The NERO reactor for ship propulsion

Citation for published version (APA):
Bogaardt, M., & Muysken, M. (1965). The NERO reactor for ship propulsion. In *Proceedings of the third international conference on the peaceful uses of atomic energy : held at Geneva, 31 August - 9 September 1964. Vol. 6* (pp. 490-497). United Nations.

Document status and date:
Published: 01/01/1965

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

The NERO reactor for ship propulsion

By M. Bogaardt and M. Muysken*

The NERO reactor design of the Reactor Centrum Nederland (RCN) has been the object of an extensive reactor development programme in collaboration with EURATOM during the past three years. The preliminary design, which formed the basis for the development programme, was the result of a commission given by several ship-builders and engine builders in the Netherlands to RCN early in 1958 to perform a study of a reactor installation suitable for marine propulsion. The development programme was drawn up in 1960. It contains several different chapters with experimental work to be performed before a final design of the reactor installation can be submitted.

On 1 December 1961 a contract was signed between RCN and EURATOM, which covered the execution of this development programme during a period of three years, starting retrospectively on 1 June 1961. The duration has since been prolonged to four years, thus the contract ends in June 1965.

Anticipating the final NERO design an interim design has been prepared during the first months of this year, which incorporates the main features of the NERO design but is in some details not as advanced as we would prefer for the final design. Before discussing the several phases of experimental work in the development programme a summary description of the interim design is first presented.

INTERIM DESIGN OF A NERO REACTOR INSTALLATION

The pressurised-water reactor system was decided on at an early stage of the studies as being the most suitable for ship propulsion for reasons of reliability and general operating experience with this type of reactor. Further requirements which were taken into account at an early stage included the provision of a high degree of safety during operation, a compact installation and a long core life.

As the design evolved from a conventional PWR several special features were already incorporated in the first stages. A system with internal recirculation inside the reactor vessel was adopted as shown on the flow sheet (Fig. 1). This was done in order to obtain a reduced size of external primary coolant system, while at the same time providing sufficient mass flow of the coolant through the core in one pass. The external flow is led to a ring of water ejectors inside the reactor vessel, as shown in Fig. 2. The external flow provides the driving force for an internal circulation having about 1.5 times the mass flow in the external circuit. Next a compact unit containing steam generator, superheater and primary coolant pump was designed as shown in Fig. 3. This eliminates part of the primary piping in comparison to conventional designs and makes it possible to fabricate, assemble and test these components in one unit in the workshop before erection in the containment vessel.

An important safety feature for a PWR system is the possibility of providing for shut-down cooling of the core under all conceivable emergency conditions, so as to prevent melting of the cladding of the fuel rods and the subsequent spread of highly radioactive fission products. In the NERO design an emergency cooling system has been incorporated which will come into operation after complete power failure on the ship and provide for sufficient shut-down cooling entirely by natural circulation.

If the external primary coolant circuits cease to operate, a passage for steam—formed by decay heat in the reactor vessel—is opened to the pressuriser. Here it is condensed against thimble-type cooling tubes and subsequently flows back as condensate to the reactor vessel. The thimble tubes in the pressuriser are cooled by a secondary system under natural circulation.

An air-cooled condenser on the deck of the ship gives off the heat to the surroundings. At the same time there is an open path for natural circulation in the reactor vessel, up through the core and down through the thermal shielding, because of the internal recirculation described above. Part of the emergency cooling system is shown on the flow sheet (see Fig. 1).

The most hazardous condition with PWR installations is of course the occurrence of a major leak in the primary system. As it is nearly impossible to provide a fail safe system to cope with this emergency, the reactor installation is erected inside a containment vessel, which in the NERO design is spherical with a diameter of 9 m. The containment vessel is designed to withstand an internal pressure of 14 kgf/cm^2.

To provide for a long life of the core of the NERO reactor the incorporation of burnable poison in the form of discrete particles, dispersed in the uranium

---

* Reactor Centrum Nederland, the Hague.

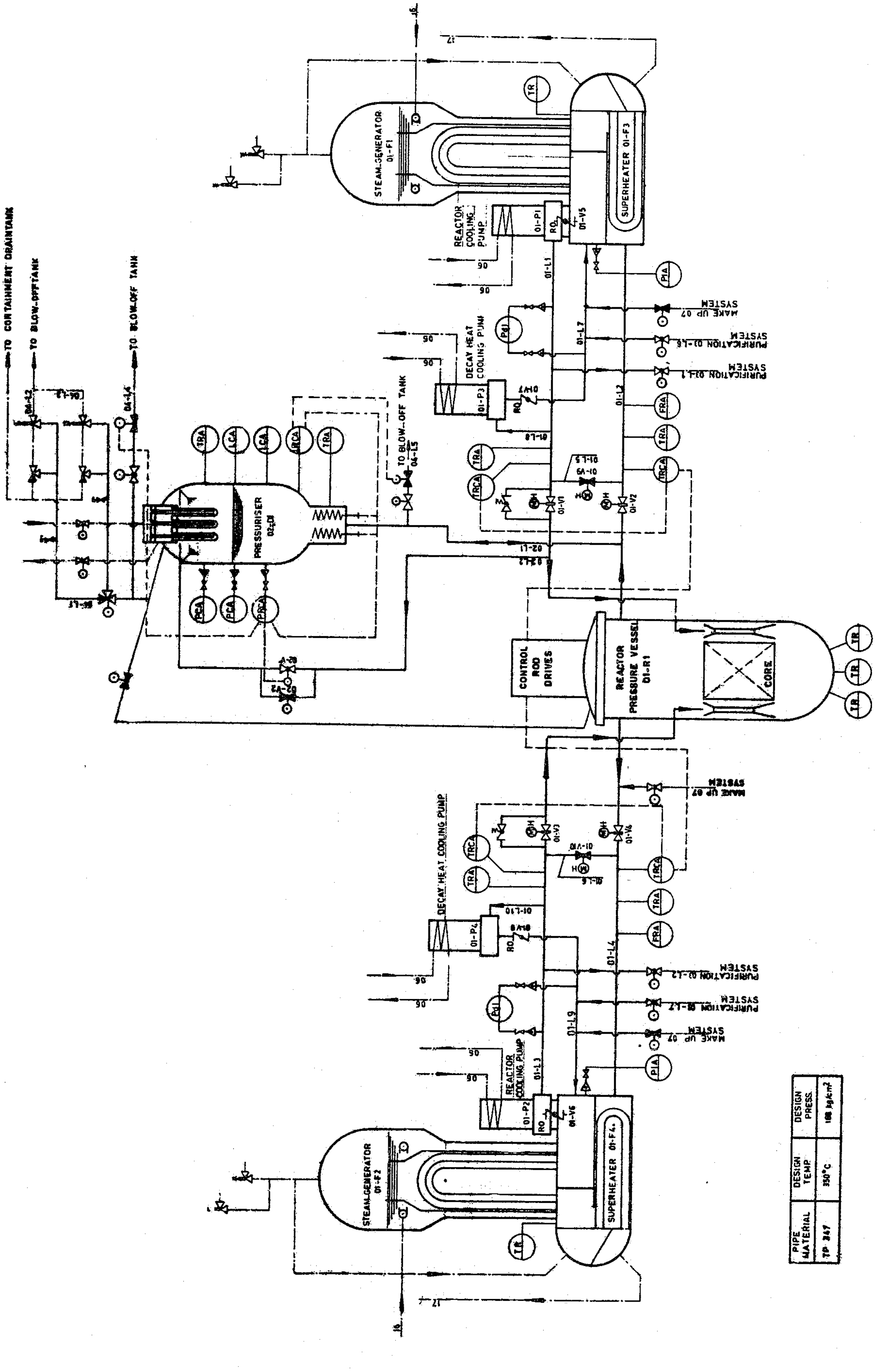
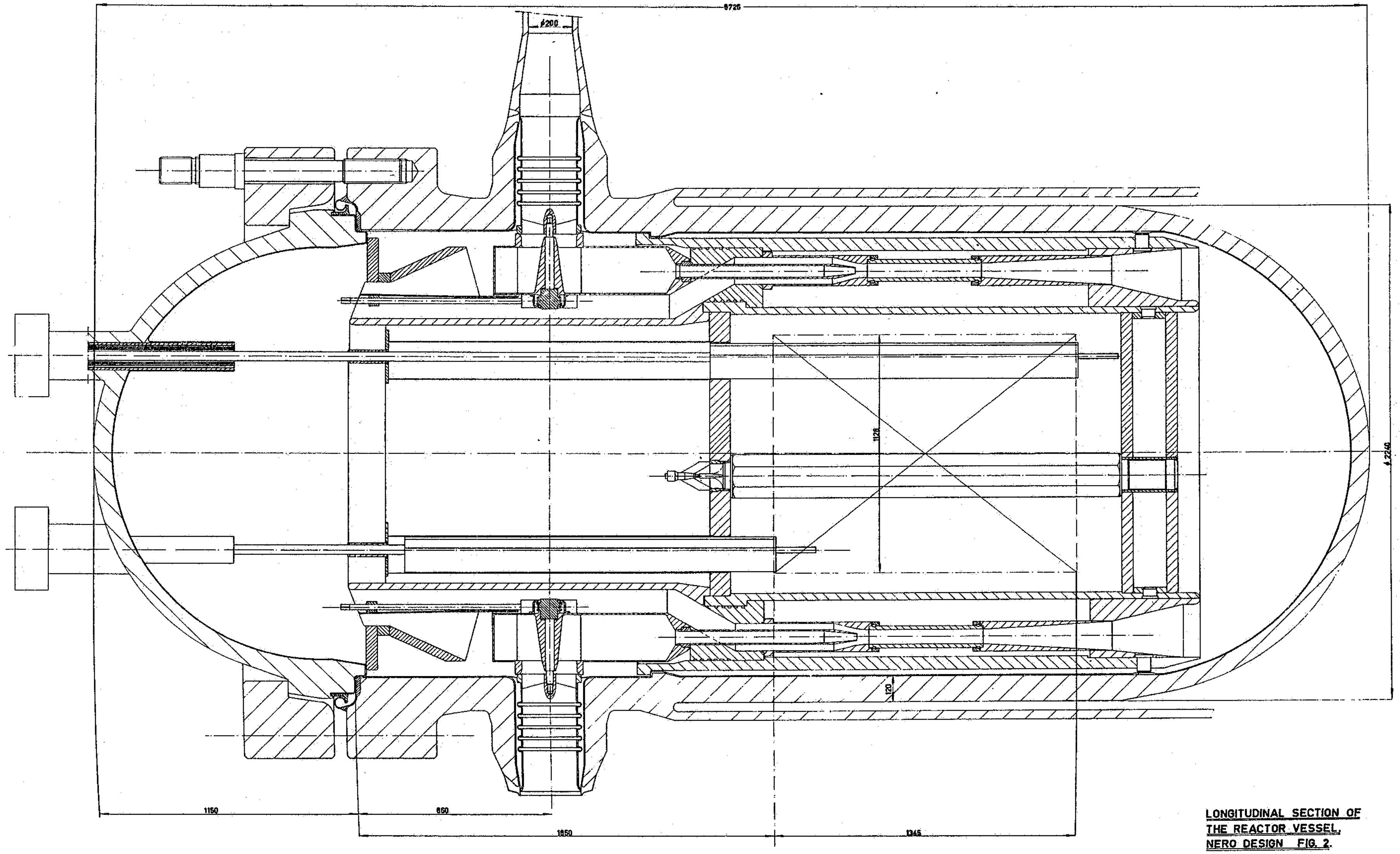
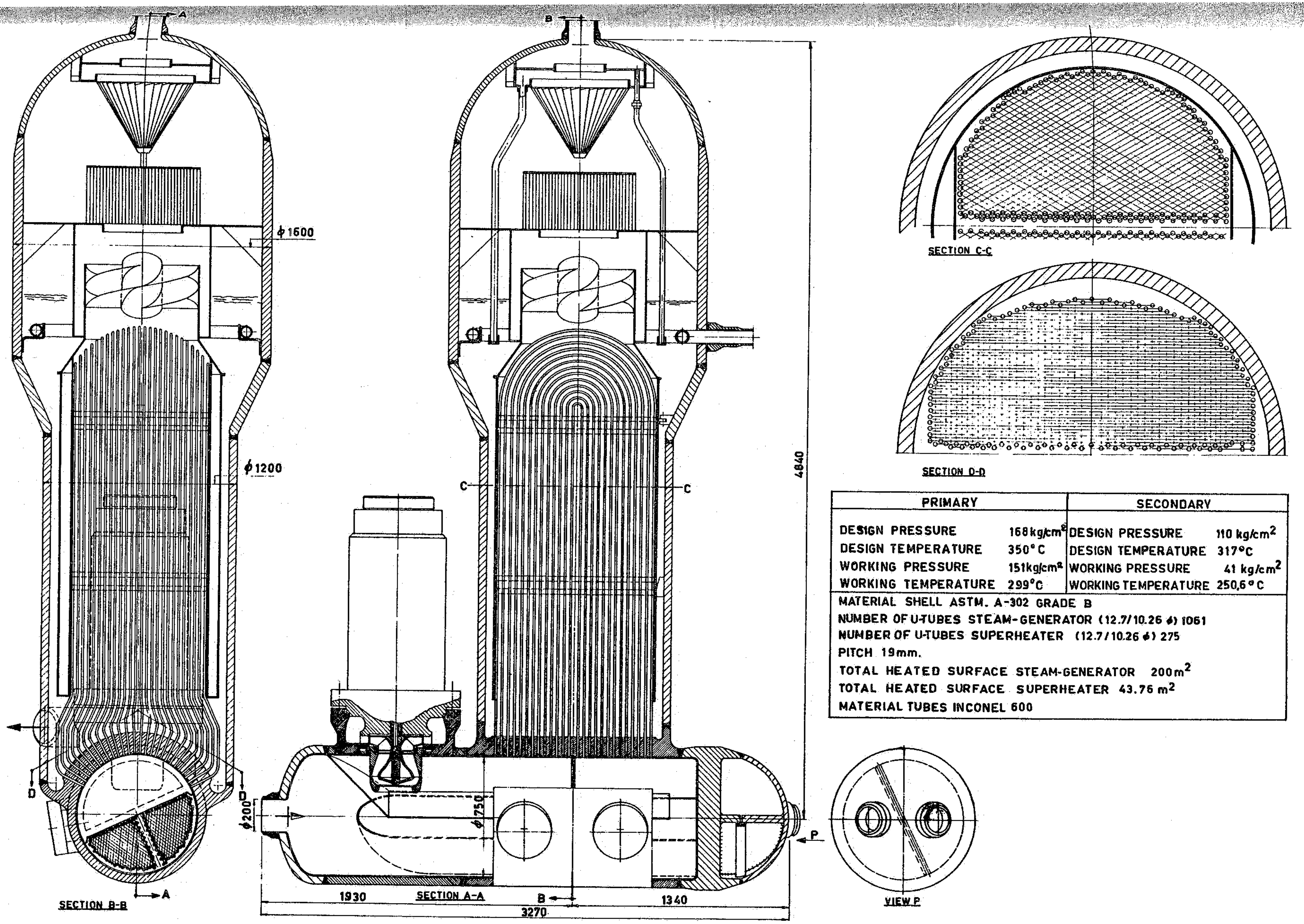


Figure 1. Engineering diagram of primary system. NERO design



LONGITUDINAL SECTION OF
THE REACTOR VESSEL,
NERO DESIGN FIG. 2.

Figure 2. Longitudinal section of the reactor vessel. NERO design



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 (12.7/10.26 ϕ) 1061
NUMBER OF U-TUBES SUPERHEATER (12.7/10.26 ϕ) 275
PITCH 19mm.
TOTAL HEATED SURFACE STEAM-GENERATOR 200 m^2
TOTAL HEATED SURFACE SUPERHEATER 43.76 m^2
MATERIAL TUBES INCONEL 600

Figure 3. Steam generator unit. NERO design

dioxide pellets in a certain number of fuel rods, is envisaged. This method of poisoning was proposed as it appears to be more reliable than using chemical shim in the moderator. It excludes the possibility of operational mistakes whereby the amount of poisoning may be reduced unintentionally. Furthermore, by selectively poisoning a number of fuel rods—for instance those which are situated in the outer row of the fuel elements next to water gaps—it is possible to reduce the power peaks which would occur if no poison was used in these rods. This allows for a flattened power distribution over the core.

The fuel rods are installed in a triangular pattern in hexagonally shaped fuel elements, shortened on one side to allow for space for 12 Y-shaped control rods between the fuel element boxes. A zirconium alloy will be used for the cladding and the fuel element boxes.

The dynamics of the system have also been studied under both normal and abnormal conditions, including the effect of failure of one of the two primary pumps on the recirculation ratio in the reactor vessel.

Table 1. Main parameters of NERO interim design

General and primary system	
Reactor power [MW(th)]	67
Steam production (t/h)	111.2
Steam pressure (kgf/cm²)	40
Steam temperature (°C)	280
Reactor operating pressure (kgf/cm²)	151
Nominal reactor inlet temperature (°C)	270
Nominal reactor outlet temperature (°C)	299
Nominal inlet temperature reactor core (°C)	288
Mass flow through reactor core (kg/s)	1 155
Mass flow through each of 2 external circuits (kg/s)	220
Reactor core dimensions	
Core height (mm)	1 327
Core nominal diameter (mm)	1 128
Number of full size fuel elements	30
Number of undersize fuel elements	12
Total number of fuel rods	4 218
Diameter of pellets (mm)	10.03 ± 0.01
Total weight of UO_2 (kg)	4 600
Cladding inside diameter (mm)	10.2
Cladding outside diameter (mm)	11.9
Pitch of fuel rods (mm)	15.0
Core volume fractions: UO_2	0.3352
Core volume fractions: H_2O	0.4402
Core volume fractions: Cladding boxes	0.1725
Core volume fractions: Control rods	0.0407
Core physics and heat transfer	
Average burn-up (MWd/t UO_2)	16 600
Initial enrichment in central zone	4.4
Initial enrichment in outer zone	4.8
Amount of burnable poison (B_4C equivalent, g)	1 240
Max heat production (W/cm rod length)	500
General dimensions	
Inside diameter of reactor vessel (m)	2.0
Inside height of reactor vessel (m)	5.5
Heat transfer surface steam generator (m² each)	200
Heat transfer surface superheater (m² each)	43.8
Inside diameter of containment (m)	9.0

It appears that the load following characteristics, as well as the behaviour under abnormal conditions, are quite acceptable.

Table 1 shows some of the main parameters of the interim NERO design. In order to specify the general requirements for the reactor installation a tanker of 65 000 ton deadweight, requiring 22 000 shp for propulsion, was chosen as the nuclear ship.

DEVELOPMENT PROGRAMME

As explained in the introduction the NERO development programme was drawn up in 1960, based on a preliminary design for a pressurised-water reactor suitable for ship propulsion. The development programme covers the experimental work to be performed before the final NERO design can be prepared.

The main items of the development programme now under way are described in the following paragraphs.

Critical and subcritical experiments

The critical experiments are being performed with a facility named KRITO erected in Petten. This facility has been described more fully in Ref. [1].

In the vessel of this facility, reactor cores are built up in the geometry of the NERO design, using aluminium as material for the cladding and the fuel element boxes instead of Zircaloy as proposed for the design. The usual measurements concerning reactivity coefficients of water height and control rods were performed. Thereafter, the flux distribution across water gaps between the fuel element boxes was measured and the reactivity effects of fuel rods—in which poisoning has been simulated by introducing thin discs of a type of Boral between the pellets in the rods—were determined in several core positions.

By foil activation measurements the thermal flux distribution across a water gap between the fuel boxes was determined in the form of a flux peak factor, defined as the ratio R between the peak flux and the undisturbed flux, with and without poisoned rods in the outer row of the fuel elements.

These measurements gave the results listed in Table 2.

Table 2. Flux peak factor in core KRITO 1

3.1% enrichment, poisoned rods with 30 pellets of UO_2 and 29 discs of Boral, thickness 0.6 mm, diameter 9.5 mm, boron content 13.4 ± 2 mg

Position	Flux peak factor R Without poison	 With poison
Between the boxes	1.6 ± 0.2	1.3 ± 0.2
In outer row of fuel pins	1.15 ± 0.05	1.05 ± 0.05

The reactivity measurements with fuel rods poisoned by different amounts of B_4C in different positions in the core gave the results listed in Table 3.

Table 3. Reactivity effect of poisoned fuel rods in core KRITO 2

(Loading No. 77–1 005, 3.8 % enrichment)

Mass of B_4C per rod, mg	Average distance from centreline	Average reactivity change
517	2 cm	94 pcm
517	14 cm	57 pcm
517	14 cm[a]	81 pcm
517	24 cm	22 pcm
517	28 cm[b]	3 pcm
517	5 cm	86 pcm
517[c]	5 cm	73 pcm
310[d]	5 cm	61 pcm
258[e]	5 cm	49 pcm

[a] Next to water gap in control rod channel.

[b] On the outer edge of the core.

[c] 38 Discs between pellets, as in the other rods with 517 mg, but grouped together, two discs every two pellets.

[d] 38 Discs with a reduced amount of B_4C per rod.

[e] 19 Discs per rod, spaced every two pellets.

The subcritical experiments will be performed in the shielding facility next to the LFR in Petten. It has a geometrically accurate triangular lattice except for the centre position for seven rods in one assembly and for a variable water gap over the diameter in another assembly. The provision of the exchangeable centre piece and the variable water gap allow for detailed measurements of the flux variations at disturbances in the clean lattice. The facility for subcritical experiments has been described in reference [2].

Incorporation of burnable poison in uranium oxide

The first part of this phase in the development programme concerns the metallurgical aspects of preparing uranium oxide pellets with burnable poison in discrete particles. Samples with B_4C and Dy_2O_3 particles of the required size in a neutral matrix have been prepared and irradiated in order to check the calculation on self-shielding properties of the particles.

Irradiation loop in the HFR

A high pressure, high temperature loop for irradiation experiments was built next to the HFR in Petten. The in-pile section of this loop consists of two adjacent pressure tubes with an inside diameter of 44 mm and a height of 60 cm, in which 6 fuel rods according to the NERO design but with reduced length can be irradiated simultaneously.

The cooling system is capable of operating at a temperature of about 325 °C and at a pressure of 140 kgf/cm^2 and allows for a heat production of about 200 kW in the sample rods.

Testing of cladding material for fuel elements

This part of the development programme started with testing of zirconium samples obtained from different suppliers in Europe. Corrosion measurements, as well as non-destructive testing, were carried out on tube samples and as a result it could be concluded that many of the samples received did not meet the requirements. Zirconium tubes have been assembled in the form of a sub-assembly similar to a section of the fuel element for testing in a forced circulation loop, which is operating at 140 kgf/cm^2 and 300 °C in the Chemistry Laboratory in Petten.

Performance tests on scale models of the heat exchanger and superheater

Experiments with separate scale models of the heat exchanger and superheater will be performed with an installation to be constructed at the Technological University of Eindhoven. Figure 4 shows a flow sheet of this facility. The main items are:

(*a*) A boiler with a capacity of about 6 MW of heat input, which raises the temperature of a circulating quantity of water from 290 °C to 314 °C, as a substitute for a reactor in the primary circuit of a pressurised-water system.

(*b*) A scale model of a heat exchanger and superheater, designed on a scale of approximately $\frac{1}{6}$ of the corresponding equipment in the NERO design.

(*c*) A circulating pump with a capacity of 218 m^3/h.

The steam formed in the heat exchanger on the secondary side and heated up further in the superheater is led to a high pressure condenser, operating at system pressure. The cooling is accomplished by spraying water on the outside surface of the condenser, which consists of a set of pressure tubes in open air. This makes it possible to simulate fast changes in load on the secondary side, by regulating the water spray. This type of operation has the added advantage that very little power is required for the feed pump.

The installation has been designed for the study of the response of the steam generator, steam drying equipment and superheater to fast load changes.

Control of primary water conditions

The measures which are necessary to control the primary water quality are studied while operating the forced circulation loop and the loop for in-pile irradiation, both mentioned previously.

Performance tests with a nearly full scale model of the pressuriser

An experimental pressuriser, built by an industrial group and erected at the Technological University of Delft in co-operation with the Royal Dutch Navy, has been equipped with a system which permits the testing of pressuriser performance under the simulated operating conditions of a pressurised-water reactor system. The installation was tested and put into operation by the original partners in this project.

As part of the development programme some changes are now being made in order to achieve an acceptable simulation of a series of subsequent surges in the system.

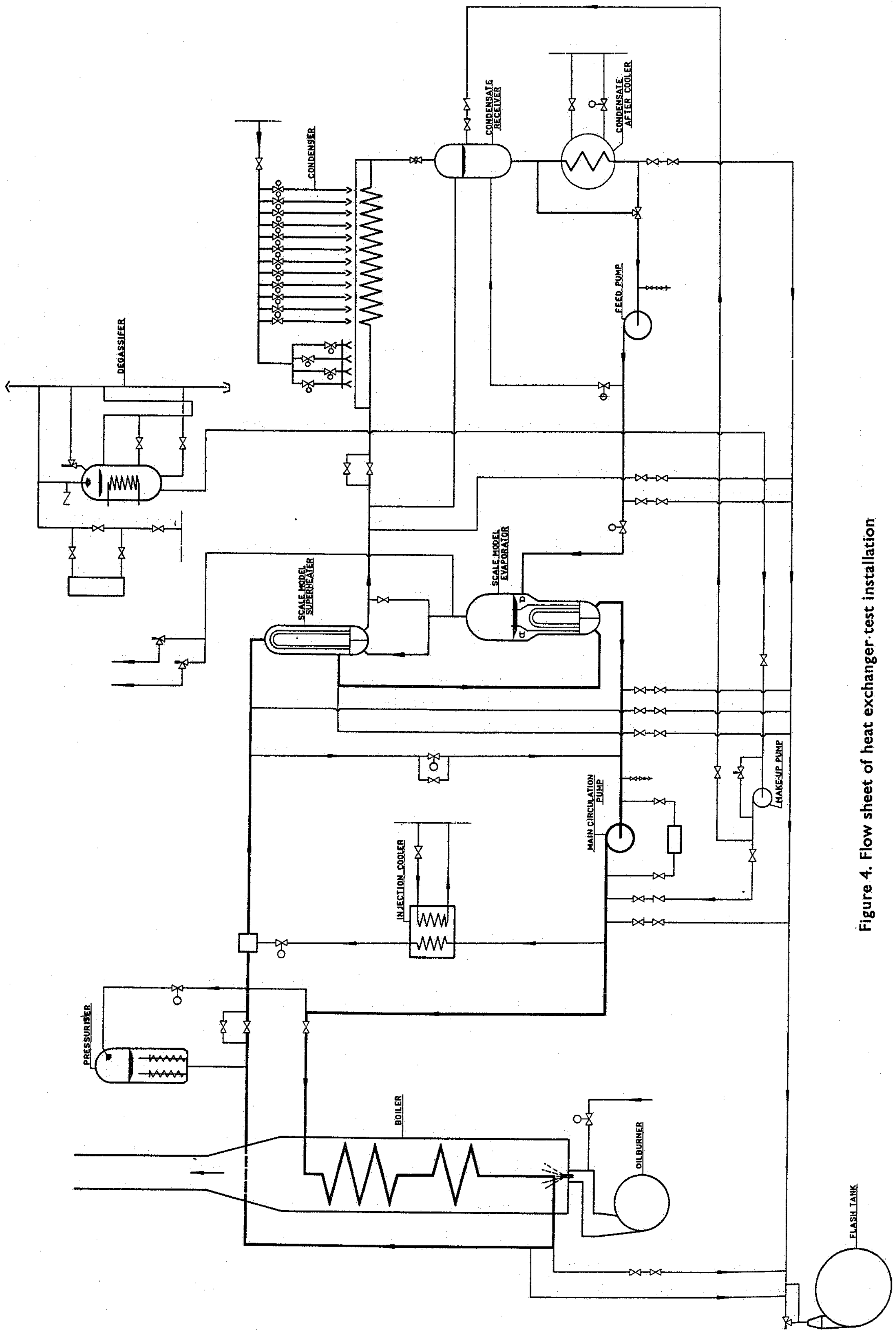


Figure 4. Flow sheet of heat exchanger-test installation

Hydraulic measurements

At the Laboratory for Aero- and Hydro-dynamics of the Technological University at Delft experiments have been performed to collect data on the hydraulic behaviour of the fuel element. These led to the design of a special type of grid for the fuel rods, which is now being tested in the corrosion loop. Experiments to check the performance of the injectors used inside the reactor vessel are now under way. The flow distribution in the upper and bottom plenums of the reactor will be studied in a 1:2 scale model with air flow.

Heat transfer measurements on bundles of electrically heated rods

A stainless steel test circuit for 140 kgf/cm^2 and 300 °C has been erected at the Technological University of Eindhoven. The loop is equipped with a 1 MW fast control direct current power supply, which makes it particularly well suited for dynamic experiments.

The first set of introductory experiments, however, was of a purely static nature. The test-bundle consisted of 12 heated rods and 17 unheated ones. Although imperfect instrumentation prevented direct results being obtained, the experiment yielded important information regarding loop operation and measuring techniques.

The present programme is mainly directed towards the investigation of mixing and of burn-out characteristics. First, a number of experiments are carried out on the so-called "cold wall effect", whereas a special test section is under construction for testing the effect of local enthalpy of the coolant and local heat flux on burn-out. In this section some of the rods are equipped with hot spots which can be heated separately from the rest of the bundle. Mixing between adjacent coolant channels is also investigated in an atmospheric, plastic, dummy fuel element.

The high pressure loop is also being used for the study of the dynamic response of the system to induced steam load variations and power oscillations. The laboratory is, for this purpose, equipped with such auxiliaries as an analogue computer, a statistical noise correlator and a transfer function analyser.

Finally, the loop is being used for the experimental study of the steam generator which is of the same principle as the actual ship reactor steam generator. These experiments serve at the same time for the development of instrumentation for the steam generator test programme mentioned above.

Shielding experiments

Shielding experiments are being carried out in the Geesthacht swimming-pool reactor in co-operation with the Gesellschaft für Kernenergieverwertung in Schiffbau und Schifffahrt (GKSS) and FIAT/ANSALDO groups. The shielding by steel/water arrangements is studied in order to check the validity of the design calculations. Moreover, measurements are carried out regarding the effect of irregularities in the shield due to large penetrations (pipes, ducts, etc.).

Pump development

A small scale canned rotor pump has been built by Dutch industry for the heat extraction loop at Eindhoven. A novel characteristic is the nickel plating of some of the mild steel surfaces by the Kanigen process. At present a larger pump is being built as a prototype of the pump that will be a part of the integrated steam generator (superheater) pump unit. One of the special features is the built-in check valve.

FUTURE DEVELOPMENT

The reactor development programme as outlined in the preceding sections will largely be completed by mid-1965. Exceptions are the irradiation experiments and the operation of the steam generator test installation. It is felt that, by that time, all the factors will have been provided which are necessary for the evaluation of the proposed design of an advanced pressurised-water ship reactor and its eventual construction. At the same time it is felt that further improvements of the system would be possible and that they would, in fact, be essential for the further establishment of nuclear reactors for ship propulsion. The Netherlands Reactor Centre is therefore considering the launching of a development programme for a Stage 2 advanced PWR for marine application. In this programme the main emphasis would be on the following three items:

(*a*) Improvement of the core, a longer core life being an essential characteristic;

(*b*) Improvement of the system, with special attention to the application of mild steel;

(*c*) Integration of the reactor with the ship, and its operation with the operation of the ship as a whole.

The extent and duration of the second stage development programme will be comparable to the first stage programme.

REFERENCES

1. Coehoorn, J., *et al.*, *The Critical Facility KRITO*, Paper presented at the IAEA symposium on Exponential and Critical Experiments, Amsterdam, 2–6 September, 1963.
2. Bustraan, M., and Tas, A., *The Subcritical Facility PUK*, Paper presented at the IAEA symposium on Exponential and Critical Experiments, Amsterdam, 2–6 September 1963.