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METHODS AND INSTRUMENTATION FOR ANALYSIS AND CONTROL OF THE MARVIKEN NUCLEAR POWER PLANT

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SUMMARY

The Marviken reactor is designed as a direct-cycle boiling heavy water reactor with natural circulation and a power output of 140 MWe at saturated steam operation and 49.5 bar pressure.

In the design stage the dynamic behaviour of the reactor core and the plant as a whole has been simulated on our analogue computer PACE 231 R first of all in order to study the degree of plant stability and later on to allow an optimization of the automatic reactor control system.

A number of different digital programs have been written in order to evaluate:

The margins to Xenon instability and burnout of fuel

The reactivity coefficients from fuel temperature, void contents, subcooling temperature and moderator temperature

General aspects regarding reactivity and power distribution

Besides the theoretical modelling for analogue and digital calculations practical full scale experimental work has been carried out in order to study hydraulic behaviour of a fuel channel in a loop with natural circulation and dimensions in close agreement to the proposed reactor systen.. The reactor fuel has been simulated by electrically heated rods.

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The measurements which are planned to be performed in the reactor core and in the plant system as a whole, after criticality has been reached, will give a mapping of mass flow, void, temperature and neutron flux in the core and characteristics of the dynamic behaviour of core and plant. These measured quantities for steady state reactor and for perturbed reactor will be used for reactivity and power distribution studies and for comparison with the dynamic model and reactivity coefficients used in the early stage of reactor design work. In order to carry out the above mentioned programme it is necessary to use extensive in-core instrumentation.

Six boiling channels will be fitted with instruments. The coolant flow will be measured with turbine meters at the inlet and at the outlet of these fuel channels. The void fraction at the outlet of the channels will be measured by means of impedance void meters. The channels will be supplied with thermocouples at the inlet and at the outlet.

The neutron flux will be measured with β-current detectors based on vanadin and with fission chambers for fast response distributed in the core to give a good picture of the flux. The temperature at various positions in the moderator and at the inlet and outlet of the instrumented channels will be measured with thermocouples.

The on-line processcomputer CONPAC 4060 as well as a separate on-line PDP-9 digital computer will be used for collection, reduction and analysing of data from the measurements.

The on-line process computer CONPAC 4060 is a vital link in plant control and plant automation. The degree of automation has been defined so that all operations which has to be fulfilled within a period of 30 minutes shall be automated. Other operations can be made manually.

The computer system includes the following main functions:

Presentation of process variables -
Registration of process variables and operations -
Alarm annunciation -
Past history record -
Automatic sequence control for
  starting up -
  normal running -
  shut down -

refuelling -
special testing of objects in the plant -
Calculation of dynamic set point for wanted nuclear power -
Calculation of channel power -

INTRODUCTION

In contrast to the first Swedish power reactor, Ågesta, the second one, Marviken, will be supplied with rather detailed in-core instrumentation for physics measurements. This is in accordance with the general trend for today's power reactors.

There are many reasons for such extensive physics measurements. First of all, it is nowadays highly desirable to operate power reactors in an optimal way to make them compete better with other sources of energy. The physics measurements will help the operator to do this, i.e., not to work uneconomically far below the safety limits and, of course, also not to exceed these limits. The measurements can also suggest improvements for future power reactors and, finally, one can use the measured results for tests of theoretical models.

Theoretical models has in Sweden extensively been used to evaluate the dynamic behaviour of a proposed reactor concept in an early stage of construction in order to find such main parameters which give an optimized degree of stability. Besides the Marviken reactor with natural circulation, other heavy water moderated and cooled boiling systems with forced and natural circulation have been studied. Analogue computer studies on not only linear models have been performed in order to demonstrate to what degree the reactivity coefficients are allowed to vary before stability limits are exceeded. The same technique has even been used in our evaluation of the behaviour of fast reactors such as sodium cooled, steam cooled and gas cooled concepts.

In the following we shall first give a short description of some relevant facts of the Marviken design. The second section will deal with the quantities to be measured. In the third section we shall describe the instrumentation and how this is incorporated in the reactor design and in the fourth section planned dynamic experiments with a PDP-9 digital computer will be described. The last section handles the control philosophy.

1. SOME DETAILS OF THE MARVIKEN DESIGN

The Marviken reactor (figure 1) is a direct-cycle boiling heavy water moderated and cooled reactor with natural circulation and a power output of 140 MWe. The reactor steel vessel is 23.5 m high and 5.4 m in diameter with a 5 mm stainless steel lining. The working pressure is 49.5 bar corresponding to the saturation temperature of 263°C.

The reactor core is 4.4 m high and contains today 147 positions for boiling channels and 32 positions for superheater channels. The first criticality experiments will be carried out with this configuration but with no superheater fuel in the superheater channels. Later on next year the reactor will be brought on power presumably with some of the superheater channels converted to test positions for boiling reactor fuel. As far as has now been found the Swedish reactor technology is more interested in making further development work with fuel for boiling reactors than for superheaters.

The reactor lattice is quadratic with a pitch of 250 mm and a boiling fuel element consists of a cluster with 36 rods of UO_2 enriched to 1.35% U^{235}. The inner diameter of the canning tube, made of Zircaloy, is 12.6 mm. The initial fuel load consists of enriched fuel elements with 1.35% U^{235} and fuel elements of natural uranium (see figure 4).

Feed-water enters from below and goes upwards through the moderator tank outside the fuel channels. During this passage the water is heated to 238°C. The water then passes - by natural circulation - through the downcomer between the walls of the moderator tank and the reactor vessel and is then sucked into the boiling channels. The temperature is now 263°C corresponding to the steam pressure of 49.5 bar. In the upper part of the boiling channels the steam is separated and passes the superheater channels on its way to the turbine.

2. QUANTITIES TO BE MEASURED

The measurements are divided in two main groups:

1. The reactor physics measurements concerning steady state conditions

2. The dynamic experiments concerning transients and transfer functions under perturbed reactor condition and under influence of natural noise mainly generated through the process of steam bubble formation

The reactor physics measurements concern the neutron flux and reactivity.

The neutron flux will be measured at various points in the moderator. From such measurements one can study the power distribution for different control rod positions and for various degrees of burn-up. Combining the core measurements with calculations of microscopic flux one can also estimate the power for single fuel channels, in particular for the instrumented boiling channels mentioned below.

The reactivity studies involve mainly the determination of reactivity coefficients from measurements of neutron flux, void fraction, temperatures and control rod position.

Transients and transfer functions measured in connection with the dynamic experiments will be used to identify the core and the dynamic parameters of the plant and to evaluate the degree of inherent stability and the performance of the automatic power control system. These measurements will allow a close comparison between reactor core and plant in relation to developed theoretical models.

3. INSTRUMENTATION

3.1 Neutron detectors

The neutron flux in the core will be measured with β-current detectors and fission chambers. The β-detectors, made of vanadium, have a sensitivity of 10^{-20} A per n/cm^2 sec. These detectors have a low burn-up rate compared with fission chambers but have a slow response because of the long half-life of V^{51} (5.4 min). The slow response is not suitable for dynamic experiments and the equipment is therefore supplemented with the fission chambers.

There are totally 48 β-detectors placed at four levels on 12 vertical probes. Four of these probes are also each supplied with two fission chambers (see figure 4).

The probes, which are interchangeable and replaceable, are pushed into the reactor from below into special guide tubes of zircaloy (OD 25 mm, ID 23 mm). These guide tubes are extended downwards to a shielded area below the reactor. The probes end with a flange arrangement at the lower end of the guide tube.

The guide tubes are open in the upper end and are filled with water during normal reactor operation. For cold reactor the water level is below the upper end of the tubes, which facilitates the replacement of a probe. Such a replacement will be desirable after a few years' operation because of burn-up in the fission chambers.

The cables from the β-detectors and the fission chambers have aluminium-oxide insulation and are taken out through the bottom flange of the probe. The signals from the β-detectors are compensated for the current caused by the γ-absorption inside the cables. The signals will possibly be fed into the on-line computer for a calculation of integrated power for each fuel element.

Special high-sensitivity counters will be used for the start-up of the fresh reactor.

3.2 Instrumented boiler channels

Most of the non-nuclear instrumentation in the core will be placed in six instrumented boiling channels. A fully equipped channel contains two turbine flow meters, one at the inlet and the other at the outlet, four thermocouples, two at the inlet and two at the outlet, and, finally, one impedance void gauge at the outlet (see figure 5).

The void gauge gives the void fraction from a measurement of the impedance at 2 kc. The void fraction can also be obtained from the signals of the two turbine meters.

A turbine rotor has sixteen blades. The rotor speed is measured by means of two pick-up coils located near the blades. At full reactor power the coolant flow velocity is about 1.1 m/sec. This corresponds to 3.5 turns/sec for the rotor. The rotor time-constant is predicted as 10 millisec. A flow straightener is placed below each turbine rotor.

Because of the difficulty to take out cables from movable fuel elements one has been obliged to arrange the instrumentation on three separate parts. The lower turbine hangs in the fuel bundle itself. The upper one and also the void gauge are mounted on an extension of the shield plug above the fuel. The pick-up coils for the turbine meters are placed on the shroud tube, which is attached to the bottom of the moderator tank. The thermocouples and a sliding connector for the void gauge are also placed on the shroud tube. All the output cables from the instrumented boiling channels are thus attached to the shroud and taken out through the vessel above the core superstructure. In case a shroud tube must be replaced one has to cut all the cables. These cables cannot be replaced when a new shroud tube is mounted.

Because only four instrumented fuel bundles and three instrumeted shield plugs will be available one cannot make use of all the six instrumented shrouds in one measurement. Only three of the positions can be fully equipped simultaneously.

The fuel element assembly for an instrumented boiler channel is provided with a burn-out detector attached to one of the 36 fuel rods in the assembly. The detector is based on the elongation of the fuel rod when burn-out takes place. Elongation is measured with a differential transformer and the transformer magnetisation and its generated signal are both transferred to and from the instrumented assembly from transformer coils in the upper part of the shroud tube. The fuel rod for the burn-out detector is slightly enriched compared to the other rods in the assembly in order to be sure that burn-out condition will be established at this rod previously to the other rods in the boundle.

3.3 Control rods

Control rods are generally moved in steps of 50 mm. The electrical indication system for the positions of the 16 regulating rods will be supplemented with data from a reactivity meter. This meter measures the total reactivity by analysing the signals from the neutron detectors.

Four of the regulating rods are equipped with special arrangements to allow rapid up and down movements of the rods. The motion will be introduced as oscillations or step movements and will be accomplished by a special program unit connected with the hydraulic system.

The changes in the positions of the regulating rods will cause changes in the power of the reactor and consequently also in void fraction and temperature. Perturbations of the reactor can also be introduced by load variation. From measurements on the perturbed reactor one can obtain the reactivity coefficients and other inherent dynamic features of the reactor system.

3.4 Instrumentation outside the core

The general processinstrumentation for reactor plant outside the core will consist of sensing elements with transmitters for pressure, flow, level, temperature, position of valves etc and will be used in connection with in-core instrumentations during static and dynamic experiments in order to evaluate the overall plant parameters.

4. PLANNED DYNAMIC EXPERIMENTS IN MARVIKEN WITH A PDP-9 DIGITAL COMPUTER

The PDP-9 digital computer will be temporarily installed at the power plant during the time reserved for the dynamic experiments.

The purpose of these experiments is to get an understanding of the dynamic behaviour of the reactor and to determine the limits for safe operation.

The dynamic models, analog as well as digital models, will be checked and compared with the results of the measurements.

A comparison will also be made with the results obtained from experiments with electrically heated loops.

Two types of experimental methods will be used; responses to introduced perturbations and studies of statistical variations (noise).

The perturbations will be introduced in control rod position, steam flow rate, feed water flow rate and feed water temperature. The perturbation sequences will be generated by a special device.

The PDP-9 will be used for datalogging, data reduction, on line calculations, on site calculation and data representation.

The PDP-9 which will be used in Marviken has 8 K of memory, 2 DEC tapes, an analog-to-digital converter, real time clock, 16 multiplexer channels, 18 bit relay output register, 6 digital-to-analog converters and a teletype. An oscilloscope can be connected to the D-A converters.

The following programs have been written:

1. Program for datalogging from a maximum of 8 channels and on line calculations of correlation functions. Some features of this program will be mentioned below.

   A start pulse on an A-D channel will start the program.

   Linear drift can be calculated and corrections made.

   Data reduction and calculation of the sum of signal products to calculate correlation functions can be performed on line. At most three signals can be correlated simultaneously.

   If the perturbations are periodic a number of periods can be added at the same memory locations and the average values can be calculated.

A high number of periods gives better statistics and this method will save core memory.

At the beginning of the measurements a number of parameters as, date, number of experiment, scale factors, number of multiplexer channels, sampling time, etc. has to be read in by means of the teletype or the paper tape reader.

The results can be printed on the teletype and/or punched on paper tape.

The correlation functions can be displayed on an oscilloscope.

2. A program for on line calculations of mean values, variances and amplitude distributions. The extrapolation from a plot of the inverse variance ($1/\sigma^2$) versus a system parameter of interest can be used to indicate the onset of instability for certain systems. The calculation of mean values and variances is based on the multi-channel analyzer idea, which is used e.g. in conventional pulse height analysis. Briefly this means now an on-line software sorting of the amplitude samples and up-dating of the "spectrum" or the amplitude distribution. Then the variance calculation is easily performed based on the accumulated data stored as distributions. In order to obtain a short execution time and minimum space of the program, the PDP-9 computation is carried out in integer arithmetics. Our computer program performs data collection and reduction. The data reduction involves sorting of samples and up-dating of amplitude distributions during a measurement. The program is designed to take care of maximum 6 signals simultaneously at 10 bit resolution (a capacity of $6 \cdot 1024 = 6144$ channels, if we compare to a multichannel analyzer) or maximum 12 signals at 9 bit resolution. Thus 6 K core memory space is occupied as data area and the 2 K remainder is reserved for program.

3. The following programs for on site calculations will be available.

   1. Fourier analyses to calculate transfer functions (results on teletype or paper tape) from periodic signals like pseudo random binary sequences.

2. Fourier analyses to calculate transfer functions from non-periodic perturbations.

3. Program to calculate the transfer functions from the on line calculated correlation functions.

The PDP-9 computer is normally connected to a PACE analog computer. All programs will be tested on this hybrid installation. The reactor plant will then be simulated on the analog computer.

5. STABILITY AND CONTROL

5.1 Stability of the plant without control system

Analytical studies have been performed with a non-linear analogue computer model of the plant and with digital computer programs for steady state calculations. Most of the simulations were performed in the power range from 40% to 100%. Figure 1 shows the flow diagram used.

The space dependence was neglected except for axial space dependence of the void variation, which was considered in a quasi-stationary manner.

The neutron kinetics was treated as a single energy group comprising four delayed groups. The contributions to the reactivity balance by the mean values of the following variables were considered: fuel temperature, exit void, subcooling, moderator temperature and xenon poisoning.

The void reactivity coefficients are some of the most important parameters. They are to some extent affected by the design of the core so the dynamic studies may influence the design. It was therefore important to describe the void reactivity feedback as accurately as possible including some space dependence although other variables were represented by their averaged values.

The void distribution varies during the transient. The stationary vertical void distribution has been calculated for different conditions around the initial state. On the basis of these calculations, the dynamic changes of the distribution were approximated with a linear function that related the changes of the exit void and subcooling. The respective coefficients are called exit void and subcooling reactivity coefficients.

These coefficients were varied over a wide range while all other parameters were fixed at their normal values, averaged for the whole reactor. The results of the simulation are represented in fig. 2.

5.2 Control of the plant

The aim of the control system is to keep the vessel pressure close to its reference value. This is performed by changing the nuclear power by means of stepwise movable control rods. The turbine valve is normally kept fully open and the reactor pressure is therefore proportional to the overall reactor power. Only in the power range of 0-25% of full power, the control valve area is reduced and controlled in order to keep the pressure constant at 12.5 bar.

A preliminary design of the control system was made by using the analogue model with the most probable void reactivity feedback coefficients. The deviation between the pressure and its reference value was used to establish the power setpoint. When the power error exceeded a deadband a rod movement (one step) was initiated. It takes 2 seconds to perform a step.

However, after some time new physics calculations indicated that the void coefficients might be more unfavourable (less stable reactor) than originally assumed.

In order to assure stability of the controlled plant and to minimize the number of rod movements in the presence of noise, a sofistication of the original control scheme was proposed (figure 3). It was assumed that a pressure deviation of $\pm$ 0.5 bar was tolerable. Therefore the integral feedback from the pressure to the power setpoint was blocked when the deviation was less than 0.5 bar. Analogue simulations further showed that when the reactor power is disturbed only by the noise from boiling and the reactivity unbalance that can appear due to the stepwise motion of the control rods, the shortest interval between two rod steps in the same direction ought to be about 10 s. This is realized by a relay circuit. If a larger deadzone ($\pm$ 6% compared to $\pm$ 4%) was exceeded the delay circuit was bypassed and a larger number of control rods was activated.

5.3 Concluding remarks

As a complement to the analogue simulations already carried out, a digital one-dimensional model has been developed. It has up to now primarily been used to study the behaviour at low power.'

The study presented above demonstrates that it may be important to perform dynamic simulations early in the design procedure, as the results of parameter studies may propose modifications in the design. In this case it became obvious that the choise of void reactivity coefficients had to be carefully made. Unfortunately the relation between these coefficients and the actual core parameters were not known with sufficient accuracy. The sofistication of the control system, which is supposed to make the closed loop system work satisfactorily in a broad range of parameters (void), was in fact necessitated by the poor knowledge of the values of the parameters.

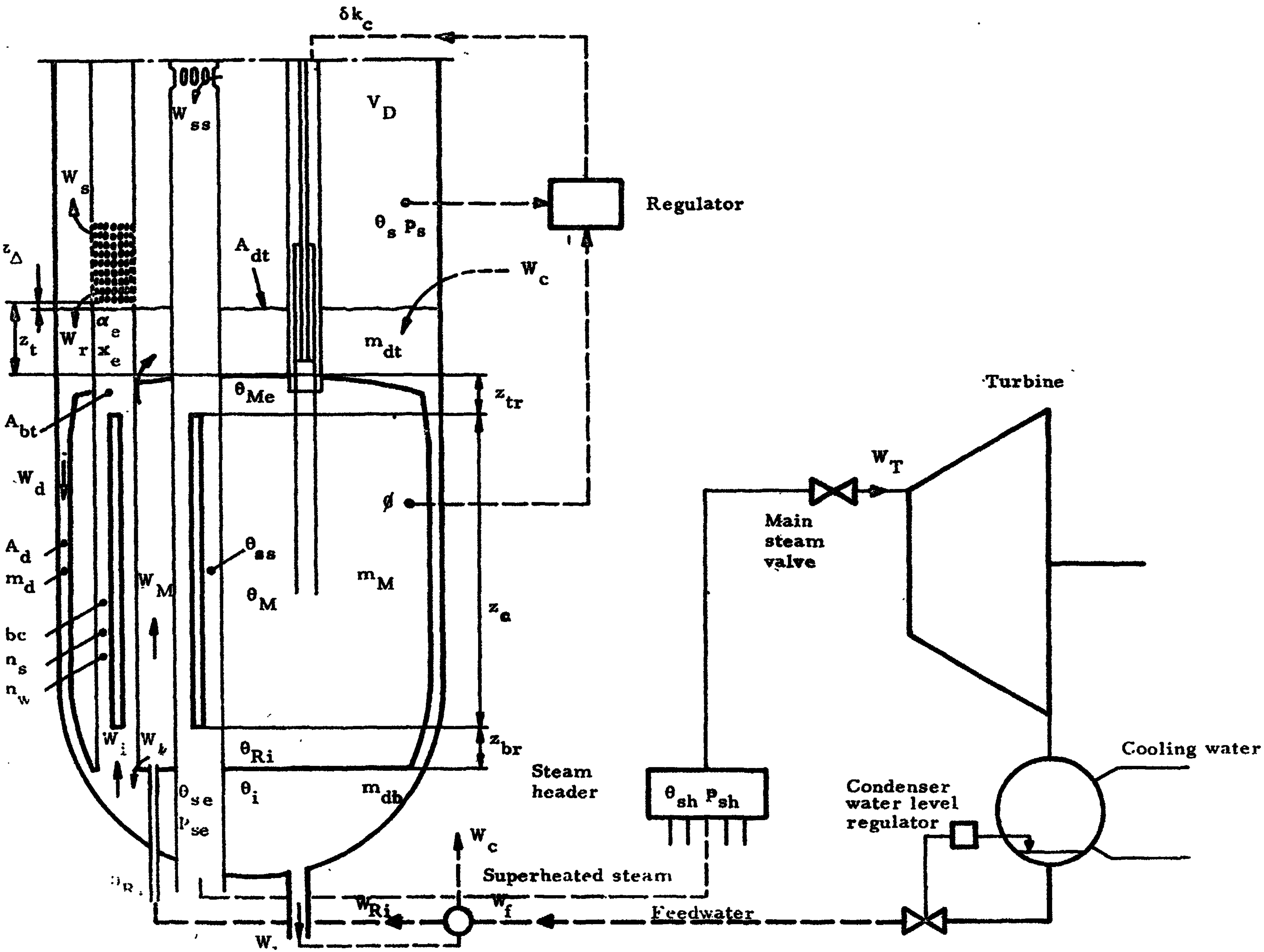


Fig. 1 Schematic diagram of the system

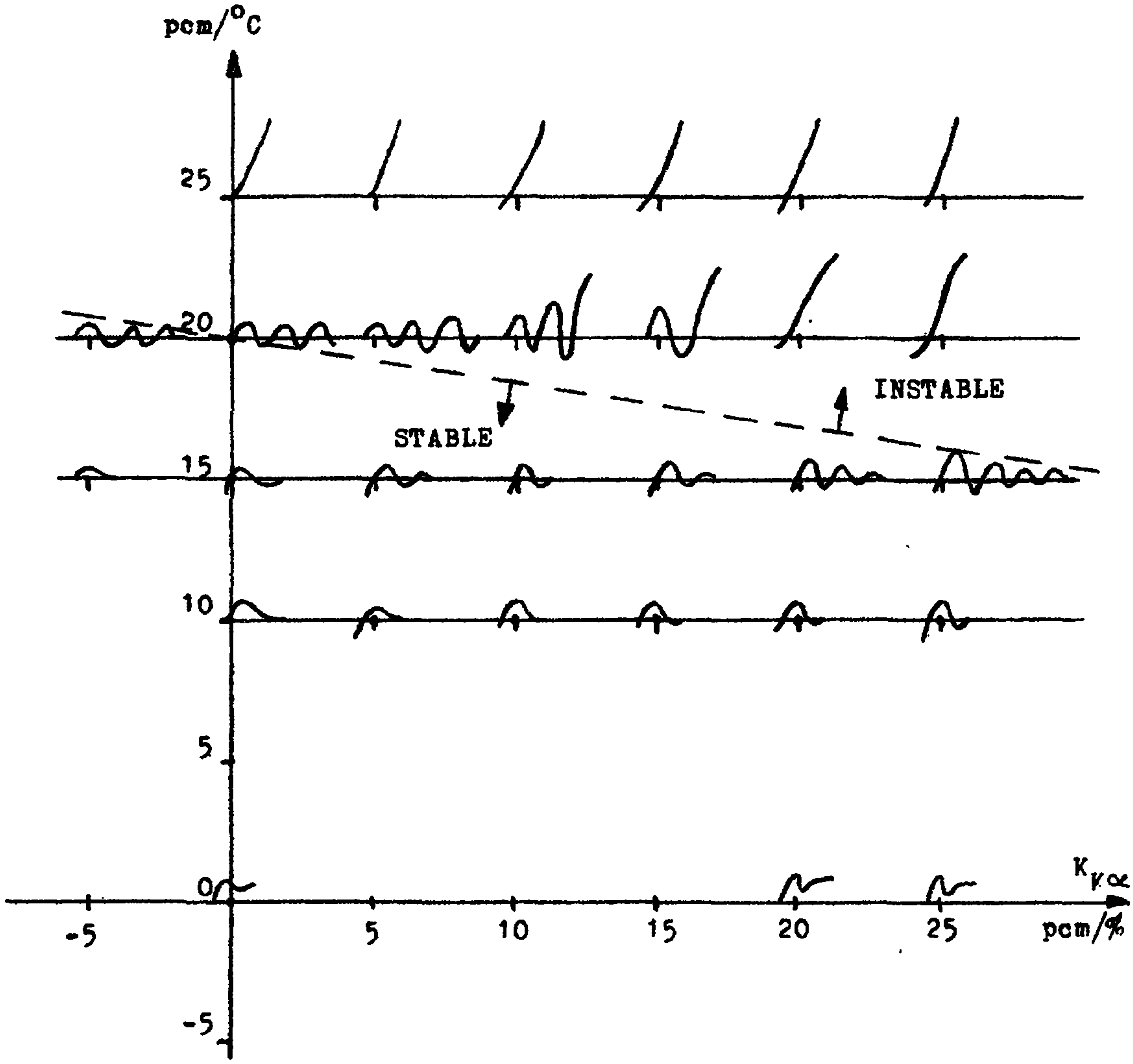
	BHWR without control system	FIG. 2

RESPONSE TO REACTIVITY STEPS

VALUE OF STEP: 10 pcm

$K_{K\alpha}$ AND $K_{K\theta}$ ARE COEFF. USED TO CALCULATE THE VOID REACTIVITY.

PERIOD= 170 SEC. (APPROXIMATELY)



POWER CONTROL SYSTEM OF MARVIKEN

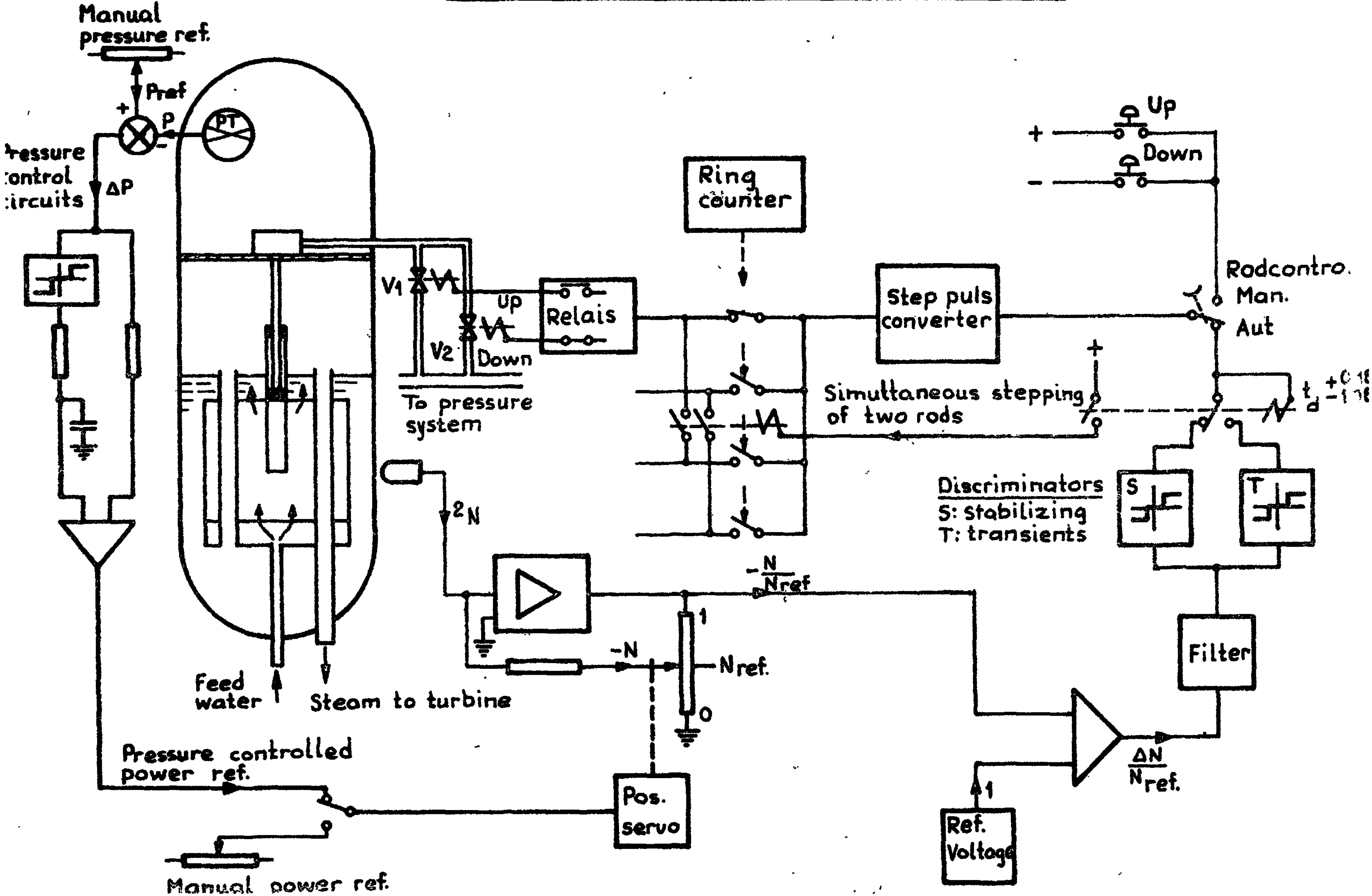
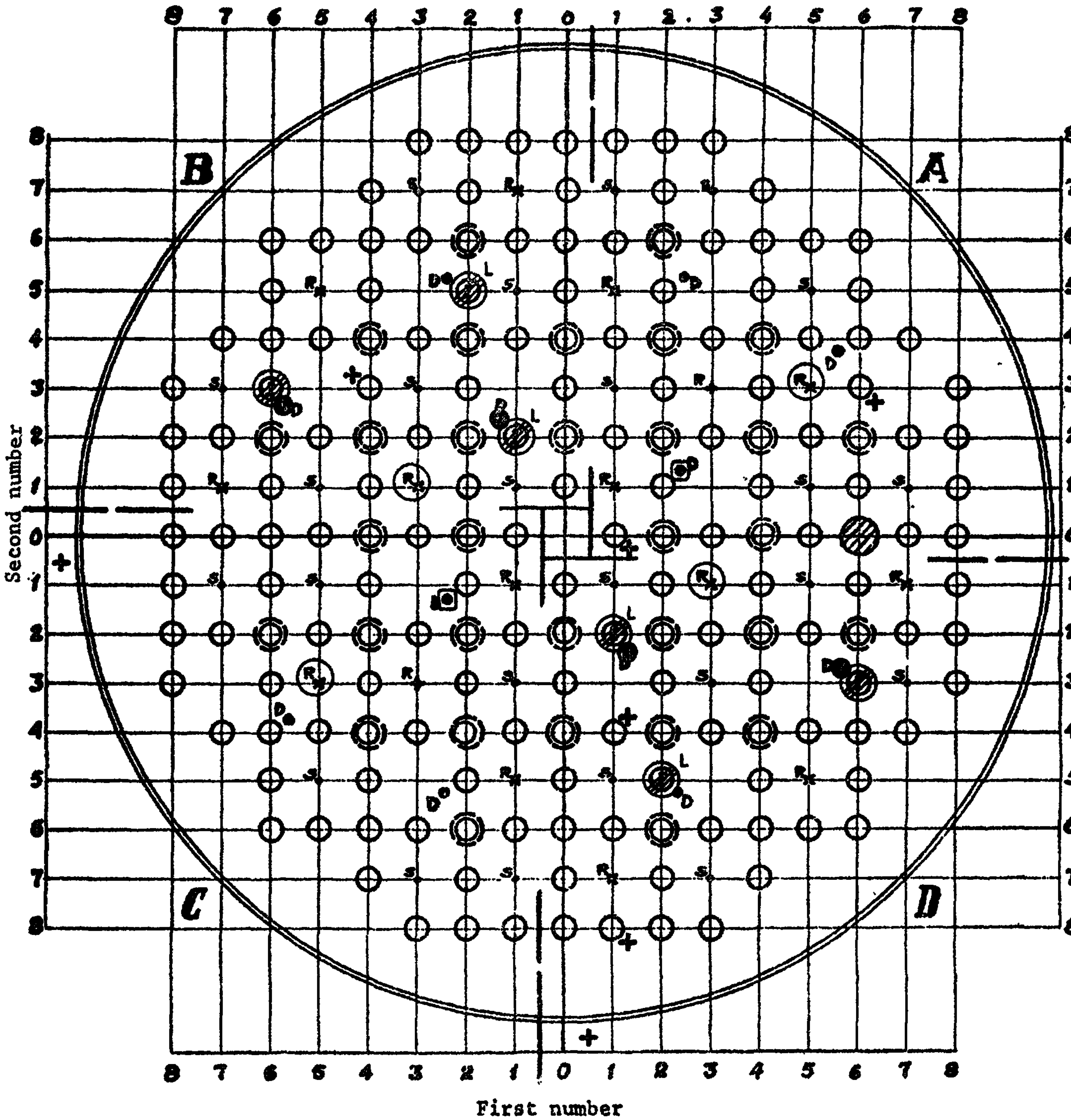


FIG. 4 MARVIKEN LATTICE



BOILER CHANNEL, 147, 6 of which are instrumented

SUPERHEATER CHANNEL, 32

CONTROL ROD, black, 14 — DYN. EXPERIMENTS

CONTROL ROD, grey, 2

SAFETY ROD, 24

DETECTOR PROBE, 12 (DYN.) (START)

THERMOCOUPLE, 20+8

LOW INLET THROTTLING POSSIBLE — REFUELLING CHANNEL

FIG. 5

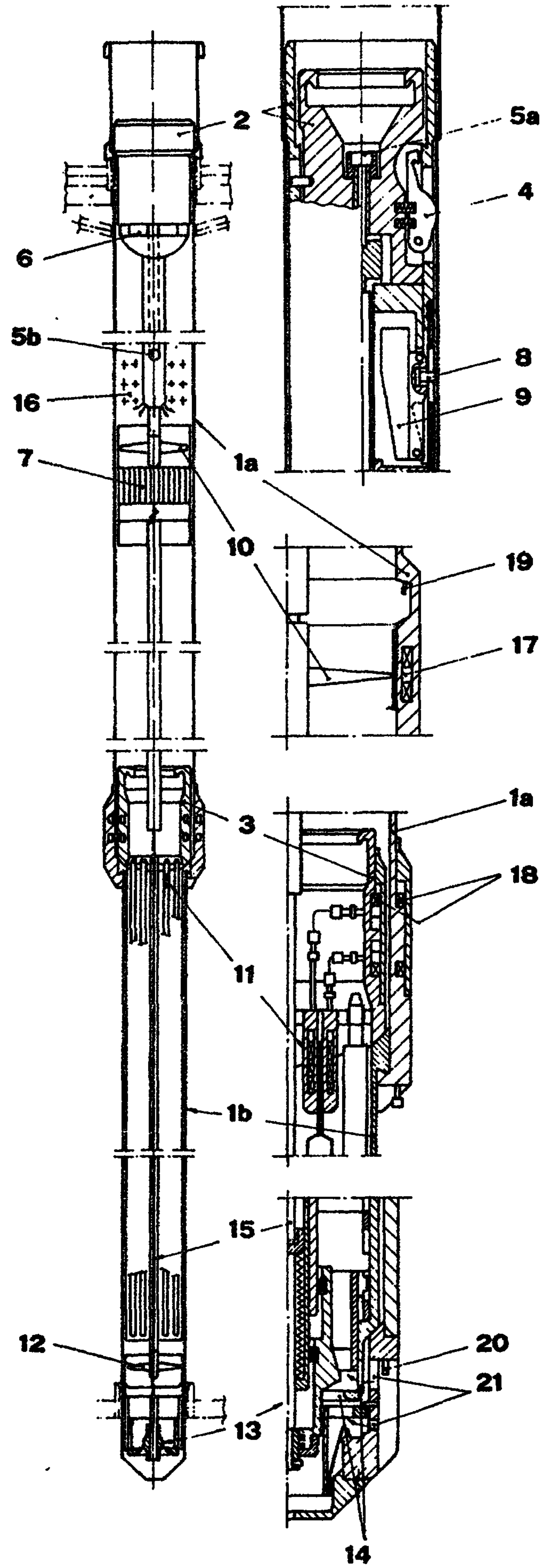


Fig. 5

INSTRUMENTED BOILER CHANNEL

MAIN PARTS:

1. Shroud tube
   a) upper part, stainless steel
   b) lower part, Zircaloy
2. Radiation shield plug
3. Fuel element assembly

THE SHIELD PLUG IS PROVIDED WITH:

4. Locking device for grab
5. Leak detecting of fuel element
   a) outlet
   b) inlet
6. Inlet for emergency cooling water to fuel element
7. Void meter
8. Void meter switches
9. On/Off mechanism for switches
10. Upper turbine-flow-meter

THE FUEL ELEMENT ASSEMBLY IS PROVIDED WITH:

11. Burn-out detector
12. Lower turbine-flow-meter
13. Plug operated throttling valve
14. Adjustable inlet throttling
15. Shield plug actuated rod for operation of throttling valve

THE SHROUD TUBE IS PROVIDED WITH:

16. Steam outlet
17. Pick-up coils for turbine-flow-meter
18. Inductive impulse transfer for p.11
19. Upper thermocouple
20. Lower thermocouple
21. Fixed inlet throttling