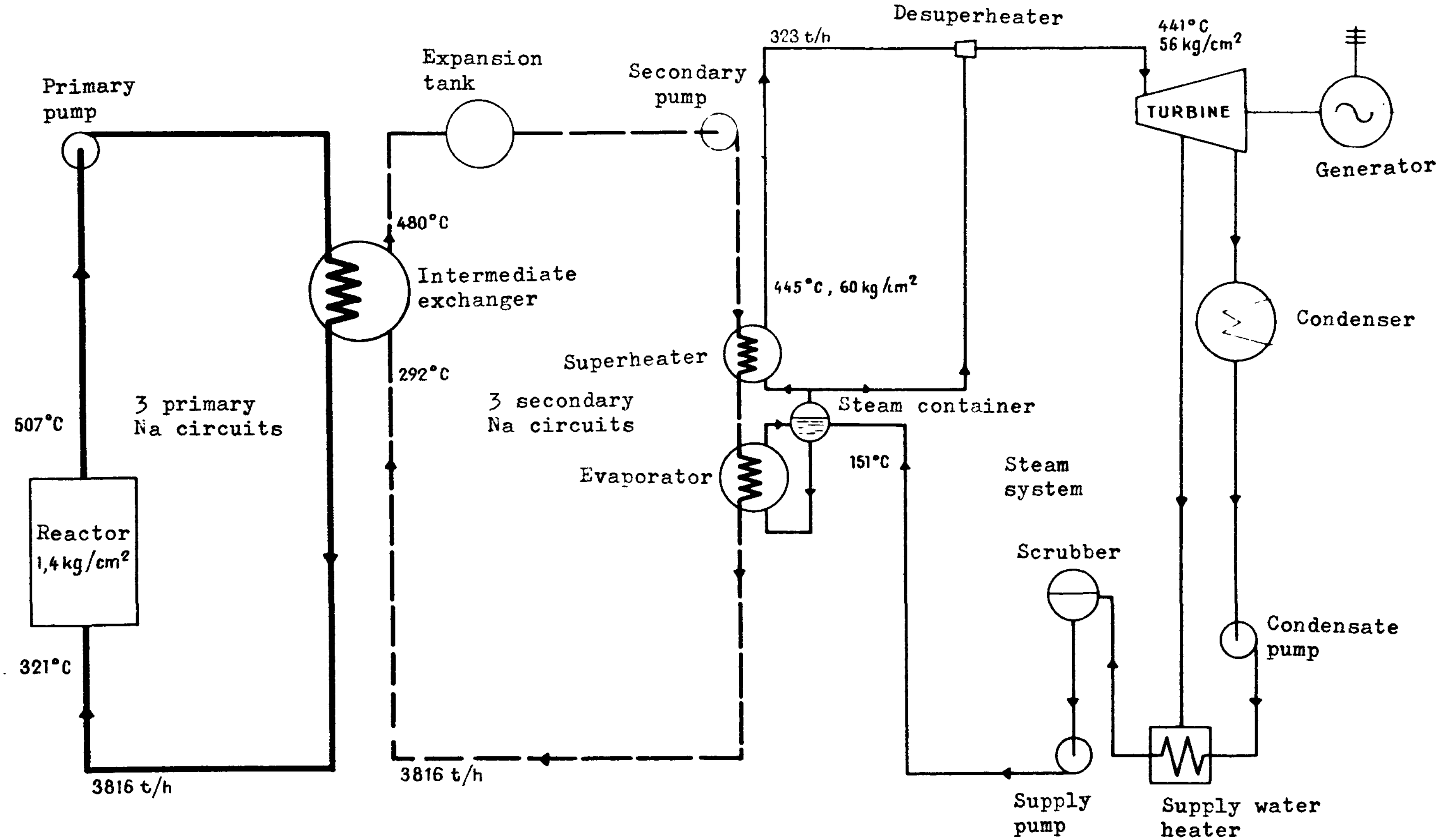
Figure : X - 12 .SRE. NEW HOT TRAP



HNPF

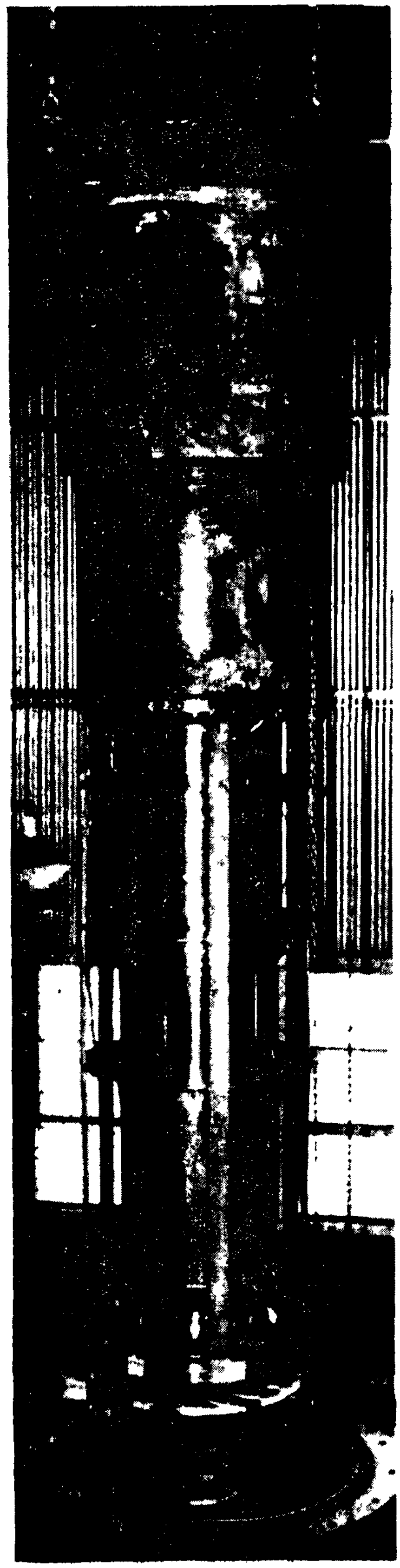
PRELIMINARY DESIGN FOR REACTOR HALL

Figure XI



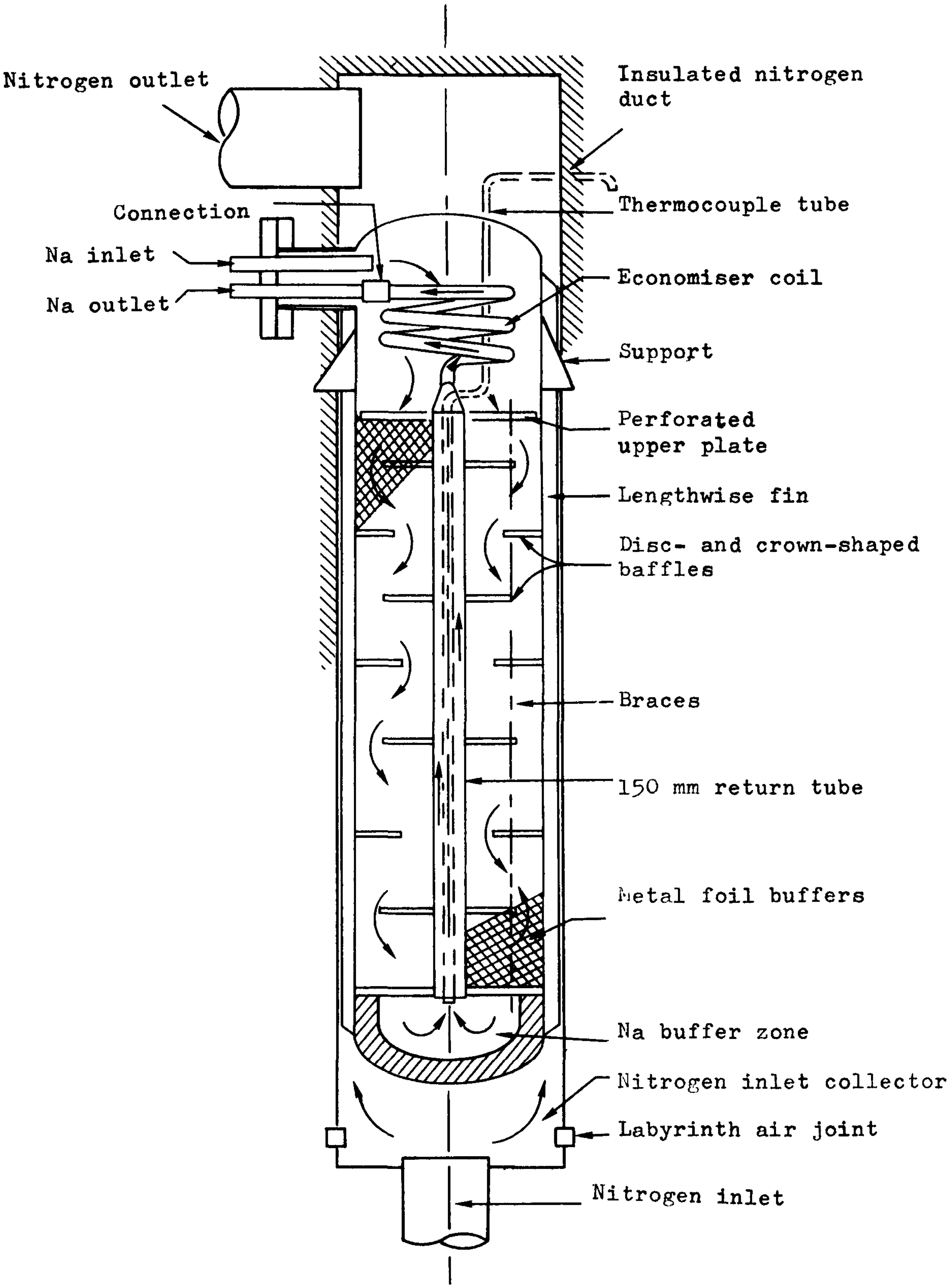
HNPF _ DIAGRAM OF THE CIRCUITS

Figure XI2



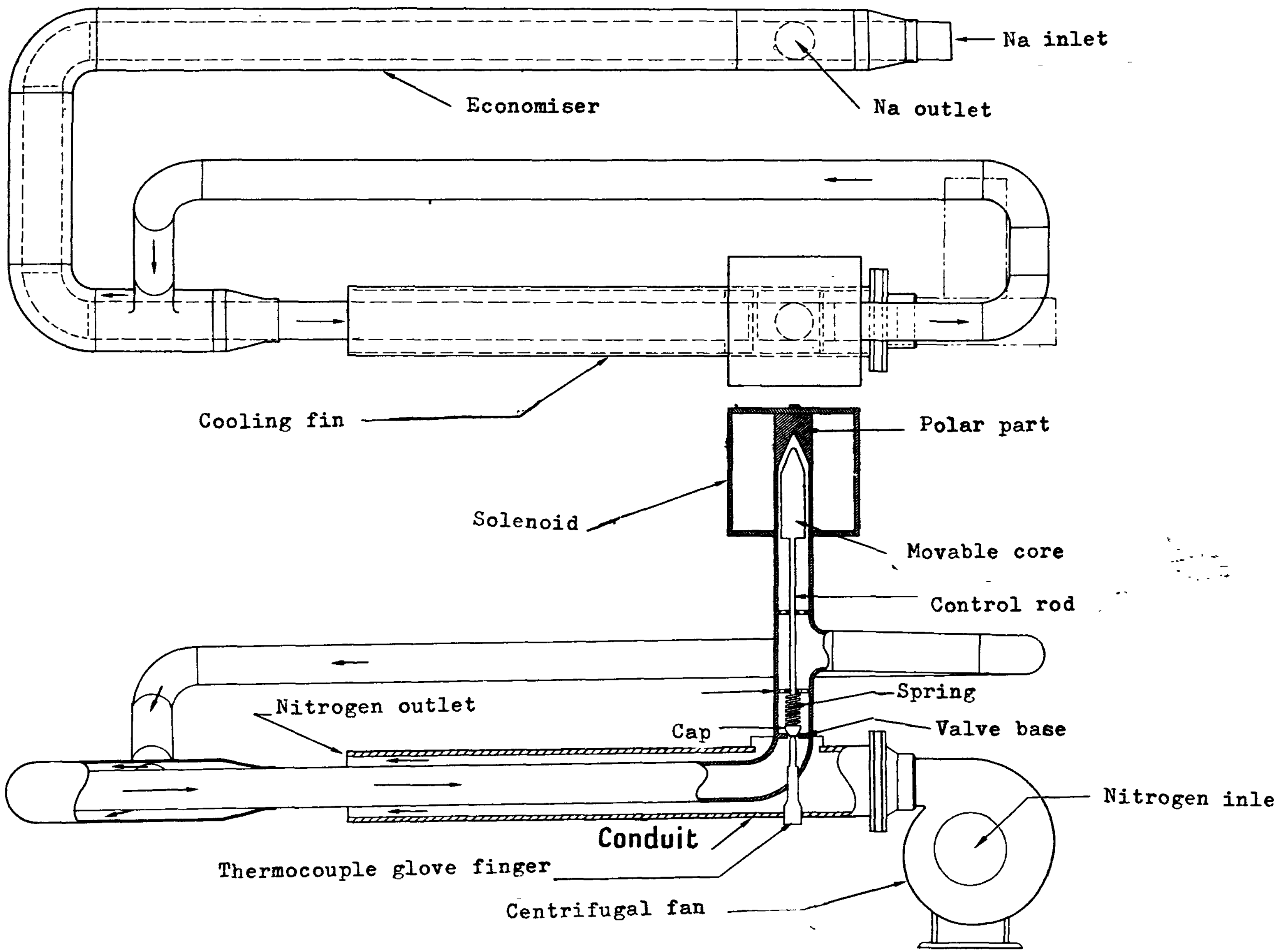
HNPF – PRIMARY PUMP

Figure XI3



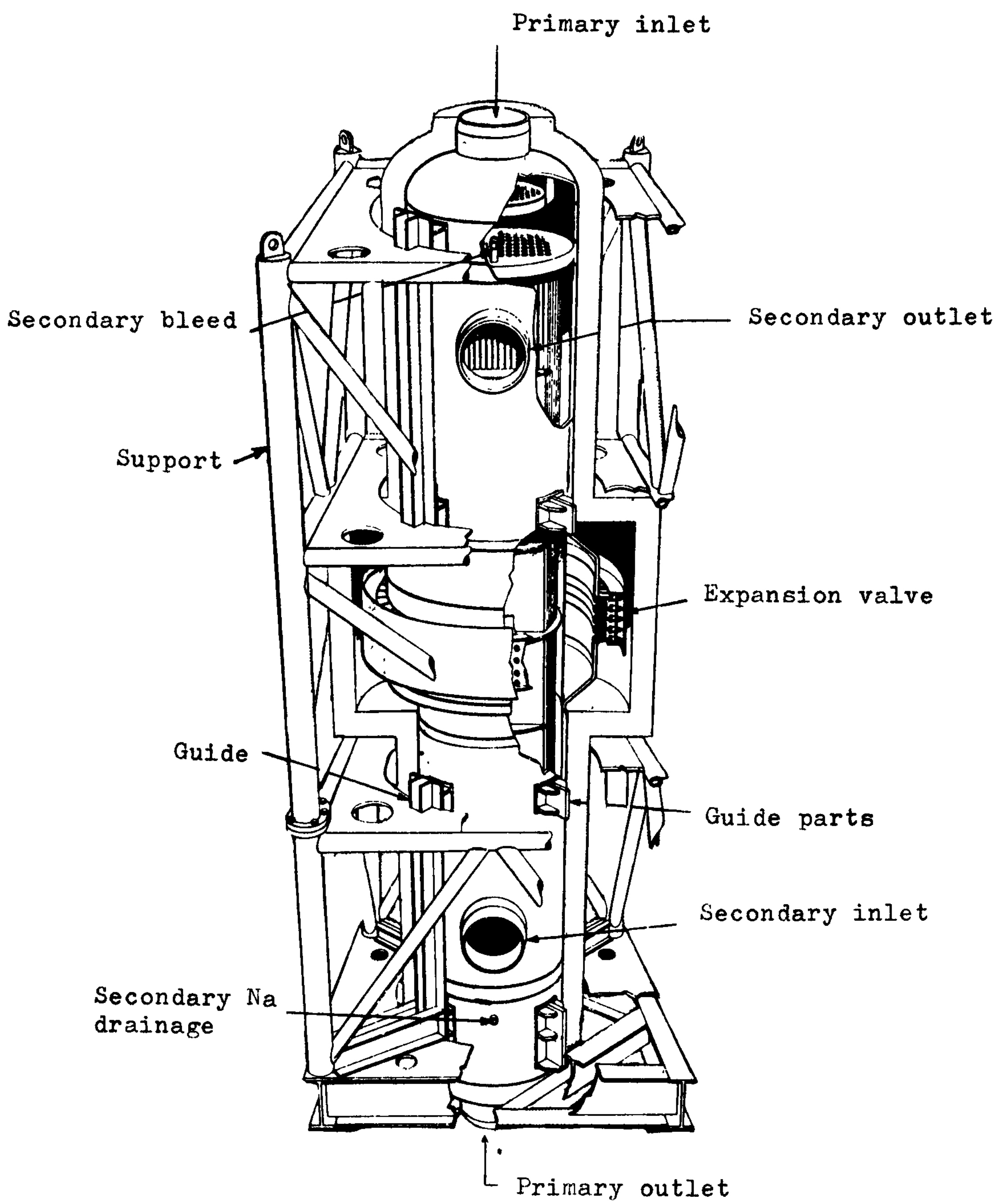
HNPF – COLD TRAP

Figure XI4



HNPF - FOULING INDICATOR

Figure XI5



HNPF – INTERMEDIATE EXCHANGER

Figure XI6

HNPF - STEAM GENERATOR

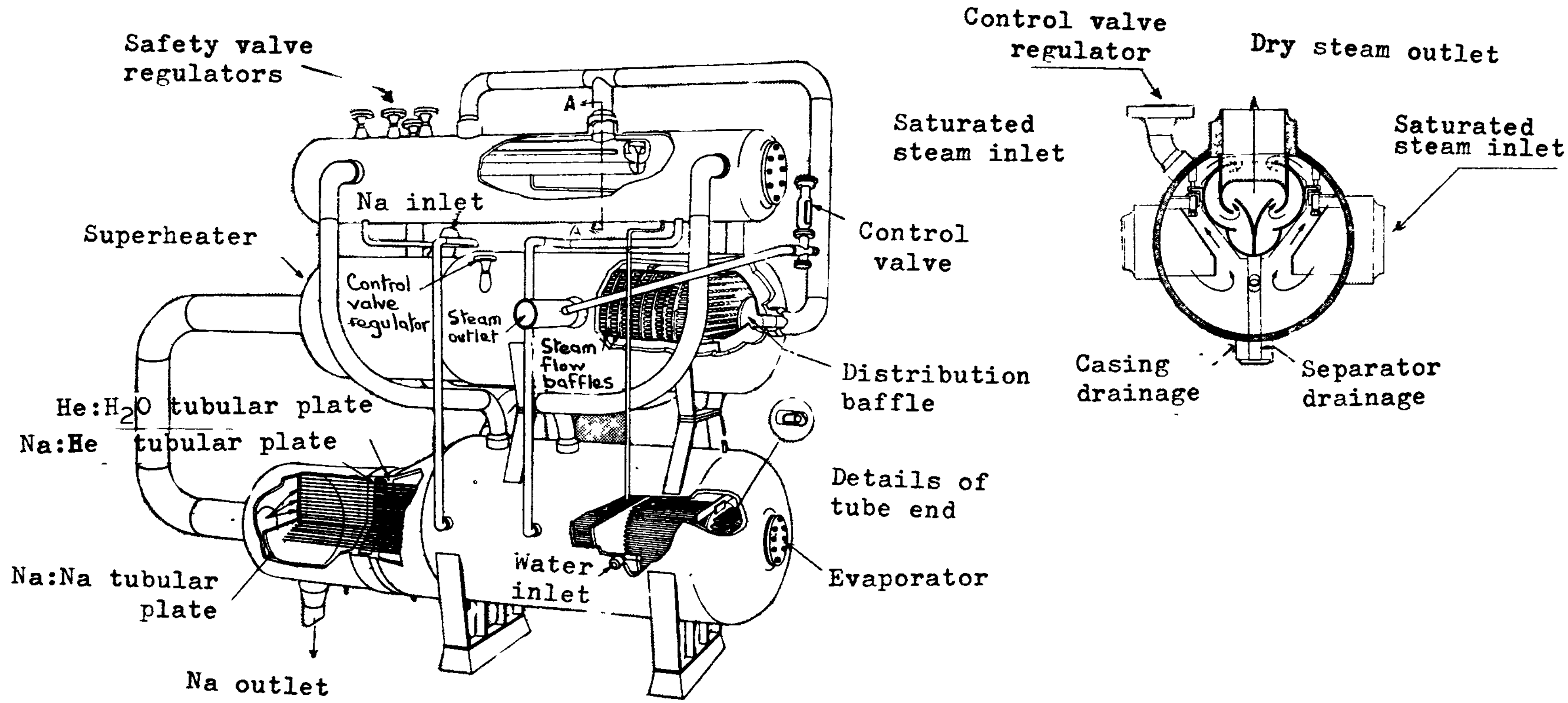
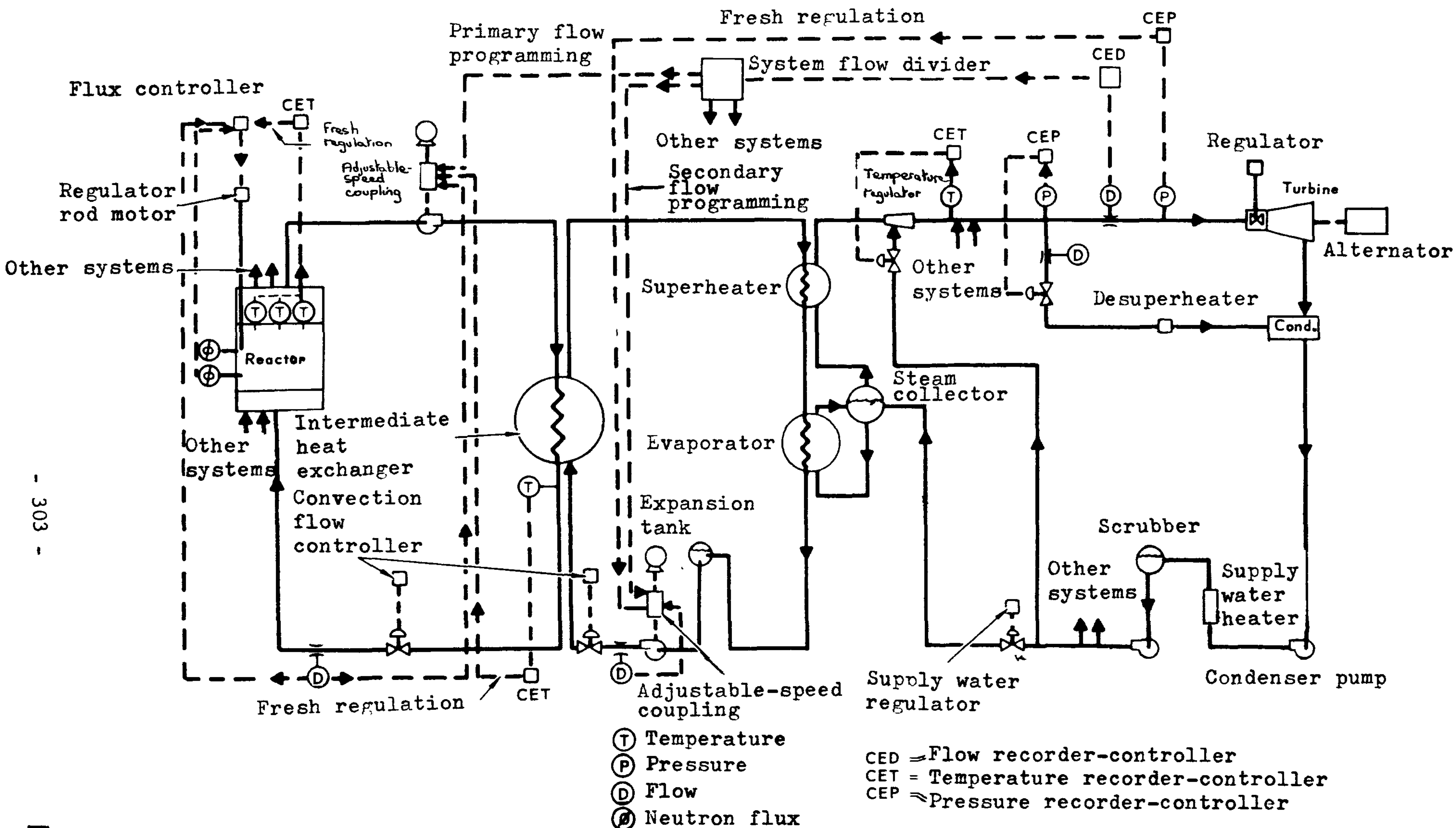
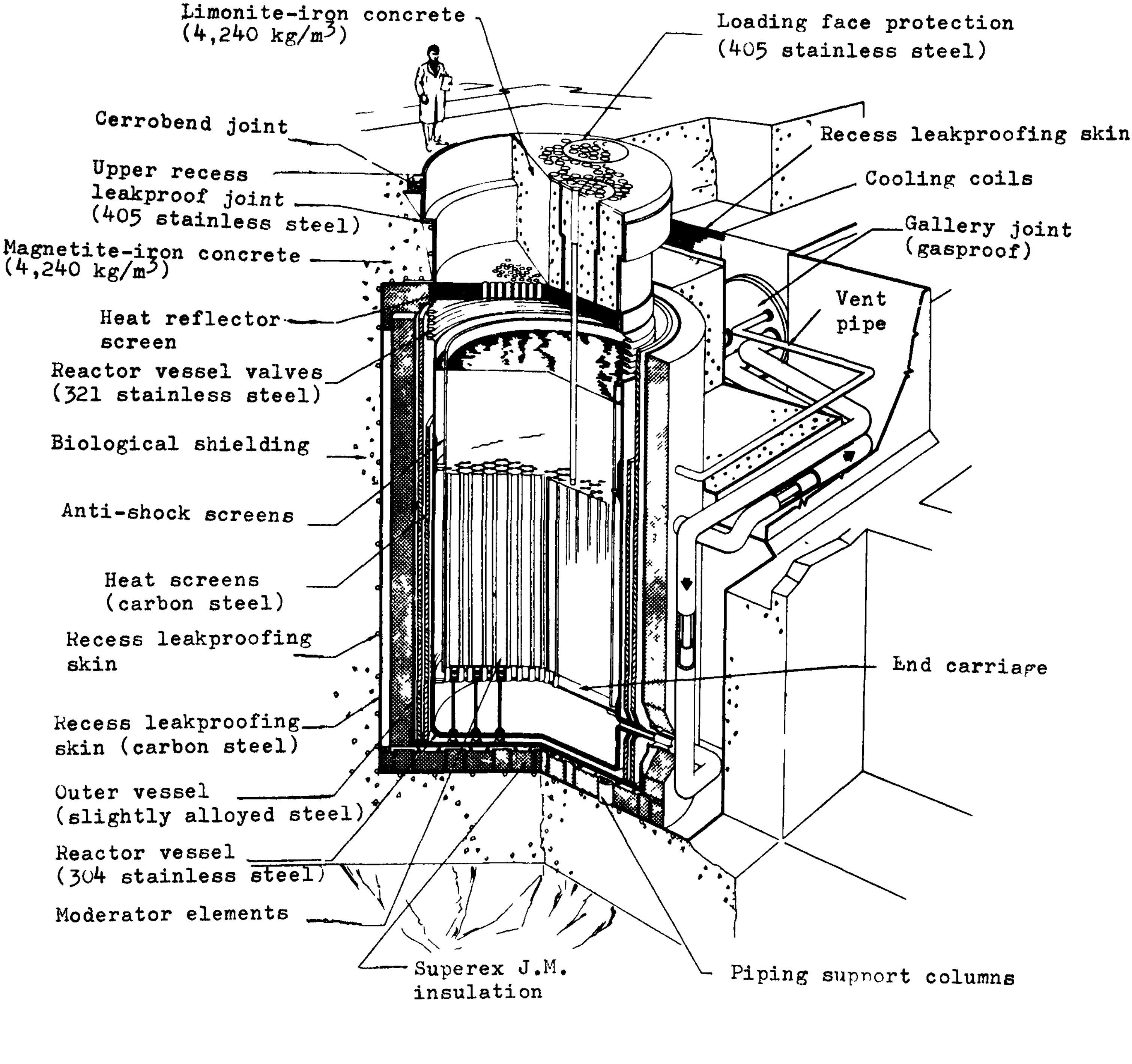


Figure XI7



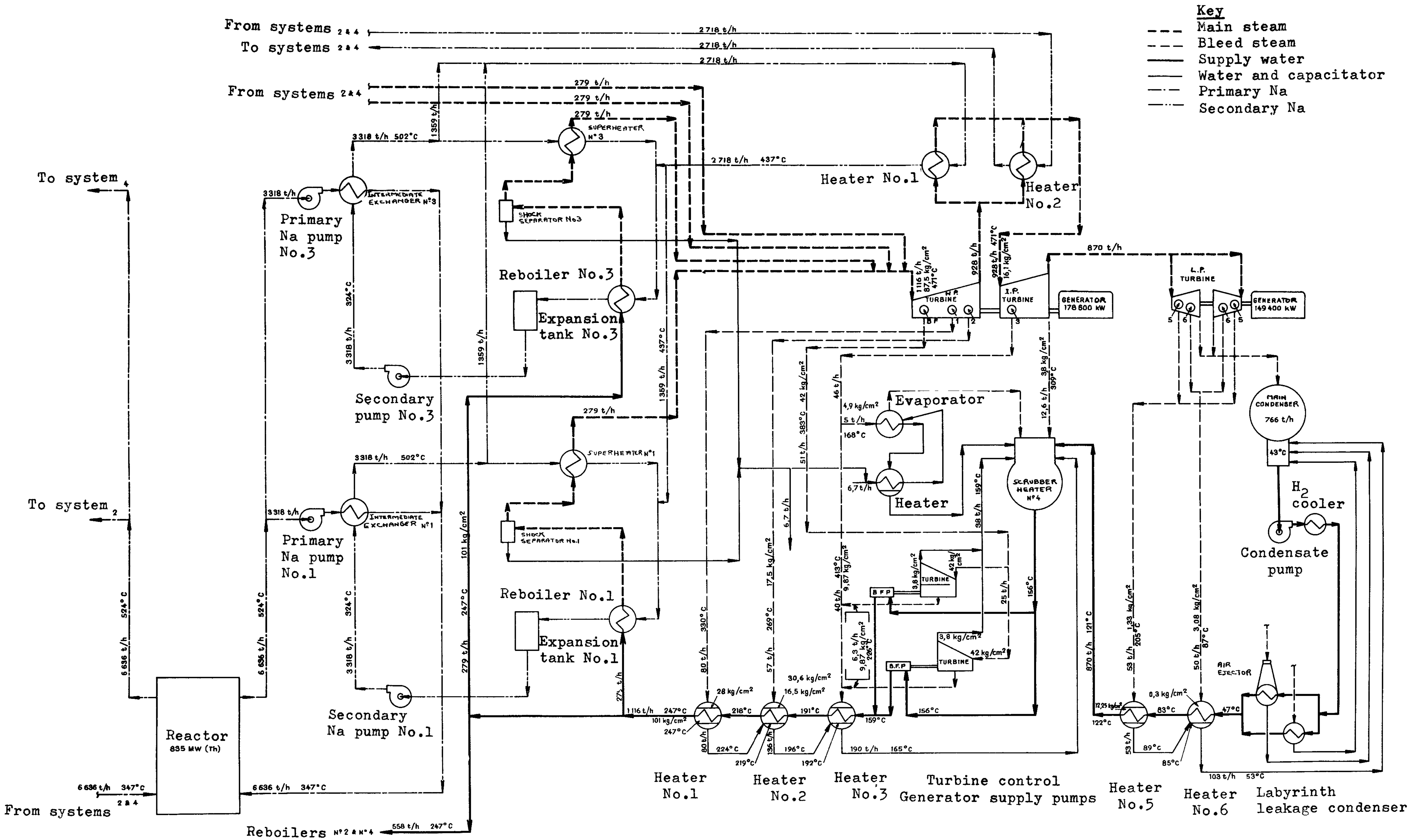
HNPF _ GENERAL CONTROL DEVICE

Figure XI8



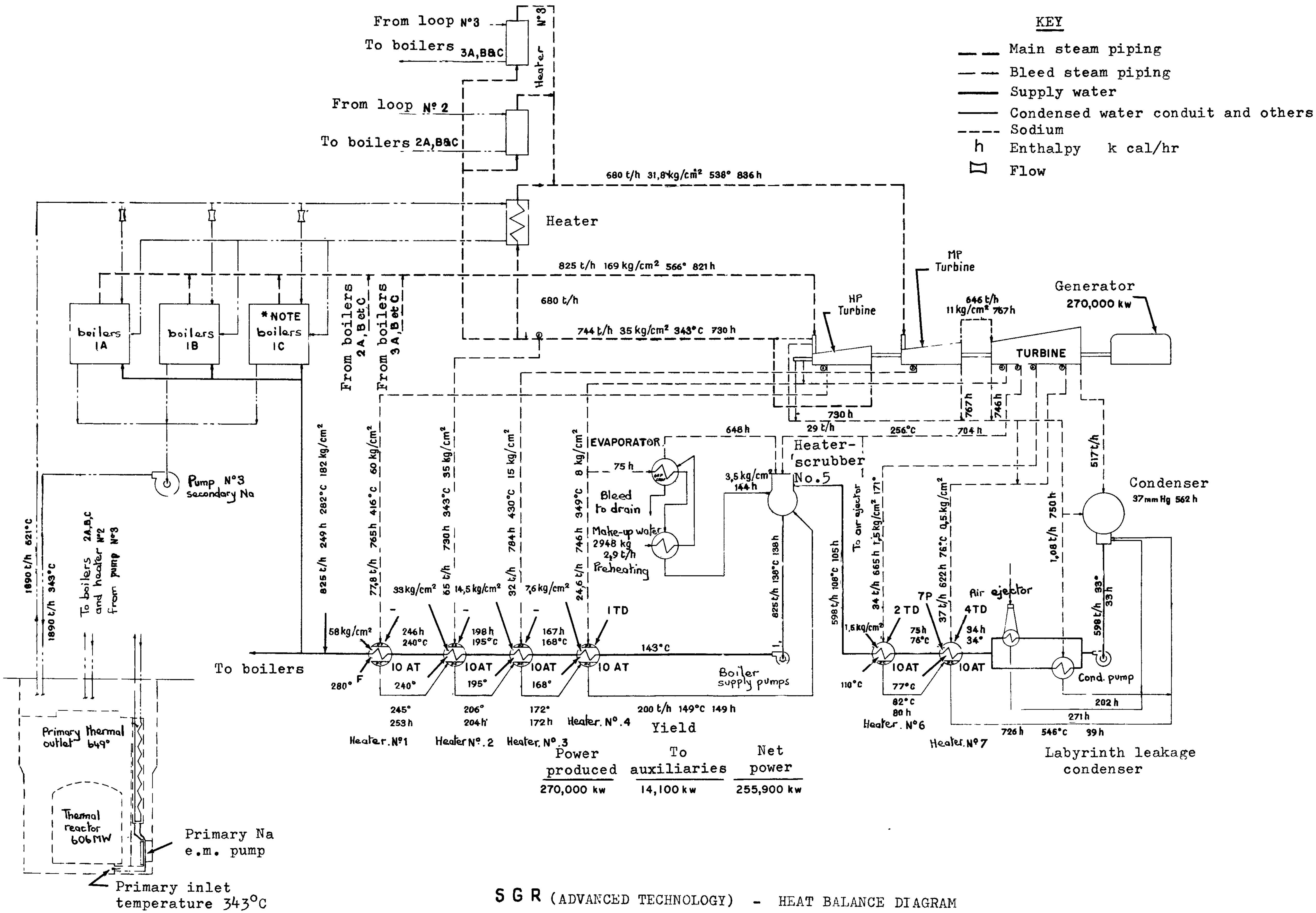
HNPF _ DETAILED VIEW OF THE REACTOR

Figure XI9



SGR (CURRENT TECHNOLOGY) - DIAGRAM OF THE SYSTEMS

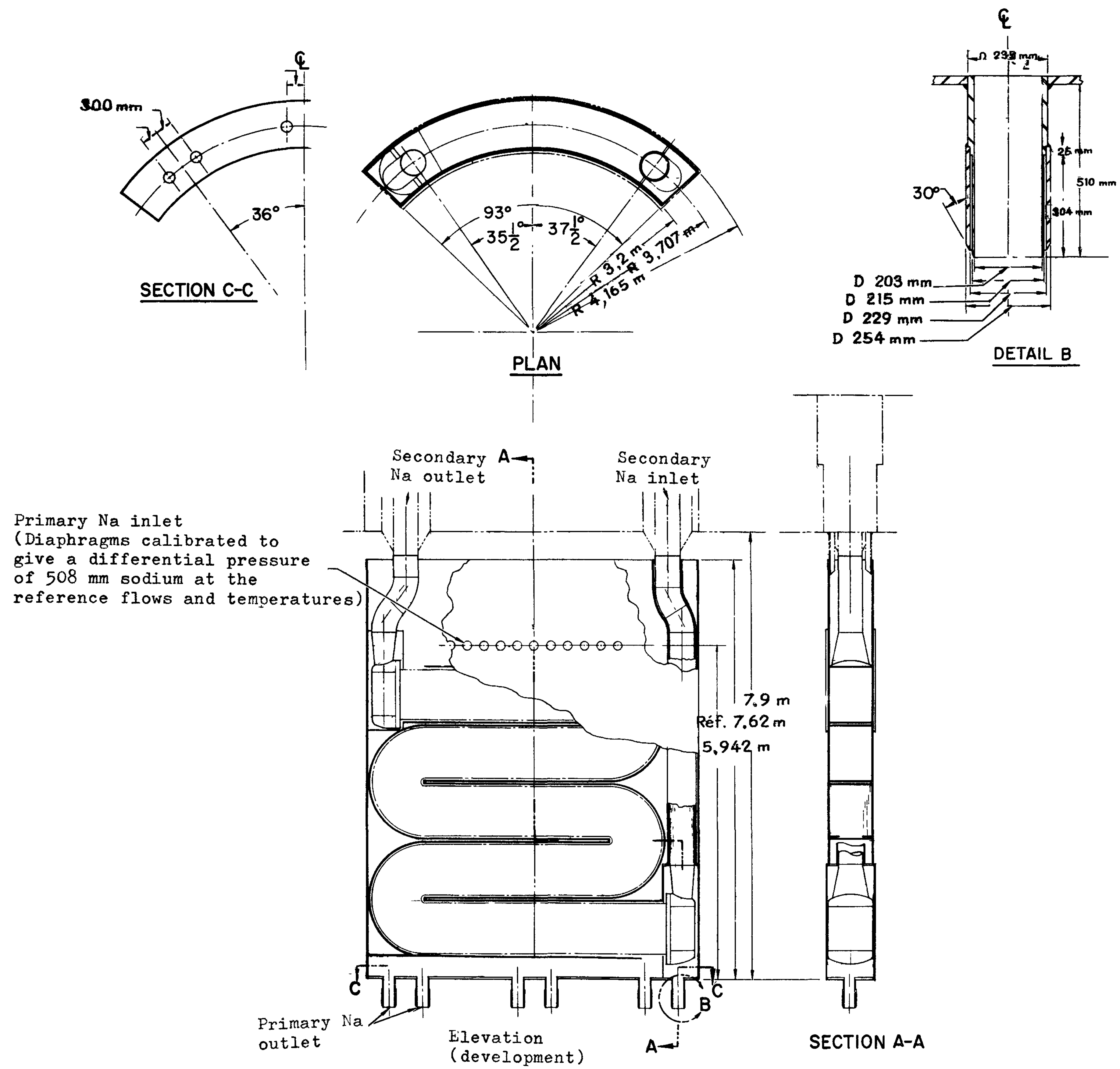
Figure XII 1

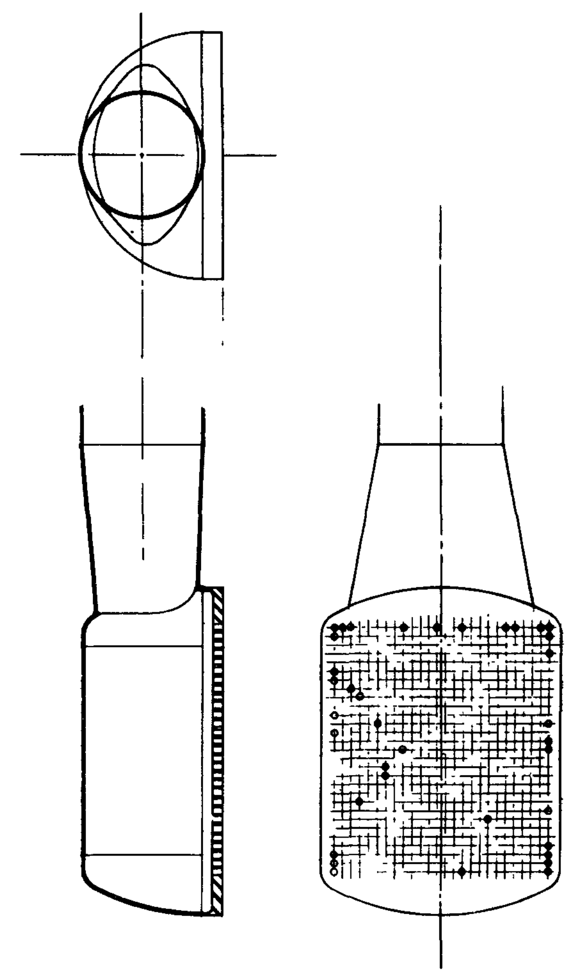


SGR (ADVANCED TECHNOLOGY) - HEAT BALANCE DIAGRAM

Figure XIII 1

Reference data		Primary (casing)	Secondary (tubes)
Flow	t/hr	1890	1890
Inlet temp.	°C	649	316
Outlet temp.	°C	343	621
Operating pressure	kg/cm^2		3.5
Ref. temp.	°C	691	691
Ref. pressure	kg/cm^2	0.5	7
Max.pressure loss	kg/cm^2	0.35	1,4

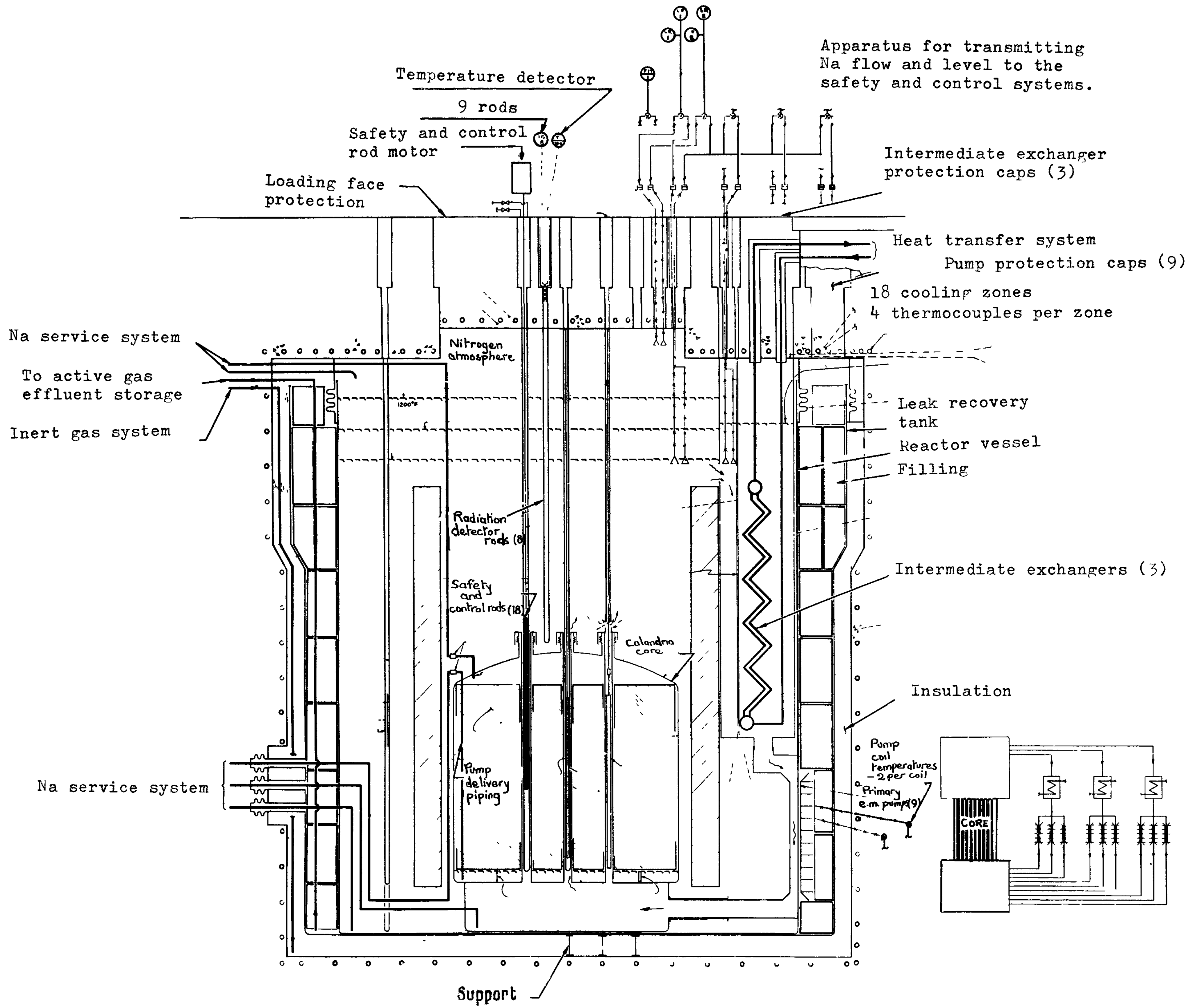




Detail of the collector

SGR - INTERMEDIATE EXCHANGER

Figure XIII 2



SGR (ADVANCED TECHNOLOGY)

- REACTOR (PIPING AND INSTRUMENTATION)

Figure XIII 3

TABLE I : ECONOMIC ASPECTS OF LIQUID-METAL-COOLED REACTORS

	EBR 1	EBR 2	EFFBR	PFFBR	DFR	SRE	HNPF	SGR (c.t)	SGR (a.t)
Capital expensiture (in millions of $)		Is not counted when a plant is built on an existing site.							
Ground			1,286	0,5		not disclosed		0,36	0,36
Fuel fabrication		2,764	3,793			0,328	2,639		
Construction cost (direct and indirect)	2,75	34,5	73,069	69,3		8,81 (approx.)	51,233 x	57,3	59,426
Research and development		28,307	31,441 x				16,236		
Total cost		65,571	104,510		75 (Millions $)		70,108 ⊕		
Original estimate of total cost		(in 1957) 29	48,500			3,5	25,110		
Price, KWe, net, installed, in $	13 000	2000	812	245		1350	680 - 575	190	232
Net electric capacity MWe	0,2	17	90	283	12	6,5	75 - 87	300	256
Annual expenditure									
Estimated operating cost for 1962, in millions of $	0,408	3,092				0,536			
Fuel cycle cost, in mills/Kwh			6.7 for 150 MWe	2.7			U-10Mo : 4.17 U-C 3.78	1.99	1.7
Total cost of power generation, in mills/Kwh			15.9 for 150 MWe	9			12.4	7.43	6.7
Date of estimate		1962	1964	1959		1962	1962		

HNPF: ⊕ Current estimates require 12 more

EFFBR: x AEC : 4,450; non AEC 26,991

HNPF: x AEC 30,642; non AEC 20,591

ML.P/590.1

TABLE II : GENERAL CHARACTERISTICS OF LIQUID-METAL-COOLED REACTORS

	EBR 1	EBR 2	EFFBR	PFFBR	LAMPRE 1	DFR	RAPSODIE	BR5	SRE	HNPF
GENERAL										
Type of reactor	heterogeneous, rapid	heterogeneous, rapid	heterogeneous, rapid	heterogeneous, fast	homogeneous, fast	heterogeneous, fast	heterogeneous, fast	heterogeneous, fast	heterogeneous, thermal, graphite-moderated	heterogeneous, thermal, graphite-moderated
Site	NRTS (Idaho)	NRTS (Idaho)	Monroe (Michigan)		Los Alamos (New Mexico)	Dounreay (Scotland)	Cadarache (B. du Rh.)	Obminsk (USSR.)	Santa Susana Mountains (California)	Hallam (Nebraska)
Constructor	ANL	ANL	APDA	APDA	LASL	UK AEA	CEA	USSR. Agency	AI	AI
Date of criticality	1951	1962	1963	Project	1961	1959	1967	1958	1957	1962
Capacity										
Thermal : MW	1,2	62,5	200 (planned for 430) *	775	1	72	20	5	20 (then 45)	240
Net electric : MW	0,2	16,5	60,9	283	0	12	0	0	5,7	75
Net electric yield, %	17	26,4	30,9	36,5		20			28,5	31,6
Max. heat flux in core, KW/m^2	997 ×	3240	2000	2100	2200	10.400	1800	1600	1320	1200
Av. heat flux in core, KW/m^2	777	2140	1200	1060	1450	5000	1160	1150	810	500
Mean specific rating Kw/kg	21,9/U_{235}	355/U_{235}	350/U_{235}	1150/Pu_{239}	40	286/U_{235}		100/Pu	250/U_{235}	240/U_{235}
Mean volume rating Mw/l core	0,174 (max : 0,235)	0,89	0,46	0,46		0,46	0,45 (max 0,7)	0,46	0,0042	0,0048
Fuel and material										
Fuel	U-2Zr	U + 5% alloy later Pu	U-10% Mo	PuO_2 - UO_2	Pu-Fe	U	PuO_2 - UO_2	PuO_2	Th - 7,6 U	U-10 Mo
% fuel enrichment (in atom %)	93,2	49	25,6	26/Pu_{239}		45,5	54		93 in terms of U present	3,6
% weight of each isotope in fuel	91,3/U_{235}, 6,7/U_{238}, 2 Zr	48/U_{235}, 48/U_{238} various alloys : 5	23/U_{235}, 67/U_{238}, 10 Mo	56,9/U_{238}, 23/Pu_{239} 8,3/Pu_{240}, O : 14,8	97,5 Pu, 2,5 Fe	29/U_{235} - 71/U_{238}	25% vol : PuO_2 ; 75% UO_2 (à 20%)		92,4 Th, 7,6 U	10 Mo, 90 U
Fuel mass Kg	52/U_{235}	366/U enriched	1940/U		25/Pu	220/U_{235}		45,7/Pu	91/U_{235}, 1160 Th	1000/U_{235}
Critical mass Kg	48/U_{235}	176/U_{235}	496/U_{235}	674/Pu_{239}	24/Pu	210/U_{235}		44,7/Pu	62/U_{235} in Th alloy	270/U_{235}
Geometry of fuel units	Cylinder : hexagonal base	Cylinder : hexagonal base	Cylinder : square base	Cylinder : hexagonal base	Cylinder : hexagonal base	Hollow cylinder, triangular design	Cylinder : hexagonal base	Cylinder : hexagonal base	Cylinder : triangular base	Cylinder : hexagonal base
Size										
overall height m	2,8	2,39	2,5	2,5	capsules	1,225	1,66	0,83	2,4	4,3
thickness between flats mm	70	58,9	67	100	9,4		49,8	26	diameter 71	408
No. of elements working in the core	217	47	105	188	140 capsules of Ta	345 fuel units	49	80	40	137 fuel units
No. of pins or rods per unit (excl. control and safety units)	36 rods	91 pins	140 pins	397 rods			37 pins	19 rods	5 rods	19 rods
Fuel cladding material	Zircaloy II	304 steel	Zr	304 steel	Ta + 0,1 W	Niobium + Vanadium	Steel	321 steel	304 steel	304 steel
Thickness of fuel cladding mm	0,55	0,226	0,125	0,225		0,5	0,45	0,4	0,254	0,254
Heat joint / thickness mm	0	Na / 0,15	Na / 0,1	Na	Na	Na	Na	Na	NaK / 0,254	Na / 0,635
Temperature										
Max. cladding temp. °C	390 tcon	584 ts	566 ts	681 ×	621 ts	600	440 ts (1st rate)	600	536 ts	507
Av. cladding temp. °C	327	460 ts		455	580 ts				425 ts	434
Max. fuel temp. in core °C	462 tc	650 tc	600		870	650	460 tc (1st rate)		620 tc	676
Av. fuel temp. in core °C	416 tc	527 tc			637			500	535 tc	477
Material										
Moderator									graphite / Zr cladding	graphite / steel cladding
Blanket and reflector	Natural U	depleted U	depleted U	depleted U + Mo	Armco iron	Natural U - no refl.	Natural U - steel	U + Ni	graphite / Zr or steel cladding	graphite
Reactor vessel	347 steel	304 steel	304 steel	304 steel	316 steel	321 steel	316 steel	Steel	304 steel	304 steel
Nuclear characteristics										
Average flux $n/cm^2/s$	$0,8 . 10^{14}$	$2,5 . 10^{15}$	$3 . 10^{15}$		$3 . 10^{14}$	$2,3 . 10^{15}$	$\simeq 10^{15}$	7×10^{14}	16×10^{13}	$8 . 10^{13}$
Maximum flux $n/cm^2/s$	$1,1 . 10^{14}$	$3,77 . 10^{15}$				$3,8 . 10^{15}$	$2,1 - 2,34 . 10^{15}$	$1 . 10^{15}$		$20 . 10^{13}$
Core										
Geometry	Straight prism with hexagonal base	Straight prism with hexagonal base	Cylinder	Cylinder	Cylinder	Straight prism with hexagonal base	Cylinder	Cylinder	Cylinder	Cylinder
Height cm	21	36,1	77,4	91,5	16	52,2	34	28	183	404
Diameter cm	18,7 (between flats)	48,3	83	152	16	52.2 (between flats)	38,7	28	183	336
Volume l	6,07	66	379	1535	3,06	130	40	17	4400	32.700

REFERENCES

× : These figures refer to the 3rd core
* : These figures refer to core A
ts : Surface temperature
tc : Central temperature
tcon : Temperature outside the cladding in the core

TABLEAU III-1 PRIMARY COOLING SYSTEMS

	EBR 1	EBR 2	EFFBR	PFFBR	LAMPRE 1	DFR	RAPSODIE	BR 5	SRE	HNPF	SGR Advanced technology
Vessel											
Material	347 stainless steel	304 stainless steel	304 stainless steel	304 stainless steel	316 stainless steel	316 stainless steel	316 stainless steel	321 stainless steel (or Ti-stabilised 316)	304 stainless steel	304 stainless steel	304 stainless steel
Geometry	Cylinder	Cylinder	Two cylinders	Cylinder	Cylinder	Cylinder : 2 walls	Cylinder	Cylinder	Cylinder	Cylinder	
Height (m)	4,5	4,9	11	11,2	3,8	6,3	8,6		5.68	10,4	11
Upper diameter (m)	0,8	2,3	3 & 4.4	2,74	0,3	3,2	2,35		3.35	5,8	8,3
Wall thickness (mm)	8	25,4	30 to 50	12,5		12,6 + 6,3	15		38	19	25
Channels											
Material	347 stainless steel	304 stainless steel	304 stainless steel	304 stainless steel	316 stainless steel	321 stainless steel	316 stainless steel	321 stainless steel (or Ti-stabilised 316)	304 stainless steel	304 stainless steel	304 stainless steel
Number of circuits	1	1 with 2 pumps in parallel, immersed in Na	3	3	1	24	2	2 : 1 single circuit for core and blanket - 1 small removable test circuit	2 (1 main - 1 aux.)	3	3
Characteristics of coolant flow											
Fluid	NaK	Na	Na	Na	Na	NaK	Na	Na	Na	Na	Na
Direction of flow in reactor	↓ blanket ↑ fuel Gravitational flow	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑
Flow											
Total mass flow t/hr	55	1600	4020 (for 200 MW)	11 280	19,9	1300	650	204	220	3816	5670
Total volume flow m^3/hr	66	1860	4560 (for 200 MW)	13 740	23,4	1500	750	24[illegible]	240	4626	
Temperature											
Reactor input °C	228	371	288	344	450	200	250 then 450	375	260	320	343
Reactor output °C	316	482	427	538	600	350	340 then 540	450	515	506	650
	88	111	139	194	150	150	90	75	255	186	307
Safety in event of a primary cooling system shutdown	Natural convection in stand-by cooling circuit with air exchanger equipped with fan.	Residual heat is dissipated by NaK flow through bayonet tubes; the NaK ends in an NaK-air exchanger	Natural convection in the circuits. Water make-up to steam generator. Auxiliary motors set up on the pumps produce 10% of full flow.	The small-flow aux. motors dissipate 4% of the thermal capacity of the reactor after 10 seconds. Heat is dissipated by slow Na flow through one or more circuits, the steam being discharged into the atmosphere.	Natural cooling of the reactor vessel by the ambient air	30' after shutdown only 3% power remains. As the e.m.pumps are supplied by 12 separate diesel units, a general cooling system shutdown is unlikely. The presence of sodium exchangers, or thermal siphoning in series in the circuits, provides additional safety.	Natural convection in the normal circuits. In the event of a piping break, stand-by cooling is possible by gas flow in the cladding around the vessel.	In the first few minutes, pump driven by stand-by unit, then natural convection in the circuits.	In event of shutdown an auxiliary circuit is put into service. If this circuit breaks down, the sodium flows by natural convection. Eddy current e.m. brakes permit the reduction in flow to be regulated.	Natural Na convection in the three circuits, each of which can deal with 4% of the full power of the reactor by natural convection.	In event of total shutdown, flow is by natural convection. If one of the 3 circuits stops, a regulator valve is used to reduce or halt the Na flow.

TABLEAU III-2 _ PRIMARY COOLING SYSTEMS

	EBR 1	EBR 2	EFFBR	PFFBR	LAMPRE 1	DFR	RAPSODIE	BR 5	SRE	HNPF	SGR Advanced Technology
Preheating		Electric immersion heating	Heating by induction and resistor	Induction heating. with thermal insulation	The circuit is the secondary loop of a transformer	When Na is used : heating of the primary system galleries by electric resistors	Heating with hot nitrogen in the cladding	Electric heating; heating around leak points is by air	Heating by electric resistor, using tubular heating elements	Heating by electric resistor.	Heating by resistor and transformers; where possible, AC heating of the pipes
Pumps											
Number	1 main pump 1 stand-by pump	2 main 1 auxiliary	3	3	2	24	2	2.	1 main, 1 auxiliary	3	3
Type	- 1 DC electromagnetic - 1 stand-by vertical shaft centrifugal pump	The primary pumps are of the free-level vertical centrifugal type, and can be removed. 1 fluid bearing, leakproof motor and labyrinth joint prevent Na vapor diffusion. Speed adjustable from 1 to 10. The auxiliary pump is electro-magnetic.	Removable, free-level vertical centrifugal pumps with 2 fluid bearings. Oil joint between argon and air with intermediate bronze mountings. Speed 900 rpm., adjustable from 35 to 100%. Aux. motor : 90 rpm.	Single suction vertical shaft centrifugal ones. Wound rotor motor, continuous operation Speed adjustable from 50 to 100%. Pump speed 870 rpm.	Monophased AC electromagnetic conduction pump	Removable flat linear electromagnetic pumps with stators	Removable fluid bearing, free-level vertical centrifugal pumps. Mechanical leakproofing by mountings. Speed adjustable from 1 to 6.	Free level vertical centrifugal pumps. Suspended shaft with bearing and joint in argon. Pressure in the motor chamber > pressure in pump	Vertical centrifugal ones with solid Na shaft joint. Speed of pumps : 1000 rpm.	Vertical centrifugal Speed adjustable from 0 to 102%	Electromagnetic
Flow (per pump) m^3/h	125	1100	2 680	4 484	22,6	72	375		240	1632	768
Delivery pressure - bars	1,75	5,8	6	5.5	1,4	1,65	2.25		0,96	3,7	2,8
Yield - %			77	80		24	70				
Supply	Rectifier 25 000 A _ 15 volts	2 480 V AC electric motors	3 60 Hz, 4800 V electric motors. Unitary capacity 745 kW. Auxiliary motors 3.7 kW.	Wound rotor electric motor. Unitary capacity 1117 kW. Auxiliary motor 3.7 kW		12 410 V diesel units. Unitary capacity 14.7 kW	Capacity 45 kW		DC motor. Adjustable speed. Unitary capacity : main pump motor : 18.5 kW auxiliary pump motor: 3.5 kW	AC induction motors Unitary capacity 250 kW	15 Hz, 220 V triphased system
Pumping capacity per pump - kW	18 - e.m. pump 10 - aux. pump	255	486	923					9,5		
Intermediate exchangers											
Number	1	1	3	3	None : cooling by air	24	2	2	1 main, 1 auxiliary	3	3
Type	Non-removable tube system	Removable tube system with ring immersed in the vessel, of the reflux and single flow type	Free-level, with removable reflux-type tube system.	Reflux type, with U tubes		Non-removable coaxial U-tubes	With casing and removable tube system. Reflux-type, free-level	Non-removable U-tube system in casing	With casing and U-tube systems. Reflux-type	Vertical with tube system and casing. The latter has an expansion band to absorb differential thermal expansion.	Reflux-type
Material	Nickel tubes	304 stainless steel	304 stainless steel	304 stainless steel		316 stainless steel	316 stainless steel		304 stainless steel	304 stainless steel	
Temperature											
- Primary Na input °C	316	482	427	538		350	340 then 540	450	515	507	650
- Secondary Na input °C	215	321	270	299		175	220 then 420	300	227	292	340

TABLEAU III-3 — PRIMARY COOLING SYSTEMS

	EBR 1	EBR 2	EFFBR	PFFBR	LAMPRE 1	DFR	RAPSODIE	BR 5	SRE	HNPF	SGR Advanced Technology
Coolant purification system											
Number of hot traps					3 in parallel	5	2 in //		2		
Number of cold traps	1	1	1	1	1 on drainage tank	15	2 in //	2	2	2	2
Fouling indicators		2	1	1	1	2 resistivity measurement devices 1 corrosion measurement device 1 sampler	2				
Inert gas	Argon	Argon	Argon	Argon	Helium	Argon	Argon	Argon	Nitrogen, helium	Nitrogen, helium	Nitrogen, helium

TABLEAU IV – SECONDARY COOLING SYSTEMS

	EBR 1	EBR 2	EFFBR	PFFBR	LAMPRE 1	DFR	RAPSODIE	BR 5	SRE	HNPF	SGR Advanced Technology
Channels											
Material	347 stainless steel	Ni-Cr 304 stainless steel	Low carbon steel with 2.25% Cr - 1% Mo	2.25% Cr - 1% Mo steel		316 stainless steel	316 stainless steel	Ti-stabilised 321 or 316 stainless steel	304 stainless steel	304 stainless steel	304 stainless steel
Number of circuits	1	1	3	3		12	2	2	2 (1 main, 1 auxiliary)	3	3
Fluid	NaK	Na	Na	Na		NaK	Na	NaK	Na	Na	Na
Flow											
Total mass flow	55.4	1172	6000 (for 300 MW)	11 280		1 400	670	204	270	3 816	5 670
Total volume flow	63,5	1372	6810 (for 300 MW)	13 740		1 610	760	260		4 626	
Temperatures in the intermediate exchanger											
Input ^{o}C	216	325	260	298		175	220, then 420	300	227	290	316
Output ^{o}C	306	460	400	493		325	310, then 510	430	482	480	620
Pumps											
Number	1	1	3	3		24 (2 in// per circuit)	2	2	2 (1 main, 1 auxiliary)	3	3
Type	Centrifugal with vertical shaft and gas leakproofing	Electro-magnetic	Centrifugal with vertical shaft	Vertical shaft, centrifugal pumps; single suction		Electro-magnetic	Vertical centrifugal pumps; axial delivery and lateral suction	Free-level centrifugal pumps with vertical shaft	Removable vertical centrifugal pumps with solid Na joint	Removable vertical centrifugal pumps with free surface and leakproof mountings	Electro-magnetic
Flow per pump m^3/hr	113	1 476	2 680	4 462		72	380			1 632	2 316
Delivery pressure kg/cm^2	1,76	4,2	1,75	2,5			1,5		2,9	3,7	2,8
Yield			80	80		24	70				
Supply		AC linear induction motor. Unitary capacity 460 kW	3 wound rotor induction motors. Unitary capacity 155 kW	Wound rotor electric motor Unitary capacity 521 kW		Independent diesel unit			DC motor. Unitary capacity : 37 kW for main pump. 3.5 for aux. pump	AC induction motor. Unitary capacity 225 kW	60 Hz, 4160 V triphased spiral rotor motor. Adjustable speed.
Pumping capacity kW	10			443					25		
Terminal exchangers											
Number	1	1	3	3		12	2	2 circuits {air, water}	1	3	3
Type	Triple-walled tubes Ni - Cu - Ni	Natural flow. Double-walled tubes without annular fluid.	Single-flow vertical type, alternate reflux-flow. Bayonet tubes. Fracture Diaphragm	Vertical one-pass single-wall tubes	The primary Na is cooled by air	Tubes immersed in copper	Cooling by air. Fin tubes	Water: double-walled tubes with Hg	Horizontal, with single flow and double-walled U-tube (with Hg in the annular section).	Casing and bayonet tubes with double walls	Single flow, with steam and water on tube side, and Na casing side
Steam : Pressure kg/cm^2	28,1	88	41,2	101		14		16	42	60	170
Temperature ^{o}C	280	455	406	466		280		400	440	445	566
Total flow t/hr	1.65	113	420	1131		90		5	27,2	336	825
Temperature of supply water ^{o}C	101	280	172	195		40			143	150 - 195	282
Purification system											
Number of cold traps	1 + 1 sintered steel filter	1	1	1		24	2	2	2 (1 main, 1 auxiliary)	1	1
Blanket gas	Argon	Argon	Argon	Argon		Argon	Argon	Argon	Helium	Helium	Nitrogen