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N.S. OTTO HAHN

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Otto Hahn, Germany's first nuclear merchant ship, is a research vessel and a 14 000 dwt ore-carrier. The $14 million ship was constructed between 1963 and 1968 and is presently owned by the author's company. The main purpose of the ship is to collect the technical and practical knowledge necessary for the development of economically competitive nuclear merchant vessels.

The nuclear propulsion plant of *Otto Hahn* is a prototype of the advanced pressurized water reactor, the so-called FDR, the main features of which are self-pressurization and integrated design.

During 1½ years of extensive trials under all possible weather conditions the ship and the propulsion plant have shown an excellent behaviour which exceeded the expectations of both the builder and the operator.

The paper describes ship and machinery and gives some detailed information about the experience gained so far.

Mr. Ulken

INTRODUCTION

The author's company is the owner of the nuclear ship *Otto Hahn*. The company was founded 13 years ago for the special task of promoting the application of nuclear power for ship propulsion. The company carries out research and development work on its own as well as in close co-operation with industry and co-ordinates all German activities in this field. Partners in G.K.S.S. are the Federal Republic of Germany, the four northern German provinces and 34 industrial and commercial companies, mainly shipyards, shipowners and machinery factories.

During the first twelve years the author's company has spent about $50 million. This includes construction costs of $14 million for the nuclear ship *Otto Hahn* and her first reactor core, without the fuel. An additional $15 million have been invested in the company's research centre at Geesthacht, near Hamburg, where amongst other installations two swimming-pool reactors, a zero power assembly and other research installations are operated. The remaining amount covers the current expenses for research and development.

Numerous preliminary investigations, studies of various projects and evaluation of different reactor types were carried out before the company, in 1961, decided to build *Otto Hahn*. This ship is an ore carrier of 14 000 dwt loading capacity and 10 000 shp, but apart from this commercial feature, she is predominantly a research ship. The ship and the reactor installation were equipped with additional measuring devices and research facilities to provide the technical and practical knowledge useful and necessary for the design of future nuclear ships.

Otto Hahn is not an economical ship in a commercial sense. Disregarding the capital costs the operational costs amount to $0·5–0·7 million per year, while, depending on freight rates, up to $0·5 million may be earned by cargo voyages.

Otto Hahn was constructed between 1963 and 1968. In view of this rather long period it must be remembered that the selected pressurized water reactor with self-pressurization and integral design (FDR) represents a first-of-a-kind prototype, requiring a number of individual industrial manufacturing procedures. In future, nuclear ships will have to be constructed in a much shorter period to meet the economic requirements. With regard to the short-term dispositions of the shipowners, the author estimates a construction period of 2½ to 3 years as the maximum acceptable time for commercial orders. This is only one question, and not the most important, which has to be solved before nuclear power becomes competitive in the field of ship propulsion. Other factors, such as availability of the plant, handling of the plant by a normal crew, port entries of nuclear ships, insurance problems and evaluation of the calculated safety measures can only be solved by operation of nuclear merchant vessels over a period of time, under all possible conditions. This is why the author's company decided to build the first nuclear merchant vessel. The results obtained from the first 18 months' operation of *Otto Hahn* have proven most useful for the work which is being done in Germany for the further development of larger nuclear ship propulsion plants.

DESIGN PHILOSOPHY OF THE HULL

At the end of 1960 the author's company invited the major German shipyards to tender for the construction of a nuclear powered tanker or of another suitable type of vessel and the following year decided in favour of the alternative tender submitted by Kieler Howaldtswerke A.G. which related to a bulk carrier of approximately 14 000 dwt. A special committee, formed by technical experts, put forward their proposals for the improvement of this design. The work was carried out by the shipyard in close co-operation with the author's company. The following modifications were recommended:

a) an increase in the volume of water ballast allowing the ship to operate at full draught during the research phase, thus obtaining full engine power;

b) an increase in accommodation and working space for expanded research and training staff;

c) a special forward bridge superstructure to ensure navigation in rivers and port waters is as safe as possible, the room under the bridge house being occupied by an auxiliary Diesel generator set;

d) an increase in watertight subdivision, as high as possible, and separating the auxiliary boiler room for better fire protection.

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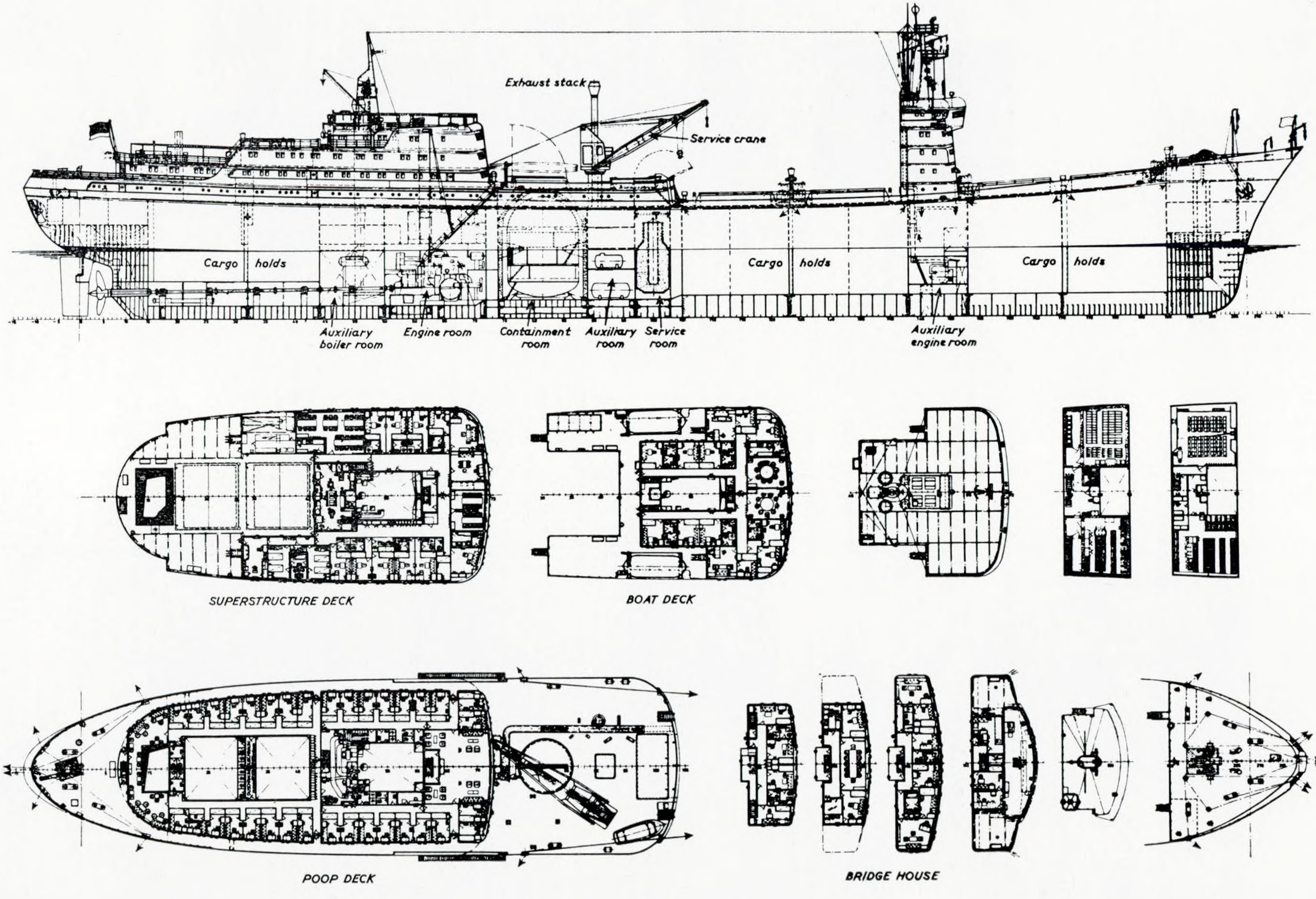


FIG. 1—N.S. Otto Hahn—*General layout*

The reason for these recommendations was that all the experts involved in these decisions felt that the minimum possible risk of hazards should be ensured for this prototype test ship. Owing to the type of bulk carrier selected it was possible to carry out the recommended changes. These changes, together with additional space in the reactor compartment for reactor auxiliaries and for the service station, as well as an increase in the block coefficient allowing space at the ship's ends to facilitate unloading by means of grabs, resulted in what was virtually an entirely new design.

This design was that of an ore carrier, since the load space for other bulk cargoes had become too small to allow the loaded draught to be attained, and the carrying capacity to be fully utilized. On November 28th, 1962, the contract was concluded between the author's company and Kieler Howaldtswerke A.G. The keel was laid on September 17th, 1963, and the ship was launched on June 13th, 1964. Construction was completed at the fitting-out dock of Kieler Howaldtswerke A.G., where also the conventional propulsion machinery, the reactor plant and the fuel elements were installed. The chosen type of ship was, under the circumstances mentioned, the most economic type. The additional major advantage over a tanker was the possibility of running the ship for different trades on different routes to various ports, thus enabling the owner to gain the widest experience.

DESCRIPTION OF THE SHIP

The nuclear ship *Otto Hahn* is constructed as an ore carrier (bulk freighter) and, because of the high number of research personnel, as a passenger vessel. Her principal dimensions and data are set out in Table I.

TABLE I—PRINCIPAL PARTICULARS OF N.S. 'OTTO HAHN'

Length, o.a.	172 m
Length, b.p.	157 m
Beam	23·40 m
Depth, moulded	14·50 m
Draught	9·20 m
Freeboard, including thickness of deck plating	5·33 m
Block coefficient	0·741
Displacement (seawater)	25 812 tons
Deadweight capacity	14 200 tons
Capacity of holds	13 328 m³
Ballast tank capacity	14 278 m³
Tonnage	16 870 grt
	7 257 nrt
Power output: normal	10 000 shp
maximal	11 000 shp
Speed (approximately)	17 knots
Auxiliary power	2000 shp
Speed (auxiliary power)	8·5 knots
Crew (including trainees)	61
Research personnel and passengers	35
Hospital	4

The ship is classified by two classification societies. It holds:

a) the highest classification of Germanischer Lloyd, as an ore-carrier, passenger vessel and nuclear ship;
b) the highest classification of Bureau Veritas, as an ore-carrier and nuclear ship.

In addition to the ship's safety, especially as regards ensuring the operational safety of the nuclear plant, the company also took into account the regulations and directives of national and international bodies. According to the German Atom Law, special permission had to be obtained from the Federal Ministry of Scientific Research, the Ministry of Labour and the Ministry of Transport of the four northern German provinces.

Fig. 1 shows the general layout of the ship. *Otto Hahn* is a single-decker with normal camber and abnormally high forward sheer. The superstructure comprises the bridge, consisting of five decks, situated on the main deck, approximately one-third of the ship's length from the bow; the after section consists of a long deck house which extends for almost half the ship's length and supports three shorter decks. The decks above the main deck comprise the poop deck, the superstructure deck and the boat deck. The short forecastle superstructure was kept as low as possible to ensure good visibility from the bridge despite the high sheer, and is of watertight construction except for some small passages, and is included in the gross tonnage calculation.

The propulsion plant is housed mainly in the after part of the ship. From aft to forward, the various engine compartments, which are separated by bulkheads, are:

1) the auxiliary boiler room;
2) the engine room;
3) the reactor room with empty side cells;
4) the reactor auxiliaries room with empty side cells;
5) the service room with empty side cells.

Under the bridge, between the longitudinal side bulkheads, is located the auxiliary engine room. Forward of this are holds 1 and 2. Between the auxiliary engine room and the service room are holds 3 and 4. At the rear of the entire propulsion plant and above the shaft tunnel cover are holds 5 and 6.

The ship has 13 watertight bulkheads as well as two cofferdam bulkheads and a small bulkhead between the after peak and the empty cell. Longitudinal bulkheads extend over the whole length of the ship except in the fore and after peak compartments, the aft empty cell and the main engine room. The holds, the auxiliary engine room and the auxiliary boiler room are bounded, on both sides, by water ballast tanks. From the forward collision bulkhead to the after peak bulkhead there is a double bottom which extends over the full width of the ship and, except in the reactor compartment, serves as ballast water room.

In the reactor compartment the double bottom and the side cells function as empty cells for collision and grounding protection. Only the upper part of the middle sections in the double bottom, which are subdivided by a watertight intermediate bulkhead, can be flooded with sea water when the ship is in dock; sea water then serves as a radiation shielding in the absence of a concrete secondary shield at the bottom.

According to the regulations, including also the SOLAS Convention regulations and recommendations, the highest standard in fire protecting construction, fire detecting and fire-fighting systems are ensured and the equipment is of the highest possible quality.

Design of the Reactor Compartment

During the design phase of the ship, new problems had to be solved by the naval architects. The design of the containment foundation, the design of the foundation of the concrete secondary shielding and the design of a collision barrier were the most interesting features. Fig. 2 shows the finally accepted solutions.

The containment vessel, together with its internal equipment, weighs approximately 1000 tons. It rests on the ship's double bottom by means of a bed structure and about halfway up it is supported laterally and longitudinally by the containment room bulkhead. The upper horizontal support acts as a horizontal hinged mounting, and the 24 lower slide bearings, the surfaces of which are uniformly distributed in a circle, each of which is at an angle of 45° in relation to the containment axis, acts as a ball-and-socket joint. Owing to the statically determined distribution of forces between the upper and the lower supports, any deformations of the ship's hull have no effect on the foundation. In order to prevent this effect from being reduced by friction in the bearings, Teflon was used as a facing material and the bolts preventing displacement of the containment are prestressed against special bushings. The horizontal support acts on four points, uniformly distributed around the circumference of the containment, from where the forces are transmitted tangentially to the containment in the longitudinal and transverse directions. This function is performed in each case by eight prestressed tie rods which are joined to the hull in the corners of the reactor room. The 24 slide bearings are located on the upper edge of a conical skirt resting on the tank top. The stress peaks occurring at the intersection points of the conical skirt and rectangular

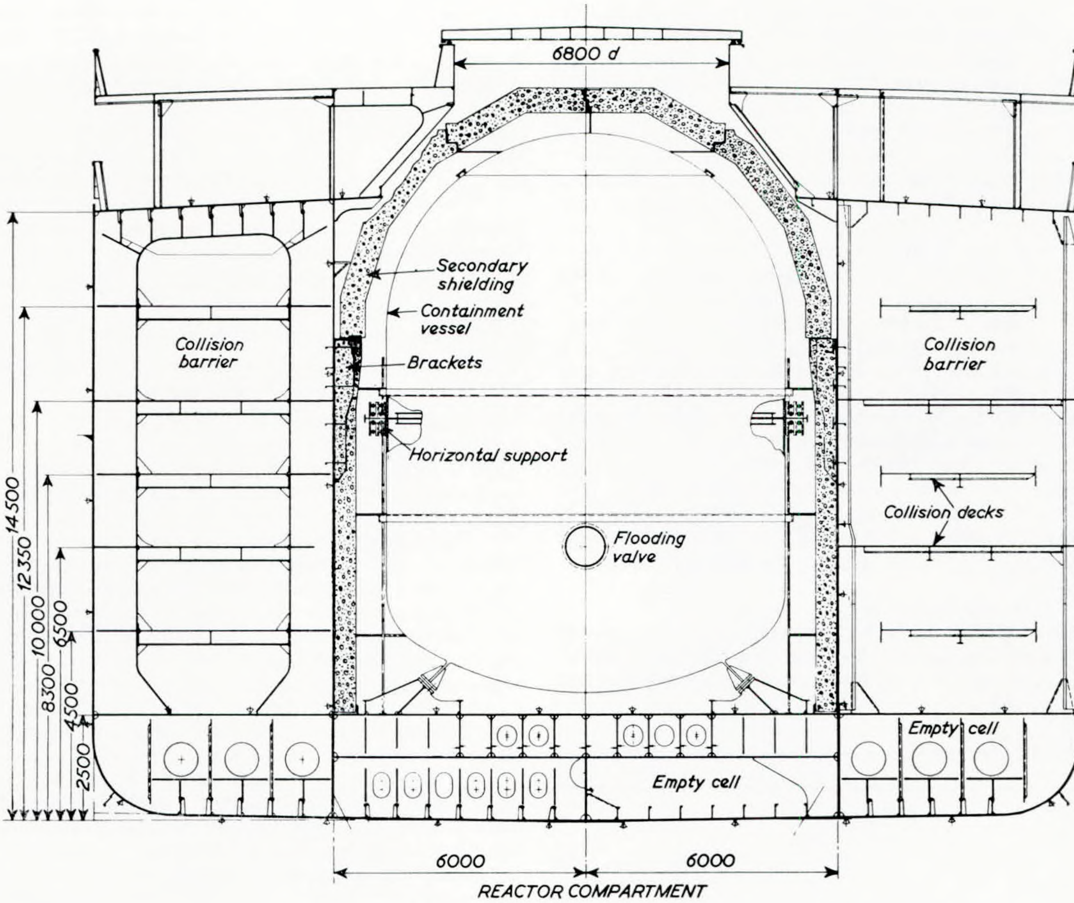


FIG. 2—*Reactor room*

beams are well below permissible values and are greatly reduced by kneeplates and curved carlings.

The secondary shielding, consisting of 500 and 600 mm thick concrete, is mounted in the ship's hull in a special manner. It consists of four flat wall-slabs and a dome. These elements are supported by four brackets, positioned in the neutral axis on the longitudinal and transverse bulkheads. At the corners of the room the reinforcing bars of the adjacent concrete walls are connected in such a way that they act as hinges with vertical axes, thus absorbing forces during the inclination of the ship. In order to avoid interactions between the concrete walls and the hull, polystyrene plates, in an airtight foil packing, are installed between the concrete and the bulkheads.

The dome of the secondary shielding rests on the brackets by means of four pairs of sliding feet, thus acting radially only but not in other directions. In the vertical direction it is secured by bolts.

On both sides of the reactor room between the outer shell and the longitudinal bulkheads, collision barriers are provided. They are formed by additional decks and web frames. Fig. 2 shows two collision decks extending over the full width of the side spaces. They are welded to the shell plating and to the longitudinal bulkheads. In the three intermediate spaces thus formed, between the tank top and the main deck, are mounted three additional decks, only between the inner flanges of the web frames. They are not welded to the bulkhead or to the plating. This construction reduces the notch effect for the longitudinal strength of the hull, since the longitudinal bending stresses are transmitted only to the wide decks. The plating of the other decks and of the tank plate in this area is increased and also the shell plating is stiffened by additional frames. The collision barrier mounted on *Otto Hahn* has been tested in a model test and the performance of the additional decks was satisfactory.

The double bottom structures in the reactor compartment provide low buckling resistance to the lower part. The load on the tank top from the containment vessel can be borne solely by the stiff structure of the upper part of the double bottom. Care was taken to ensure adequate strength of the lower part for docking purposes.

For both the reactor compartment and the entire ship the following design values were considered additionally as safety values for the construction:

a) additional accelerations ... 1·0 g in all directions
b) periodic rolling motion ... 45° to each side
c) periodic pitching motion ... 12° up and down
d) permanent list ... ... 45° to port or starboard
e) trim ... ... 12° down by head or stern

Design of the Reactor Plant

The reactor plant of *Otto Hahn*, i.e. the so-called FDR, is an advanced pressurized water reactor. It has been developed for nuclear ship propulsion by a working group of the German Babcock and Wilcox Dampfkesselwerke A.G. at Oberhausen and Interatom, at Bensberg. The reactor type was selected by the author's company in November, 1963. The main reasons for this choice were some promising advantages of the FDR design, i.e. the compact construction of the whole plant, the avoidance of large high pressure pipes, the simple control system and the relatively high steam quality up to 36°C superheating.

For the final design and for the construction of the reactor plant a number of subcontracts have been given to several firms in the European Community areas, within the planned participation contract existing between Euratom and the author's company.

The most important design features of the FDR are the integrated construction and the self-pressurization. The heat

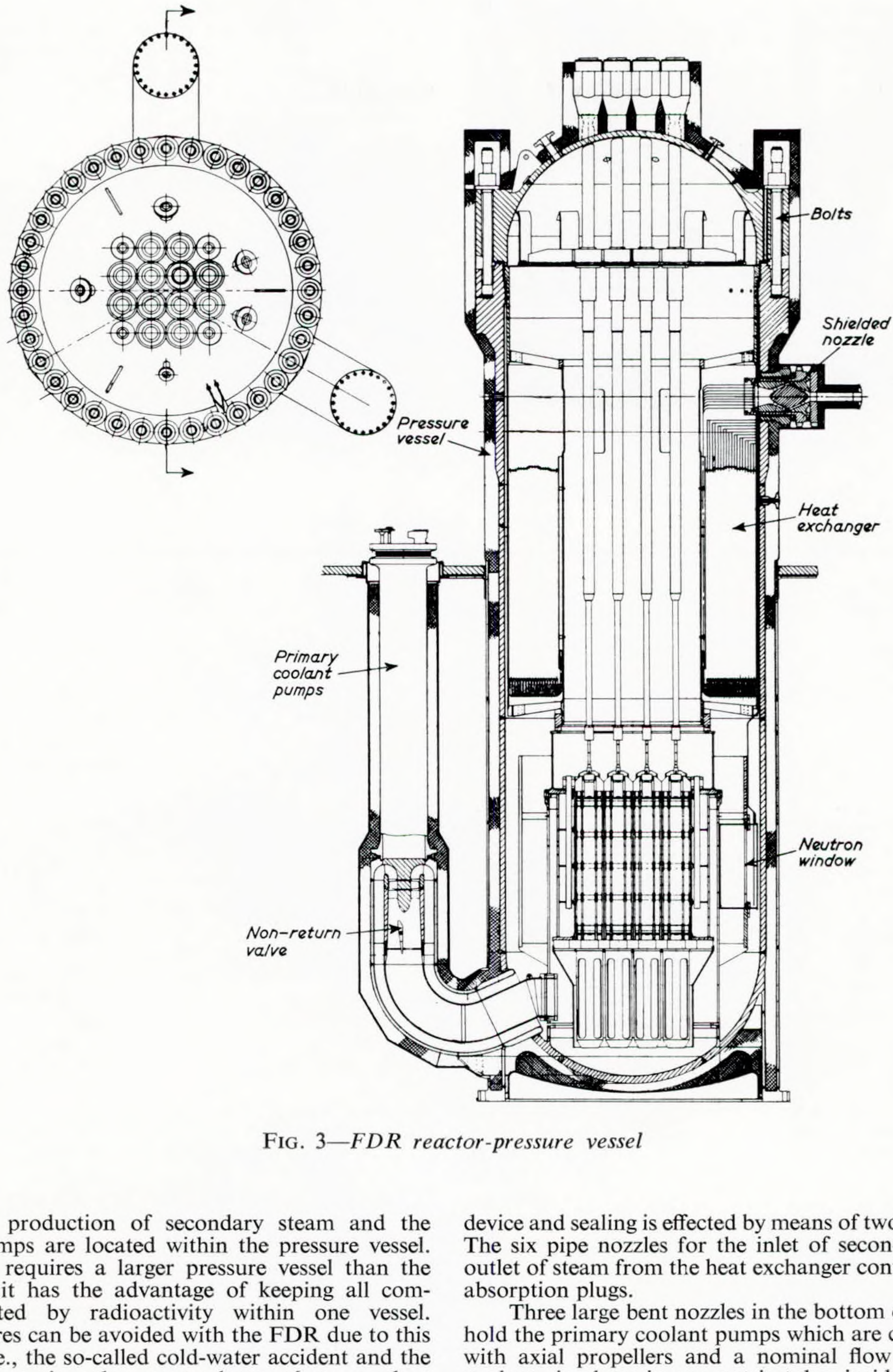


FIG. 3—*FDR reactor-pressure vessel*

exchangers for the production of secondary steam and the primary coolant pumps are located within the pressure vessel. Though this design requires a larger pressure vessel than the conventional PWR it has the advantage of keeping all components contaminated by radioactivity within one vessel. Moreover, two failures can be avoided with the FDR due to this integrated system, i.e., the so-called cold-water accident and the loss of coolant accident, since there are no large primary coolant pipes.

Pressure Vessel and Internal Equipment

Fig. 3 shows a cross-section of the FDR reactor pressure vessel with its installed components. The vessel itself consists of forged rings and half spheres of fine grain steel and has an internal plating of about 8 mm thickness of 18/9 Cr Ni steel for corrosion protection. The wall thickness of the pressure vessel has been calculated for a pressure of 86 kg/cm^2 and a temperature of 300°C. As the reactor works with self-pressurization the operation pressure is 63·5 kg/cm^2 at an operating temperature of 278°C. The cover of the vessel is fixed on to the cylindrical part by 36 bolts of 100 mm diameter equipped with an hydraulic tension device and sealing is effected by means of two large metal O-rings. The six pipe nozzles for the inlet of secondary feed water and outlet of steam from the heat exchanger contain special radiation absorption plugs.

Three large bent nozzles in the bottom of the pressure vessel hold the primary coolant pumps which are canned motor pumps with axial propellers and a nominal flow of 1025 m^3/h. The coolant circulates in concentric tubes inside the nozzles. In the event of one of the pumps failing, a non-return valve in the return line is closed automatically. The two remaining pumps are capable of maintaining 74 per cent of the normal flow rate thus enabling the reactor, with slightly reduced neutron flux scram point to 110 per cent ensuring the necessary burnout safety, to operate at nearly 100 per cent power under normal sea conditions. As the pressure losses in the primary circuit are very low compared to the normal PWR the head of the primary pumps is only 0·33 kg/cm^2, requiring a power of 15 kW for the electric motor. For this reason a rather high reactor power, and especially the decay-Gamma heat, can be removed from the core by natural circulation. The reactor core being located in the lower part of the pressure vessel is maintained in position by a special structure

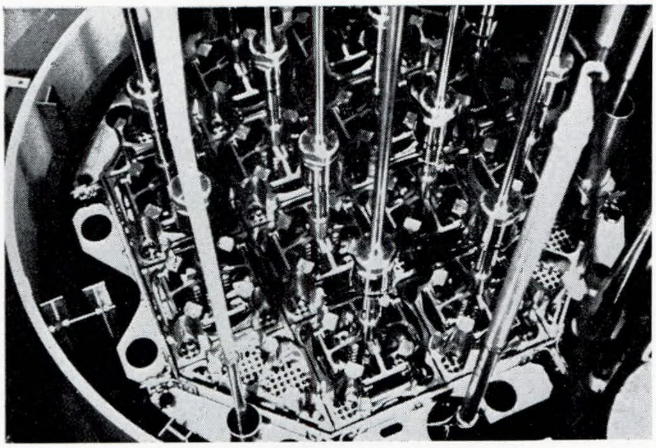


FIG. 4—*The core arrangement*

to withstand additional *g* forces up to 1 *g* in all directions.

Fig. 4 shows the arrangement of the core consisting of 12 square and four triangular fuel elements. Each square fuel element consists of 17 × 17 fuel rods and burnable poison rods arranged with a 15·8 mm square spacing. Four central T-shaped cutouts permit the lowering of the absorber rods. The fuel consists of sintered UO_2 contained in 0·35 mm thick stainless steel cans having an outer diameter of 11 mm. The rods are guided at the top and bottom by plates equipped with five spacers consisting of square soldered pressings. The supporting frame of the fuel element is formed by 12 zincalloy struts. The four triangular corner elements are of similar design. They contain about half the number of fuel rods but no absorber rods. The core is designed for an operating time of 500 full power days and for an average burn up of 7 260 MWd/t. To obtain flat neutron flux distribution and uniform fuel burnup the core is divided into four radial enrichment zones with 2·77, 3·20, 3·89 and 4·87 per cent of U 235. The average enrichment is 4·03 per cent. The T-shaped cruciform absorber rods (see Figs. 3 and 4) contain a large number of small steel tubes filled with boron carbide in a

TABLE II—PRESSURE VESSEL

Reactor pressure vessel		
Diameter/internal height	2360/8580 mm	929/3378 line
Internal volume	35 m^3	1166 ft^3
Wall/plating thickness	50/8 mm	20/3·15 line
Design pressure	85 kg/cm^2	1209 lb/in^2
Design temperature	300°C	572°F
Test pressure, cold	127·5 kg/cm^2	1813 lb/in^2
Material	—	15 Mn Mo Ni V 53/austenite
Weight (empty)	100 tons	98·4 long tons
Primary system		
Operating pressure	63·5 kg/cm^2	903 lb/in^2
Flow rate (3 pumps)	$2{\cdot}4 . 10^6$ kg/h	$5{\cdot}28 . 10^5$ Imp gal/h
Inlet/outlet temperature	267/278 °C	513/533°F
Flow, cross section	0·61 m^2	0·73 yd^2
Flow, velocity	1·7 m/s	1·86 yd/s
Primary water volume	25 m^3	5499 Imp gal
Reactor core		
Thermal output	—	38 MW/th
Operating period at full load	—	500 d
Average burn up	7260 MWd/t UO_2	7136 MWd/long tons UO_2
Weight of UO_2	298 tons	293 long tons
Average enrichment	—	4·03 per cent
Average thermal neutron flux	$1{\cdot}1 \times 10^{13}$ cm^{-2} s^{-1}	$7{\cdot}1 \times 10^{13}/in^2/s$
Number of fuel elements/rods	—	16/3144
Equivalent core diameter	1150 mm	453 line
Active core height	1120 mm	441 line
Fuel rod diameter	11 mm	4·33 line
Wall thickness of cladding tubes	0·35 mm	0·137 line
Cladding tube material	—	× 10 Cr Ni Nb 189
Control rods		
Number	—	12
Absorber length/material	1020 mm B_4C	402 line/B_4C
Type of drive	—	rack and pinion
Lifting speed	12·7 cm/min	5 in/min
Scram time (from 2/3 height)	—	1·4 s
Weight	81·5 kg	179·7 lb
Steam generator		
Design flowrate of feedwater	64 m^3/h	2260 ft^3/h
Feedwater/steam temperature	185/273°C	365/523°F
Steam pressure	31 kg/cm^2	441 lb/in^2
Superheat	36°C	65°F
Heating surface of heat exchanger	465 m^2	556 yd^2
Number of system/tubes	—	3/162
Type	—	once-through, forced circulation
Tube dimension	19 × 1·2 mm	7·48 × 0·47 line

stainless steel cladding. They are connected to the drives, which are located vertically above the core on the cover of the vessel, by large tubes. The drives each consist of an internal toothed rack unit, a sealing water gland and an external unit comprising the electric motor, gears, magnetic clutch, scram unit, shock absorber and position indicators. The drives can be operated individually or in groups, automatically or manually.

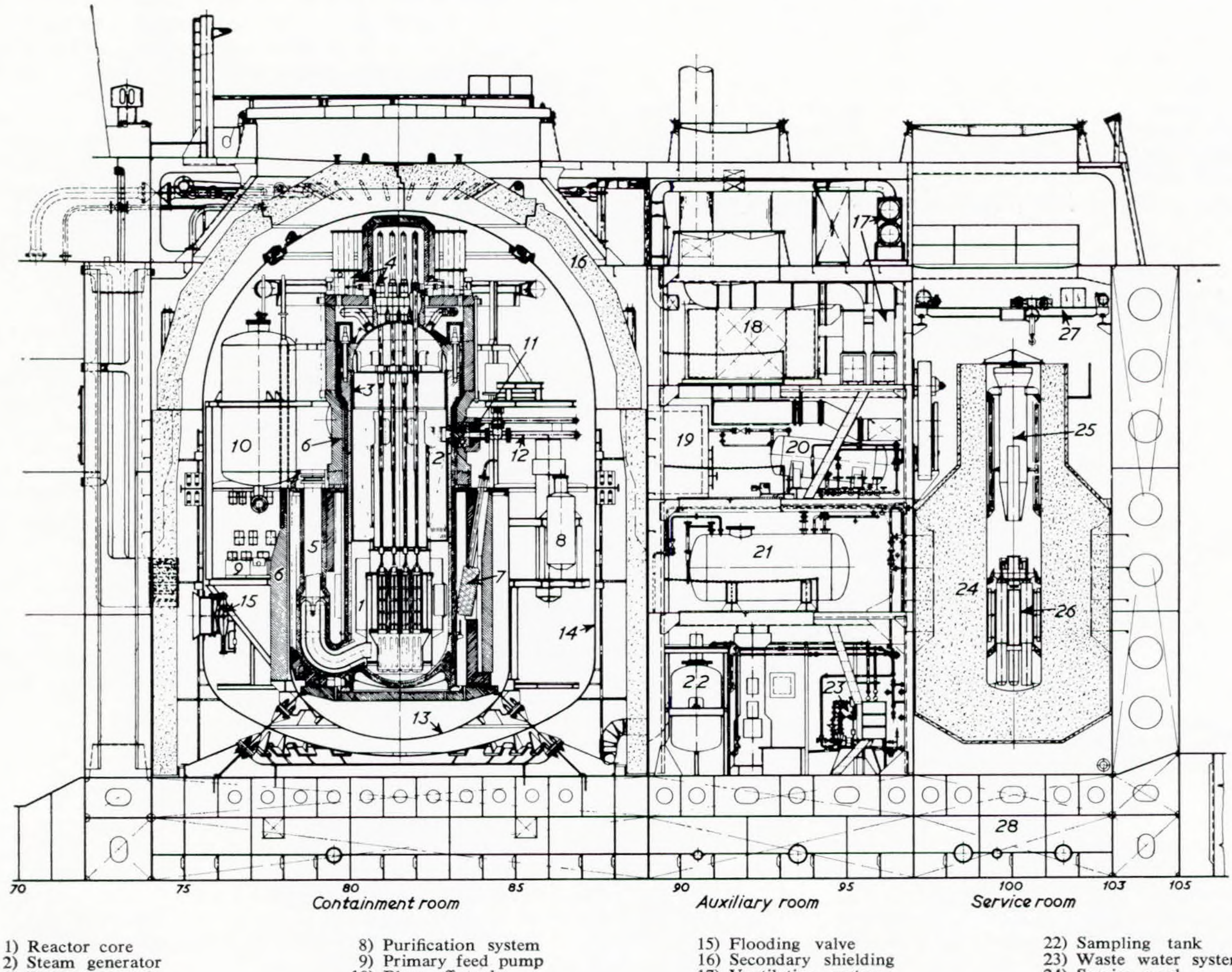
The central compartment of the pressure vessel is surrounded by a duct for the primary coolant flow. In the annular chamber, between the pressure vessel wall and the duct the steam generator is installed. It operates on the forced circulation-once-through-principle and supplies 3 × 21·4 t/h of slightly superheated steam at 31 kg/cm² and 273°C. The primary water from the core flows through the duct, entering the steam generator at a temperature of 278°C and being discharged at the bottom at 267°C. The secondary feed water enters the feedwater inlet at 185°C and 45 kg/cm², flows downstream through tubes on the outer wall of the duct and then passes upwards through the steam generator in helically arranged tubes. The steam generator is divided into three parallel systems, the ends of which branch out separately and are grouped in plates at the inlet and outlet nozzles (see Fig. 3). Additional data are given in Table II.

CONTAINMENT VESSEL AND AUXILIARY SYSTEMS

Fig. 5 shows the pressure vessel and its equipment surrounded by the dry safety containment vessel which also accommodates the principal auxiliary systems containing the primary coolant and the primary shielding. The containment vessel is gastight and is capable of withstanding the overpressure produced, even in the event of a major accident. It is designed for a pressure of 14·5 kg/cm² at 200°C and was tested at 20 kg/cm² and 20°C by a cold water pressure test. The containment vessel is housed in a special compartment which is shielded at all sides.

The secondary shielding has the shape of a concrete shell which ends on the floor. Normally the floor does not need any special shielding, but if the ship is drydocking the 1 m high upper part of the double bottom can be flooded, the containment being then fully included in equivalent secondary shielding. Along with the primary shielding full biological protection is provided against radiation dissemination outside the reactor compartment. According to the German radiation protection regulations the radiation doses must be lower than 0·02 mrem/h in the crew's living quarters. The control room and the machinery space in *Otto Hahn* are also designed as free access areas and the mrem/h is maintained lower than 0·054 for a 56-hour week.

The structure of the containment vessel is provided with penetrations for a personnel air lock, four flooding flaps, six hot pipe penetrations, 19 cold pipe penetrations and 74 cable penetrations. The bottom is penetrated by a cruciform ring which transmits the forces resulting from the weight of the containment to the ship's bottom. The personnel air lock has a spherical shape of 2 m diameter and penetrates the dome of the containment in the forward starboard corner of the reactor room. The containment vessel is accessible for limited periods even



1) Reactor core
2) Steam generator
3) Pressure vessel
4) Control rod drives
5) Primary coolant pumps
6) Primary shielding
7) Neutron chamber
8) Purification system
9) Primary feed pump
10) Blow off tank
11) Steam nozzle
12) Steam pipe
13) Shield tank
14) Containment vessel
15) Flooding valve
16) Secondary shielding
17) Ventilation system
18) Active carbon filters
19) Sampling system
20) Waste gas system
21) Active water system
22) Sampling tank
23) Waste water system
24) Service pool
25) Lead cask
26) Fuel element rack
27) Crane
28) Double bottom

FIG. 5—*The containment vessel and auxiliary systems*

under full load operation. The dose rates are limited to 15–20 mrem/h.

The flooding flaps in the lower part of the vessel prevent damage to the containment structure in the event of the ship being wrecked. They open at an external pressure of 2·5 kg/cm^2 and close again before pressure equilibrium is attained. The compact primary shielding mounted round the pressure vessel is adapted to the integrated design of the reactor. The lower part consists of an annular space tank, containing multiple layers of cast steel and water extending up to 5 m from the lower dome of the pressure vessel and above the core. In view of the adequate level of water in the pressure vessel it is sufficient to provide shields of cast steel above it. Additional reactor auxiliary systems housed in the containment vessel are:

a) the primary purification system;
b) the buffer seal system;
c) the blow off system;
d) the primary feed system;
e) the air circulation system.

The primary purification system consists of two canned motor-type pumps, one of which is in operation, each pump has a throughput of 6 tons/h for a head of 60 m, two regenerative heat exchangers, one aftercooler and two mixed bed ion exchangers, one of which is in operation. The system maintains the corrosion and erosion particles in the primary system at a minimum level. Moreover, it is used permanently to supply feeding water to the buffer seal system which has no special pumps, and in case of failure of all steam generator systems the purification system is used for emergency cooling of the plant through the aftercooler.

The buffer seal system supplies water to the packings of the 12 control rods for sealing off the environment against the escape of water vapour and hydrogen from the pressure vessel and for cooling purposes. The water required is branched off from the purification system downstream of the aftercooler and the ion exchanger. The pressure is reduced inside the packings to the blow-off-tank pressure.

The blow-off system consisting of the blow-off valves, the necessary piping and the blow-off-tank draws off steam through the safety valves into the blow-off-tank, where it is condensed, in the event of an inadmissible pressure rise in the pressure vessel. The time taken up by condensation should enable the personnel in the containment to make their way out before the blow-off-tank blows off into the containment atmosphere.

The primary feed system is used to feed back into the pressure vessel the primary water which enters the blow-off-tank from the buffer seals, from the make-up-water system or from the sampling system. The high pressure differential is overcome by two parallel piston pumps, one of which normally is in operation; intermittent operation is also possible.

The air circulation unit in the containment is a closed system, which draws off the heat released by the plant components in the containment so that the air temperature in it does not exceed a preset value. It consists mainly of two blowers, one of which is actuated, and a cooler which is operated by means of intermediate cooling water.

The remaining reactor auxiliaries, which in *Otto Hahn*, as a research ship, occupy a large amount of room, are located in an adjoining compartment (Fig. 5). The principal elements are:

a) the intermediate cooling system;
b) the ventilation system;
c) the active water system;
d) the waste water system;
e) the waste gas system.

These systems do not carry a high rate of radioactivity under high pressure and are not, therefore, necessarily included in the containment vessel.

The intermediate cooling water system supplies cooling water to the individual components in the containment, the reactor auxiliary room and the service room, thus conveying the heat produced in these spaces to the sea water through the re-coolers. The system consists of two recoolers, the buffer tank, filters and two circulating pumps. The recoolers are fed from the common sea water line of the engine room.

The ventilation system circulates air to the entire controlled area, i.e. all the auxiliary rooms, the containment room, the service room, the laboratories and the wash rooms and changing rooms. The heat is drawn off and a specified underpressure is maintained in relation to the environment in these rooms, so that the air from the reactor compartment cannot escape uncontrolled into the surrounding parts of the ship. In addition the system is designed for flushing out the containment air prior to entry, if necessary. The ventilation system consists of special intake and exhaust units. Under normal operating conditions one of the two air-intake ventilators draws air in from the atmosphere by means of a pre-filter, a pre-heater, a coarse filter, a fine filter, a cooler and an afterheater. The air is drawn off through one of two axial fans in the exhaust air line, after having passed through fine filters, absolute filters and active carbon filters.

The active water system collects, purifies and recycles the active water originating from various sources which is liable to contain corrosion particles and fission products, and which must be ready for re-use, or pumped into the waste tanks. The waste water system collects and stores all water in the controlled area, including the laboratories, the wash rooms, the service room, the containment, which may be radioactively or chemically contaminated, thus becoming unserviceable for reactor operation. The water is tested and discharged to the sea through the condenser main cooling sea water line after passing a monitoring point. The system consists basically of two pumps, two sampling tanks and two waste water tanks of 15 m^3 capacity.

The waste gas system, which is only operated after opening of the pressure vessel, collects the gases present in the pressure vessel, in the vapour spaces of the blow-off-tank and in the primary water in the form of solution. It stores the gases in shielded containers, thus discharging them to the atmosphere after monitoring.

Fig. 5 shows a second reactor auxiliary room, the so-called service room. It consists mainly of a large concrete service pool with an inner stainless steel cladding. The pool is mounted on the bulkheads by means of brackets as in the case of the secondary shielding, and serves as a storage pool for used fuel elements.

During the design phase of *Otto Hahn* it could not be decided, whether or not to build a land based service station. Therefore the ship was fitted with all the necessary equipment, even that for changing used fuel elements, without a land based installation. Today it is apparent that this equipment will not be needed for future ships as complete fuel cycle service has been developed for land based power plants, which also can be used for nuclear ships.

Only one of the necessary auxiliary systems for the FDR is mounted in *Otto Hahn* in the main engine room: the make-up-water system, which also acts as an emergency feed system through the pipes of the primary feed system. The make-up-water system supplies all water consuming units in the containment and in the auxiliary room with demineralized water. The water for the make-up system is supplied from two distillate collection tanks in the engine room, where distilled sea water from the evaporators is stored. This distillate is demineralized in a cation exchanger and subsequently in a mixed-bed-filter and pumped to the blow-off-tank in the containment vessel. In case of emergency it is possible to pump distilled water directly by a high pressure feed pump to the pressure vessel.

REACTOR CONTROL AND INSTRUMENTATION

Since the reactor has good self-regulating properties, a relatively simple cascade-type control system is sufficient. The reactor pressure, in the pressure vessel, is the controlled variable and under load operating conditions it is kept constantly at a value of 63·5 kg/cm^2, regardless of load. The required reactor power is obtained in the master controller from the pressure deviation and the main perturbation variable (the steam flow rate). The required reactor power controls the neutron flux. A change in the turbine load produces a change in the steam flow and the rate of exchanged heat in the heat exchanger. The subsequent temperature or pressure change in the primary system results in the displacement of the control rods by means of the pressure and neutron flux regulator, thus counteracting the change in these operational parameters. The reactor control, even during power operation, can be switched off totally, so that the reactor only is controlled by its self-regulating characteristics.

The reactor plant is subjected to periodic accelerations in all directions in heavy sea. As in the core there is always a certain void fraction, the vertical component of the acceleration has a marked effect on the change of reactivity. During constant power operation, the control system does not necessarily affect the occurring neutron flux change by altering the position of the control rods. In heavy seas, therefore, the control rods are not displaced until pre-set limit values of the neutron flux have been exceeded, thus limiting the number of movements and increasing the lifetime of the drives. The control system itself, however, remains in action.

The nuclear instrumentation provides information on the thermal neutron flux and thus on the reactor's power level in three zones with slight overlap by a decade. The start-up is monitored by two parallel connected B F 3 counter tubes; in the intermediate range two parallel gamma-compensated logarithmic ionization chambers, coated with boron, are operated on a one-out-of-two system; the derived period indication has a set-back function. In the power range three linear ionization chambers without gamma-compensation are operated on a two-out-of-three system. These are also coated with boron. In addition to power monitoring the instrumentation has the function, in conjunction with other measurements, of safeguarding the reactor against dangerous operating conditions. For this purpose particular attention has been paid, in its design, to ensure the reliability of the equipment and the components used. For reasons of operating safety and simplified maintenance all the nuclear instrumentation equipment is housed in the air conditioned amplifier room. The equipment itself is fully transistorized. All necessary indicating and recording equipment is centralized in the control room below the amplifier room, where also all instruments of the main engine and conventional auxiliary systems are located. From here the ship's entire propulsion and reactor installation can be monitored, controlled, started and stopped.

The electrical energy for the reactor consumers is supplied from the ship's mains via the reactor's switchboard. This switchboard is divided into two parts; one of which is the emergency switchboard. Control systems and the instruments are fed by a special constant voltage supply system, to prevent these sensitive consumers from disturbances of the ship's net.

CONVENTIONAL MACHINERY AND PROPULSION PLANT

The conventional part of the machinery is installed in four separate rooms, i.e. the main engine room, the auxiliary boiler room, the auxiliary engine room and the emergency Diesel room on the upper deck. The main engine room and the auxiliary boiler room are located in the after part of the ship. The auxiliary Diesel room is situated midships under the bridge house. Separation of the auxiliary engine room from the after machinery spaces ensures that the former will remain intact in case of breakdown of the entire afterbody as a result of severe damage. In the main engine room the main propulsion plant is located with the necessary and well-known auxiliaries. Only the main turbine and the water system are different from those of conventional ships.

The propulsion unit is a two-casing geared turbine with the astern section in the low pressure casing. The high pressure turbine consists of a single row Curtis wheel as the control stage and five impulse stages; the low pressure ahead section is made up of six impulse stages, and the low pressure astern section comprises two double row Curtis wheels. The high and low pressure rotors are connected to the two-stage articulated-type reduction gearing by means of multitoothed couplings. The normal power output is 10 000 shp at 6050 rev/min for the H.P. turbine and 3185 rev/min for the L.P. turbine; the maximum output is 11 000 shp and that of the astern turbine is 4000 shp. The gearing reduces the speed of the turbines to 97 rev/min at normal power and to 100 rev/min at maximum power. The turbine is equipped with cam-operated multiple-nozzle group valves controlling the steam admission, the steam quality at the main valve being 28 kg/cm² and 268°C. The design of the main turbine differs from that of the turbines usually installed only in respect of steam quality. Steam wetness occurs earlier and this factor has been taken into account by incorporating a steam dryer in the cross-over pipe between the two turbines and by providing special drainage facilities in the L.P. turbine.

The auxiliary power for electrical energy is normally generated in two 450 kW, 380 V, 50 cycle geared turbo alternator sets. The generator turbines work with the same quality of steam as the main turbine and blow off to the main condenser. In case of failure in the main condenser they can be switched over to an auxiliary condenser. The main condenser is designed for a vacuum of 95 per cent and is of the two-path type.

The two auxiliary water tube boilers are installed for two reasons, i.e. according to the rules for nuclear ships the so-called "take-home drive" must be installed for a non-proven nuclear reactor plant. For the first-of-a-kind power plant in *Otto Hahn* a number of pre-operational tests had to be carried out without fuelling the reactor.

For these two services steam is required and it must be produced by the boilers with the same quality as by the reactor. Each of the boilers can produce 8 t/h steam. This is sufficient to produce about 2000 shp to give the ship a speed of between 8 and 9 knots.

The boilers are designed for quick start up. Under normal

TABLE III—POWER PLANT

Main propulsion plant				
Output main turbine		normal	10 000 shp	
		maximal	11 000 shp	
		astern	4000 shp	
Number of revolutions		normal	97 rev/min	
		maximal	100 rev/min	
		astern	49 rev/min	
Trial speed			17 knots	
"Take home" power			2000 shp	
Steam pressure before	main valve		28 kg/cm²	398 lb/in²
Steam temperature	main valve		268°C	514°F
Steam throughput	main turbine		49 tons/h	48 long tons/h
	turbo generator		2·75 tons/h	2·7 long tons/h
Output turbo generator			—	2 × 450 kW
Steam production	heat exchanger		3 × 21·5 tons/h	3 × 21 long tons/h
	auxiliary boiler		2 × 8 tons/h	2 × 7·8 long tons/h
Vacuum main condenser			95 per cent	95 per cent
Turbo feed pump			67·5 tons/h	66·4 long tons/h
Electric feed pump			25 tons/h	24·6 long tons/h

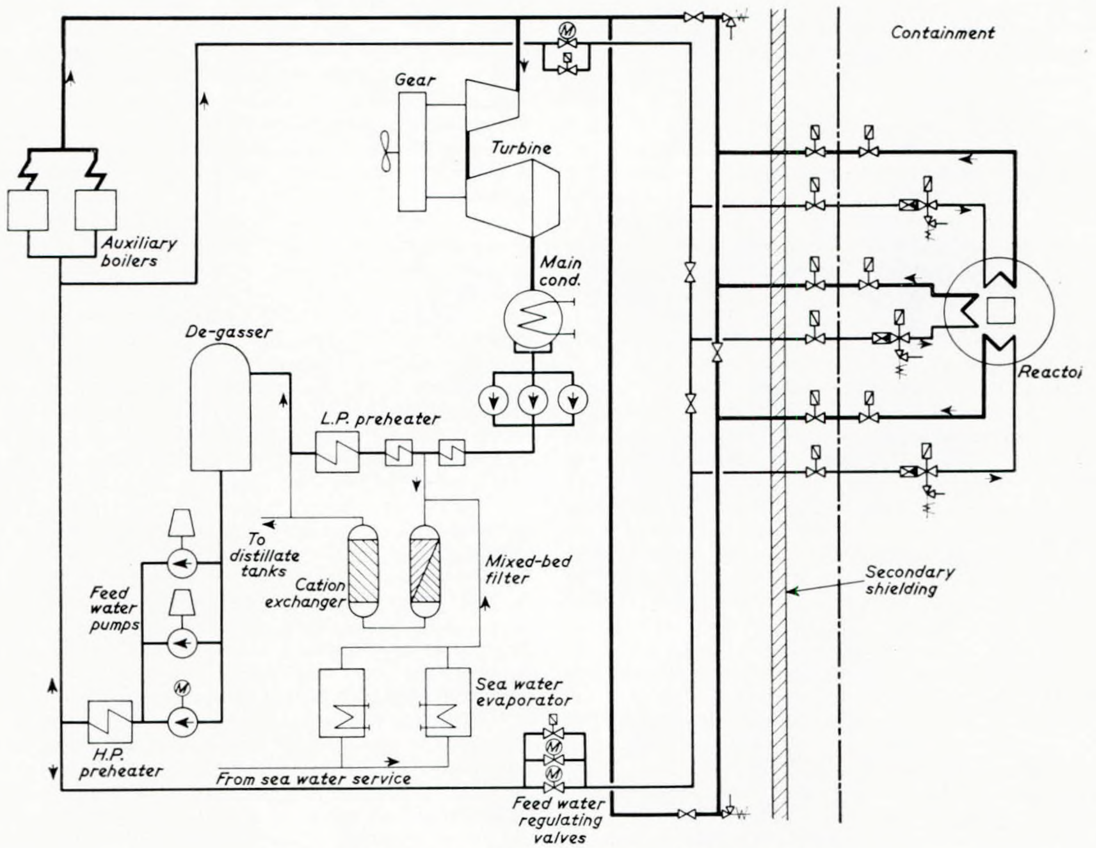


FIG. 6—*Secondary system—demineralization plant*

operating conditions they can be pre-heated by means of steam from the reactor, thus shortening the time for start up. Additional data of the whole power plant are given in Table III.

Two Diesel generator sets provide additional electric power, one being the 450 kW auxiliary Diesel generator set in the lower part of the bridge. The second is an emergency Diesel generator set with a capacity of 240 kW. Emergency and auxiliary generator pick up the load automatically from the emergency switchboard in case of failure in the main switchboard within 7–30 s. The emergency switchboard located near the emergency Diesel generator set and normally fed from the main switchboard, carries all main consumers of the reactor and the necessary navigational equipment.

Fig. 6 shows a simplified flow diagram of the secondary circuit. From the steam generator in the reactor pressure vessel, the steam flows to three main steam lines passing through the containment wall and the secondary shielding where they join the cross connexion line of the main steam ring pipe supplying the consuming equipment in the engine room. The condensate is pumped to a deaerator where it is deaerated at 134°C and 3·1 atm and circulated by the feed pumps through the high pressure preheater to the steam generator in the reactor. Two turbo feed pumps, each of which is designed for the full reactor power, and an electric feed pump are installed.

Owing to the once-through principle adopted for the steam generator, the secondary system is run on demineralized water, which is prepared in an evaporation and distillation plant and is continuously monitored for impurities. The sea water distillate produced by normal marine evaporators has a salt content of about 2 mg/l.

The distillate undergoes further treatment in an ion exchange unit consisting of a cation exchanger and a mixed-bed-filter. The quality of the water is monitored by means of a conductivity meter at the ion exchanger outlet. Data of the water are given in Table IV. The resins in the ion exchangers can be regenerated by flushing with acid or caustic solution. Besides producing demineralized water for the secondary system, the ion exchange unit is used for treating the make up water for the reactor plant. If the impurities in the feed water exceed the permissible limits, the secondary system can be cleaned by pumping a feed water bypass stream of 2 tons/h through the ion exchangers. In *Otto Hahn* experience has proven this bypass stream under normal power conditions is satisfactory.

The control of the secondary system has to maintain constant pressure at the steam generator outlet regardless of the steam quantity required by the main turbine, thereby ensuring uniform

TABLE IV—SECONDARY SYSTEM WATER QUALITY

	Design values	Measured values (behind deaerator)
*p*H	7·5–8·3	7·5
conductivity (μS/cm)	0·5	1
O_2 (ppm)	0·02	0·03
Si O_2 (ppm)	0·04	0·04
Fe (ppm)	0·04	0·03
Cu (ppm)	0·02	0·009

steam quality. The steam generator regulating circuit is arranged as a cascade control. The control condition is the steam pressure, which is maintained at 30 kg/cm^2. From the pressure variation and the steam throughput, the controller regulates the feed water throughput. In the sequential controller the control of the feed water throughput is compared with the actual value, and the output of the sequential control circuit is taken on the drive of the regulating valve. The feed pump maintains constant pressure before the regulating valves.

OPERATIONAL EXPERIENCES

On August 26th, 1968, the FDR installed on board *Otto Hahn* for the first time reached criticality, after having been tested in an extensive zero power test programme. The nuclear operation with the reactor was taken up after pressure and thermal testing, which lasted a few weeks. The first power tests were carried out with the ship moored to a quay at the Kieler Howaldtswerke shipyard in Kiel. Here the main propulsion turbines produced up to 60 per cent of the rated output. The first trial voyage, under nuclear power, took place on October 11th, 1968, and full power was reached on October 12th. At a power of 38 MW_{th} the ship achieved a speed of 17 knots. After completion of an extensive testing programme in the Baltic Sea, the reactor was handed over to the owner on December 17th, 1968. Numerous crew training and test voyages began in the Baltic Sea until February 6th, 1969, when approval was given for worldwide trial voyages. After visits to the German harbours and several demonstration voyages, the first research sea voyage began on March 8th, 1969. Until February 1970 a great number of research trips under different sea conditions and in different areas were undertaken, and ship and reactor plant proved to be highly reliable. During these trips a number of questions which had been put forward for the further development of the integrated reactor system could be solved. In February 1970 the third operating phase of *Otto Hahn* began with the first visit to a foreign port. By the end of May 1970, *Otto Hahn* had travelled a distance of about 70 000 nautical miles under reactor power.

Fig. 7 shows the number of operating hours of the reactor plant from start-up to the 31st of March 1970, i.e. 8450 h. The main turbine operated for about 5000 h. The difference arises from the relatively long periods of time during which the reactor was operated in harbours for generating electrical power only. The turbo generators which also have been operated by the auxiliary boilers during the start-up phase of the reactor, indicate the whole operating time of the plant. It should be remembered that the auxiliary boilers which, according to international regulations, must be installed in the ship, have not been used for take-home purposes and could be removed in a second ship. The burn-up of the reactor core (see Fig. 7) in percentage of the calculated days of full power operation is plotted against the time. The burn-up during the first year of operation was not very high, and *Otto Hahn*, which, when preparing for the next trip, requires long harbour-times, will not have many days of full power in a given period of time, compared to modern tankers or container ships. Fig. 8 shows that the availability of the reactor plant during the first part of the second year of operation is impressively high, nearly 100 per cent. When the ship is in port, only 10 per cent full power, the so-called "hotel load", is needed. The reactor is then used for the turbo generators only.

Year	1968	1969	Sum total 31 March 1970
Reactor	1541	4724	8450
Turbine	678	3212	5018
Turbo-generators	3400	8200	9500
Fuel burn-up	2·76%	23·27%	29·24%

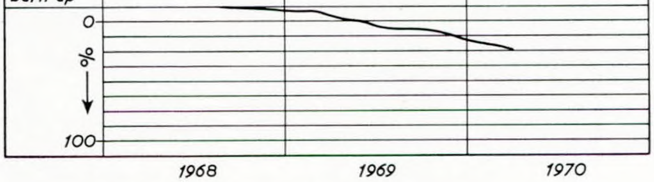
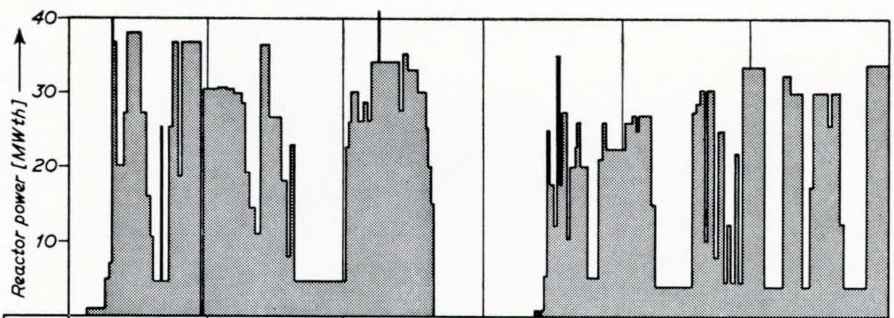


FIG. 7—*Summary of operating hours*

During the extended research voyages numerous measurements and tests have been made.

The manoeuvrability of the ship reactor on *Otto Hahn* was the subject of the first extensive measurements, and this phenomenon has also been observed extensively during all following trials as it is one of the most important information for ship operators and, in the author's opinion, it is the most advantageous aspect of the FDR type reactor. During a docking manoeuvre the power demand from the reactor often varies between about 10–70 per cent within a few minutes. The propulsion plant on board the *Otto Hahn* is designed for nominal load changes of 1 per cent over the whole power range between 0–100 per cent; for emergency operations load changes of the order of 4 per cent/s are possible. That means, that in the normal manoeuvring power range of the order of 10–70 per cent the load can be taken up and down within 15 s. Figs. 9, 10 and 11 show actual load changes on shipboard. Figs. 9 and 10 give normal load changing operations, while Fig. 11 shows a quick closing manoeuvre of the main throttle valve, before the turbine. In these figures the reactor primary pressure, reactor primary temperature neutron flux and the secondary steam flow and pressure are plotted against the time. It is interesting, that the reactor system pressure, even under the most severe load change, hardly changed. The second interesting fact is, that the power can be brought down to "hotel



Month	October	November	December	January	February	March
	1969			1970		
V_T	80·5%	100%	96·8%	93·5%	100%	100%

V_T = Availability

FIG. 8—*Power history*

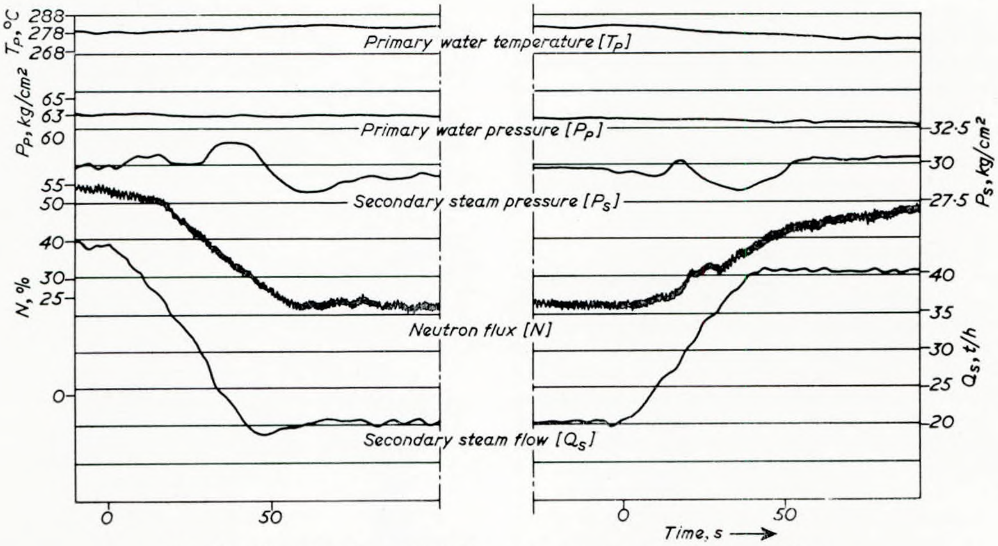


FIG. 9—*System characteristics at 1 per cent/s load variations*

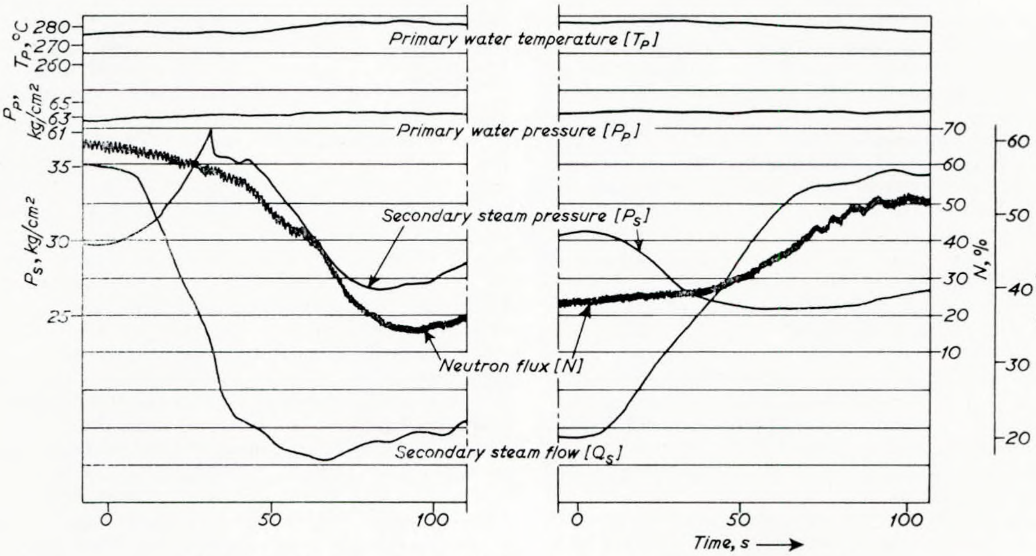


FIG. 10—*System characteristics at 4 per cent/s load variations*

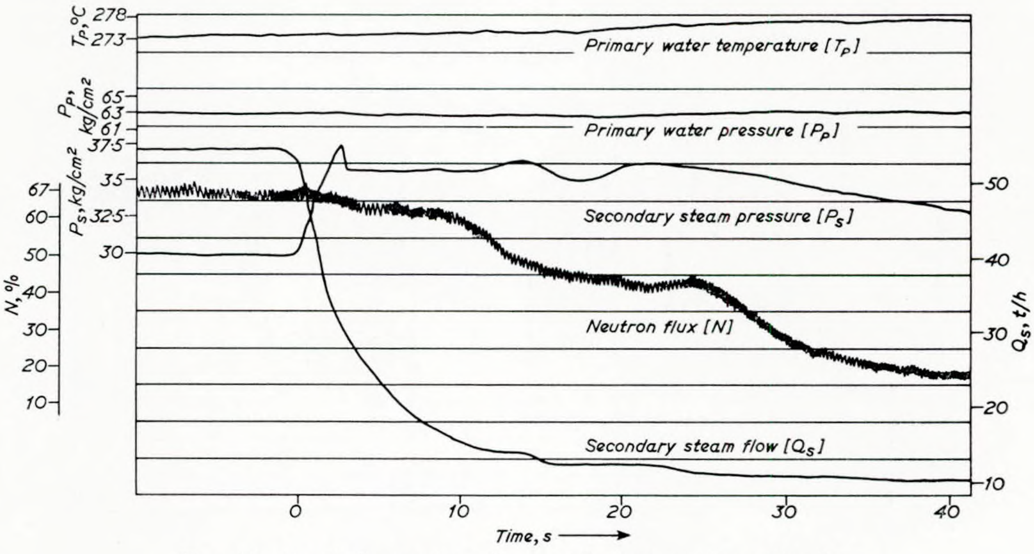


FIG. 11—*Load fluctuation after quick-closing valve actuation*

load" controlled with no tendency to swing over. The curves of the secondary pressure show that the problem of power control for once-through heat exchangers was not quite satisfactorily solved. The turbine-driven feed pump, which changes its revolutions according to the load changes, is controlled by means of a pneumatic control system. The control valve before the steam generator is electrically operated. During the early stages of the tests these systems did not perform satisfactorily together, and the feed pump was unable to follow the quick electrically operated control valve. The system had to be re-optimized and now works better on the secondary side. It may be added that, in spite of these facts, the secondary pressure rose to a level where safety valves blow off for some seconds only in the case of quick closing. This had been expected, during the design phase, for less severe load changes and, therefore, a special pipe, i.e. the dump line, had been installed in the condenser. This pipe has not yet been used and therefore it has been closed. During the manoeuvring operation, all the men in the control room have to do is to open and to close the main throttle valve by remote control.

Further proof of the extraordinarily stable behaviour of the FDR reactor with self-pressurizing system, have been a number of power tests without reactor control. If the control rods are not displaced during the load changes, by switching off the control, the pressure in the primary system increases with a decreasing load and decreases with a higher load. Fig. 12 shows the

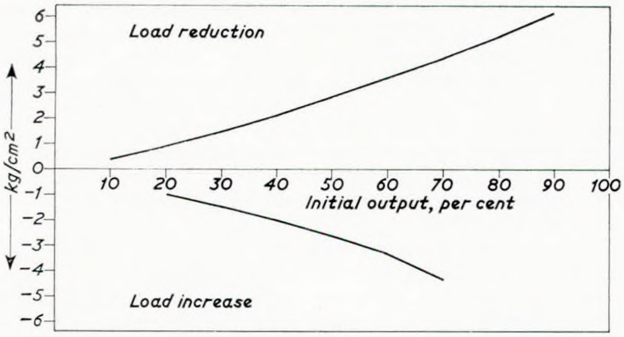


FIG. 12—*Resultant change of primary pressure after ±20 per cent load variation*

behaviour of the plant with power changes of the order of 20 per cent, starting from different power levels. The pressure change in the primary system is plotted against the nominal load from which the change was started. Starting from 90 per cent of power, the maximum changes of the primary pressure can be observed. Fig. 13 shows the pressure difference plotted against the time following a load change equal to 20 per cent, and that the system is reacting very slowly on the load change, and

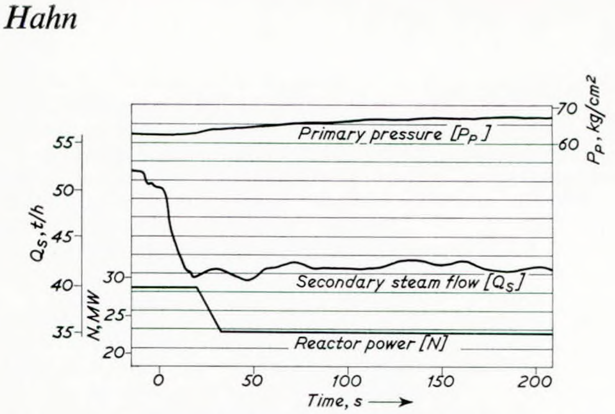


FIG. 13—*Primary pressure during load reduction with uncontrolled reactor*

that this characteristic is stable. This very promising feature of the FDR will play an important role in further development.

A third interesting factor was the behaviour of the self-pressurized reactor under ship motions. As in a boiling water reactor, the variation of the acceleration due to gravity has an influence on the production of the steam bubbles and thus on the density of the moderator and therefore on the neutron flux also in the FDR-type of reactor. Careful measurements of this phenomenon therefore were undertaken on board *Otto Hahn* under all weather conditions. A number of instruments for measurement of acceleration were installed all over the ship. The neutron flux movements were measured by a special incore instrumentation which is installed in two fuel elements in the FDR. Fig. 14 shows one curve below the acceleration in *g* whereas the upper curve gives the neutron flux measurement by an ion chamber. Both are plotted against time. The reactor power is about 38 MW (full power), and the maximum acceleration values are ±0·2 g. The behaviour of the reactor power under these conditions is shown without any control from the control rods. Only the self-controlling characteristic of the reactor limits the load changes to about ±1 MW. This influence is slight and is far less than had been expected. It cannot be measured on the steam side of the heat exchanger and therefore has no influence on the turbine and the main propulsion plant. It is, however, an interesting phenomenon for studies of the dynamic behaviour of this kind of reactor. The power variations, due to gravity changes, can also be measured by temperature measurements inside the fuel elements as also it has been done on board *Otto Hahn*.

The design values for accelerations which have to be taken into account for power operation of nuclear ship reactors in Germany are ±0·5 *g* in all directions. On board *Otto Hahn* measurements have been undertaken under different and extreme weather conditions with wind velocities up to 11 Beaufort. Between wind velocity 8–11 no difference could be observed in the

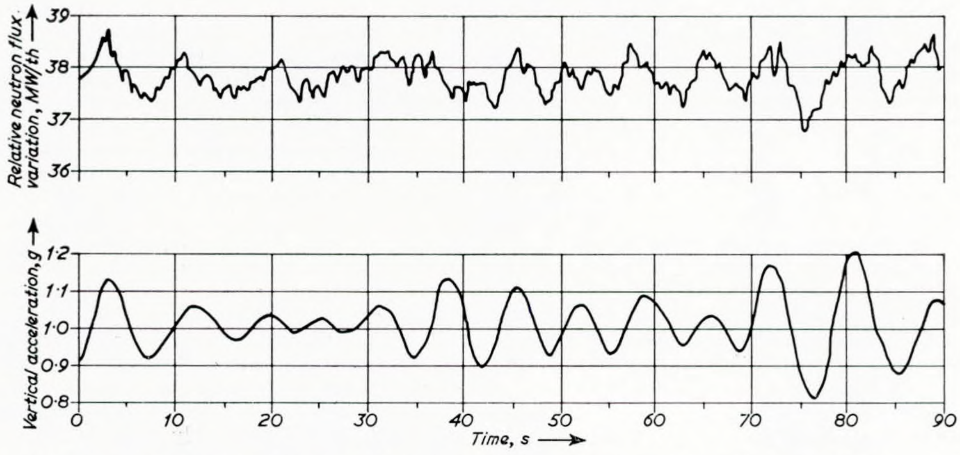


FIG. 14—*Power fluctuation against vertical acceleration with uncontrolled reactor*

acceleration variations due to gravity and the maximum measured value was ±0·2 *g*. Therefore the author does not expect, in the case of *Otto Hahn*, that the design values can ever be reached, but he is sure that even under these circumstances, a self-pressurized water reactor could operate under full power conditions; for nautical reasons this is not possible. Therefore the design limits, if this should be necessary, could be reduced, perhaps to 0·3 *g*, depending on the position of the reactor.

CONCLUSION

The author would like to state that the trial voyages with *Otto Hahn* so far have shown that the principle of the advanced pressurized water reactor is well suited to marine service in the propulsion system of merchant ships. The behaviour of the plant in heavy seas and under extreme climatic conditions has exceeded the expectations of both the builder and the operator. It appears, therefore, that the development and research on this reactor design, as is done in Germany at present, is particularly promising. The author expects that intensive detail work on this kind of reactor will lead to the production of an economic marine reactor of the power needed nowadays for merchant ships. Conventional ships have already reached a power range in which nuclear propulsion should be economically competitive. The experience gained with *Otto Hahn* shows that nuclear ships can be as simple and reliable as conventional merchant ships. The advanced pressurized water reactor with its self-adjusting control will perhaps be better suited for overall automatic control than the conventional boilers.

ACKNOWLEDGEMENTS

The author wishes to thank his collaborators in the Institute of Nuclear Ship Propulsion of G.K.S.S., especially Mrs. Hartmann, Mr. Kühl and Mr. Völtzer, for their assistance in the preparation of the paper.

Discussion

Mr. T. B. Webb said that he had been fortunate to have had the opportunity of visiting a number of times, the works where the integral reactor was assembled, the shipyard, and of sailing in the ship, and had been impressed by the simple direct approach; for example the way in which the fuel was loaded: they simply waited for a fine day, picked it up by crane and put it in the reactor.

This paper was valuable because it was based on experience, and it had been said that an ounce of experience was worth a ton of theory. He had been most impressed by the performance under transient conditions. We all knew how many miles of computer print-out were produced to forecast the behaviour of a reactor at sea, and this was very necessary in the absence of practical experience. We now had the real answer in Fig. 14—in the roughest of seas the power swung by four per cent. This was the kind of solid information that could not be obtained any other way.

In their studies for advanced reactors, had G.K.S.S. yet detected any limitation in size for the integral concept?

Did the author prefer to leave the pumps where they were, on stalks at the base of the reactor vessel, or would he rather see them on the top of the lid?

How long did it take to remove and replace a pump in *Otto Hahn?*

Was there any indication of formation of deposits inside the steam generator tubes after the 1100 hours' operation mentioned?

The last time Mr. Webb stood in this "dock" was eight years ago, when discussing the operation of *Savannah*.* When would the next time be? Whose achievement would we be praising—the Japanese, the Americans or the Germans for a second of such vessels? The Americans were busy; he knew of one contract recently awarded for a one-year study of advanced marine reactors costing $650 000. Or would it be a British ship they would be discussing? The Ministry of Technology had been making a report, which he understood was to be published soon. We were told that their conclusions were pessimistic. Was it a case of "They are all out of step except our Johnny"?

Mr. A. H. Syed, B.Sc., A.M.I.Mar.E., said that they had been shown graphs of transient conditions in the reactor and it was stated that load changes of the order of four per cent/s were possible. Was this sufficient for the crash full speed ahead to full speed astern manoeuvres? Could the reactor, as against a turbine, sustain the effects in such a case?

What were the activity levels as measured in the various compartments etc., in *Otto Hahn*, from the point of view of radiological protection and how did they compare with the design figures?

* Landis, J. W. 1963. "Operating Experience with Nuclear Propulsion: Start-up and Initial Operation of n.s. *Savannah*" *Jnl. Nuc. Mar. Prop.*, Vol. 7, p. 1.

Dr. O. O. Ejiyere said that the nuclear marine propulsion of ships with nuclear reactors had potentialities for radioactive pollution of the water and the atmosphere. Water pollution included drinking, river, sea and ocean waters; atmospheric pollution included harbour and other atmospheres within contamination reach of the radiation wasted from the ship.

There were engineering problems regarding containing radiation from contamination of the environment, including river and sea waters, and the harbour. Radiation escape from nuclear reactors, through the secondary circuits, steam turbines, stacks, air and water ducts, into the waters and atmosphere was mostly possible when the reactor was critical. During repairs and maintenance, the radioactive wastes were dumped into the sea or harbour waters.

The heavily contaminated heat exchangers, due to irradiations from the pressurized water reactor (P.W.R.), which produced particles on exchange and non-exchange forces interactions, caused the secondary circuit coolants and steam generators to be considerably contaminated with slowed, thermal, epithermal, absorbed and captured nuclei and particles. The processes of the secondary coolants and the steam generated involved the irradiation and contamination of secondary plants.

Deuterons and other radiation were formed when neutrons, gamma ray and other particles interacted with the steam atoms and the secondary coolant circuit. This caused radioactive steam and coolants.

Sea water was radioactive and contained such elements; the radioactivity within the water, and its emission to the atmosphere produced health hazards. The pollution of the already polluted marine environment by nuclear ships' radioactive wastes and ionizing radiation were problems to be contained by marine nuclear propulsion. Constant atmospheric monitoring and water sampling for radiation measurements were essential for a healthy marine environment.

Nuclear ships ionizing radiation and radioactivity in air and water retained their potential for the contamination of cargoes, staff quarters and harbours. Nuclear ships' stacks polluted the air constantly with radiation, while in harbour. This had health hazard potentialities for harbour workers, crew's quarters and cargoes. Harbour water was heavily contaminated when irradiated water was formed from the steam, and water from the secondary coolants was wasted when the ship was critical and at anchor, or on maintenance, repairs, off-loading cargo etc. Men, food and drinking water were all exposed to nuclear ship radiation.

Fish in the water contaminated by nuclear ships could cause health hazards if eaten, because individuals eating such fish might exceed the maximum permissible dosage and exposure. Cargoes such as petroleum, contaminated by nuclear ship radiation, would inevitably emit radiation wherever and whenever used, unless the mean life of the radioactivity was wasted through decay. Cargoes of food, and those for agricultural, industrial, medical, scientific and engineering purposes, produced the same genetic ionizing radiation and radioactive contamination.

There were some advantages from marine radiation contamination and marine atmospheric pollution. Nuclear ships ionizing radiation and radioactivity could cause the sterilization of male marine insects, including flies, butterflies etc, and the eggs of insects could also be affected. This meant the extirpation of marine insects which might be harmful to man and to cargoes of food, pharmaceuticals and industrial supplies. Nuclear ship radiation on cargoes might also help to destroy bacteria in food, agricultural, medical and other supplies.

Fish life could be fatally affected by nuclear ship radiation, which might impede breeding. Effects were variable if the sources of radiation had a short mean life, and the radiation came from radiochemicals used to promote fish breeding.

Nuclear ship waste could cause contamination of drinking water, if the waters of the harbour or sea which had been contaminated were used for the drinking water supply, and if these found their way into the national water resources.

Thus, there were several problems which arose regarding marine biology, fisheries, food cargoes and medical supplies, and with regard to personnel, which must be taken into account in connexion with the control of marine nuclear radioactive waste disposal.

Mr. P. Weiss, in a contribution read by Mr. T. McDuff, stressed that this nuclear ship had been an outstanding technical success, if not an economic one; as emphasized by the author, the main purpose was to achieve a collection of practical and technical knowledge.

With the necessary background knowledge, the author's company and their associates were undoubtedly in a strong position to embark on a second nuclear ship. Were the organizations concerned now prepared to do so. If so, would the author expect to achieve an economic break-through on the second nuclear ship? Would the financial arrangements be similar to those for N.S. *Otto Hahn?* Had the author any decided views as to the type of a second nuclear ship—a fast container ship or a large tanker?

It was noted that the author foresaw several economic benefits arising from a less conservative approach in the design of certain special safety provisions. Could the author elaborate on those provisions, made in *Otto Hahn*, which, in the light of experience, would not be repeated in a second nuclear ship. The classification societies were always ready for further studies which might lead to the achievement of more realistic safety requirements.

Mr. T. McDuff said that some six years ago, he made an unfortunate statement at the B.N.E.S., that with the facility of nuclear propulsion, what had to be done was to achieve something which could not be achieved with Diesel engines or turbines, and one had to do something out of the ordinary. This was not the case in the thinking of the two present papers because both tended towards large container ships.

He was not against such ships, but there were fairly large owners who said that they were just a passing fancy. However, container ships as such had the difficulty that one must gather the 2000 containers precisely at a certain point in time, and get them into the ship as quickly as possible. Investigation would find that several container ships already operating were running part full. So this consideration needed to be taken into account; was this done in these two papers, and what percentage of the ship was full of containers?

In designing a ship for nuclear propulsion, one had to think in terms of something like a large tanker of 200 000 dwt, some 230 m long, and probably as full as a tanker, because with unlimited power to play with, one might as well use it, e.g. make it a Lash ship, as it could take bulk cargoes left at the dockside and even satisfy the port authorities. So, he would recommend a large concept.

He thought that the author would be the first to admit that G.K.S.S., was considerably helped throughout this project by Euratom and that *Otto Hahn* was a rather unique co-operation of many countries in Europe, most of whom did their little bit. The sooner we were in the Common Market, doing a big bit, the better for us all.

Mr. J. T. H. Moorby said that he was particularly interested in the transient responses presented in the paper. He could not understand the curves given in Fig. 13. If the captions were not wrong, he found it surprising that such an ideally shaped ramp reduction in neutron power should result from the very complex reduction in steam generator power demand, especially as no rods were used.

Although he could find no mention of gas over-pressure in the paper, he was led to believe that one was present. If so, he would be glad to know how the gas distributed itself between the steam and liquid phases of the water; how it affected bubble production in the core; whether a gas or steam bubble was likely to form in a pump, thereby reducing pumping efficiency; and whether loss of over-pressure would significantly affect the dynamic behaviour of the plant.

Mr. G. Greenhalgh asked how soon did the author plan to build a second ship and what sort of ship would it be? How soon would the shipowners wish to be associated with such a project? Would this be built as a German national project, or did the author envisage international co-operation?

Correspondence

Professor Dr. Ing. G. Grossmann, M.I.Mar.E., in a written contribution, submitted several questions for Mr. Ulken and thought perhaps Mr. Wilkinson might also like to answer them.

Concerning the control behaviour of the ship-reactors discussed; he asked:

a) which load changes could be carried out by the reactor (no crash-stop-manoeuvres)?
b) did the size of this load change depend on the load-direction?
c) did the size of load change depend on the size of the base load?
d) which were the corresponding figures of comparable boilers?
For information only: boiler of 100 ton/h capacity; maximum load change: 2–3 per cent/s without safety-valve actuating.

On circuits and manning, he wished to know:

i) could the primary coolant system and the auxiliary system be simplified essentially?
ii) was it possible to operate the reactor plant of third generation nuclear ships unmanned, as in turbine-driven ships today?
iii) did the author believe that a slightly extended training at engineering academies would be sufficient for nuclear ships in the future?

Regarding total plant, Professor Grossman asked:

1) was it possible to build nuclear ships of the third generation with as little engine room space as present large container ships?
2) could the secondary system be simple or was it necessary to obtain high feed water preheating for reactor thermodynamic reasons?

Referring to safety aspects, he asked:

a) did the author have any knowledge of radiation accidents in currently operating nuclear ships?
b) had any canning failures occured to date?
c) what was necessary for primary and secondary coolant conditioning?

Author's Reply

Dipl.-Ing. Ulken, in reply to the discussion, expressed his thanks for being invited to speak to the Institute of Marine Engineers and also thanked the contributors to the discussion.

Mr. Webb has asked whether in their studies for advanced and large reactors the author's company had detected limitations in size for the integral concept. Together with Interatom they had made some studies in the past on the further development of the integral reactor. These studies went to about 200 000 shaft horsepower and they did not find any limitation up to that point for the integrated design concept. Perhaps there might be some change in the primary pressure or the location of the pumps, as shown in the most advanced CNSG-design, but the design principle did not appear to need changing. Up to about 50 000 shaft horsepower in the EFDR-design also, the location of the pump did not need to be changed considerably. In their latest design studies the pumps had nearly the same location as in the FDR, in *Otto Hahn*. There might possibly be a change for higher power. If the pumps, for example, were put on the top of the lid, pressurizing of the primary system by a special pressurizer seemed necessary.

Replacement of a primary coolant pump in *Otto Hahn* took about eight days, including opening and closing the containment vessel, and leak rate testing after closing.

Several questions had been raised by Mr. Syed and Professor Grossmann on the dynamic behaviour of the plant. Load changes of 4 per cent/s were possible under any condition. The size of this load change did not depend on the load change direction or on the base load. It could be obtained over the full power range. The comparable figure for boilers should be about 1 per cent/s. The limiting factor for load changes was not the reactor, but the turbine. With 4 per cent/s the size of the load change, even for crash full speed ahead to full speed astern manoeuvres was higher than thought to be sufficient for conventional turbine plants.

Regarding the heat exchanger tubes and the deposits about which Mr. Webb enquired, they had made a few tests during the last two years of operation and found no increase in pressure drop over the once through heat exchanger tubes. Of course, they could not look into the tubes, but believed that there was not much deposit there although they could not measure it.

Mr. Moorby had asked about gas over-pressure. In *Otto Hahn*, a small amount of hydrogen was put into the blow-off tank in order to give suction head for the primary feed pumps and to accelerate a recombination of oxygen and hydrogen in the primary system. However, there was no gas pressurization of the plant, it was entirely self-pressurizing.

The lower curve in Fig. 13 was an idealized one. Interest should be directed only to the upper curves, the lower one was only to give an indication of the reactor power.

Mr. Syed had asked about the activity levels in the various compartments of *Otto Hahn*. To give an overall view, the author said that, according to the ICRP norms, the engine room was a free accessible area, the auxiliary reactor room a controlled zone with unlimited accessibility for working personnel and the safety containment had a limited accessibility of some hours per day under full reactor power. All living rooms and deck areas were freely accessible to crew and passengers.

Dr. Ejiyere had remarked on radiation protection in ships and on the different possible reasons for danger from nuclear ships. In the case of *Otto Hahn* radiation could not escape from the nuclear reactor through the secondary circuits, the steam turbines or air and water ducts into water and atmosphere, and radiactive waste was not dumped into sea or harbour waters during repair phases. All reactor ships, like *Otto Hahn*, would have a large waste water system and could operate for a long time without dumping active water.

Contamination of the secondary system could not be measured in *Otto Hahn* and, in his opinion, could not be caused by gamma radiation.

Every nuclear ship would be built to the rules and recommendations of the International Commission on Radiological Protection, and thus the operator would be prevented from polluting the marine environment. According to the ICRP norms there were 12 to 14 decades between the radiation doses which could issue from a nuclear ship and those which could, for example, cause sterilization of insects, conservation of food or give any hazard to the biological environment or the cargo of the ship.

It was agreed that monitoring and water sampling were essential for a healthy environment. On board *Otto Hahn* continuous measurement was made of water and air leaving the nuclear plant and to date the limits set by the ICRP had not been reached by a long way.

Regarding further development of nuclear ships in Germany, the question which had been raised by Messrs. MacDuff, Greenhalgh and Weiss, and Professor Grossmann, the author said that G.K.S.S., had been working for some years with German shipowners and German shipyards on studies of nuclear driven big bulk carriers and big, fast container ships, which might possibly have twice the power of the bulk carrier. They were optimistic that, in the near future, nuclear ship propulsion would be economically competitive in the currently ordered power range of container ships. The owner of the second nuclear ship in Germany would still need help from the Federal Government, as laid down in the Third German Atomic Programme. The second ship would not be owned by G.K.S.S., but would be ordered by a German shipowner. Only that cost exceeding the fixed cost of the plant and the operation cost of a conventional ship of similar size and power over its lifetime would be subsidized by a once only grant from the State.

In their studies of economy of nuclear container ships G.K.S.S. started, as Mr. MacDuff had imagined, from the case of a full container load, but in later studies they also took into account the fact that several container ships were operating not fully loaded.

In answer to Mr. Weiss, there had been considerable thought about the economic benefits arising from a less conservative approach and the redesign of certain safety provisions, but Mr. Ulken was not in the position to say at present which safety requirements in *Otto Hahn* would be changed in the future. He thought that there should be some consideration of the "get-you-home" drive, the *g*-forces and perhaps some other details, but they had no fixed stand-point up to now. There was a possibility of simplifying the primary system and auxiliary systems essentially; There was the technical possibility, as Professor Grossman pointed out, of operating the reactor plant of nuclear ships, of the third generation, unattended as in conventional turbine driven ships and the author was sure that it would be possible to train nuclear ship staff at the ship engineers' schools, in the future, when more nuclear ships were in operation.

Their most recent studies had shown that nuclear power plants did not need more engine room space than conventional power plants and the secondary system could be simplified considerably.

To date the author had not heard of any radiation accident in an operating nuclear ship, in spite of there being about 190 reactors in operation on board ships. There had been no canning failures so far and the conditioning for primary and secondary coolant were similar and relatively simple. It was done by a bypass demineralizing plant consisting of a mixed-bed filter.

Finally, Mr. Ulken said that he had omitted to mention that Euratom had worked with G.K.S.S. during the constructional and the first operational phases of *Otto Hahn*. Euratom had spent $4 million on the construction cost of the vessel and had helped G.K.S.S. in many other directions.