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European Atomic Energy Community - EURATOM
Reactor Centrum Nederland, Den Haag, Netherlands

THE INTERIM DESIGN FOR A DUTCH SHIP REACTOR

by

M. BOGAARDT, M. MUYSKEN and W. HOFMAN
(RCN)

1965

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Reprinted from
3. Jahrbuch der Studiengesellschaft zur Förderung der
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The Interim Design for a Dutch Ship Reactor

By M. Bogaardt, M. Muysken and W. Hofman

Reactor Centrum Nederland, Den Haag, Netherlands

VERLAG KARL THIEMIG KG · MÜNCHEN 1964

The Interim Design for a Dutch Ship Reactor

By M. Bogaardt, M. Muysken and W. Hofman Reactor Centrum Nederland, Den Haag, Netherlands

1. Introduction

In December 1961 a contract was signed between the Netherlands Reactor Centre and the European Community for Atomic Energy regarding the joint development of an advanced pressurized water ship reactor. The development programme was based on a design study that had been carried out by the Reactor Centrum Nederland (R.C.N.) and which led to the establishment of a number of unknowns in the design. The target design that emerged from this study is referred to as NERO, Netherlands reactors design.

The programme contains roughly 16 development chapters which deal with items like core development, hydraulic studies, development of the steam generators, the pressurizer, pumps, etc. At present the programme is well under way. Special facilities have been erected at the R.C.N. reactor site and at the technological universities of Delft and Eindhoven. It is anticipated that in the course of the remaining development period, which is to end mid 1965, the bulk of the development problems will have been solved. For some of the items, such as the fuel irradiation programme, an extended period of research will be necessary.

Although at this moment the development work to be carried out under contract is far from completed, it was thought to be opportune to prepare at this stage a design that reflects the present state of knowledge and technology, particularly so because it is felt that sufficient knowledge and information has already resulted from the NERO Development to serve as a sound basis for the design of an advanced pressurized water reactor system. This design is somewhat less advanced than the NERO target design, as some of the NERO target design parameters which still have to be proven in the NERO Development Programme have been modified to essentially proven values, or values which are believed to be safe and reliable.

When new data and information concerning core design or performance result from the development work under the NERO Development Programme, the design will be subsequently improved or modified to satisfy the new data, requirements or insight. Thus the core design is constantly kept up to date with the ultimate state of the technology. Especially on burnable poisons, burn-out effects under direct influence of a non-heated wall and steam generator performance, more essential information is required to prove the present design. It is expected, however, that this information will result from the NERO Development Programme in due time, and will confirm our belief that the values taken for the various design parameters will be feasible and guaranty safe and reliable reactor operation with appropriate safety factors.

Some of the characteristics of the original NERO design were:

a) Uranium-dioxide as fuel, with burnable poison incorporated in the fuel to achieve a 4 year core lifetime without excessive control rod requirements.

b) Internal recirculation of primary coolant in the reactor pressure vessel to achieve high burn-out ratios in the core with an as compact as possible external coolant circuit, and to enhance the safety of the reactor.

c) Moderately superheated steam to improve the cycle efficiency and to ease the problems of water extraction from the steam system and the steam turbines.

It was decided in the second half of 1963 to evaluate the feasibility to incorporate steam reheat between the low pressure and the high pressure turbine. Preliminary studies have indicated that reheating with live steam taken directly from the steam generators is technically feasible, will yield an improvement in the overall cycle efficiency in the order of 1 per cent, will ease the design of the turbine and will consume only a modest space in the engine room. More detailed studies are presently being carried out and it is our belief that incorporation of the reheater is an improvement which is economically justified.

To avoid confusion and eventually misinterpretation of the various parameters used in the NERO target design and the design described in this paper, this latter design is given the code name NEREUS. This NEREUS design is based on the following considerations:

a) The design is based as much as possible on the NERO target design and the experimental data, knowledge and fabrication technology already obtained from the work carried out in the NERO Development Programme.

b) The design parameters are taken as advanced as our present knowledge of the technology allows, without, however, taking unknown risks which may endanger the safety or the reliability of operation.

c) The design of the various systems is such that the advanced NERO target design parameters can be incorporated once they have proven to be feasible.

d) The design is applicable to a 65,000 tons dwt oil tanker with about 22,000 shaft horse power.

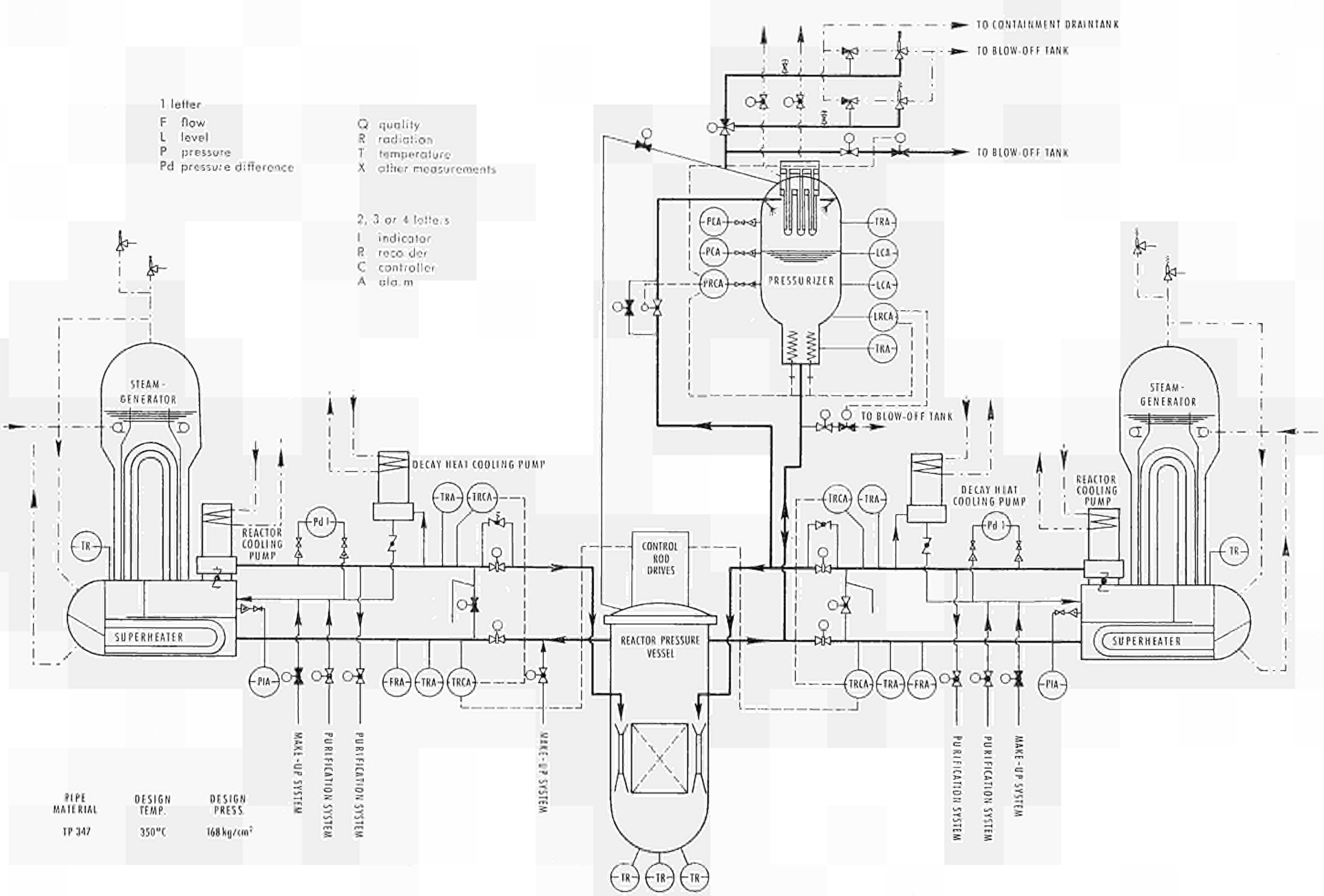
e) The design is based on the "Provisional Rules for the Classification of Nuclear Ships" of Lloyd's Register of Shipping, the International Conference on the Safety of Life at Sea, the Recommendations of the International Commission on Radiological Protection, and the applicable Dutch Rules and Codes.

The NEREUS design as detailed further in this paper is still not completed. Some of the parameters given are to be considered as preliminary values. The main design parameters, however, are firm values which will not be changed unless data resulting from the NERO Development Programme will indicate this to be necessary.

2. Summary description

The NEREUS reactor system is designed to serve as a nuclear propulsion system for a 65,000 tons dwt, 22,000 shp oil tanker. This results in a nuclear steam supply system with a reactor power of 67 MW thermal, delivering moderately superheated steam of 40 kg/cm^2 and 280° C at the superheater outlet.

In the design the safety, the compactness, the operation reliability and the flexibility are emphasized. Especially in considering the safety, maximum attention is given to the reactor safety features, the emergency cooling system and the incorporation of the reactor and its containment vessel into the ship structure. Also the safety requirements as detailed in Lloyd's Provisional Rules are fully incorporated into the design. To ease operational problems concerning radioactive waste storage and disposal, the various systems are designed to release minimum quantities of radioactive effluent.



1 letter

F	flow
L	level
P	pressure
Pd	pressure difference
Q	quality
R	radiation
T	temperature
X	other measurements

2, 3 or 4 letters

I	indicator
R	recorder
C	controller
A	alarm

PIPE MATERIAL	DESIGN TEMP.	DESIGN PRESS.
TP 347	350°C	168 kg/cm²

Fig. 1: Engineering diagram primary system

The reactor core is designed to operate 1200 days at its maximum continuous power rating of 67 MWt, which is evaluated to be equal to 4 calendar years of operational service of the ship. Each 4 years a complete refuelling of the reactor core loading will be required.

Reactivity control is performed both by the 12 Y-type control rods, containing boron carbide as absorber, and the burnable poison, also in the form of boron, in the fuel. A chemical shut down system, by means of which a boron solution can be introduced into the primary system, is provided as an additional, completely independent shut down mechanism, should the control rods fail to function properly and not be able to shut the reactor down.

The reactor primary coolant system (fig. 1) consists of 2 closed cooling circuits connected in parallel to a single reactor pressure vessel containing the reactor core. The reactor is a one pass flow core, with internal recirculation within the reactor vessel (fig. 2). By means of hydraulic ejectors the pressure vessel inlet flow is mixed with part of the core outlet flow before entering the reactor core at the bottom side. The flow through the core is upwards in one pass. The hydraulic ejectors arrangement is such that without forced flow sufficient natural circulation will be induced by the decay heat of the core to transport the heat from the core to the upper plenum in the reactor vessel where it is removed either by the decay heat removal system or the

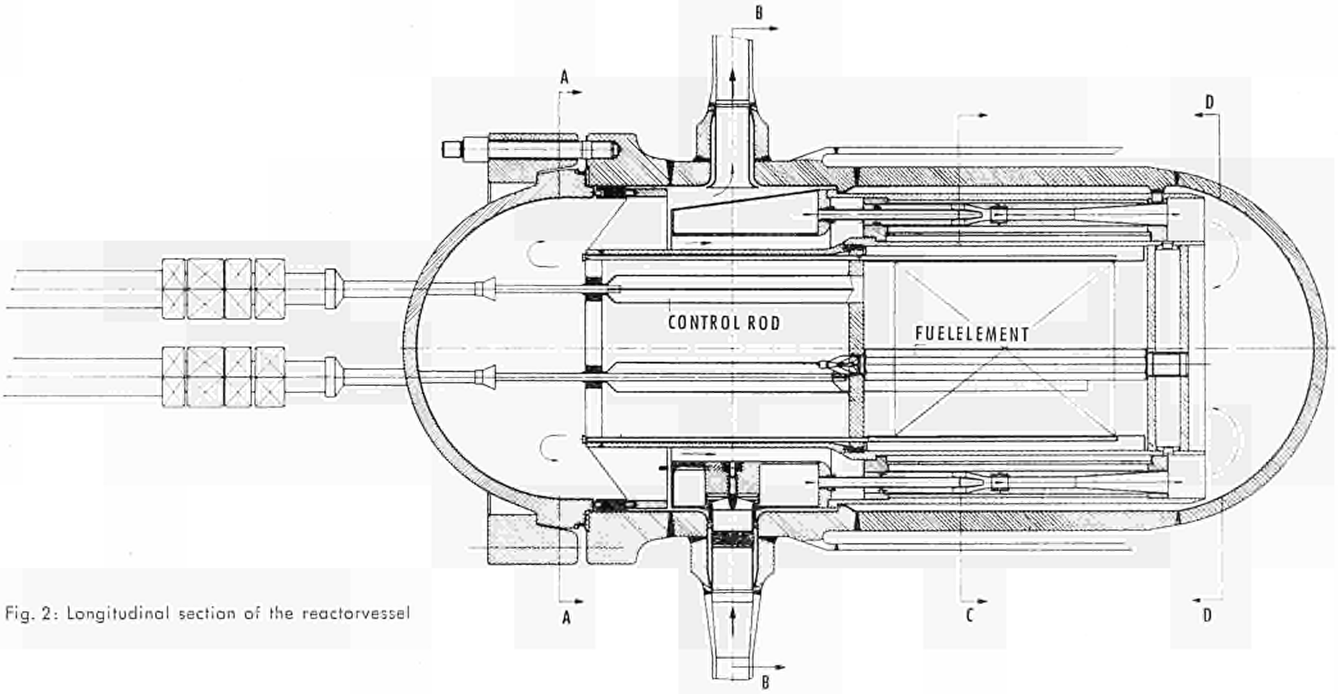
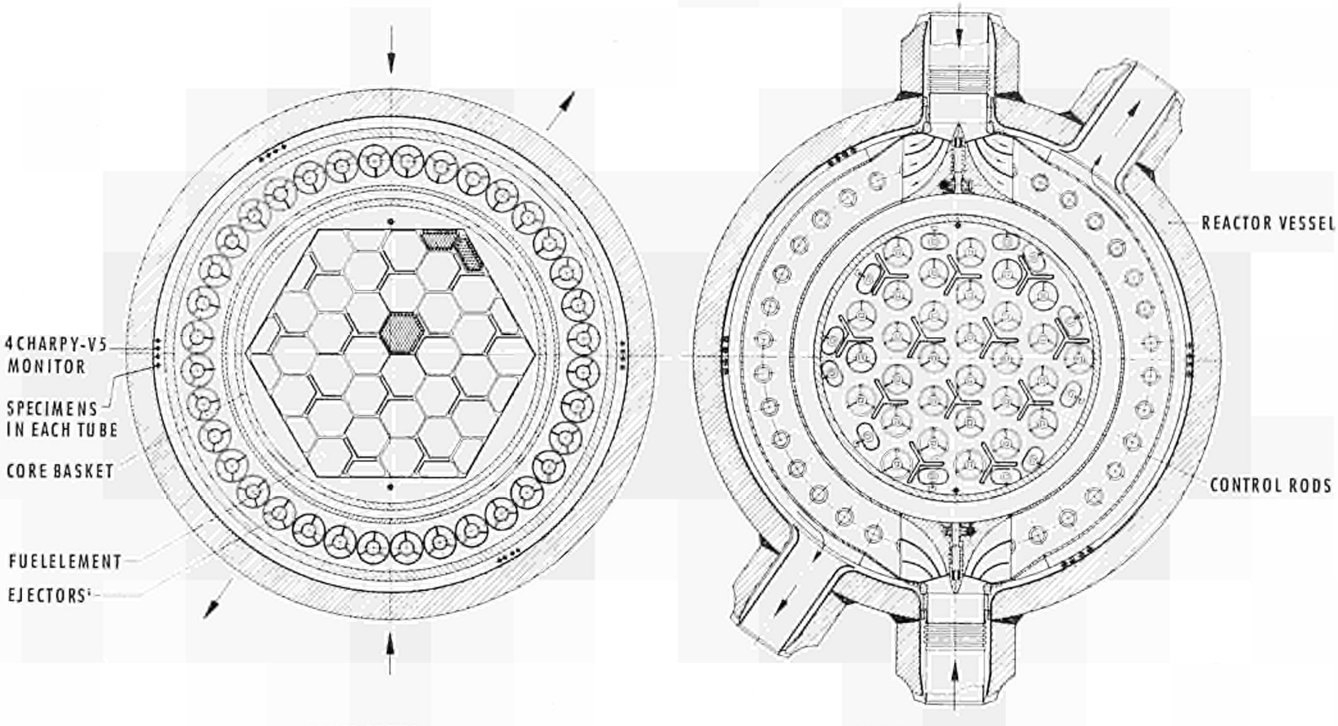


Fig. 2: Longitudinal section of the reactorvessel



CROSS SECTION C-C

CROSS SECTION B-B

Fig. 3: Cross section of the reactorvessel

emergency cooling system. The core itself contains 42 zirconium alloy cladded, mechanically assembled fuel elements. Thirty fuel elements are loaded with 120 fuel rods (fig. 3 and 4), six elements with 55 fuel rods and six elements with 48 fuel rods. The sub-size fuel elements are all situated at the core boundary.

Each of the primary coolant circuits consists of a vertical U-tube bundle steam generator with an integral superheater and canned motor pump (fig. 5), and the associated piping and valves. Each of the circuits can be completely isolated from the pressure vessel by means of 2 gate valves.

To maintain the operating pressure between well defined pressure limits, an electrically heated pressurizer is connected to one of the outlet branches of the reactor vessel (fig. 6). The operating pressure is high enough to prevent bubble detachment in the core. The core is designed so that there is a fair transient burn-out safety margin at the operating pressure.

Pressures in excess of the system design pressure are prevented by an arrangement of safety valves. The effluent of all these primary safety valves is contained in a specially designed blow-off tank, where the released steam is thoroughly mixed with water and condensed. This tank is constantly cooled by internal cooling spirals connected to the fresh water intermediate cooling system, which in its turn is cooled by sea water.

The blow down tank is a dual purpose tank, since all "clean" leaks, vents and drains from the primary system also are led to this tank. From this tank the necessary primary make up water is taken and pumped back into the primary system, thus reducing the amount of primary waste water to a minimum.

The very stringent water conditions of the primary system are maintained by the high pressure purification system, which is linked to the reactor coolant system, taking a continuous by-pass flow through filters and a mixed bed ion exchanger. Although all surfaces in contact with the primary coolant water are of stainless steel, zircaloy or inconel and corrosion inhibitors are added to minimize the corrosion, a certain amount of corrosion products is formed which must be continuously removed, otherwise the radiation from the activated corrosion products would seriously hinder maintenance and repair work inside the containment during reactor shut down periods.

In addition the purification system is designed to remove uranium-dioxide and fission products that may be released into the cooling water if the fuel element cladding fails. The system is sized to be able to take the amount of activity released when a maximum of 1% of the fuel rods would fail. The primary coolant activity due to impurities will then be kept below 30 μc per milliliter.

The complete primary system with its associated systems (i. e. purification system, pressurizing system, blow down system, containment drain system) is enclosed by the spherical containment vessel, constructed of steel. This containment vessel is designed to withstand the pressure resulting from the maximum credible design accident. Access to the containment, possible only after shut down of the reactor, is via airtight airlocks. The containment is equipped with an internal ventilation system with sufficient cooling capacity to remove the heat released by convection and radiation inside the containment. Fig. 7 shows the installation inside the containment.

The steam produced in the steam generators and superheated in the superheaters is transferred to the engine room through the main steam header which penetrates the containment vessel wall. The necessary feed water for the steam generators is returned from the engine room in the conventional way with a turbine driven feed pump.

The containment vessel is, as required by Lloyd's, placed in a watertight reactor compartment. The reactor compartment is situated aft of the engine room, directly above the shaft tunnel.

The load following characteristics of the reactor are excellent. The system operates very stably and follows load changes from the turbines without any difficulty by response on the induced primary water temperature changes. Thus direct power control of the reactor through neutron flux measurements and control rods is not incorporated. To limit, however, the primary water volume surges resulting from turbine load transients a fully automatic control system which keeps the reactor outlet temperature constant by control rod action, is installed. With this control the reactor is capable to follow load transients of 100—10% of full power in 2 seconds and from 10—100% of full power in 60 seconds without blowing off steam through the pressure relief valves. This response can be considered well within the requirements put on for manoeuvring of the ship. For loads of less than 10% of full power the reactor control is taken over to manual. It is envisaged, however, that this will occur rather seldom since the minimum power consumption of ship and reactor auxiliaries under normal conditions exceeds the 10% of full power.

Decay heat during shut down of the reactor plant is normally removed by blowing off steam from one of the steam generators to one of the turbo-generator condensors.

If all power systems on board fail, or the normal decay heat removal system is out of operation, the decay heat is removed by an independent emergency cooling system, operating with natural circulation (fig. 8). The heat still produced in the reactor core is transferred to the pressurizer in the form of steam. In the top part of the pressurizer a specially designed emergency cooler is installed. In this cooler the heat is transferred from condensing steam on the pressurizer side to boiling water inside the cooler tubes. The steam formed flows upwards through a steamline, which penetrates the containment vessel wall, to an air cooler installed on the upper deck in the open air. The steam is here condensed, and the condensate flows back by gravity to the emergency cooler in the pressurizer. This system is designed to operate satisfactorily up to a ship list of 50°.

Two other means to transfer heat from the primary system during shut down are the cooler in the primary purification system and the cooler in the blow down tank. These systems, however, are normally not used for decay heat removal but can be considered as an additional safety feature.

The nuclear instrumentation system is of a proven design to obtain maximum reliability. In total 10 neutron flux measuring channels will be installed. Two low level start-up channels using sensitive BF_3 proportional counters, two high level start-up channels using fission chambers, three intermediate range (logarithmic) channels in 2 out of 3 coincidence, using compensated ionization chambers and 3 power range channels (linear) using uncompensated ionization chambers.

In table 1 the various design parameters of the reactor system are tabulated.

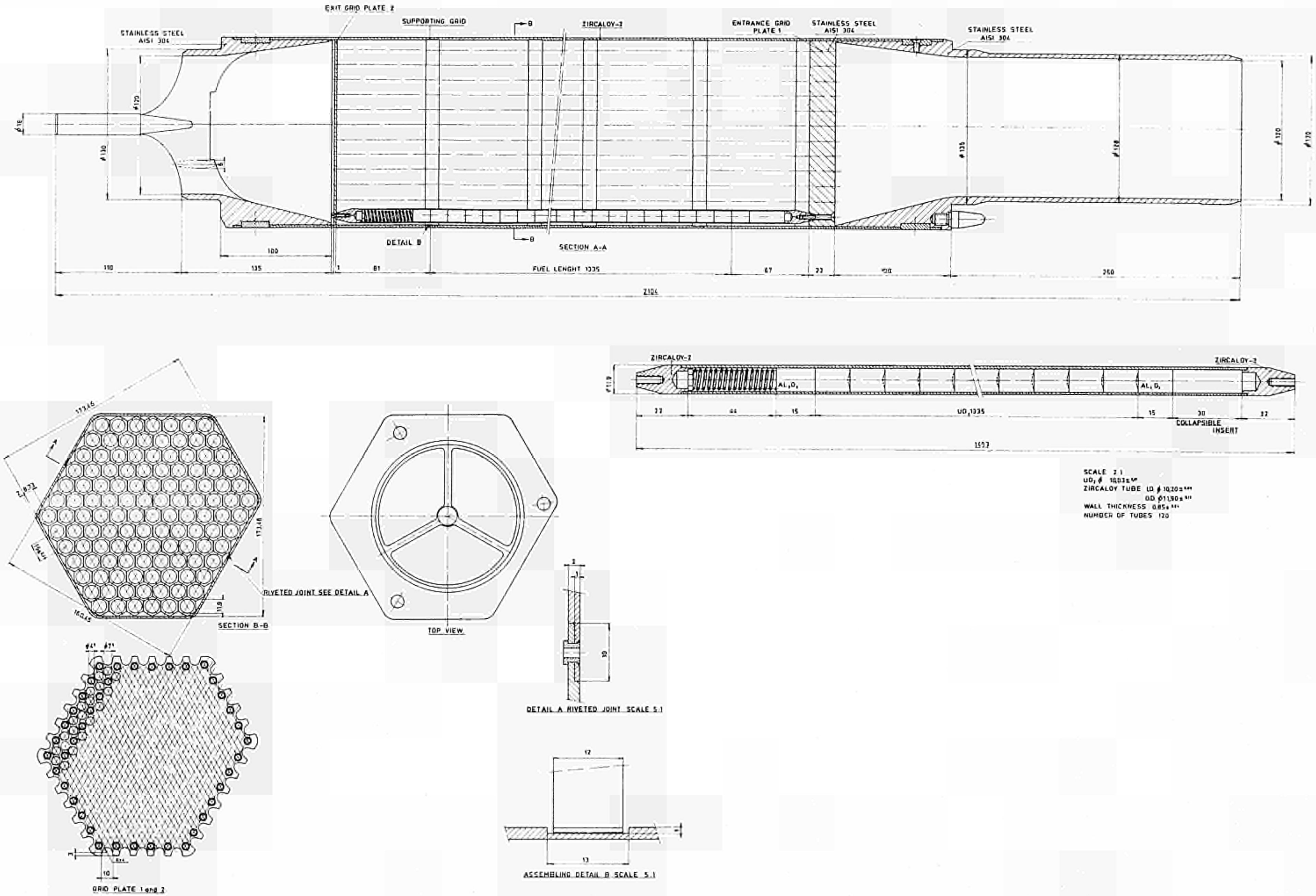
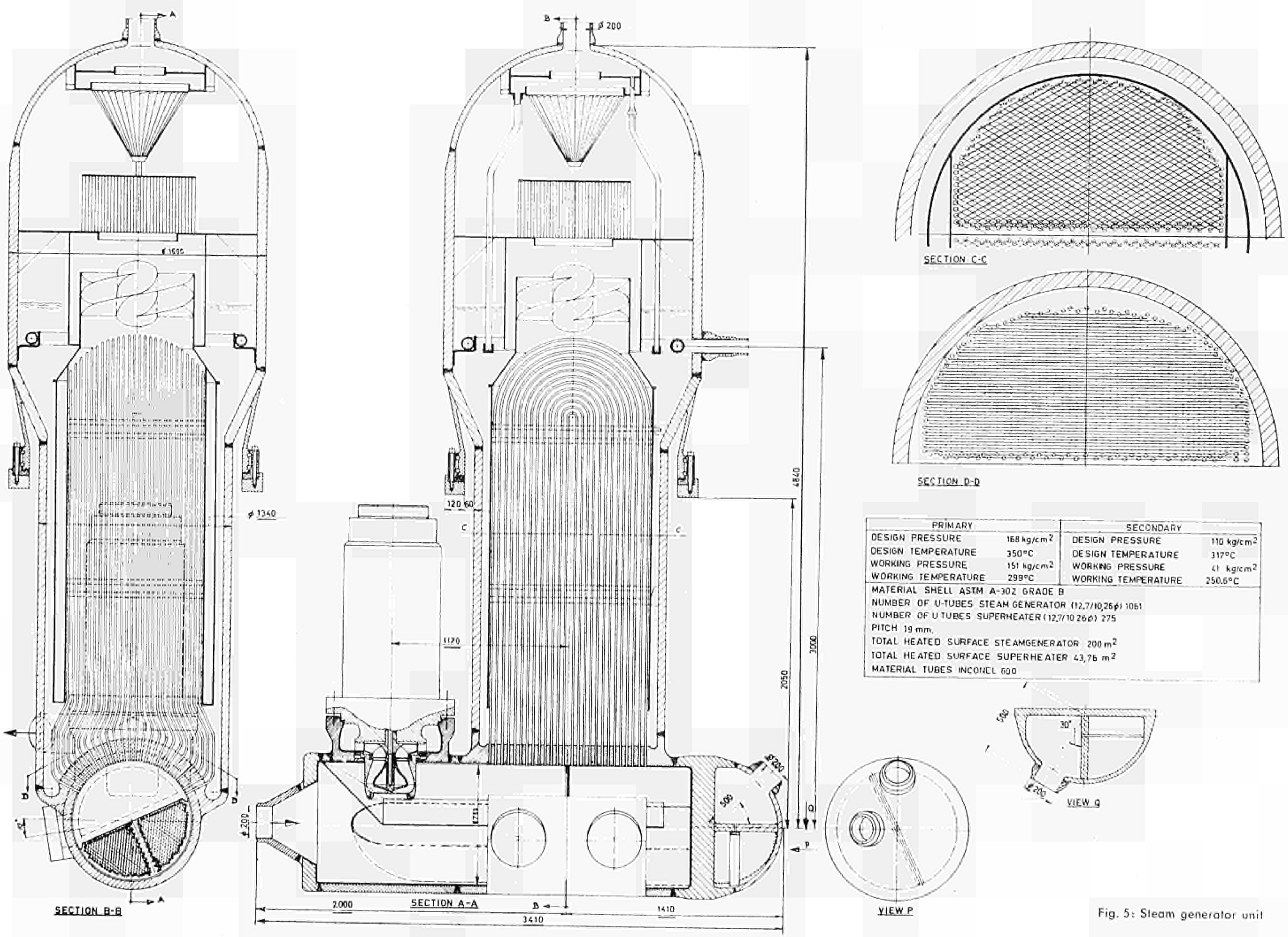
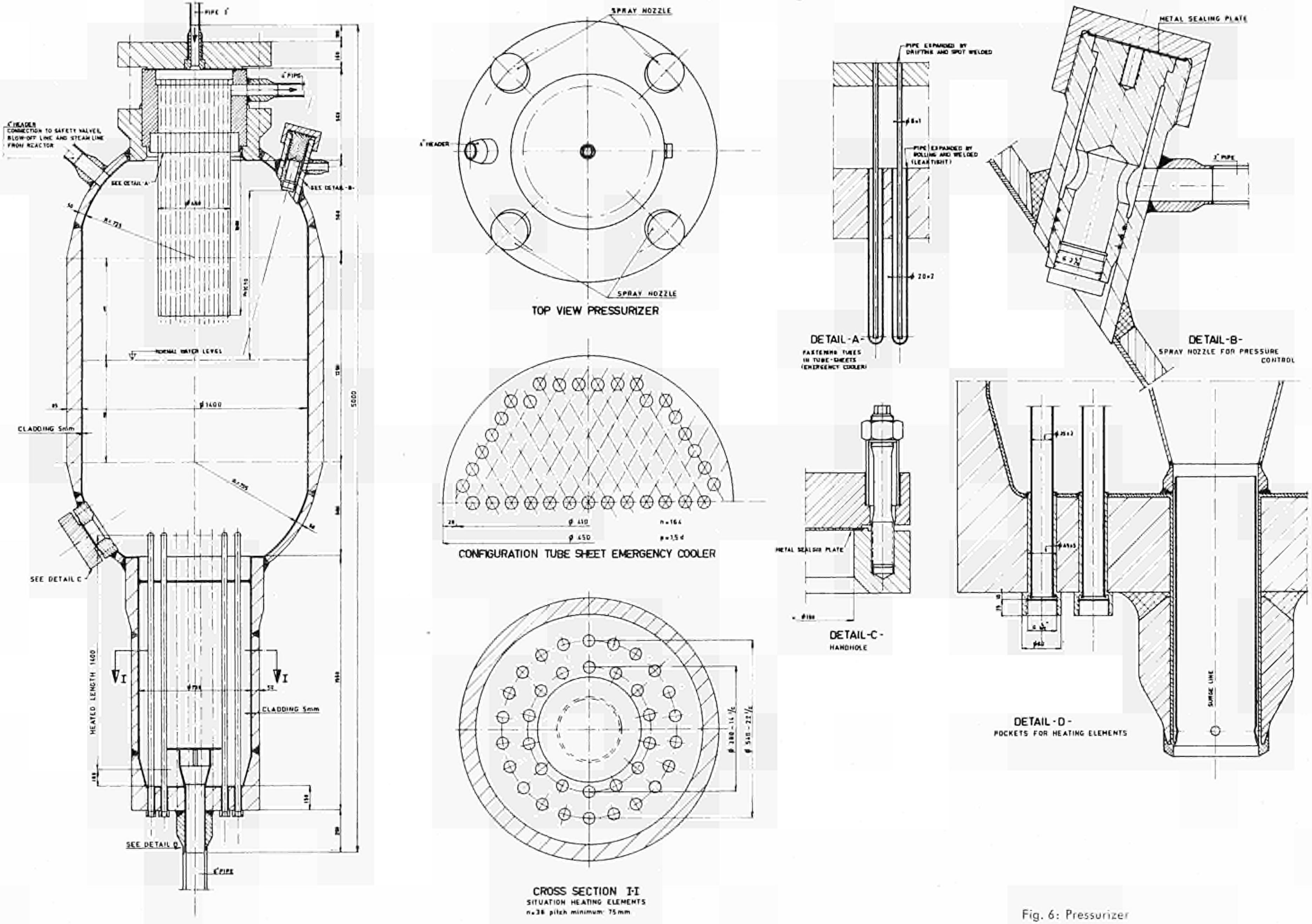


Fig. 4: Fuel element



PRIMARY		SECONDARY	
DESIGN PRESSURE	168 kg/cm^2	DESIGN PRESSURE	110 kg/cm^2
DESIGN TEMPERATURE	350°C	DESIGN TEMPERATURE	317°C
WORKING PRESSURE	151 kg/cm^2	WORKING PRESSURE	41 kg/cm^2
WORKING TEMPERATURE	299°C	WORKING TEMPERATURE	250,6°C
MATERIAL SHELL ASTM A-302 GRADE B			
NUMBER OF U-TUBES STEAM GENERATOR (12,7/10,26ø) 1061			
NUMBER OF U TUBES SUPERHEATER (12,7/10 26ø) 275			
PITCH 19 mm.			
TOTAL HEATED SURFACE STEAMGENERATOR 200 m^2			
TOTAL HEATED SURFACE SUPERHEATER 43,76 m^2			
MATERIAL TUBES INCONEL 600			

Fig. 5: Steam generator unit



TOP VIEW PRESSURIZER

CONFIGURATION TUBE SHEET EMERGENCY COOLER

CROSS SECTION I-I
SITUATION HEATING ELEMENTS
n=36 pitch minimum: 75mm

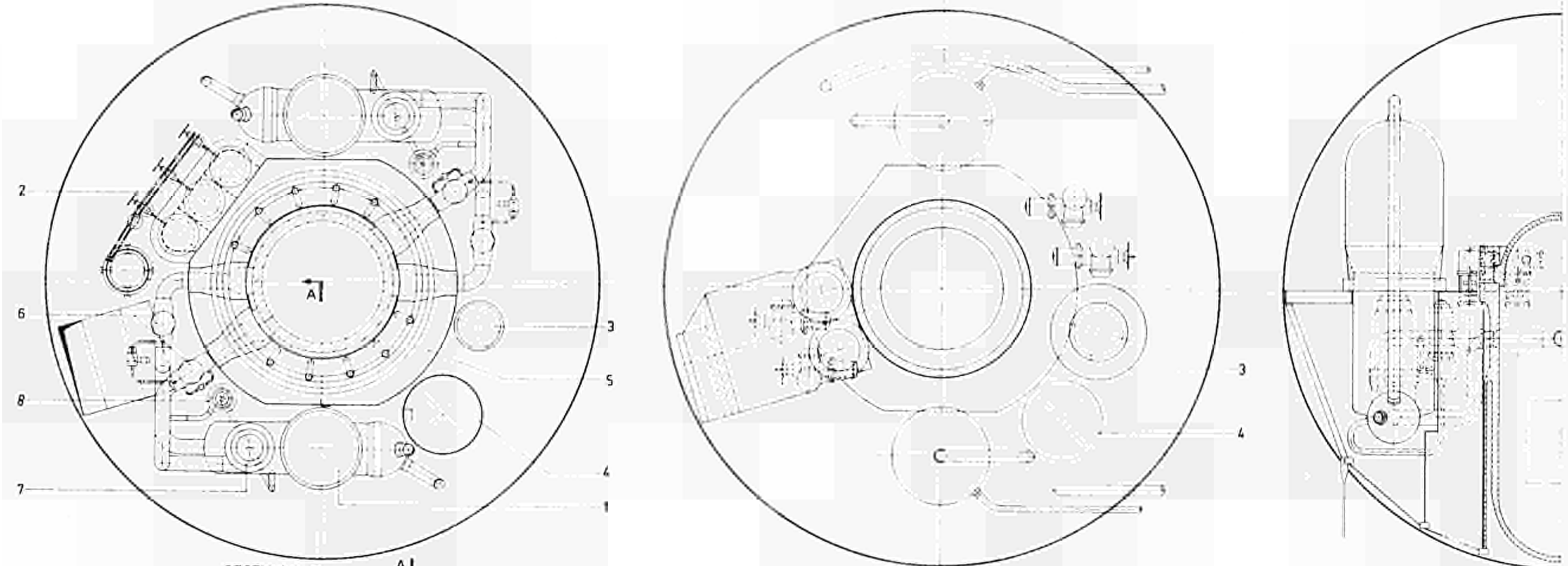
DETAIL -A-
FASTENING TUBES IN TUBE-SHEETS (EMERGENCY COOLER)

DETAIL -B-
SPRAY NOZZLE FOR PRESSURE CONTROL

DETAIL -C-
HANDHOLE

DETAIL -D-
POCKETS FOR HEATING ELEMENTS

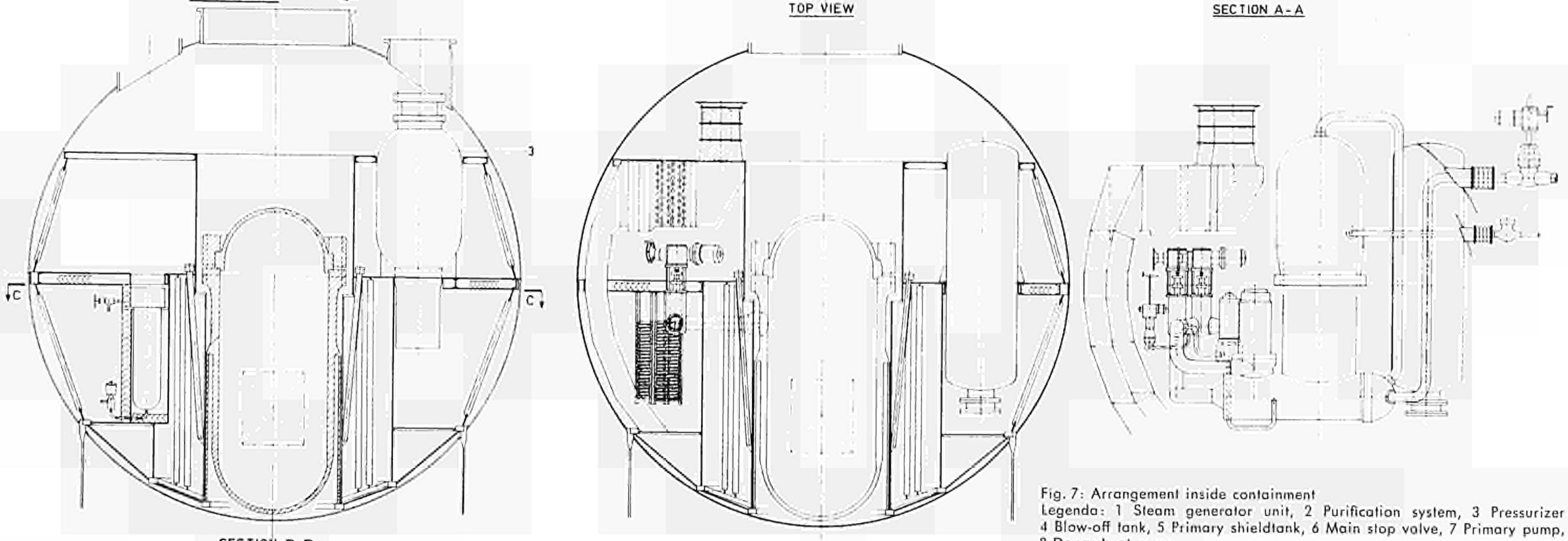
Fig. 6: Pressurizer



SECTION C-C

TOP VIEW

SECTION A-A



SECTION B-B

Fig. 7: Arrangement inside containment
Legenda: 1 Steam generator unit, 2 Purification system, 3 Pressurizer 4 Blow-off tank, 5 Primary shieldtank, 6 Main stop valve, 7 Primary pump, 8 Decay heat pump

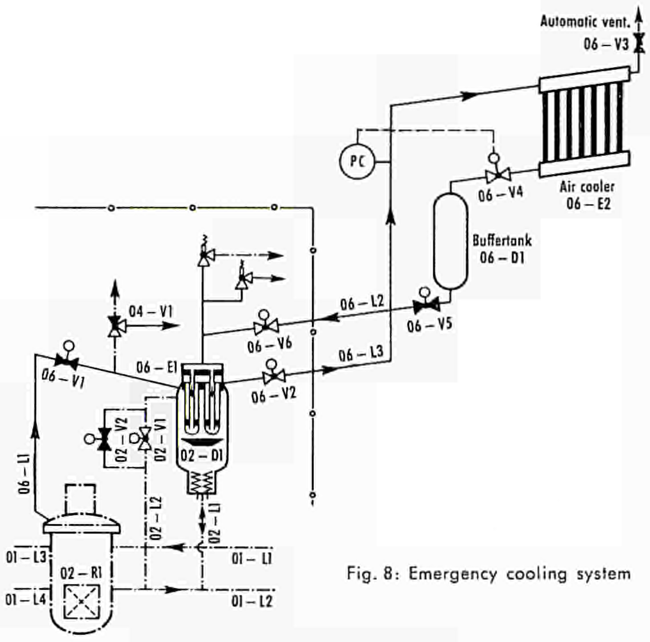


Fig. 8: Emergency cooling system

Table 1: NEREUS Design Parameters

General	
Reactor, type	Pressurized water
Ship shaft horse power, max. continuous	22,000
Reactor power, MW thermal	67
Reactor operating pressure, kg/cm²	151
Steam production, tons/hr	111.2
Steam pressure, kg/cm²	40
Steam temperature, °C	280
Operational core life, days at full power	1200
Refuelling period, years	4
Primary cooling system	
Number of cooling circuits	2
Design pressure, kg/cm²	168
Design temperature, °C	350
Nominal reactor outlet temperature, °C	299
Nominal reactor core inlet temperature, °C	288
Mass flow through fuel elements, kg/sec	1100
External mass flow total, kg/sec	440
Recirculation ratio reactor core	2.6
Pressure drop over reactor core, kg/cm²	0.5
Pressure drop over reactor vessel, kg/cm²	3
Pressure drop over cooling circuit, kg/cm²	2
Pumping power per pump, kw	260
Reactor core dimensions	
Core height, active length, mm	1327
Average core diameter, mm	1128
Number of fuel elements, 120 rods	30
Number of fuel elements, 55 rods	6
Number of fuel elements, 48 rods	6
Diameter of fuel pellets, mm	10.03 ± 0.01
Cladding diameter, outside, mm	11.90 ± 0.12
Cladding thickness, mm	0.85 ± 0.04
Triangular lattice pitch of fuel rods, mm	15.0 ± 0.25
Cladding material	zirconium alloy
Volume ratio H_2O/UO_2, cold Control rods out	1.4344
Total weight UO_2, kg	4600
Number control rods	12
Core physics	
Core life at full power, days	1200
Average burn-up, MWD/ton UO_2	16,600
Initial enrichment central zone, %	4.4
Initial enrichment outer zone, %	4.8
Core heat transfer and hydraulics	
$\int$ kdt-max., W/cm	40
Max. heat flux, W/cm²	113.5
Total flow cross section, m²	0.4
Reactor vessel	
Inside diameter, m	2.0
Inside height, m	5.5
Wall thickness cylindrical part, mm	115
Material	ASTM A 302 — Grade B
Cladding	Stainless — 304
Steam generators	
Type	Vertical, U-tube
Number	2
Primary coolant inlet temperature, °C	297.5
Primary coolant outlet temperature, °C	269.5
Feed water inlet temperature, °C	175
Steam temperature, 100 % power, °C	250.6
Total tube surface, m²	200
Tube material	Inconel-600
Plate material	ASTM A 302 — Grade B
Cladding	Inconel-600
Tube plate	Stainless — 304
Primary side	
Superheaters	
Type	Horizontal, U-tube
Number	2
Heat load per superheater, MW	1.62
Inlet temperature primary coolant, °C	299
Outlet temperature primary coolant, °C	297.5
Steam temperature inlet, °C	250.64
Steam temperature outlet, °C	280
Total tube surface, m²	43.76
Containment	
Configuration	Sphere
Inside diameter, m	9.0

Diskussion: Leitung Prof. Dr. E. Bagge, Kiel.

Frage: Welche Aufgabe haben die VENTURI-Düsen im Reaktor, und wie arbeiten sie?

Antwort: (Abb. 2) The point in having these VENTURIES is, that we want to have a high water-velocity in the core but also to reduce the flow rate in the outer part of the system in order to be able to build the whole system very compactly. If you have to circulate less water you can reduce your pipe diameter and you can construct a bit more compactly than otherwise would be possible. The recirculation rate as was mentioned is 2.6 which means that we circulate in the reactor core 1,100 kg per sec. of water and in the outer circuits about 220 kg per sec. each. The cool water, coming from the pumps is forced through the VENTURIES and creates a pressure-drop here, which is sufficient to attract primary water from the top of the vessel through the throat back to the bottom-chamber of the reactor. Of course, one has to pay for that kind of trick in pressure-drop. The pressure-drop over the core is about ½ kg per sq.cm and the total pressure-drop from inlet to outlet is about 3 kg per sq.cm. In picking the value for the recirculation rate we have to go through a complete economic study to see where the optimum recirculation rate would be, also costwise, and it turns out that by making this arrangement we gain in safety of the system and in compactness of the system but also in total pumping power requirements for the whole reactor-system. The pumping requirements are about 260 kW per pump.

Frage: Bei diesem Reaktor ist ein Borinjektionssystem vorgesehen. Wie schnell wirkt dieses System, um den Reaktor abzuschalten? Kann es eine Coreschmelze verhindern?

Antwort: I am sorry, I cannot answer your question in any reasonable detail. The main function of this system would be to provide an extra safety for the reactor. I am not sure at present that its action would be fast enough to prevent the core-melting-down in the worst possible case.

Frage: Es ist üblich, den Reaktor an der sichersten Stelle, also dort anzubringen, wo das Schiff am breitesten ist. Aus Ihrem Vortrag ging hervor, daß der Reaktor in diesem Fall am Ende des Schiffes angebracht werden soll, und die Frage ist nun, ob der Britische Lloyd mit dieser Konzeption einverstanden ist oder überhaupt schon damit konfrontiert worden ist.

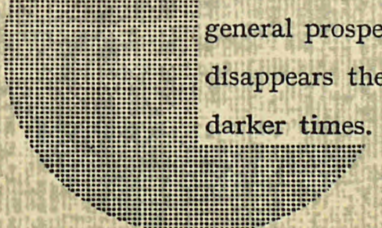
Antwort: We have not discussed this particular location of the reactor on the ship with Lloyd's but we have provided the space for the collision barrier as specified by Lloyd's; therefore I think, as far as that goes, there is no trouble to be expected. I should mention, as we are talking about the 65,000 t tanker, the dimension of the ship is so large, that it is not too difficult to find sufficient space to put the reactor in and leave sufficient room for the proper collision barriers. We think, we meet all the requirements there.

Frage: Does the burnable poison have the same concentration all over the core?

Antwort: This is not absolutely so. We are particularly interested to put the poisoned pellets near to water gaps in the system and this is what we may eventually prefer to do so as to reduce flux peaking near the water gaps which are left open when the control rods are removed from the core. In principle the burnable poison is incorporated in the fuel in the form of small particles. It is sintered together with the uranium-oxyd.

Frage: How many kW per pump are essential?

Antwort: As I have mentioned, 260 kW per pump.



> To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel