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ABSTRACT

The report contains analysis of transients "Loop connection" and "Steam generator tube rupture" for nuclear power plants (NPP) with VVER-440. To obtain more detailled information about NPP's dynamic characteristics, various variants of initial and boundary conditions are considered.

Calculation of these transients was performed using the SiTAP code developed at the Nuclear Safety Institute of the Russian Research Centre "Kurchatov Institute". SiTAP code is a multifunctional computer tool for fast analysis of transient and accidental processes of VVER type reactors for engineers working in the field of NPP dynamics.

SiTAP can be used for comparative analysis of several variants of accident scenarios to find out the conditions leading to most serious consequences from a safety point of view. In such cases, additional analyses using best-estimate codes should be carried out.

The results of SiTAP for a faulty loop connection leading to a boron dilution accident are intended to be used as boundary conditions for a more detailled analysis with the aid of the three-dimensional reactor core model DYN3D, developed in the Research Centre Rossendorf for the simulation of reactivity initiated accidents.

Contents

1. Analysis of the transient "Loop connection"

1.1. Description of possible accidental situations

Each loop of the primary circuit of NPP with VVER-440 has two Main Isolating Valves (MIV), one on the cold leg and the other on the hot leg. MIVs are controlled by the remote control system. Its management is executed from the NPP's Main Control Room in automatic and regulated modes. Separate management of MIVs on cold and hot legs is possible. MIVs availability permits the disconnection of any loops, during work of all others, for example, in the case of leaks or failure of any element of equipment. If the loop is disconnected for repair, it can be depressurized after plant has been shut down.

1.1.1. Rules of loop connection

After repair, the connection of a loop to a reactor is executed in the following order:

Filling	The loop is filled with coolant with H_3BO_3 concentration corresponding to the concentration in other loops. Coolant temperature in the disconnected part of the loop after filling is equal to approximately 100 °C.
Pressurization	Rise of pressure is effected by submission of water on the Main Pump Leaks Locking System (MP LLS) by the Primary Circuit Feeding System (PCFS) and by the system of boron control. As the result of this operation, the pressure rises up to a value of approximately 123 bar, temperature and boron concentration do not change.
Heating	of the disconnected part of a loop is effected by circulation of its coolant through regenerative heat-exchangers of PCFS. Alignment of pressure in connected and disconnected loops occurs simultaneously. Heating is continued until the coolant temperature reaches approximately 250 °C. Then alignment of coolant temperatures is effected by the opening of the MIV on the hot leg of the disconnected loop. As a result of the preparatory operations, pressure, coolant temperature and concentration of boron acid, in the connected and disconnected loops are equal.
The connection	of a loop is effected by the opening of the MIV on its cold leg and by the turning on of the MP.

Main Isolating Valves on loops are equipped with an automatic system that prevents them opening if the following conditions are not fulfilled:

- Difference between maximum coolant temperature in the cold leg of working loops and coolant temperature in the hot leg of disconnected loop is less than 15 K;
- Difference of boron acid concentration in connected and disconnected loops is less than 0.1 g H_3BO_3 / kg H_2O.

MIVs automatic control system effects its stepwise opening with given intervals of delay. The time of the total MIV opening is 298 s. A diagram of MIV pivot position during its opening is shown in fig. 1. The main pumps are equipped with devices, permitting their start only after complete MIVs opening.

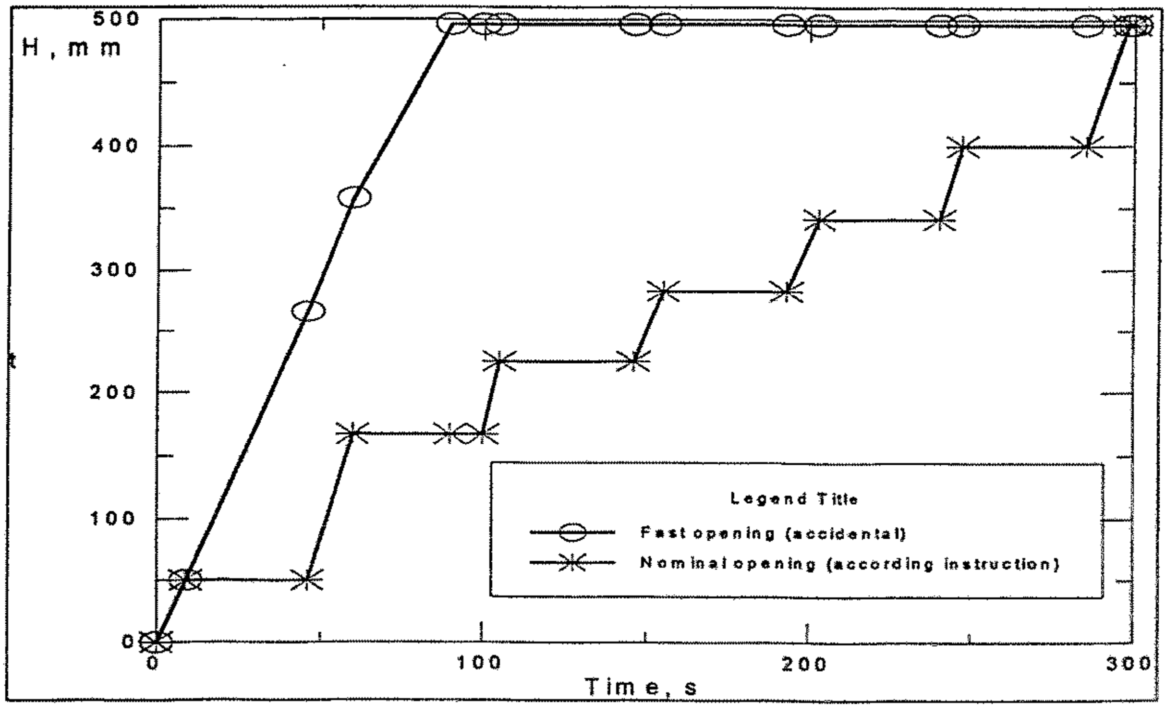

Fig. 1: Time dependence of Main Gate Valve pivot position

1.1.2. Description of possible infringements of the loop connection rules and possible equipment failures

For the analysis of possible infringements and equipment failures, events capable of causing significant raising of reactor power and exceeding of core heat safety limits, were considered.

Thus it was assumed, that any incorrect actions of staff and any safety systems failures, down to failure of the reactor scram system are possible. Thus, the measuring systems function normally, but have the outmost error of measurements.

The following possible infringements of the rules and failure of equipment are taken into account:

- Failure of the reactor scram system;
- Failure of the system blocking the MIV opening;
- Malfunction of PCFS operation, causing the filling of the disconnected part of the loop with cooolant with lowered or zero boron acid concentration;
- Malfunction of MIV control system operation, causing the possibility of its opening with maximum speed provided by the drive (90c);
- Not-fulfillment by staff of actions relating to the alignment of the temperatures of the connected and disconnected loops;
- Start of MP on disconnected loop when MIV was not opened completely.

As a result of the events described above, cold coolant from the disconnected part of loop will probably pass into reactor core. It will cause an increase in the neutron flux as a result of negative feedback. On the other hand, the growth of the reactor power will cause an increase in the coolant temperature, that will conduct to the subsequent reduction neutron flux. However, the amplitude and duration of the power splash can be such that the fuel rods will be damaged. Similar phenomena will be observed in the case of insertion of boron diluted coolant from the disconnected part of the loop into the reactor core.

The significance of the effects described above will vary at different times during the fuel cycle. At the beginning of the fuel cycle, the effect of boron dilution will be determining. But, at the end of the fuel cycle reduction of coolant temperature will be more important. Moreover, in both cases the speed of receipt of the coolant from the disconnected part of the loop and the degree of its mixing in the reactor plenums will be important factors.

Lack of mixing can cause repeated splashes of reactor power after each coolant circulation cycle has been completed. It can be assumed that these repeated reactor power splashes will be also dangerous.

Considering the above, it is possible to allocate the following factors determining the degree of emergency in the transient "Loop connection":

- Degree of boron dilution in the disconnected part of the loop;

- Degree of coolant subcooling in comparison with connected loops;
- Speed of travel of coolant from the disconnected part into the core;
- Degree of coolant mixing in downcomer, lower and upper plenums;
- Initial level reactor power;
- Serviceability of reactor safety systems;
- Reactor core conditions (moment of fuel cycle).

1.2. Tasks of the analysis

The aim of the preliminary analysis is:

- To evaluate the importance of each of the factors (see c.1.1.2.), its influence on the degree of danger;
- To determine the most dangerous combination of such factors and to specify the corresponding transient sequences;
- To evaluate the amplitude and duration of reactor power splashes and the behaviour of core and primary circuit parameters.

The preliminary calculational analysis was executed by use of the code - SiTAPv1.0 [1]. This code describes the joint work of all main systems of the primary and secondary circuit. SiTAPv1.0 is intended for the execution of estimated accounts of transients and accidents with minimum demands of computer resources and time for preparation of initial data and processing of the results.

After fulfilling the preliminary analysis for the most dangerous transients, calculations using the best-estimate code DYN3D [2] will be carried out. This code comprises a space-dependent model of reactor neutron kinetics and a model of its thermohydraulics. The use of 3D will allow a decision on the following tasks:

- More precise estimation of the amplitudes of reactor power splashes and distribution of neutron fluxes in the core at the most dangerous transients.

- To evaluate the probability of local damages to fuel rods.

The comparison of results from these two programs for similar modes will also allow an evaluation of the opportunity of using SiTAP for the analysis of reactivity accidents.

1.3. Description of initial data

Taking into account the factors described above (see i.1.1.2) and tasks (see i.1.2), a list of transients, which should be considered in the preliminary analysis is determined. This list is shown in table 1.1.

In table 1.1:

- "ideal mixing" means that the boron concentration and coolant temperatures at the inlet of all fuel assemblies are distributed uniformly;
- "absence of mixing" means that the coolant from each loop is inserted into the corresponding group of fuel assemblies;
- "real mixing" means partial mixing of coolant at the inlet and outlet of the plenum, according to specified coefficients.

SiTAP takes volumes of lower and upper plenums into account when calculating coolant parameters (temperatures and boron concentrations) at the inlet of the core and outlet of the reactor. But DYN3D neglects these volumes calculating mixing effects in the plenums. This will be one of the factors causing some differences in the results obtained from these codes.

For the purpose of comparison of SiTAP and DYN3D codes, a special calculation of one transient with assumption of "zero" volume of the plenums will be fulfilled.

The "Scram fault" means that all 4 stages of reactor scram system are not working.

Initial values of main plant parameters are shown in table 1.2. Reactivity coefficients corresponding to "fresh fuel" and "used fuel" are shown in table 1.3. the "ARK" control rod group and the scram rods reactivity characteristics are shown in fig. 2 and 3.

List of transients considered during preliminary analysis

Table 1.1

Transiant name	Fuel	Initial power level (%)	Disconnected loops			Connected loops			Scram	Mixing	MP start, s	MGV opening start, s	MGV complete opening duration, s
			Temperature, K	Boron conc. g/kg	Number	Temperature, K	Boron conc. g/kg	Number					
v46_1	fresh	88.00	537.00	0.00	1	537.00	1.53	5	available	Ideal	-200.00	1.00	90.00
v46_2	fresh	88.00	373.00	1.53	1	537.00	1.53	5	fault	Ideal	-200.00	1.00	90.00
v46_3	fresh	88.00	537.00	0.00	1	537.00	1.53	5	fault	Ideal	-200.00	1.00	90.00
v46_4	fresh	88.00	373.00	0.00	1	537.00	1.53	5	fault	Ideal	-200.00	1.00	90.00
v46_5	fresh	88.00	373.00	0.00	1	537.00	1.53	5	fault	absence	-200.00	1.00	90.00
v46_6	fresh	88.00	373.00	0.00	1	537.00	1.53	5	fault	real	-200.00	1.00	90.00
v46_7	used	88.00	373.00	0.00	1	537.00	0.00	5	fault	Ideal	-200.00	1.00	90.00
v46_8	used	88.00	373.00	0.00	1	537.00	0.00	5	fault	absence	-200.00	1.00	90.00
v46_9	used	88.00	373.00	0.00	1	537.00	0.00	5	fault	real	-200.00	1.00	90.00
v43_1	fresh	50.00	373.00	0.00	1	537.00	1.53	3	fault	Ideal	-200.00	1.00	90.00
v43_2	fresh	50.00	373.00	0.00	1	537.00	1.53	3	fault	absence	-200.00	1.00	90.00
v43_3	used	50.00	373.00	0.00	1	537.00	0.00	3	fault	Ideal	-200.00	1.00	90.00
v43_4	used	50.00	373.00	0.00	1	537.00	0.00	3	fault	absence	-200.00	1.00	90.00

Description of initial data for calculations of "Loop connection" transients

Table 1.2

Nr.	Description	Value
	Initial conditions	
1	Full reactor power, MW	1210.00
2	Primary circuit average pressure, bar	122.90
3	Pressurizer pressure, bar	122.60
4	Reactor pressure drop, bar	3.01]
5	Core pressure drop, bar	2.07
6	Coolant flow rate through reactor, t/s	8.73
7	Coolant temperature (reactor inlet), K	538.00
8	Coolant temperature (reactor outlet), K	568.20
9	Average fuel temperature, K	980.00
10	Fuel temperature distribution - see i.e. fig.8	
11	Boron concentration in reactor vessel, g/kg	1.53
12	Boron concentration in nominal loop, g/kg	1.53
13	Nominal hot legs average temperature, K	568.30
14	Nominal SG core average temperature, K	546.40
15	Nominal cold legs average temperature, K	537.90
16	Coolant flow rate through 1 nominal loop	1.56
17	Boron concentration in disconnected loop, g/kg	0.00
18	Hot legs average temperature (in disconnected loop), K	373.0/537.0
19	SG core average temperature (in disconnected loop), K	373.0/537.0
20	Cold legs average temperature (in disconnected loop), K	373.0/537.0
21	Coolant flow rate through disconnected loop	0.00
22	Nominal SG secondary side pressure, bar	47.50

	Continuation of table 1.2	
23	Nominal SG steam mass flow, t/s	0.135
24	Nominal SG feed water mass flow, t/s	0.133
24	SG (on disconnected loop) secondary side pressure, bar	5.0/44.0
25	SG (on disconnected loop) steam mass flow, t/s	0.00
26	SG (on disconnected loop) feed water mass flow, t/s	0.00
	Geometric characteristics	
27	Total primary circuit volume (include PRZ), m^3	194.70
28	Hot legs volume, m^3	4.64
29	SG core volume, m^3	6.80
30	Cold legs volume, m^3	4.44
31	Upper plenum volume, m^3	20.40
32	Lower plenum volume, m^3	36.50
33	Reactor core volume, m^3	8.00
34	Pressurizer total volume / water volume, m^3	44.00/26.00
35	SG secondary side volume, m^3	74.50
36	Reactor vessel volume, m^3	67.60
37	Loop vertical projections height, m -hot leg -SG core -cold leg -downcomer	 -1.39 0.0 2.79 7.58
38	Hydraulic diameters, m -hot leg -SG core (single tube) -cold leg -downcomer	 0.492 0.0132 0.492 0.250
39	Heights, m -core -upper plenum -lower plenum	 2.5 4.0 2.1

	Continuation of table 1.2	
40	Plenums characteristics:	
	-upper	
	-cross section, m^2	0.9
	-hydraulic diameter, m	0.917
	-effective length, m	4.29
	-effective heat transfer area,m^2	166.7
	-lower	
	-cross section, m^2	6.45
	-hydraulic diameter, m	0.678
	-effective length, m	4.0
	-effective heat transf. area,m^2	93.6
41	Core bypass characteristics:	
	-cross section, m^2	0.256
	-hydraulic diameter, m	0.0056
	-length, m	2.5
42	Rods cassette characteristics	
	-cross section, m^2	0.00884
	-hydraulic diameter, m	0.086
	-fuel mass, t	0.136
	-length, m	2.5
	-number of rods	126

Reactivity coefficients

Table 1.3

1	Core state conditions	beginning of cycle	end of cycle
2	Reactivity cofficients		
	-by fuel temperature ($d\rho/dt_f$), 1/K	$-0.34*10^{-4}$	$-0.298*10^{-4}$
	-by coolant temperature ($d\rho/dt_m$), 1/K	$-1.66*10^{-4}$	$4.94*10^{-4}$
	-by coolant density ($d\rho/dg_m$), $(m^3/kg)^{-1}$	$+0.80*10^{-5}$	$+0.76*10^{-5}$
	-by boron concentration ($d\rho/dc_b$), $(g/kg)^{-1}$	-0.125	-0.103
	-by pressure ($d\rho/dP$), 1/bar	0.	0.
	-by power ($d\rho/dQ$), 1/MW	$-0.14*10^{-7}$	$0.16*10^{-6}$

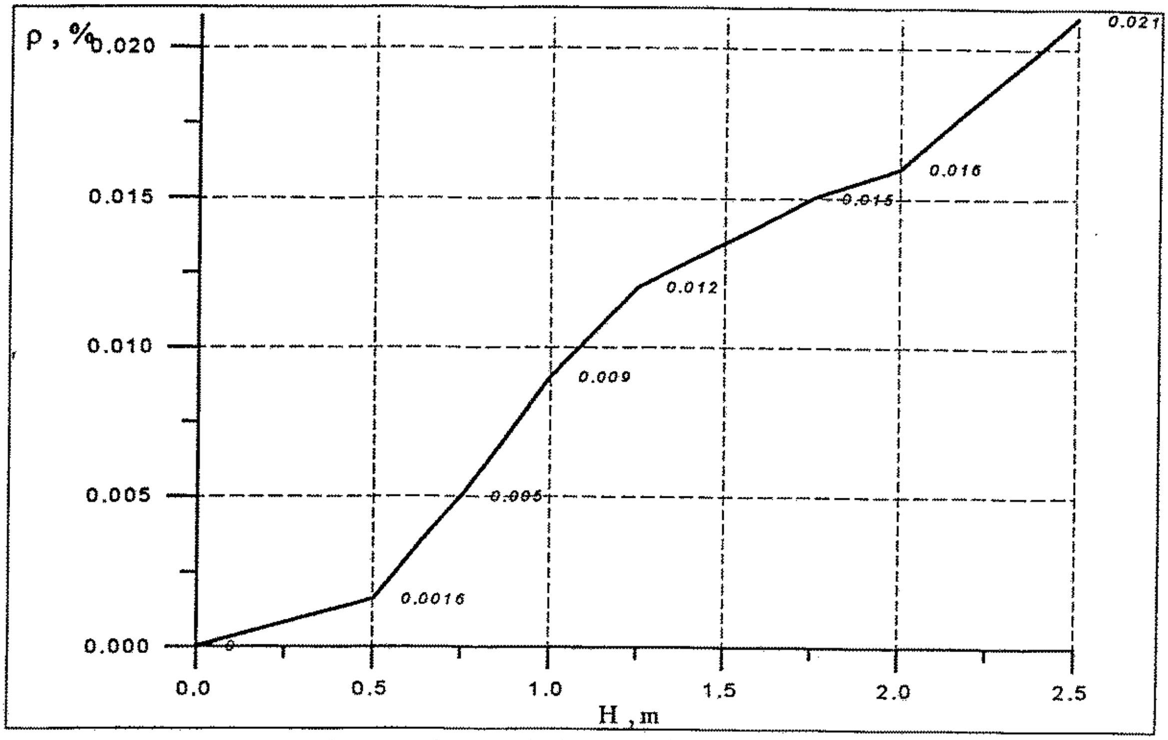

Fig.2: "ARK" control rod group integral characteristics

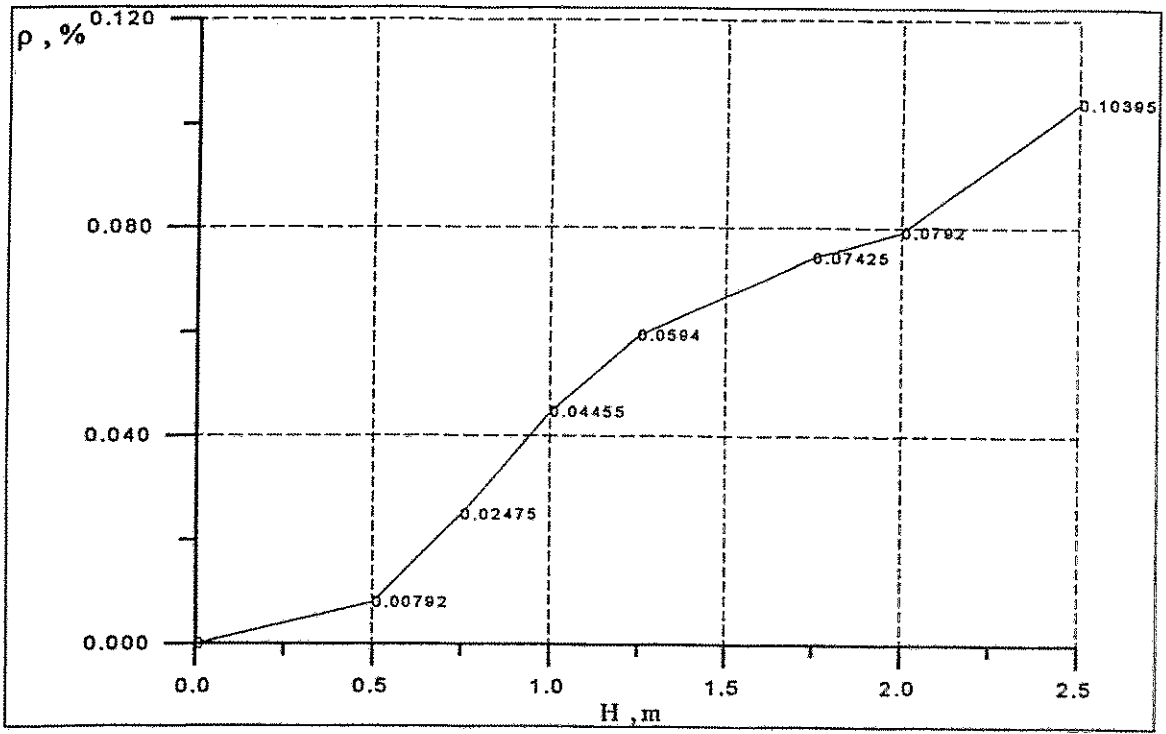

Fig.3: Scram rods integral characteristic

1.4. Results of the preliminary analysis

Results of calculations, performed during preliminary analysis are shown in fig. 4-81. These diagrams contain the most important parameters for the analysis of "Loop connection" transients. All the information about the results of calculations is contained in library LOOP_4. Using the utility Viewer (entering in a structure of the SiTAP code) the user can receive hard copies of any diagrams obtained after these calculations. The list of output variables is adduced in Appendix A. User Guide for Viewer utility is adduced in [3]. The transients named in the headings of items 1.4.1. -1.4.8. correspond to the "NAME" column of table 1.1. In addition, a calculation of a transient of "Loop connection under normal conditions" type was carried out in order to compare the results with results obtained from literature [4]. The results correspond well. For example, the time until the neutron power level of 93% is reached by SiTAP- calculation = 5 sec and according to [4] it is 4 sec.; maximum fuel temperature: SiTAP - 1100 °C, [4] - 1180 °C.

1.4.1. Mode V46_1

Results of the calculation are shown in fig. 4-9. Aim of the analysis (according to i.1.2.) - to determine the degree of danger of the following erroneous actions:

- The opening of the MIV with maximum speed while the MP is working;

- Insertion of boron diluted water into core.

As the results of the calculation show, after commencing opening of the MIV opening, boron diluted coolant from the disconnected part of loop reaches the core after 6.5 sec. It causes growth of neutron power. After 9 sec of this, the transient scram system is activated by the signal "Excess of Permited Neutron Power" (setpoint " Excess of the permited period of the reactor " was not achieved because of the low speed of coolant insertion). The sequence of events after scram activation corresponds to ordinary transient "Shutdown of the reactor". A maximum level of neutron power - 1397 MW, maximum fuel temperature - 1090 K, maximum coolant enthalpy in the reactor core -1350 kJ/kg was reached.

1.4.2. Mode V46_2

The purpose of the calculation of this mode is to evaluate the influence of temperature effects in the transient "Loop connection". For more exact evaluation the following assumptions were made:

- The emergency protection of a reactor is faulty;
- Boron concentrations in the disconnected part of the loop and in other loops are the same.

As is the case in the previous mode (v46_1), the cold coolant from the disconnected part of loop reaches the core after 6.5 seconds, which causes an increase in reactor power due to the of water temperature negative feedback effect. As coolant passes through the core, its temperature increases, causing a reduction of influence of this feedback. Therefore, a maximum increase of power and fuel temperature is observed in the bottom part of the core (see fig.14). When the coolant has left the core, the insertion of water with normal temperature will start. It will cause a decrease in the reactor power. The process is stabilized at a new level of power after approximately 90 sec after the MIV has begun to open.

The maximum level of neutron power in this mode is 1420 MW, maximum fuel temperature is 1160 K and the minimum DNB ratio is 2.8 (according to the formula GKAE). The results of the calculation are shown in fig. 10-15.

1.4.3. Mode V46_3

The calculation of this mode is similar to the previous calculations, however, in this case, the influence of the boron dilution effect was evaluated.

The maximum level of reactor power in this mode is 2560 MW, the maximum fuel temperature is 1600 K and the minimum DNB ratio is 1.7 (according to the formula GKAE). The results of the calculation are shown in fig 16-21.

1.4.4. Mode V46_4

In the calculation of this transient following factors were considered:

- Insertion of coolant (with zero boron concentration) into the reactor core;
- Insertion of subcooled coolant (maximum degree of subcooling - temperature 100 °C) into the reactor core;
- Failure of the reactor scram system;
- Maximum possible speed of the MIV opening.

In this case, the influence of all factors described above was considered simultaneously . The results of account are adduced in fig. 22-27.

This transient is similar to cases V46_2 and V46_3, with the exception that parameters of the unit reach higher levels. The maximum level of neutron power is equal to 2676 MW (195 %), the maximum fuel temperature is 1630 K, and the minimum DNB ratio is equal to 1.57 (according to the formula GKAE).

1.4.5. Mode V46_5

The purpose of the calculation of modes V46_5 and V46_6 is to evaluate the influence of coolant mixing. Here, the assumption about absence of mixing was made. However, using the Euler form for momentum and energy equations in SiTAP code causes "wave front deformation" [5]. This means that SiTAP has a "numerical mixing" property .

Initial and boundary conditions in this mode are the same as in V46_4. Absence of mixing (or a small degree of it) causes repeated power splashes. Its amplitudes are greater than in cases with "ideal mixing". This can be explained by the fact that coolant from the disconnected part of the loop, after passing the whole circuit, is again inserted into the core. The amplitude of the second splash is considerably less than that of the first one because the coolant temperature has increased during the first passage through the core. In addition, the difference in boron concentrations has decreased due to partial mixing.

The maximum power level during the first splash is 8400 MW, during the second it is 3400 MW. Maximum temperatures of fuel are 2350 K and 1780 K respectively. At 16 sec of transient the DNB ratio was less than the critical value (during 6 sec). The results of the calculation are shown in fig. 28-33.

1.4.6. Mode V46_6

Here the assumption about "real mixing" in plenums was made. The meaning of the term "real mixing" is considered in i.1.3. The values of coefficients were taken from the materials [6] and adapted for use with the SiTAP code.

The maximum level of power during the first pulse is 4050 MW, during the second - 2600 MW. Maximum temperatures of fuel are 1960 K and 1600 K respectively. The results of calculations are shown in fig. 34-39.

It is interesting to note, that in modes V46_4 - V46_6, third splashes of power (in the region of 100 -140 sec.) occur. This third splash is explained by the following reason. As result of the power increase, pressure in the SG increases up to level of BRU operation (BRU-A and BRU-K). Operation of these devices causes a drop in the SG pressure. This means that heat transfer conditions are improved. The last increase in reactor power is caused by a decrease in the coolant temperature at the reactor inlet. The last burst of reactor power differs from the previous ones by the fact that it is of small value and long duration.

1.4.7. Modes V46_7, V46_8, V46_9

This group of modes has the same boundary conditions, as cases V47_4 - V46_6 respectively. However, another state of the core (at the end of a reactor cycle) is considered here. Therefore, the effect of boron dilution has no essential significance. On the other hand, feedback by coolant temperature, in this case, is considerably greater, than in the case of variants V46_4 - V46_6. Analogous to the modes described above, "ideal" (V46_7), "absence" (V46_8) and "real" (V46_9) mixing in the plenums is considered here. The results of the calculations are shown in fig. 40-51. They allow us to arrive at the following conclusions:

- For the given state of a reactor core, transients of type "Loop connection with infringement of the rules" there have less serious consequences, than in similar cases calculated for the beginning of a fuel cycle;

- The influence of mixing (for the given state of the core) is only of significance for the size of the first power splash.

The last conclusion is explained by the following reason: the main effect, in the considered case, is caused by the coolant temperature at the core inlet, but not by the boron concentration. During the second insertion of coolant from the disconnected part of the loop into the core, its temperature is essentially higher (due to heating during first crossing through core). This can be seen in the drawings mentioned above. The value of the maximum power splash in these modes is equal to 2200 MW (V46_8).

1.4.7. Modes V43_1, V43_2, V43_3, V43_4

The most dangerous combinations of initial events in variants V46_1 - V46_9 were considered with the assumption that 1 loop is connected to 3 operating loops. The analysis was conducted for two conditions of the core: at the beginning (V43_1, V43_2) and at the end (V43_3, V43_4) of the reactor cycle. Cases of "absence" (V43_2, V43_4) and "ideal" (V43_1, V43_3) mixing were considered. The case of "real" mixing was not included into the analysis due to the lack of experimental data.

The results of the calculation of these modes are shown in fig. 52-67. They correspond well to the conclusions drawn above (see V46_1-V46_9). Absolute values of maximum power levels, in these variants, are lower, than in previous ones. The maximum power splash was achieved in mode V43_2, being equal to 1590 MW.

However, relative splash amplitudes in these variants are greater than in corresponding previous ones. This is explained by the fact that the share of coolant in the disconnected part of a loop is higher in the relation to the weight of the water in the working part of the circuit.

1.5. Conclusions of the preliminary analysis

The results of the preliminary analysis allow us to arrive at the following conclusions:

- The most dangerous modes are variants V46_4 - V46_6. In these cases, the effect of boron dilution has a greater influence on the size of a power splash, than the effect of insertion of cold coolant into the core. These modes are recommended for consideration during the detailled analysis stage (using the DYN3D code);
- Transients "Loop connection with infringement of rules" at the end of a reactor cycle have less serious consequences;
- The power splashes due to repeated coolant perturbation insertion into the core do not have more serious consequences than the first power splash;
- Apart from damage to the fuel rods, there is another serious consequence i.e. the release of radioactivity from the primary circuit, caused by PRZ relief valves operation;
- The potential danger is presented by the increase in the reactor power caused by coolant subcooling during BRU operation.

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FIGURES

Part I

Fig. 4 - 67

VVER-440. Transient name: 1 of 6 loops connection (v46_1).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is available.

Disconnected loop parameters: T=573 K, Cb=0.0 g/kg.

Pressurizer parameters

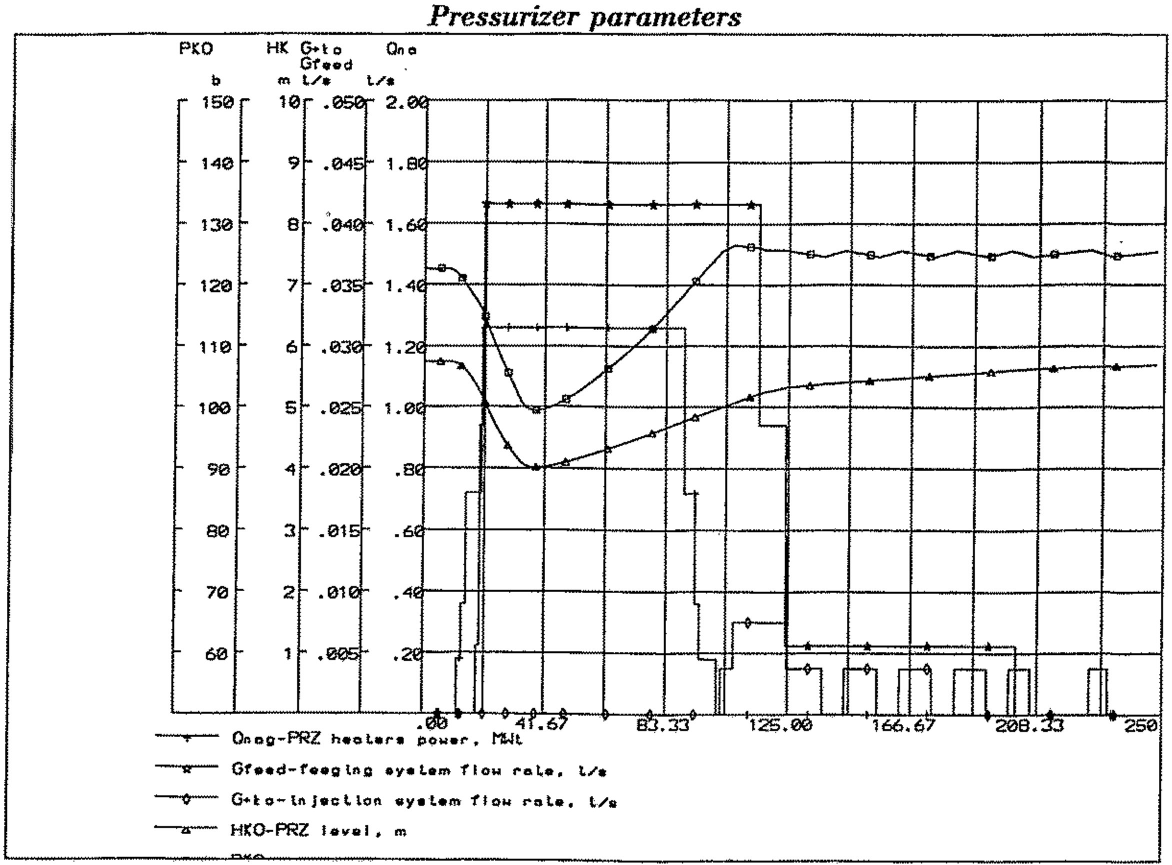

fig 4.

Primary circuit parameters.

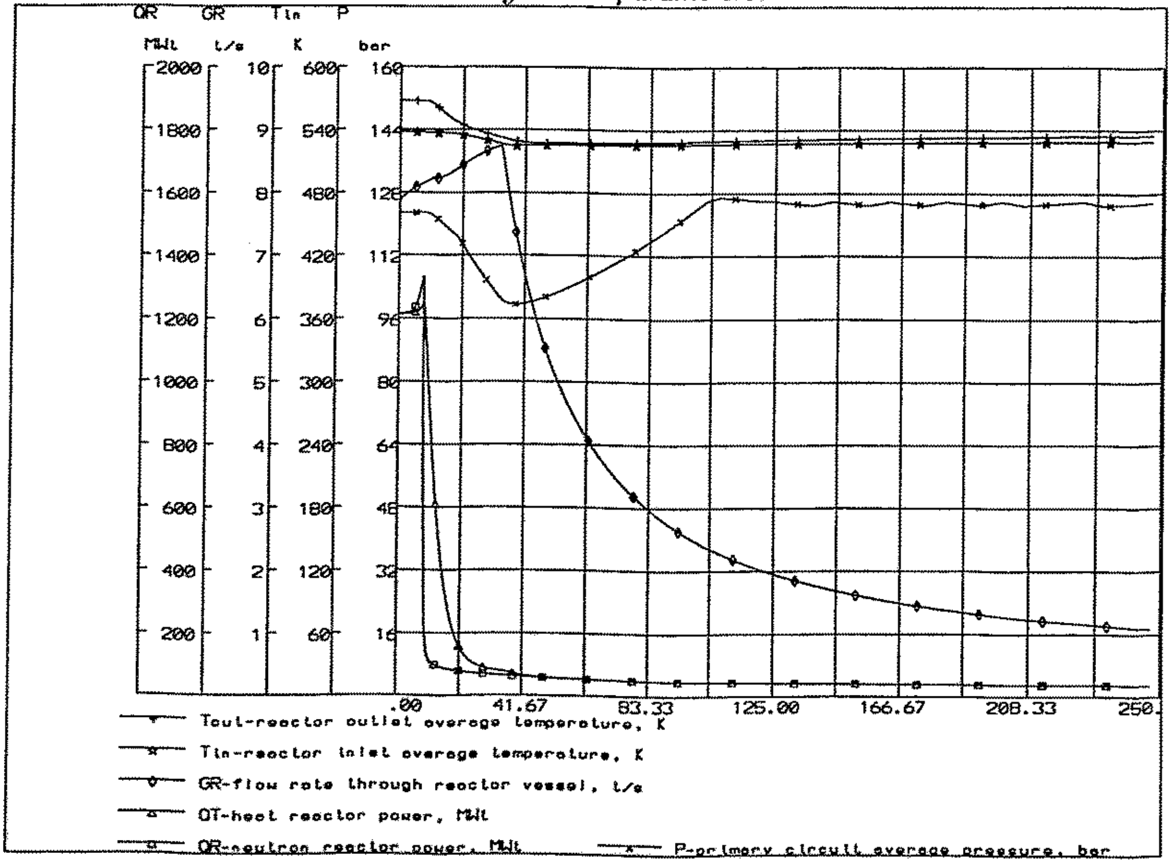

fig 5.

VVER-440. Transient name: 1 of 6 loops connection (v46_1).

Initial power level - 1210 MWt, at the begin of fuel cycle. Scram is available.
Disconnected loop parameters: T=573 K, Cb=0.0 g/kg.

Core parameters

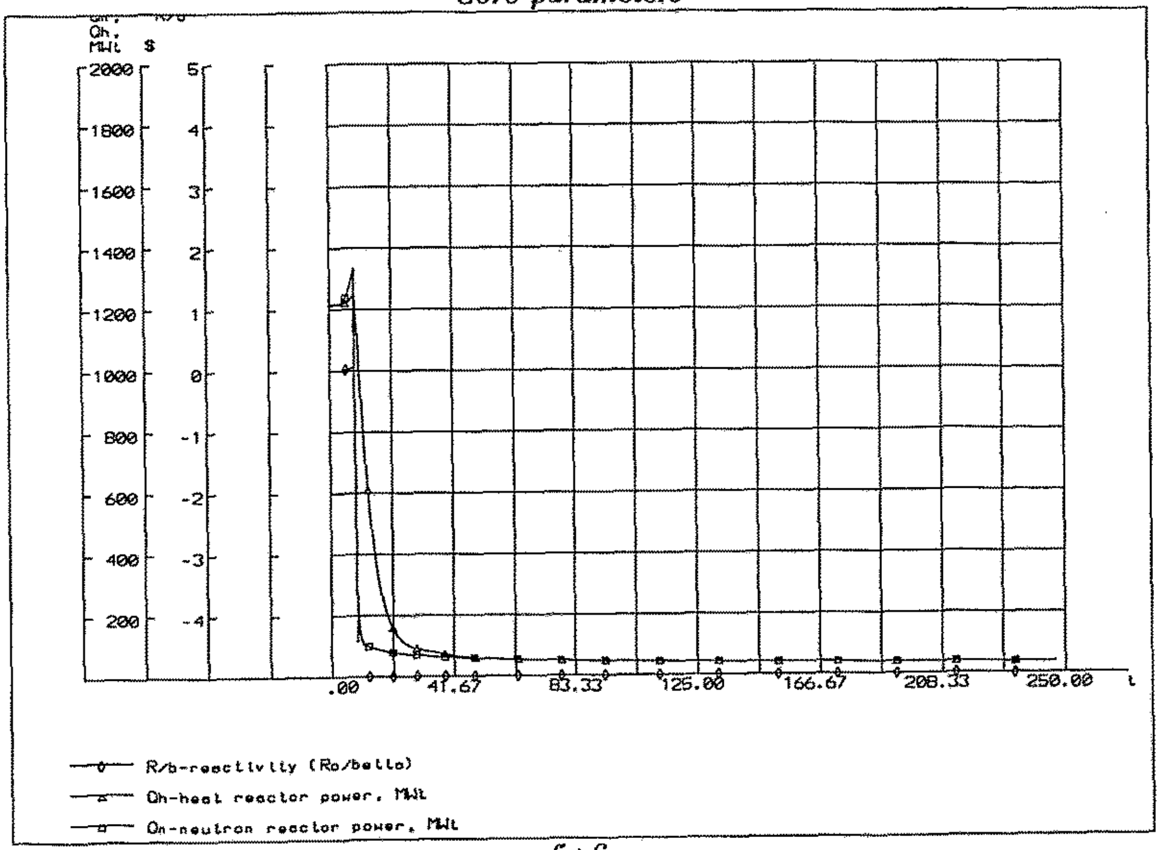

fig 6.

Boron concentrations

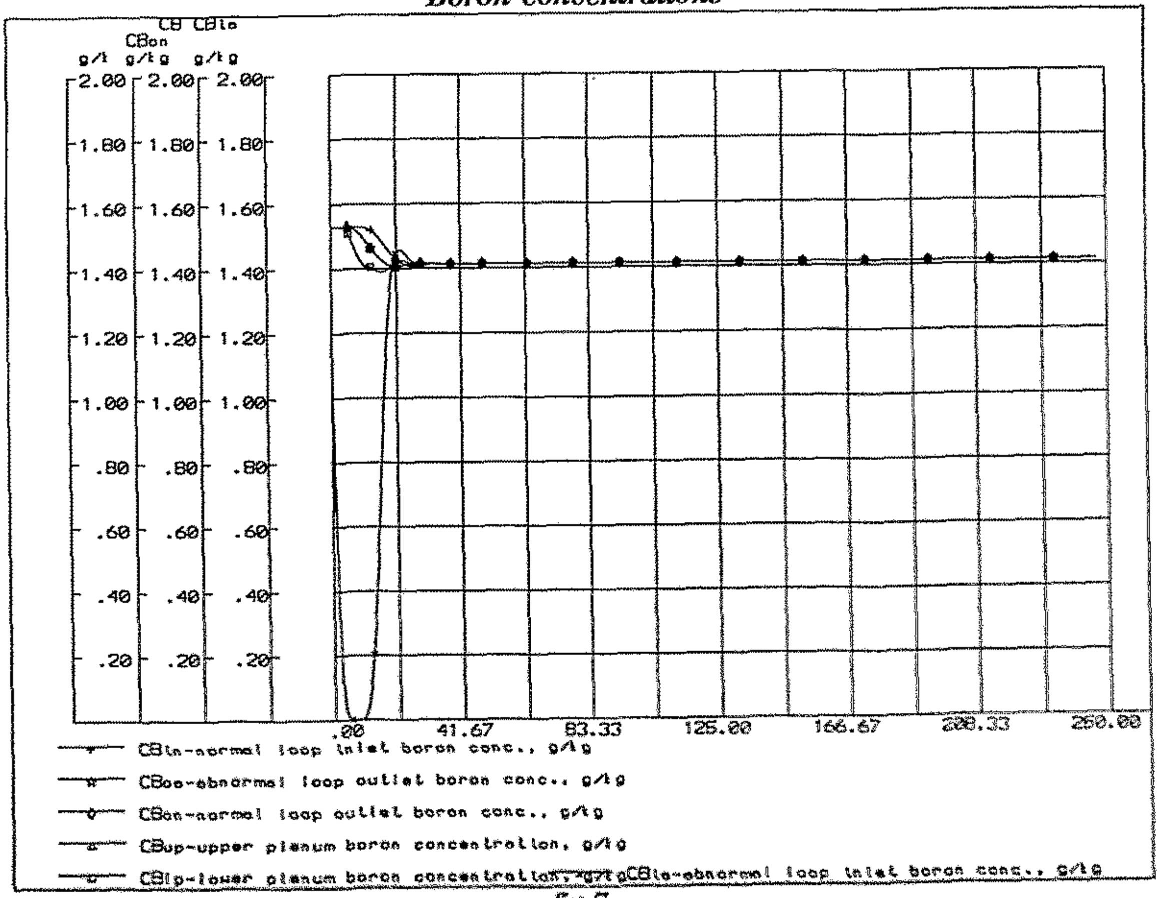

fig 7.

VVER-440. Transient name: 1 of 6 loops connection (v46_1).

Initial power level - 1210 MWt, at the begin of fuel cycle. Scram is available.
Disconnected loop parameters: T=573 K, Cb=0.0 g/kg.

Fuel temperature distribution (hot channel)

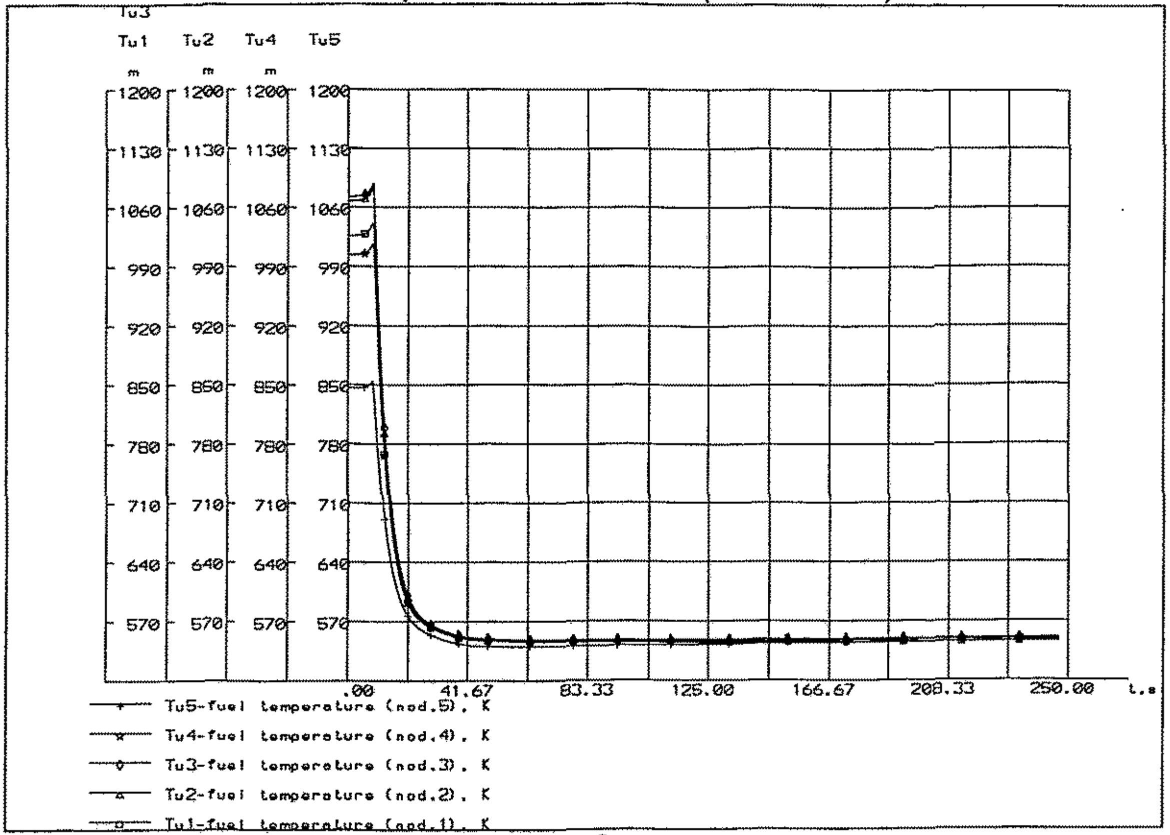

fig 8.

Coolant enthalpy distribution (hot channel).

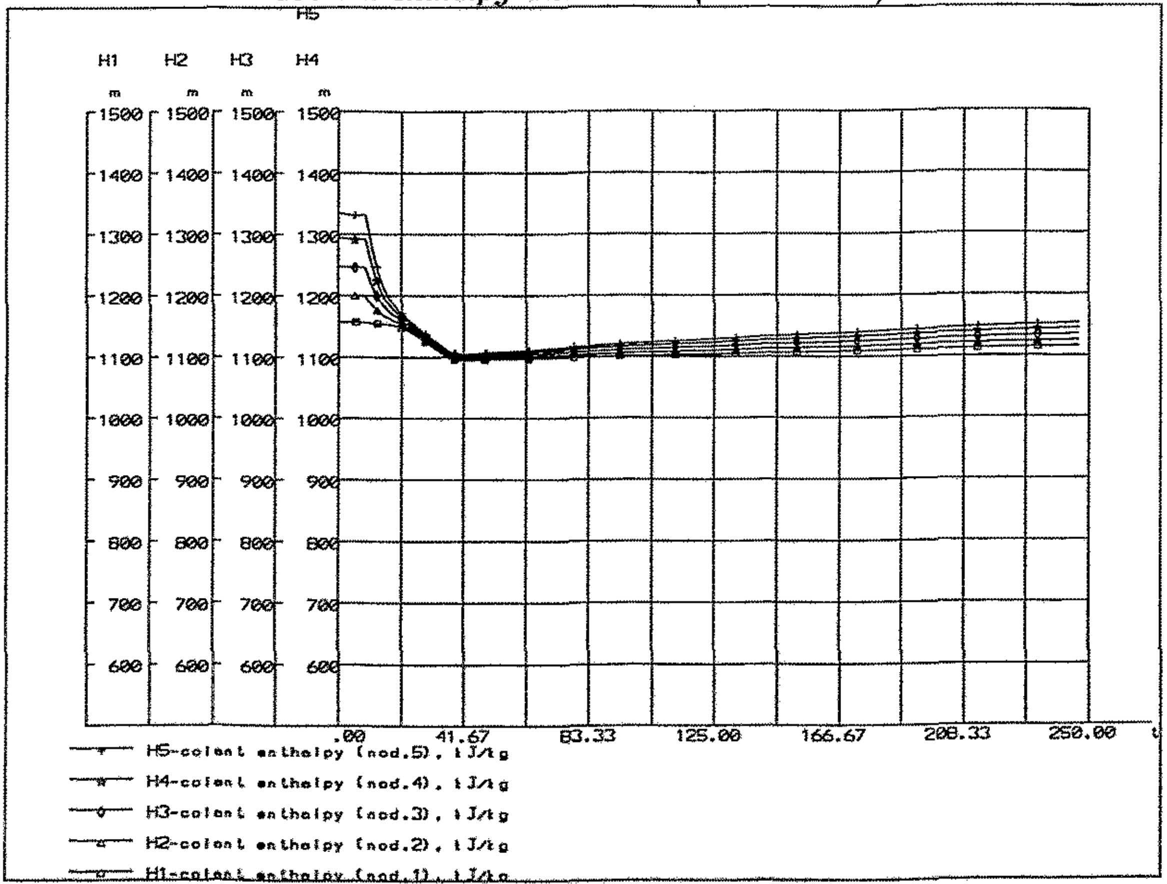

fig 9.

VVER-440. Transient name: 1 of 6 loops connection (v46_2).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=1.53 g/kg.

Pressurizer parameters

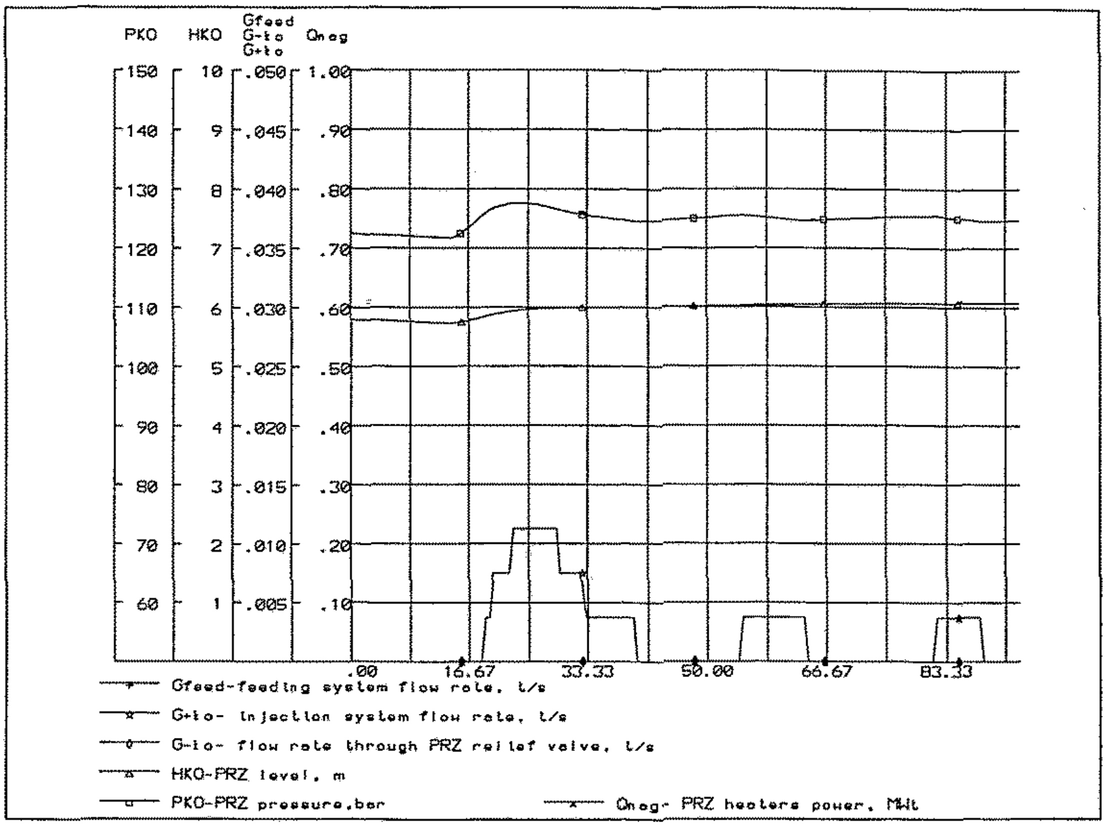

fig 10.

Primary circuit parameters.

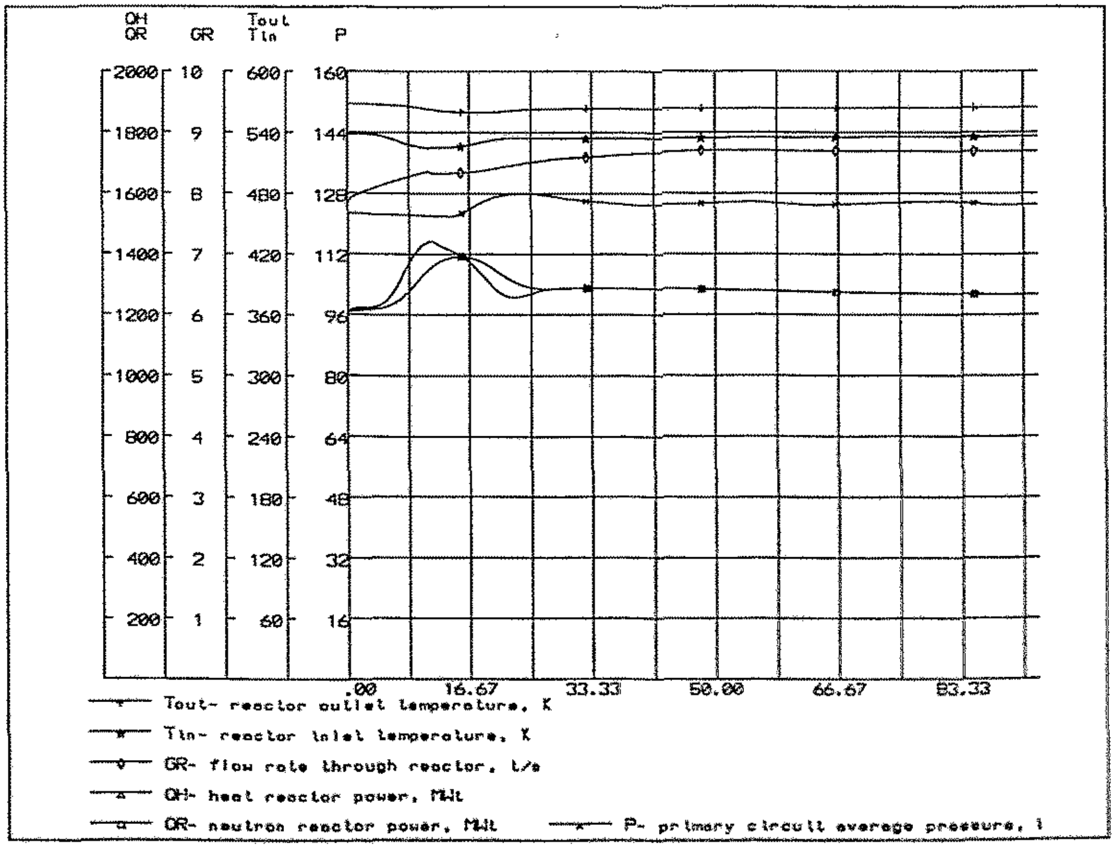

fig 11.

VVER-440. Transient name: 1 of 6 loops connection (v46_2).

Initial power level - 1210 MWt, at the begin of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=1.53 g/kg.

Core parameters

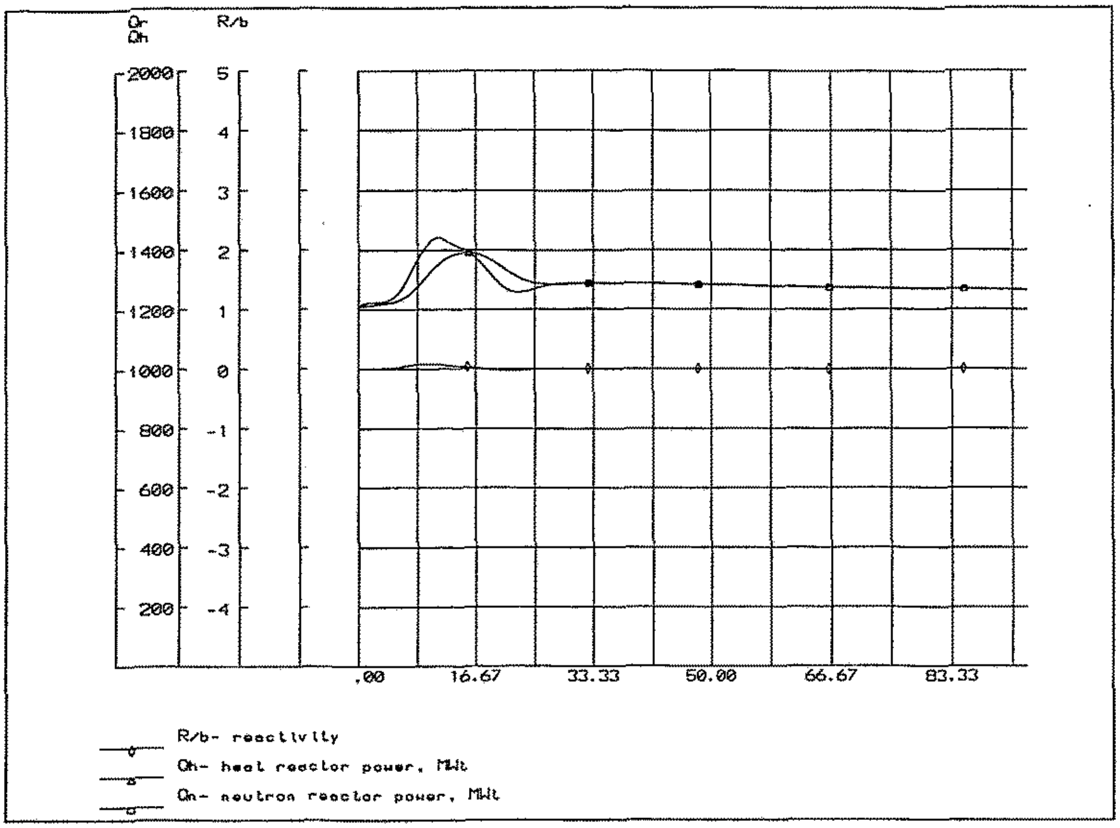

fig 12.

Boron concentrations

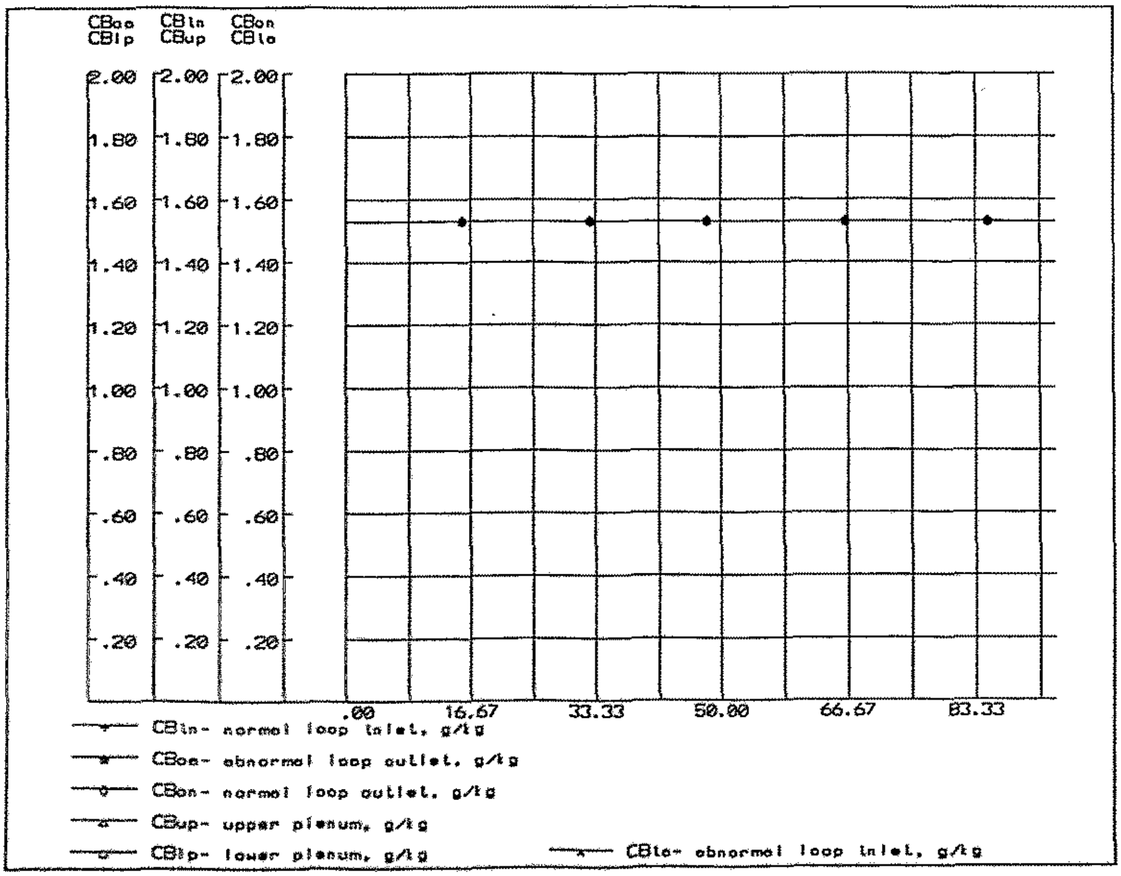

fig 13.

VVER-440. Transient name: 1 of 6 loops connection (v46_2).

Initial power level - 1210 MWt, at the begin of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=1.53g/kg.

Fuel temperature distribution (hot channel)

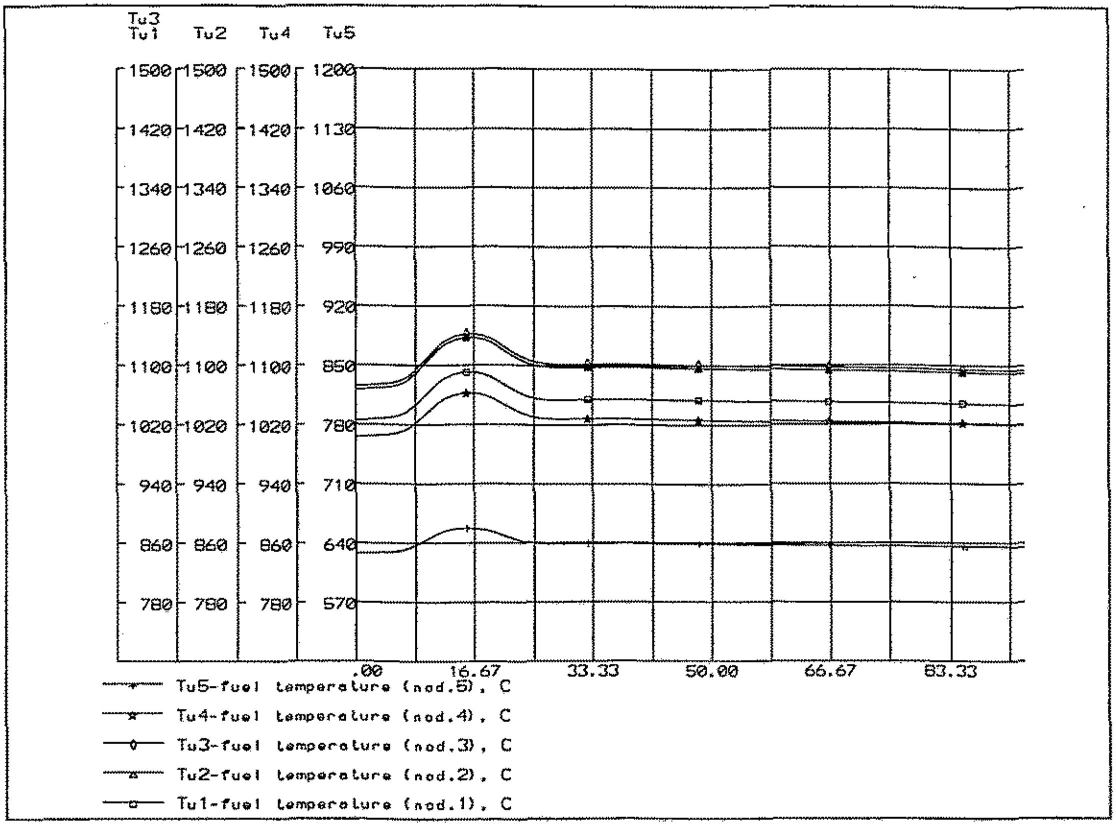

fig 14.

Coolant enthalpy distribution (hot channel)

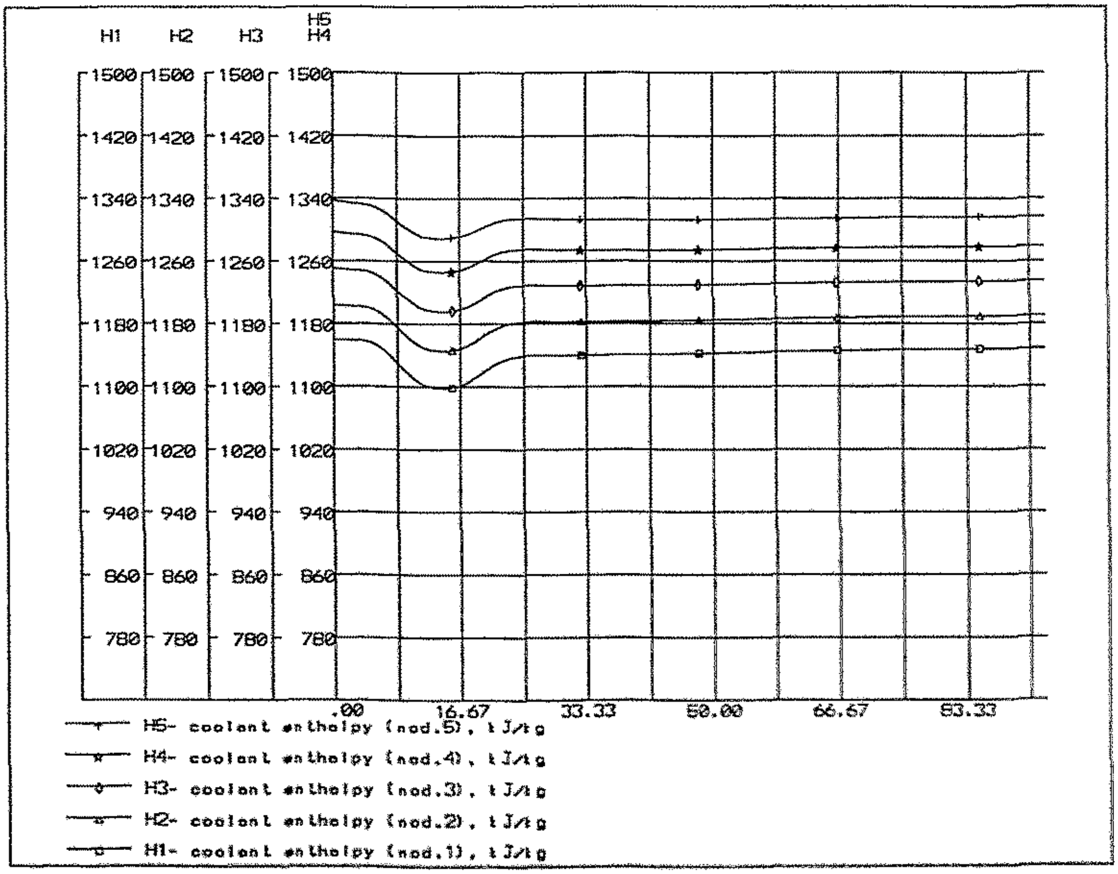

fig 15.

VVER-440. Transient name: 1 of 6 loops connection (v46_3).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=537 K, Cb=0.0 g/kg.

Pressurizer parameters

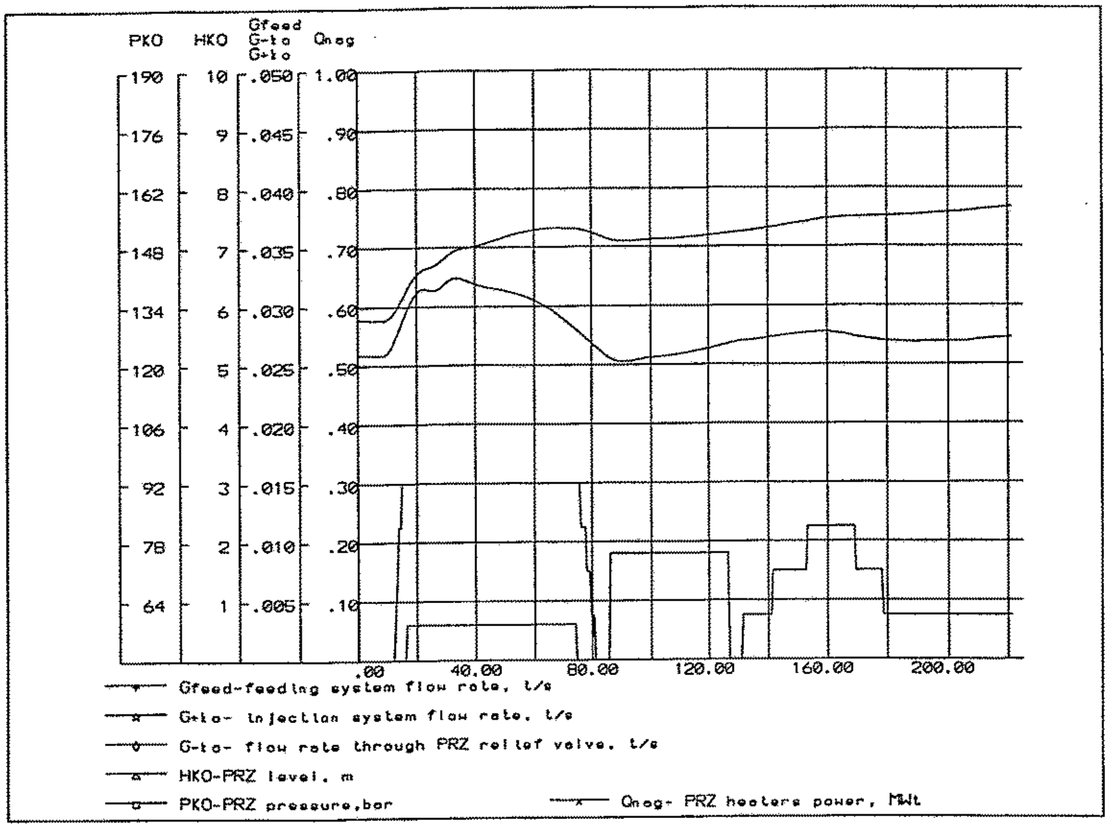

fig 16.

Primary circuit parameters.

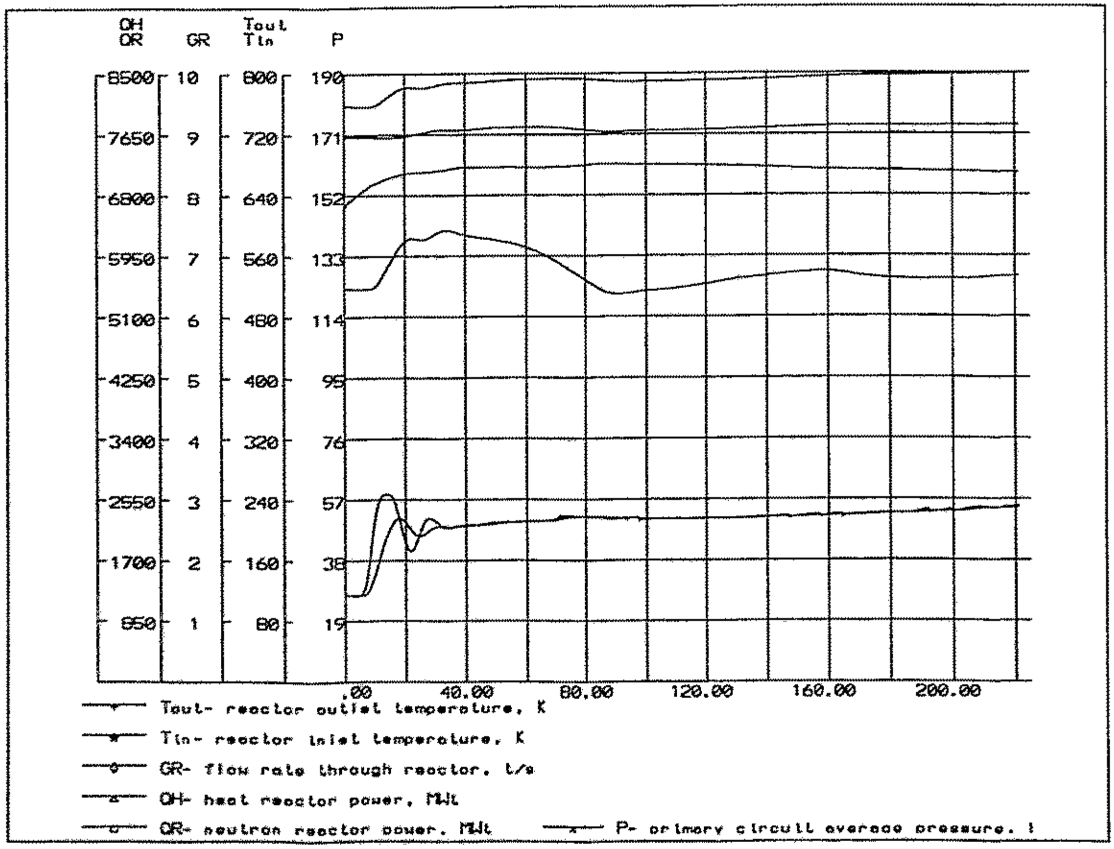

fig 17.

VVER-440. Transient name: 1 of 6 loops connection (v46_3).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=537 K, Cb=0.0 g/kg.

Core parameters

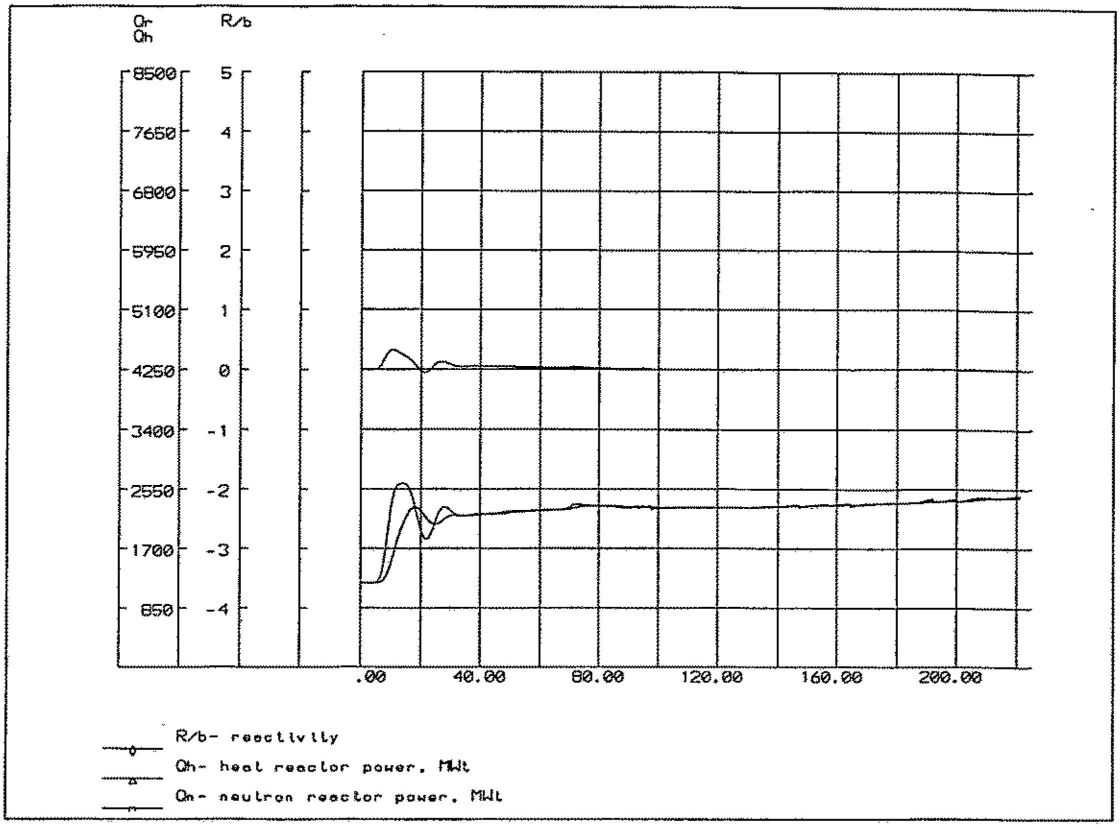

fig 18.

Boron concentrations.

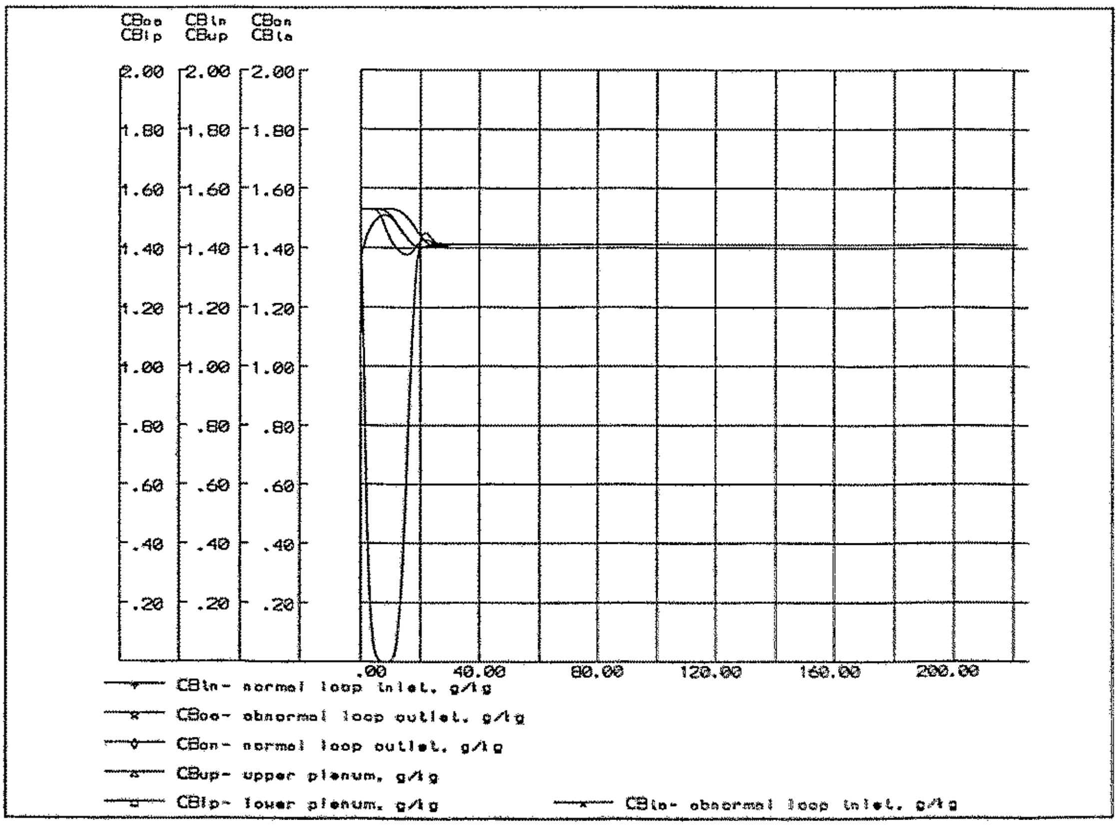

fig 19.

VVER-440. Transient name: 1 of 6 loops connection (v46_3).

Initial power level - 1210 MWt, at the begin of fuel cycle. Scram is fault.

Disconnected loop parameters: T=537 K, Cb=0.0g/kg.

Fuel temperature distribution (hot channel)

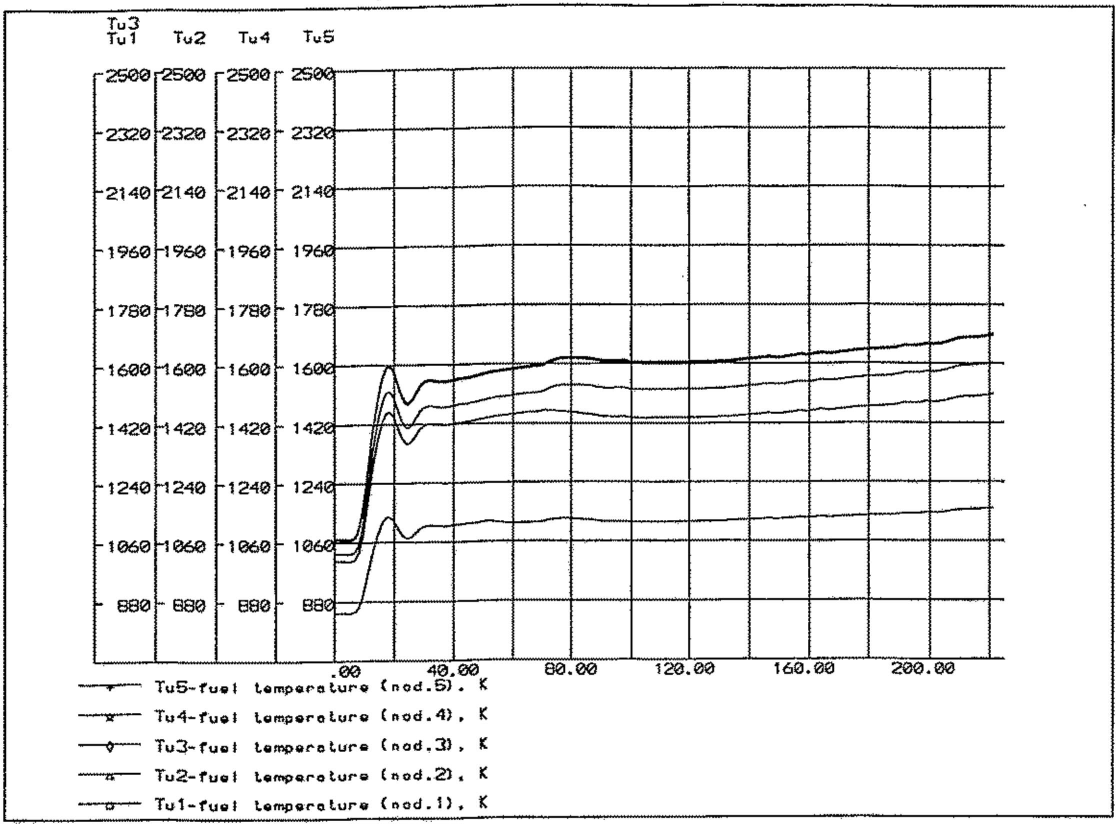

fig 20.

Coolant enthalpy distribution (hot channel)

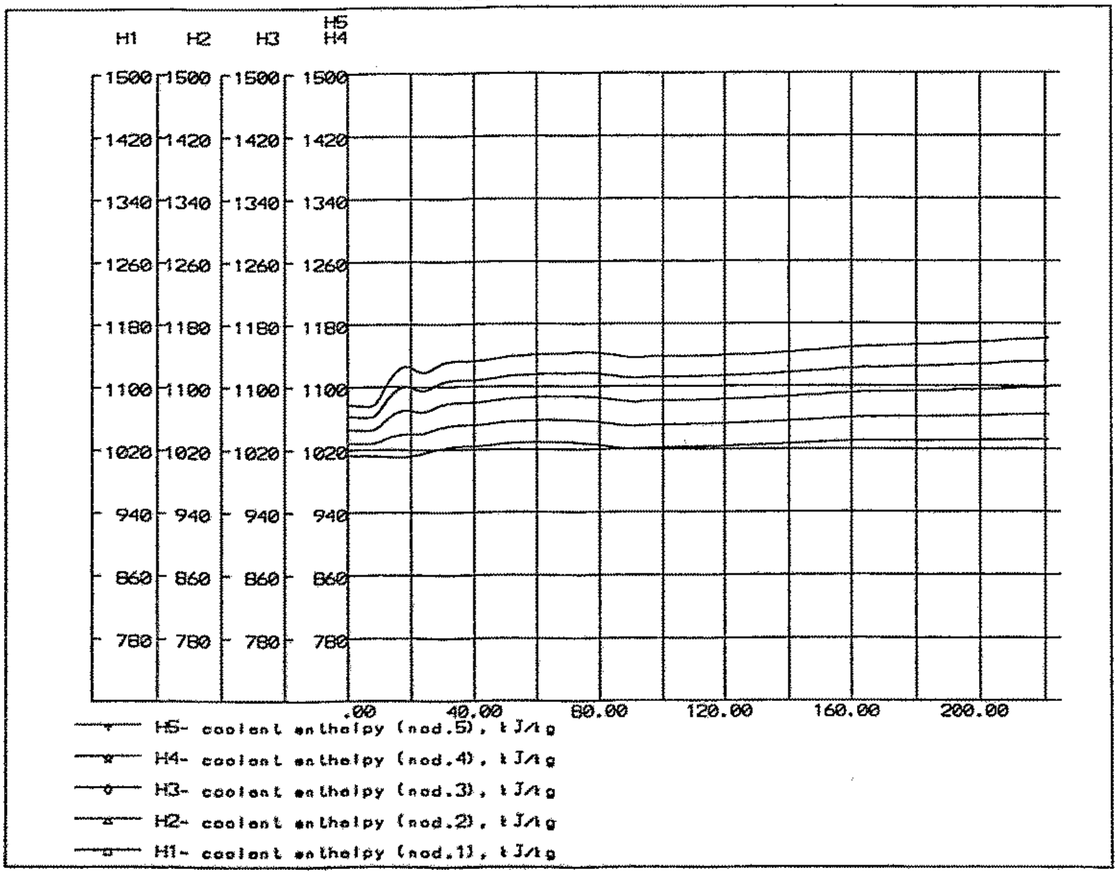

fig 21.

VVER-440. Transient name: 1 of 6 loops connection (v46_4).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg.

Pressurizer parameters

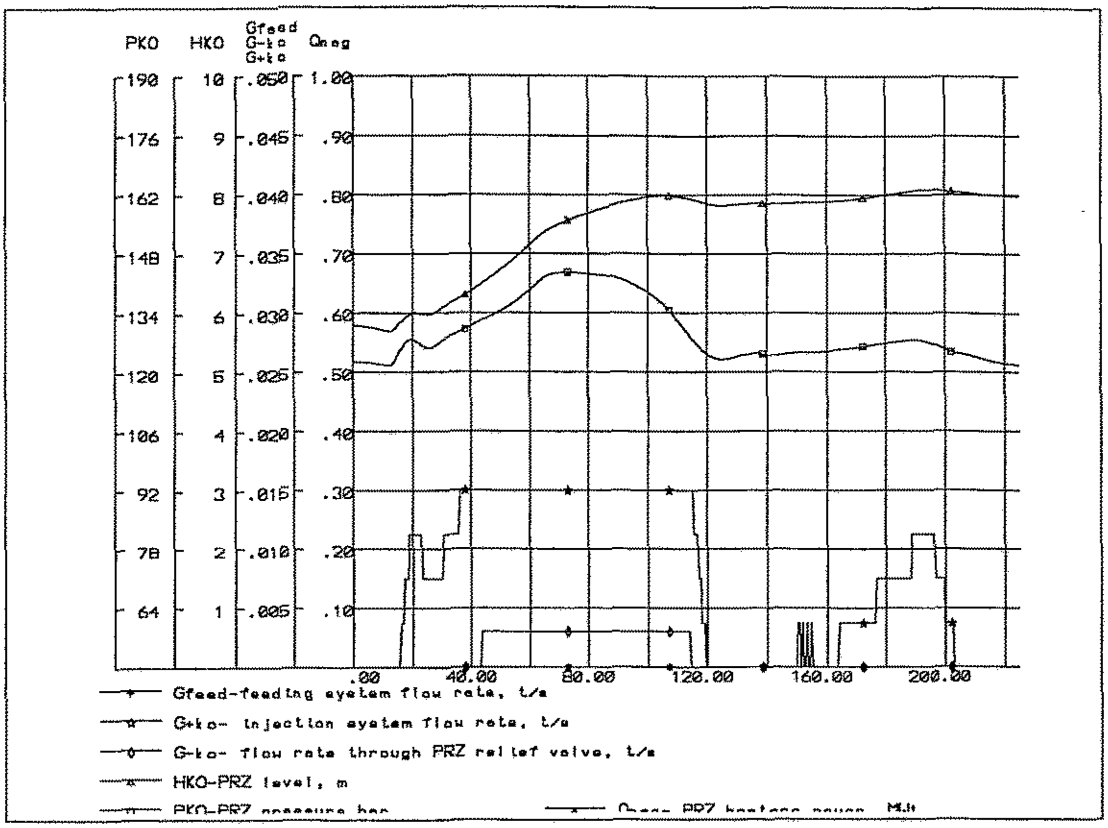

fig 22.

Primary circuit parameters.

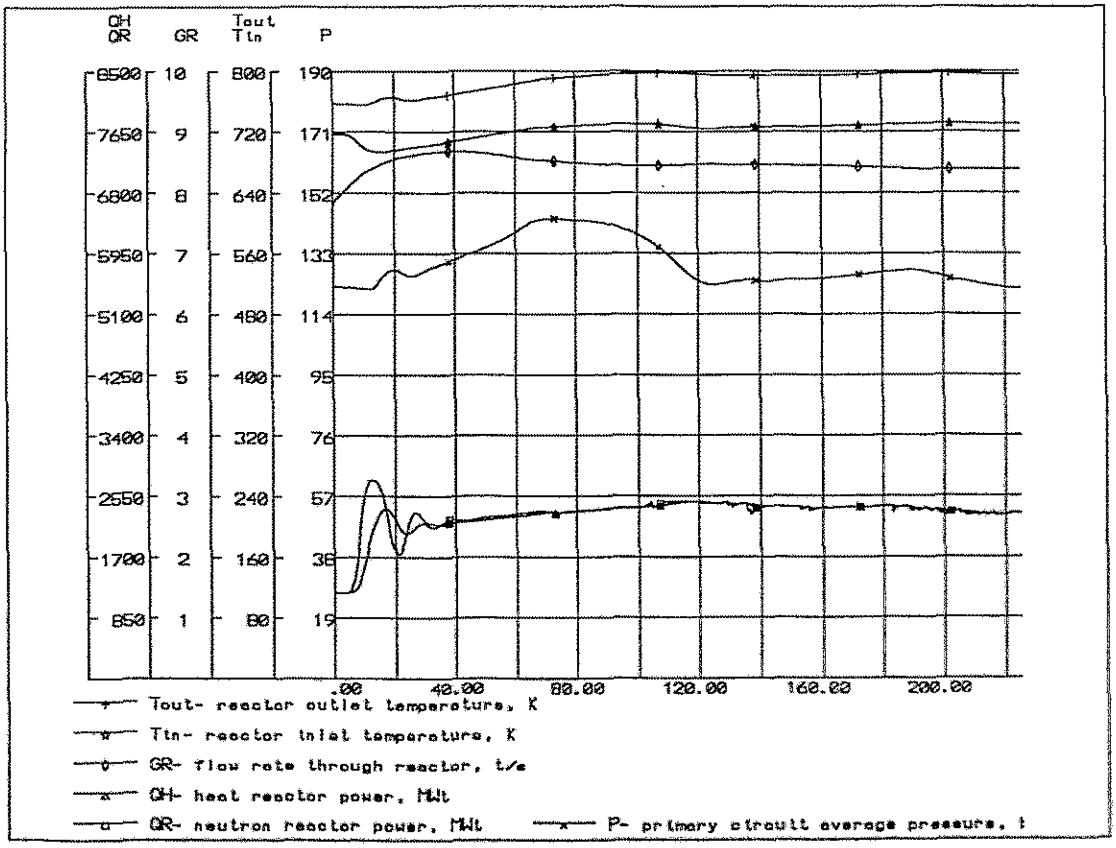

fig 23.

VVER-440. Transient name: 1 of 6 loops connection (v46_4).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg.

Core parameters

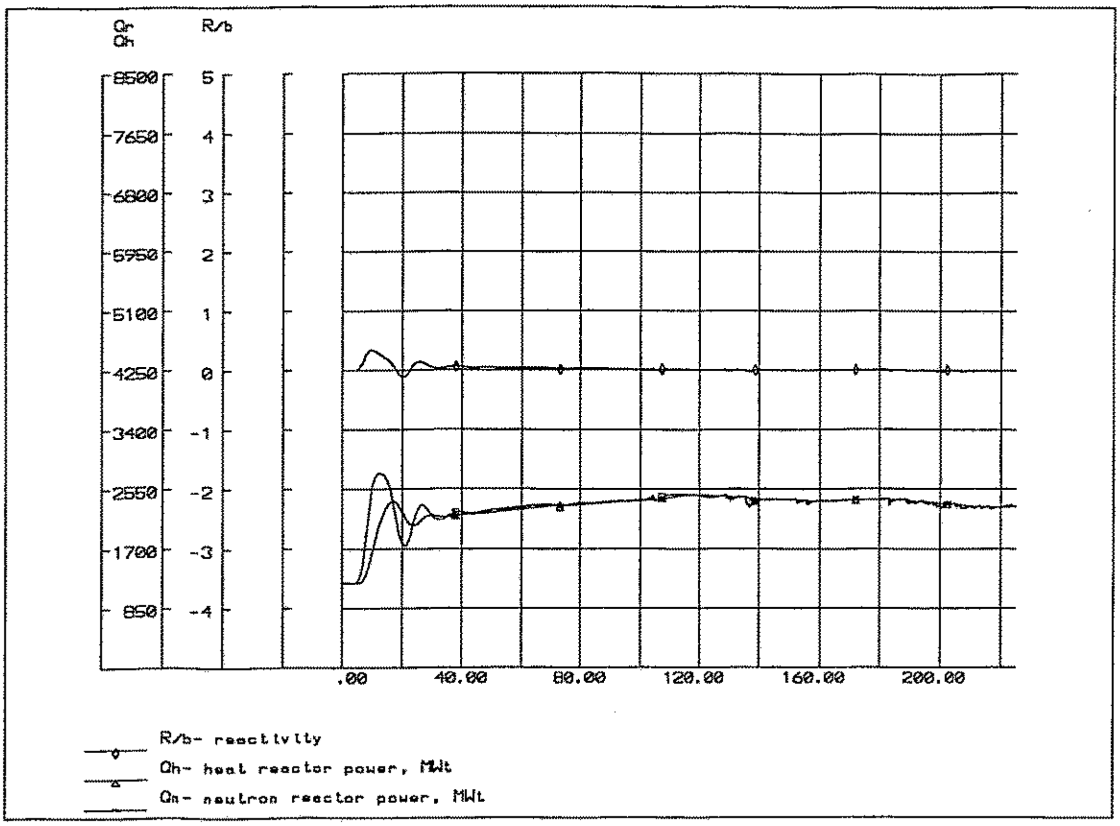

fig 24.

Secondary side.

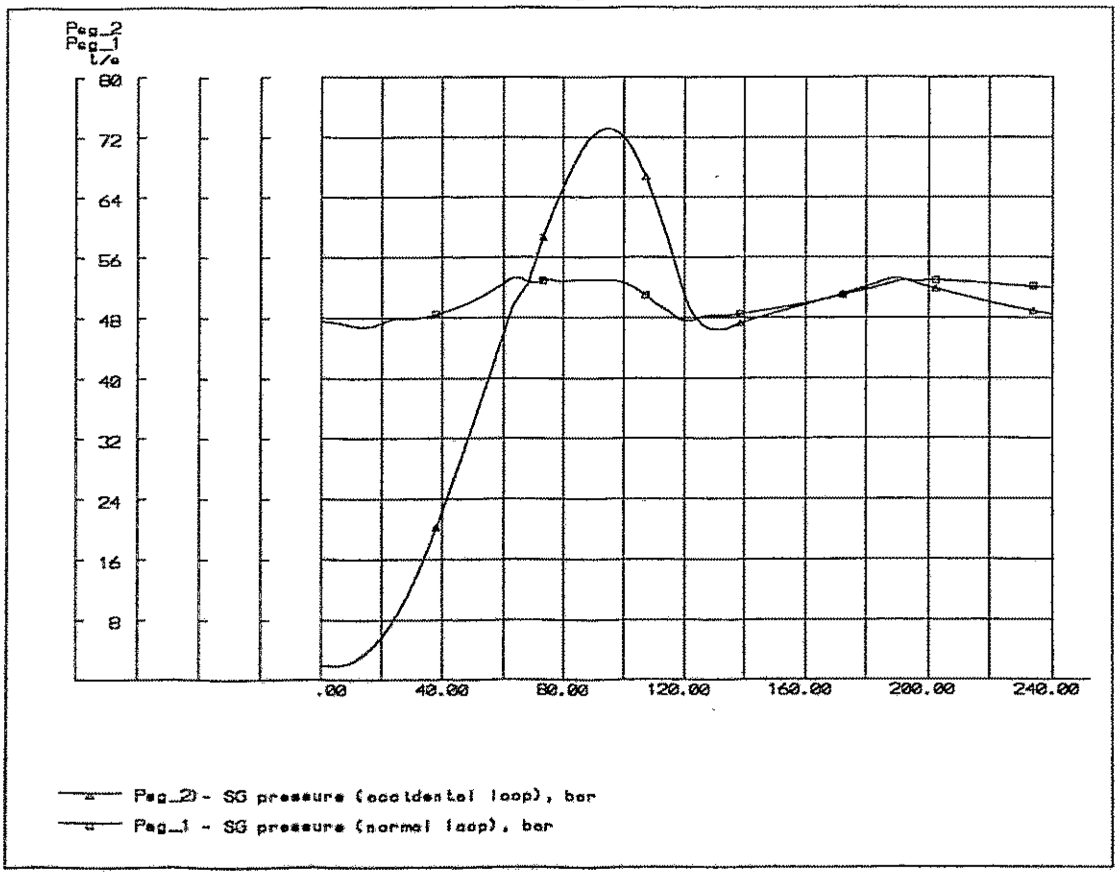

fig 25.

VVER-440. Transient name: 1 of 6 loops connection (v46_4).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0g/kg.

Fuel temperature distribution (hot channel)

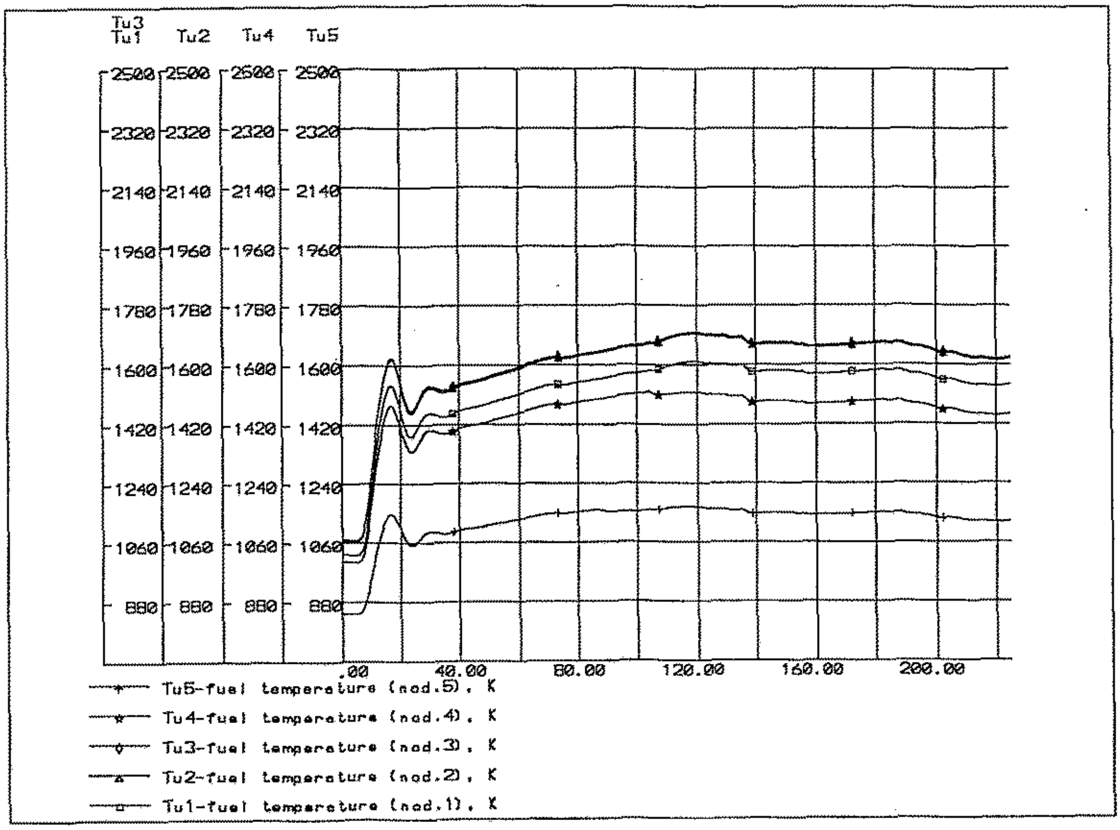

fig 26.

Coolant enthalpy distribution (hot channel)

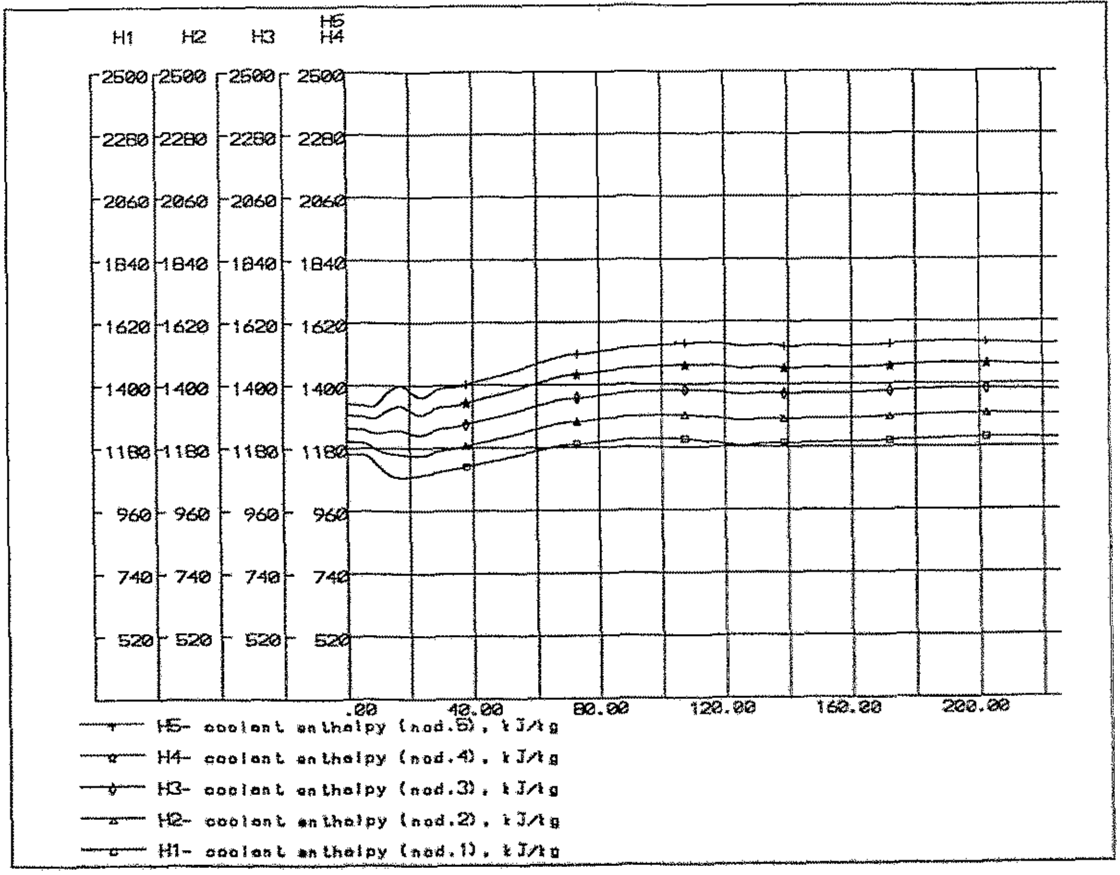

fig 27.

VVER-440. Transient name: 1 of 6 loops connection (v46_5).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (no mixing)

Pressurizer parameters

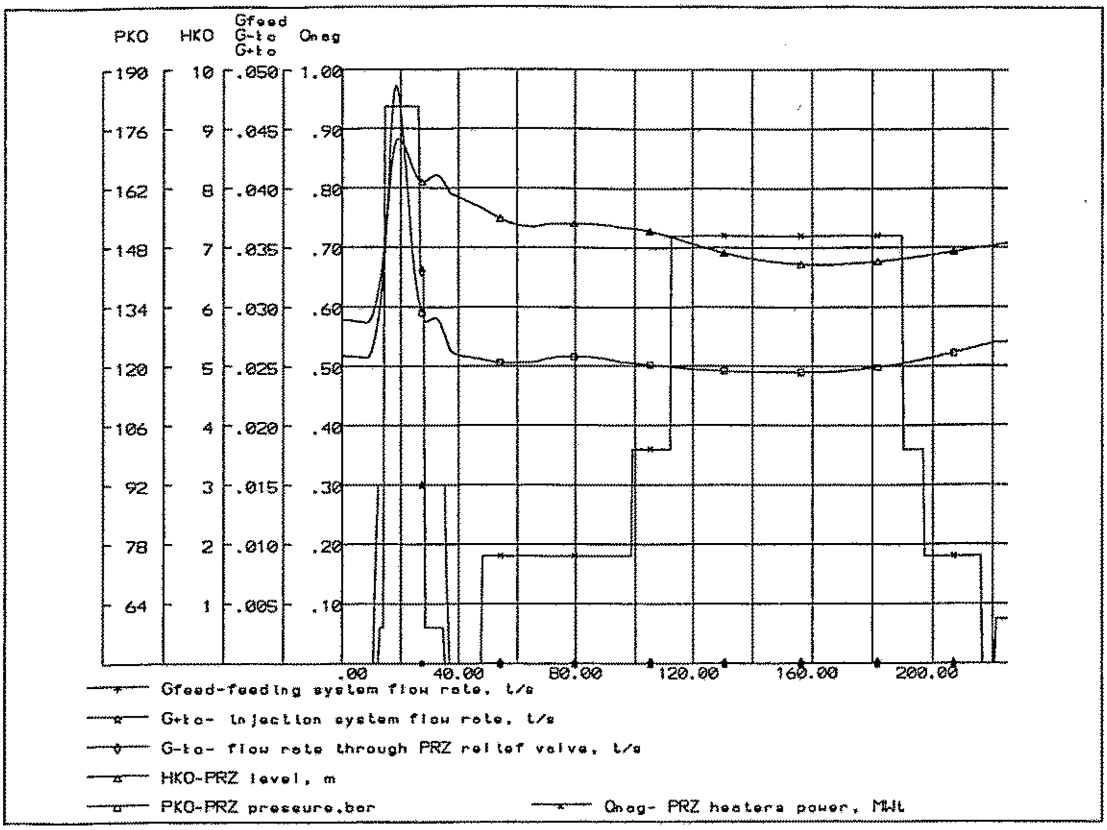

fig 28.

Primary circuit parameters.

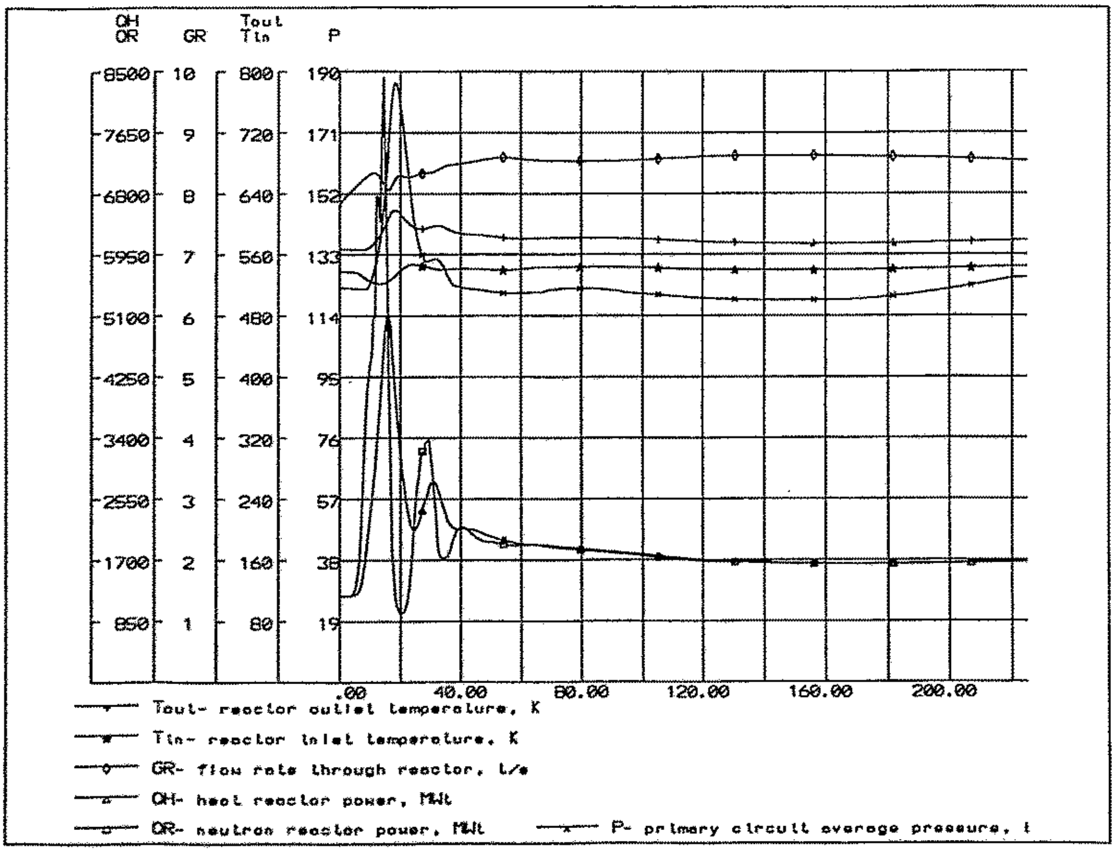

fig 29.

VVER-440. Transient name: 1 of 6 loops connection (v46_5).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (no mixing).

Core parameters

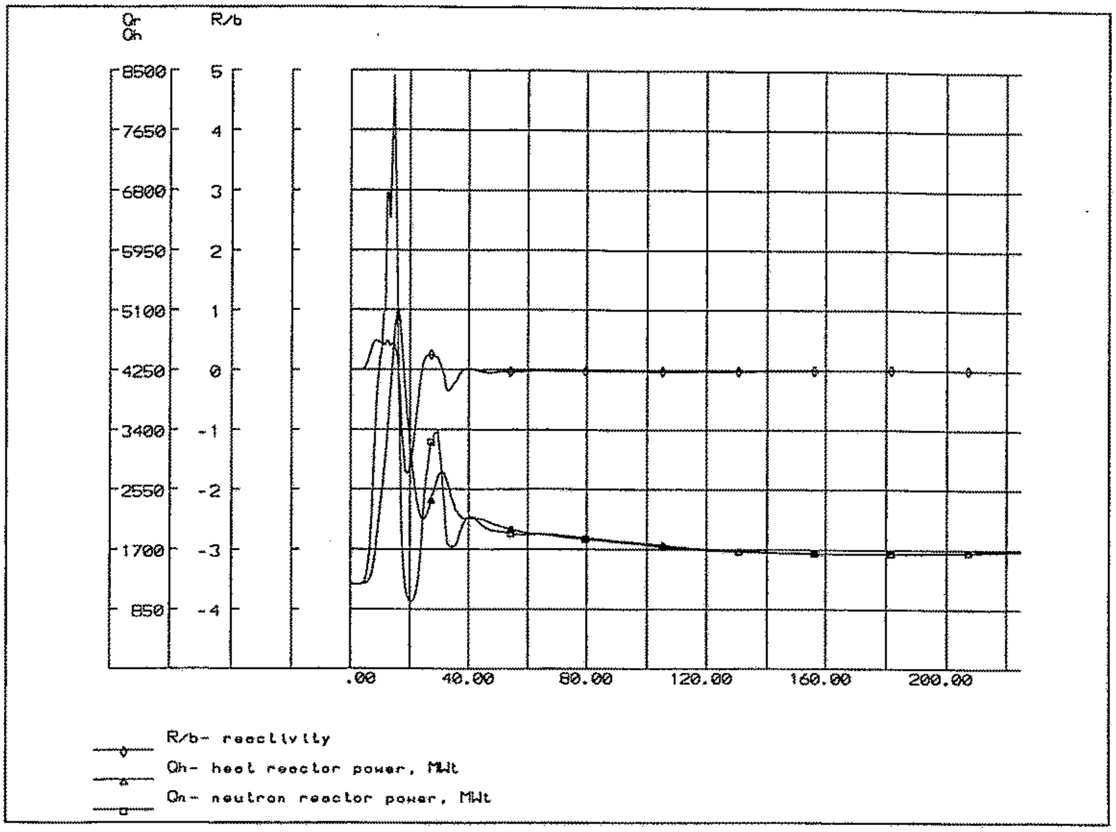

fig 30.

Boron concentrations

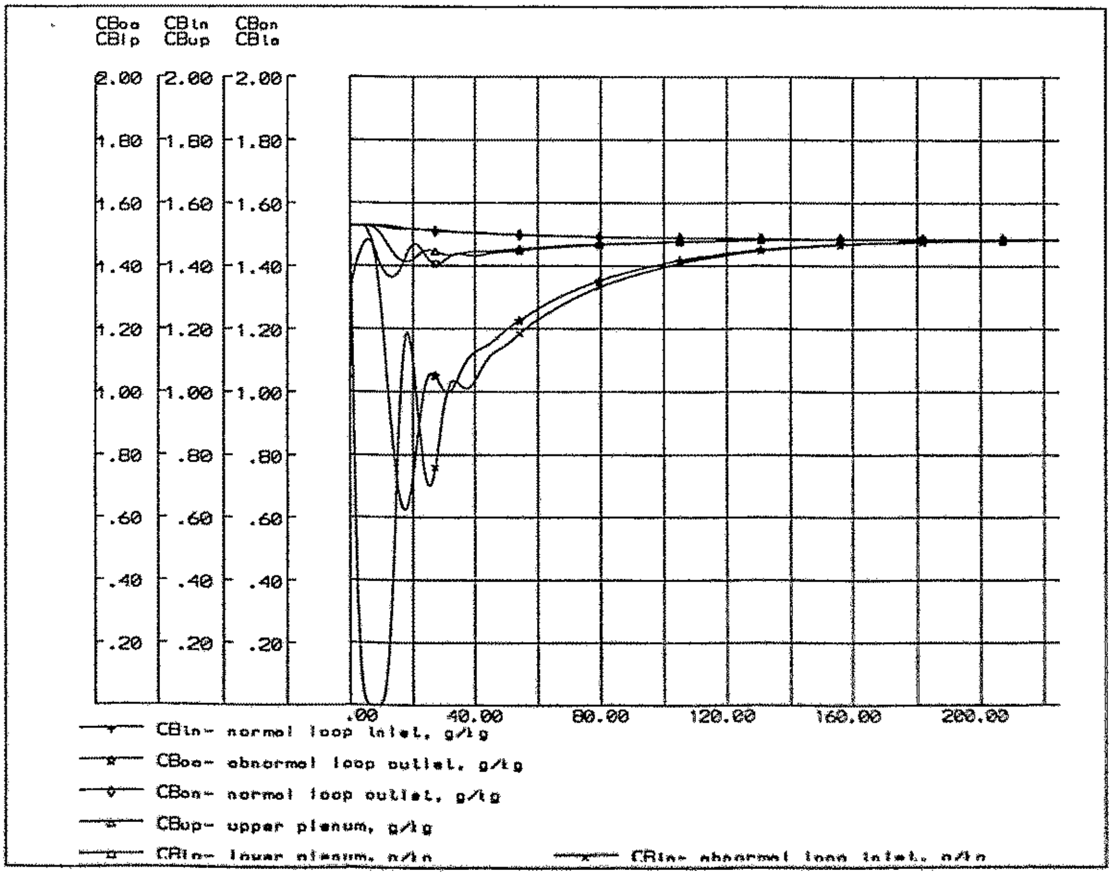

fig 31.

VVER-440. Transient name: 1 of 6 loops connection (v46_5).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0g/kg, (no mixing).

Fuel temperature distribution (hot channel)

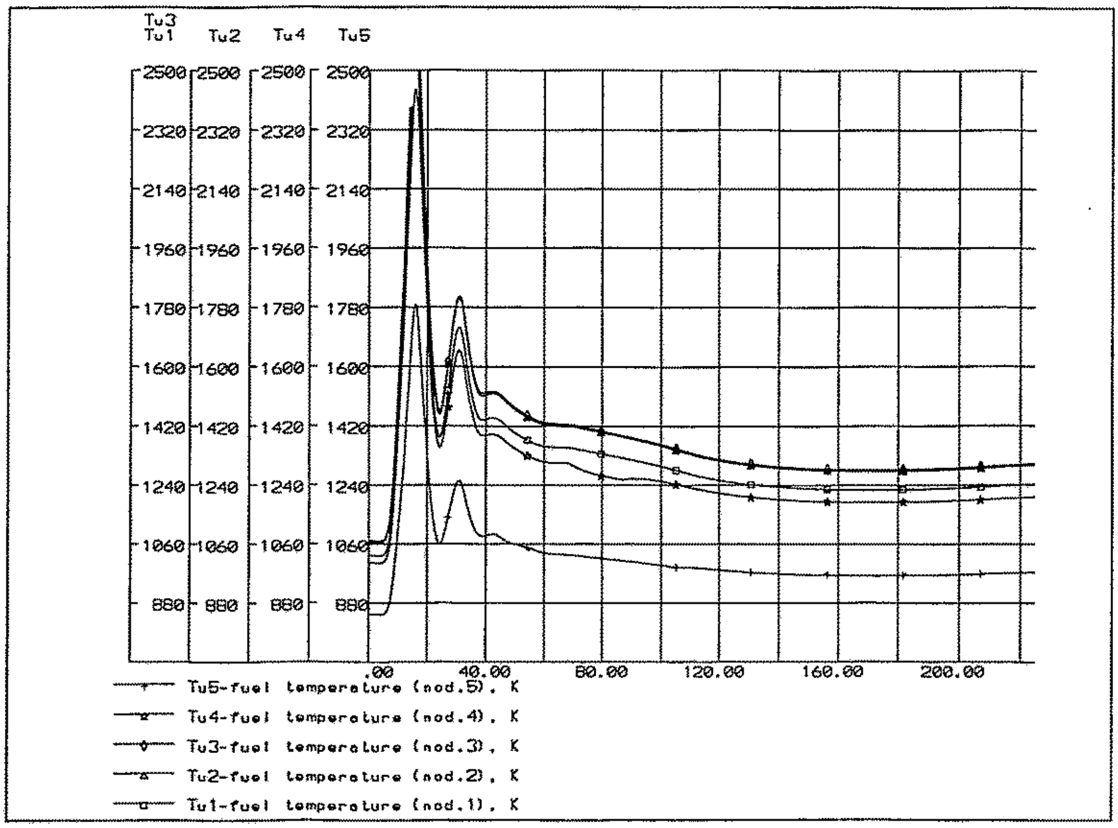

fig 32.

Coolant enthalpy distribution (hot channel)

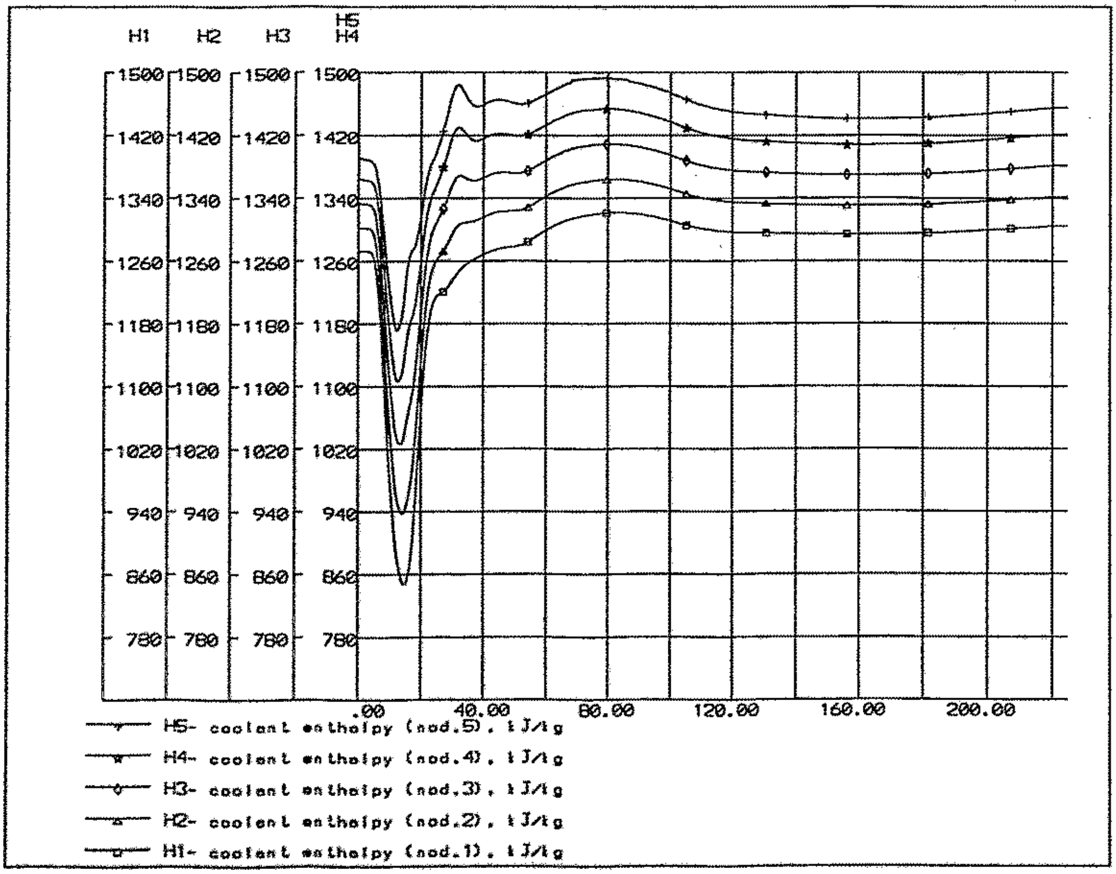

fig 33.

VVER-440. Transient name: 1 of 6 loops connection (v46_6).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg ("real" mixing).

Pressurizer parameters

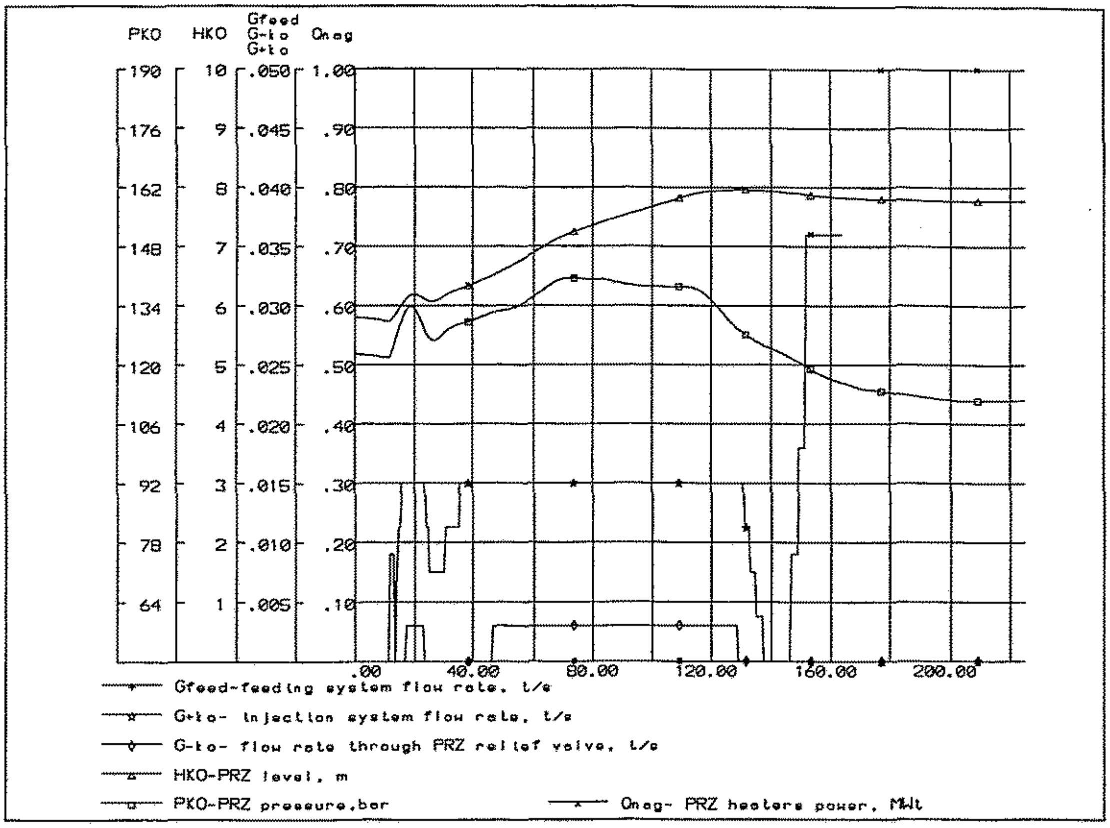

fig 34.

Primary circuit parameters.

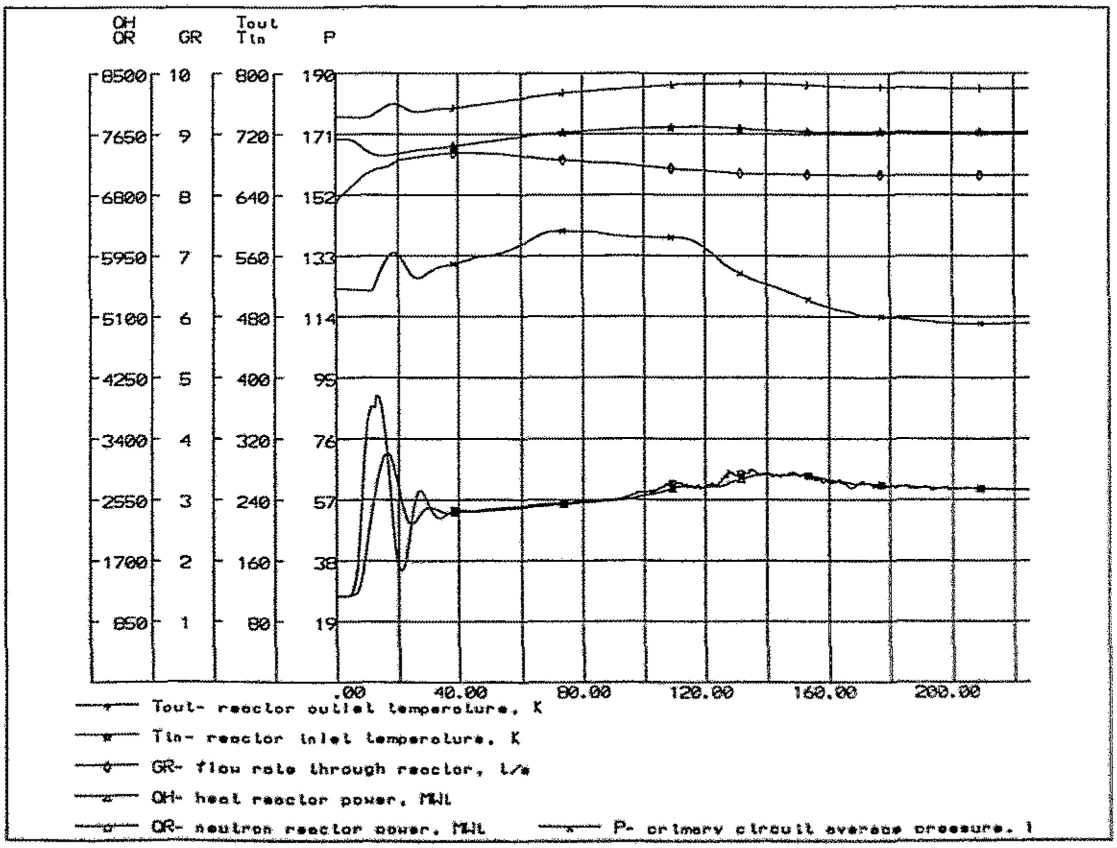

fig 35.

VVER-440. Transient name: 1 of 6 loops connection (v46_6).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg ("real" mixing).

Core parameters

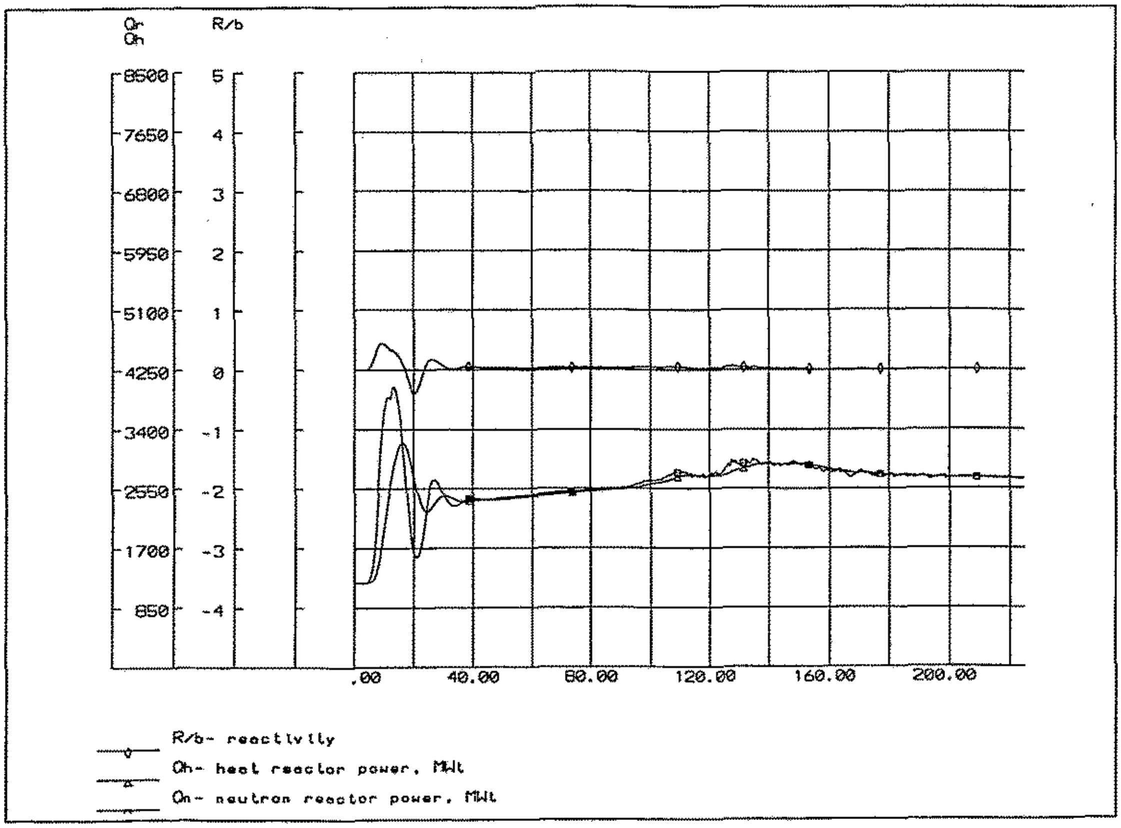

fig 36.

Secondary side

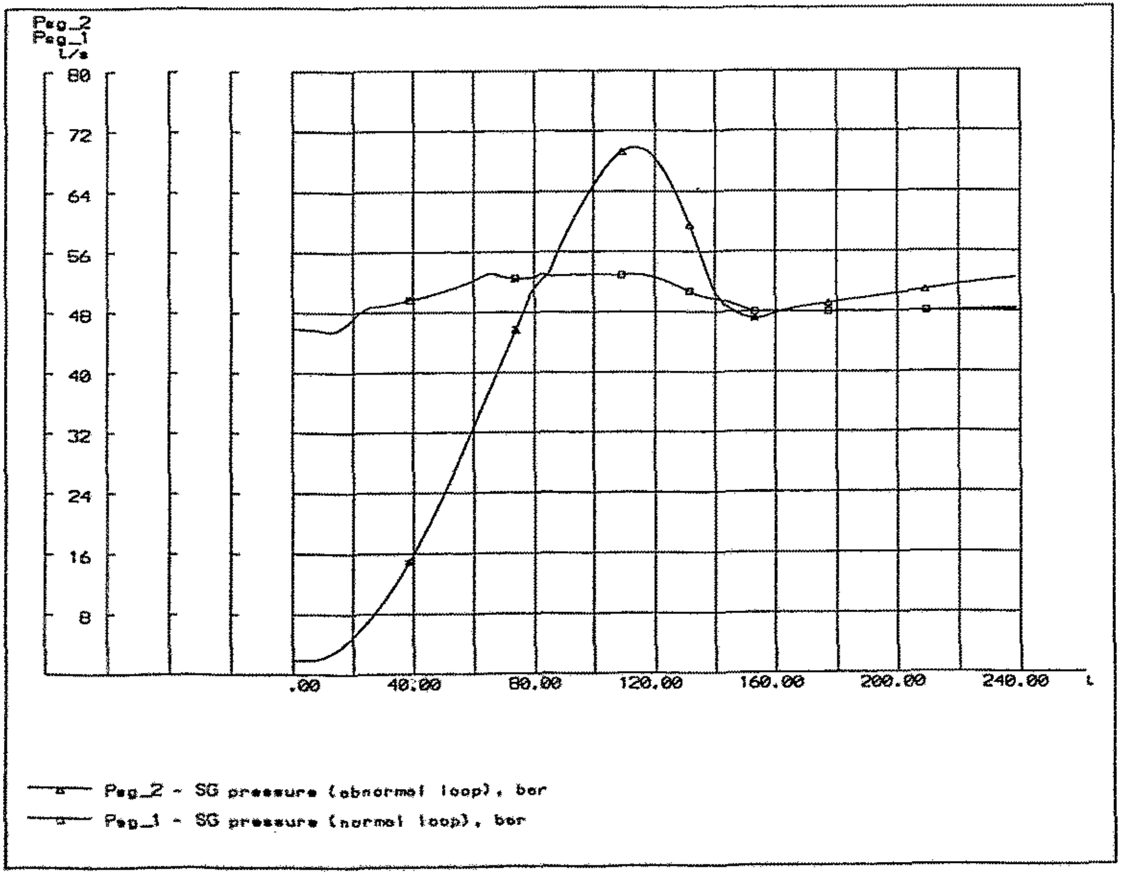

fig 37.

VVER-440. Transient name: 1 of 6 loops connection (v46_6).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0g/kg ("real" mixing).

Fuel temperature distribution (hot channel)

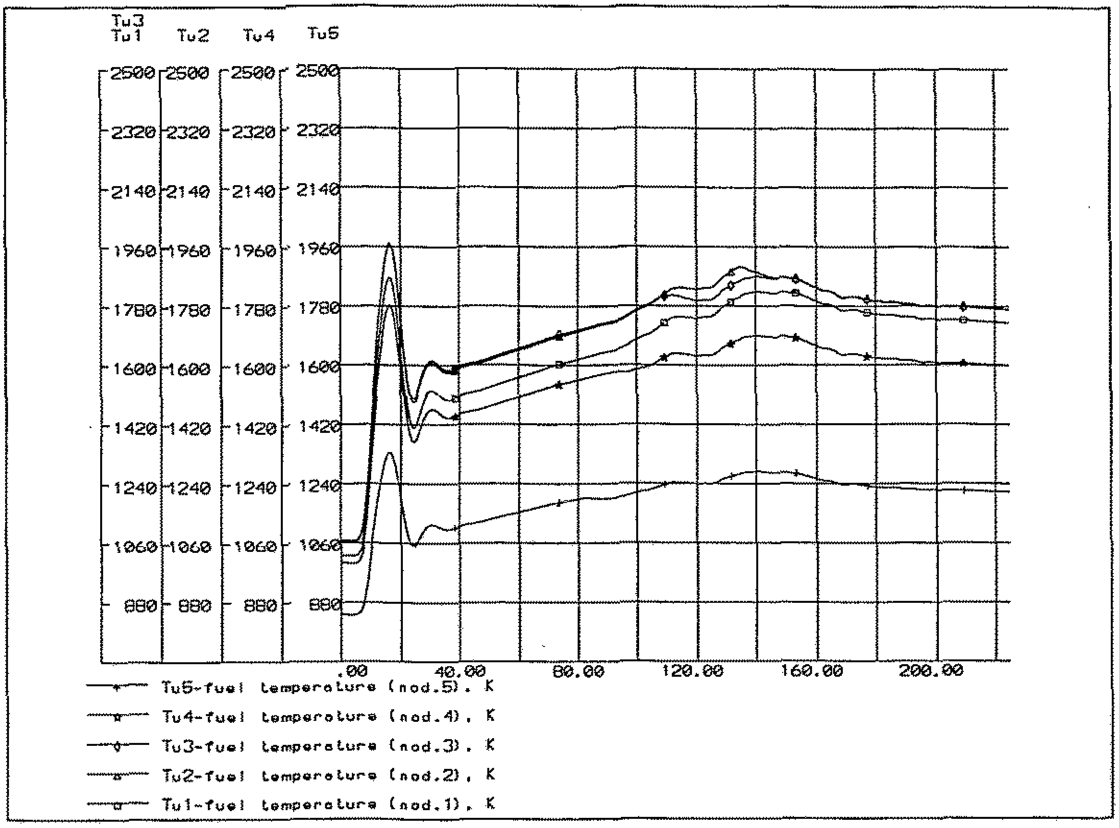

fig 38.

Coolant enthalpy distribution (hot channel)

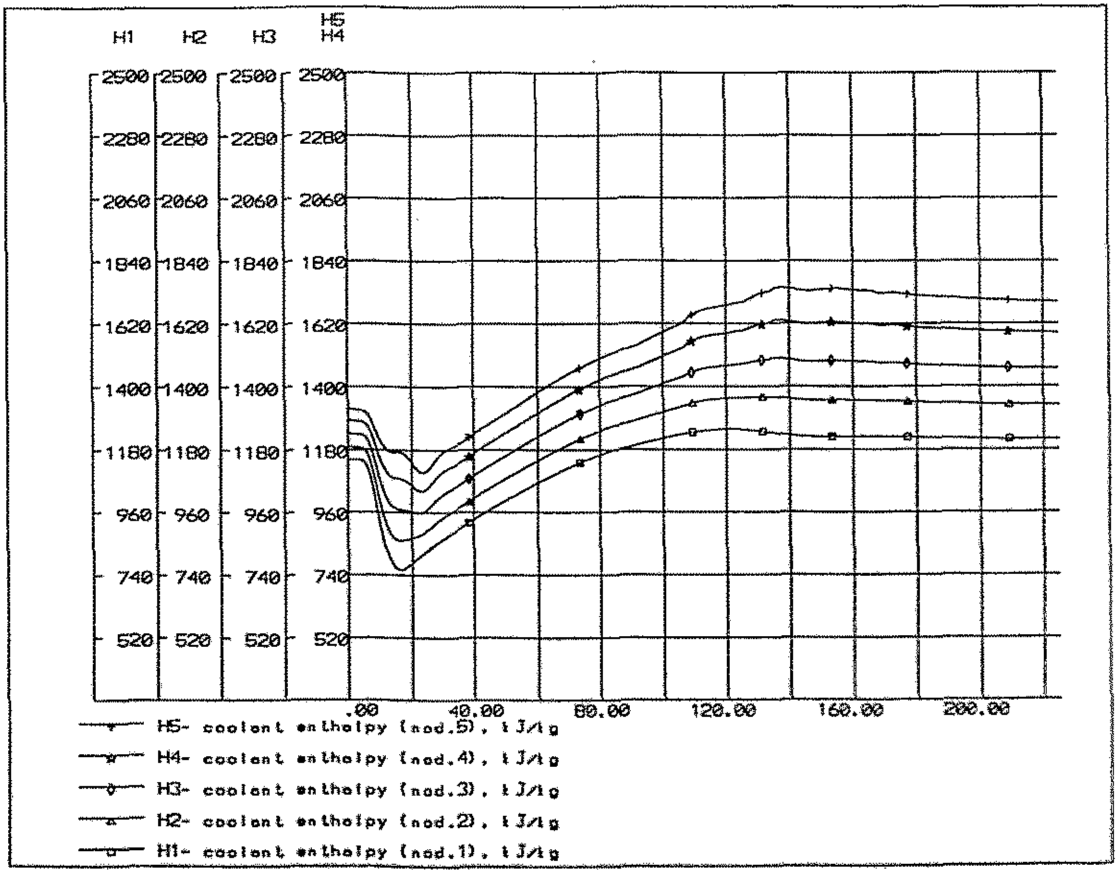

fig 39.

VVER-440. Transient name: 1 of 6 loops connection (v46_7).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (ideal mixing)

Pressurizer parameters

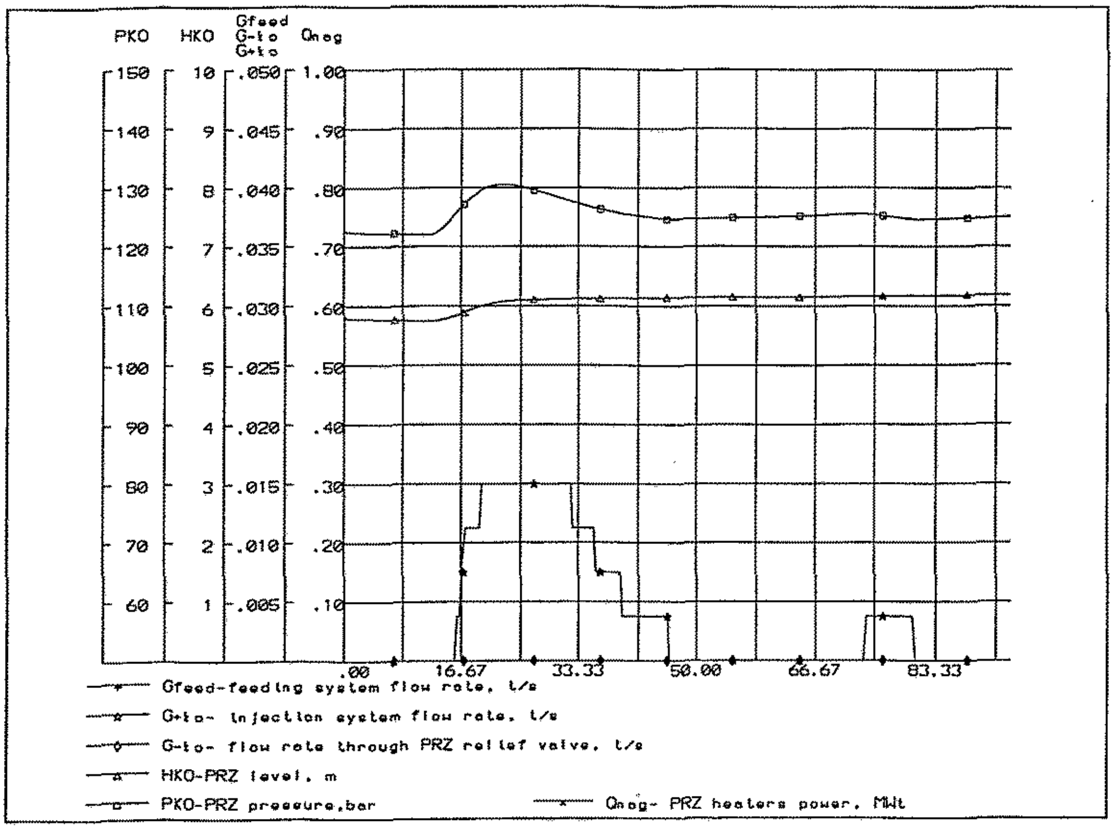

fig 40.

Primary circuit parameters.

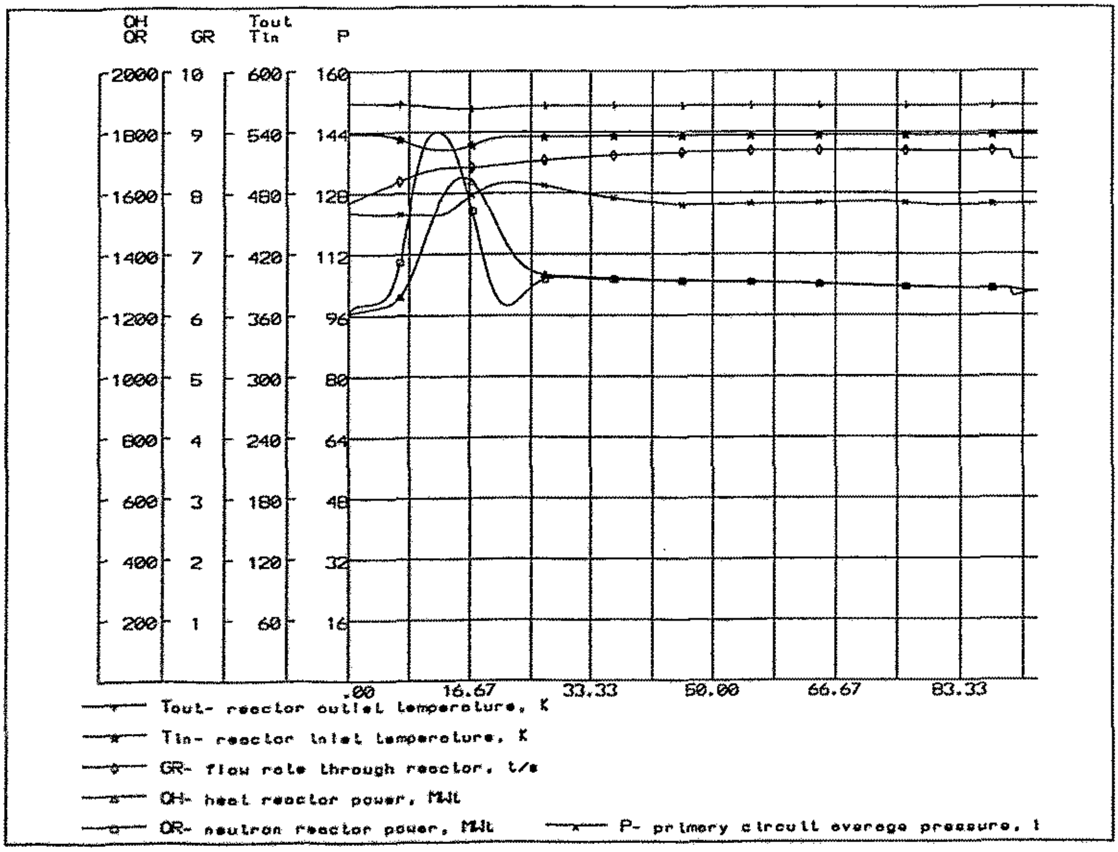

fig 41.

VVER-440. Transient name: 1 of 6 loops connection (v46_7).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (ideal mixing).

Core parameters

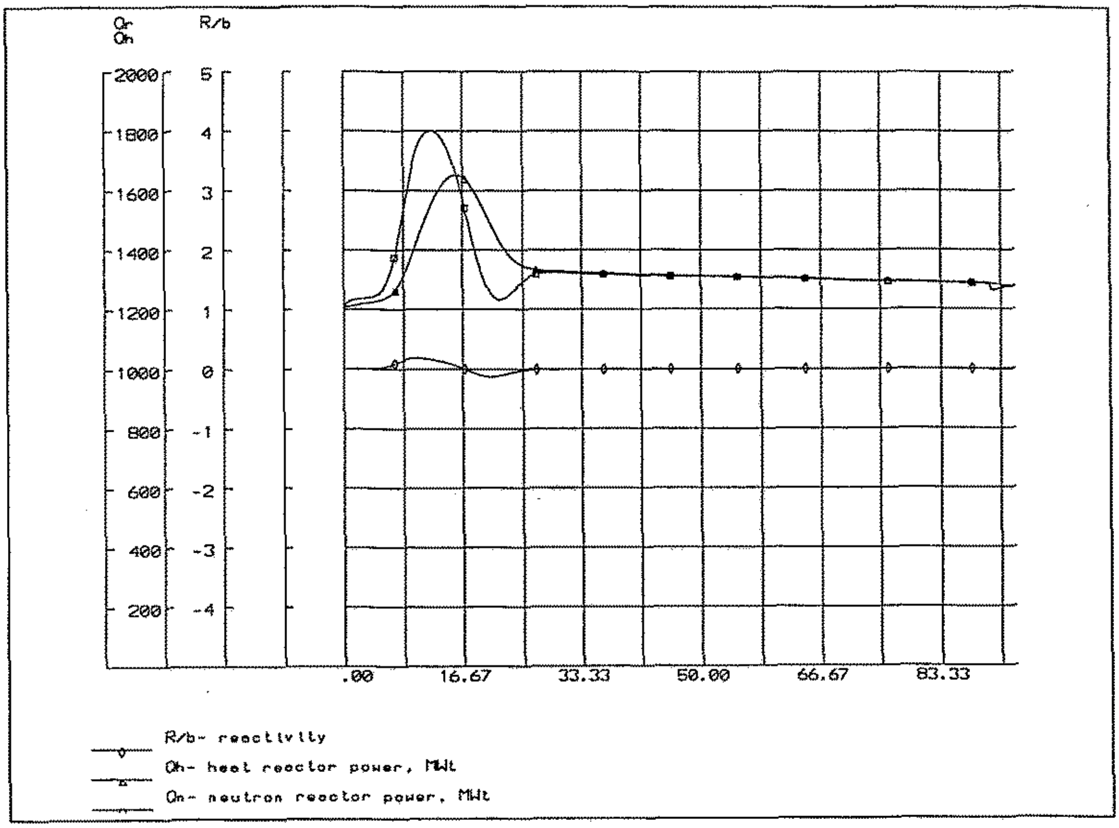

fig 42.

Fuel temperature distribution (hot channel)

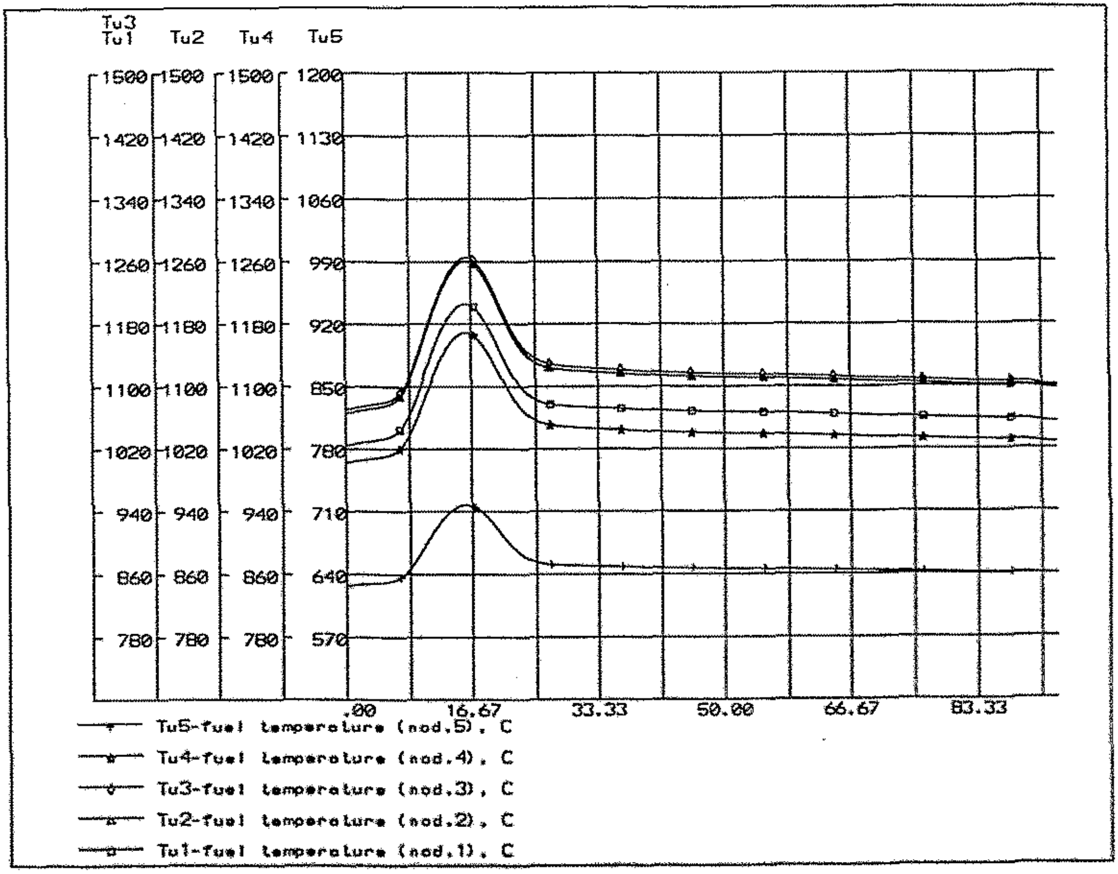

fig 43.

VVER-440. Transient name: 1 of 6 loops connection (v46_8).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (no mixing)

Pressurizer parameters

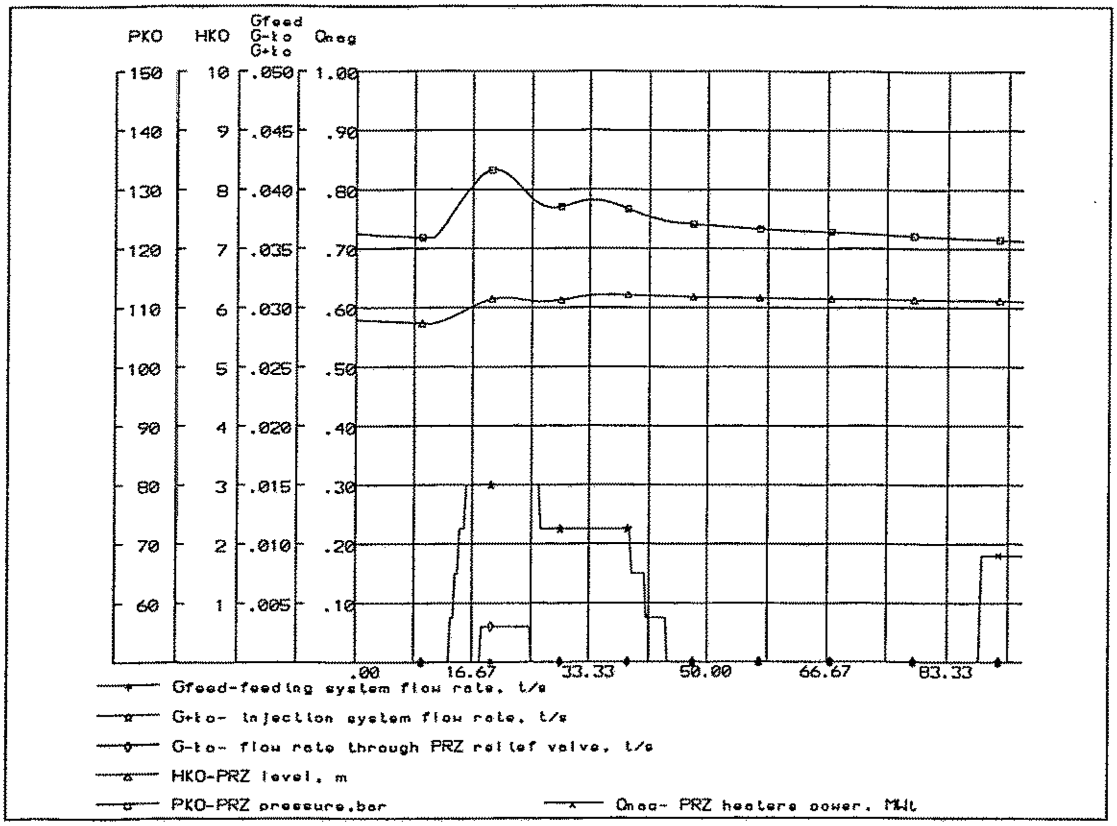

fig 44.

Primary circuit parameters.

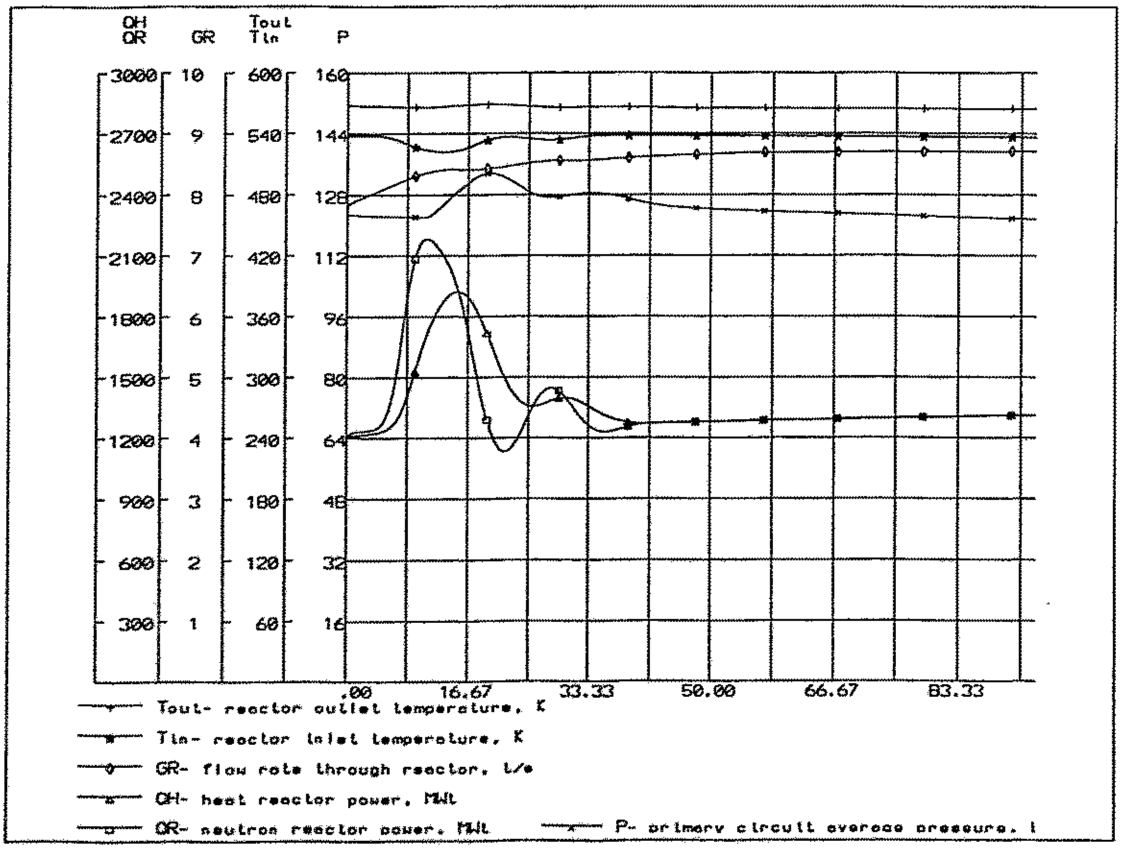

fig 45.

VVER-440. Transient name: 1 of 6 loops connection (v46_8).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (no mixing).

Core parameters

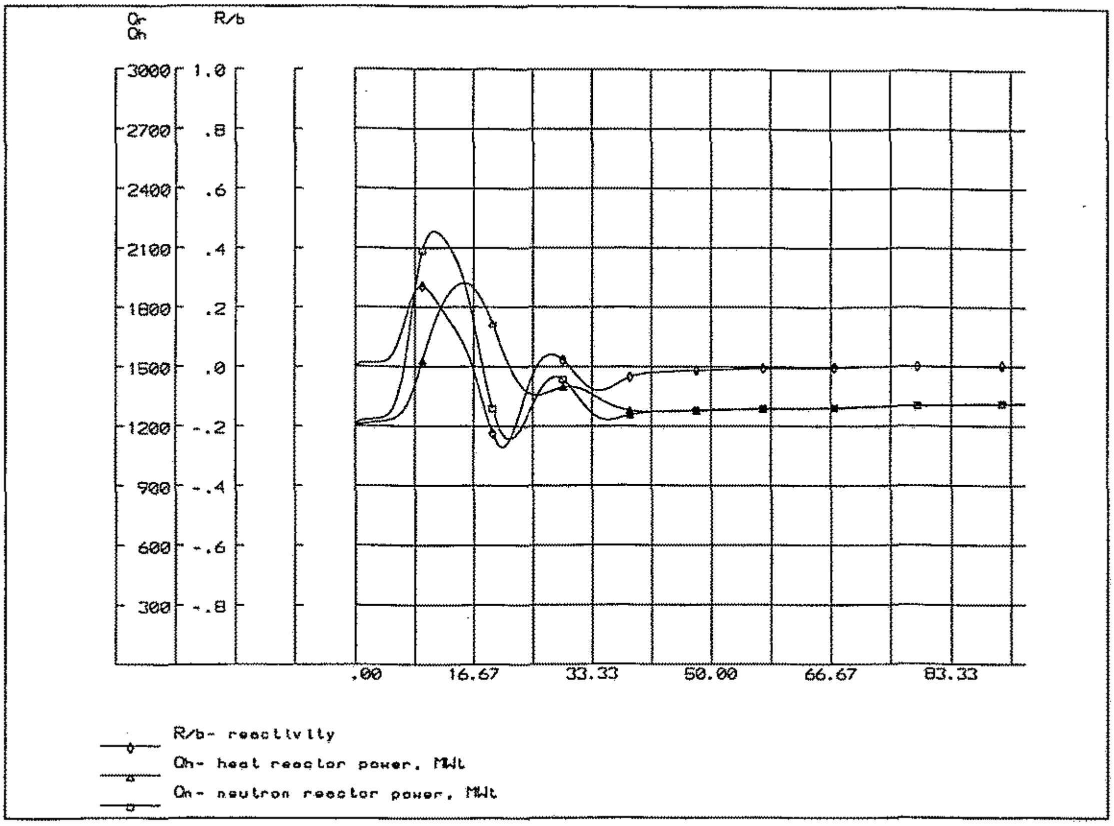

fig 46.

Fuel temperature distribution (hot channel)

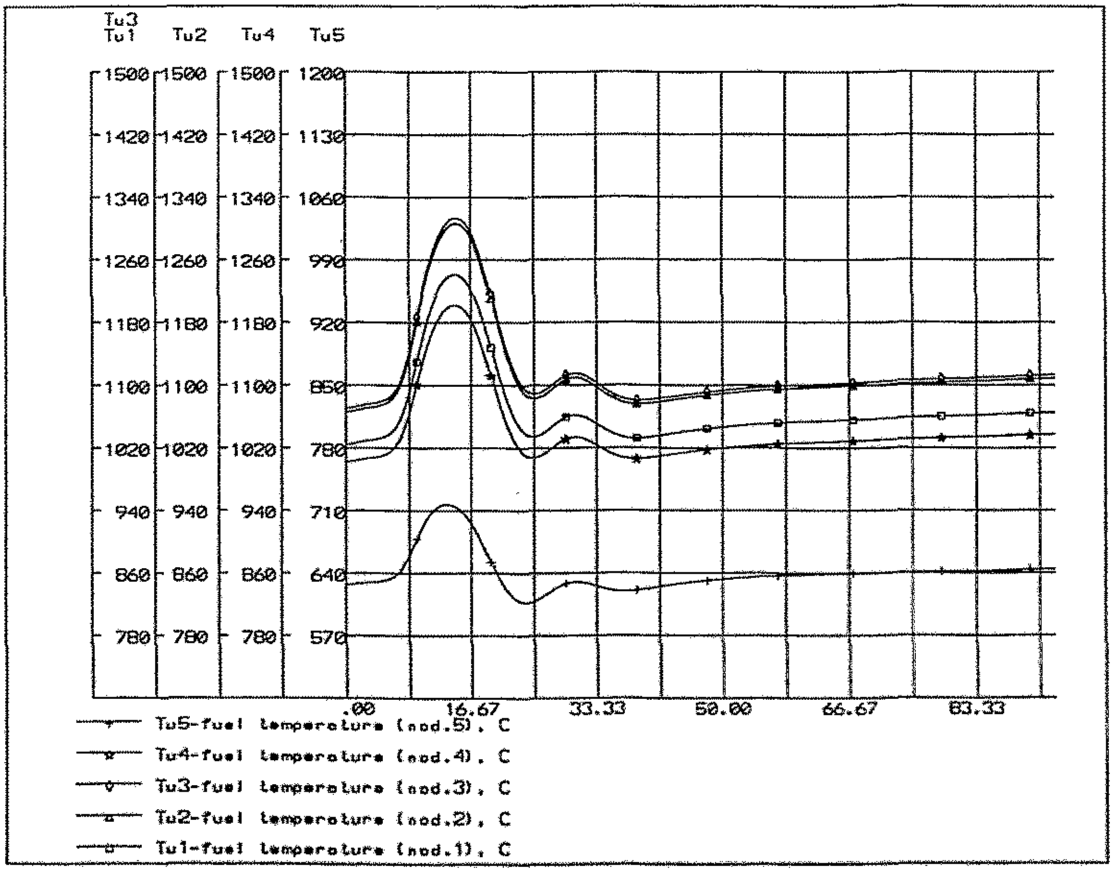

fig 47.

VVER-440. Transient name: 1 of 6 loops connection (v46_9).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. ("real" mixing)

Pressurizer parameters

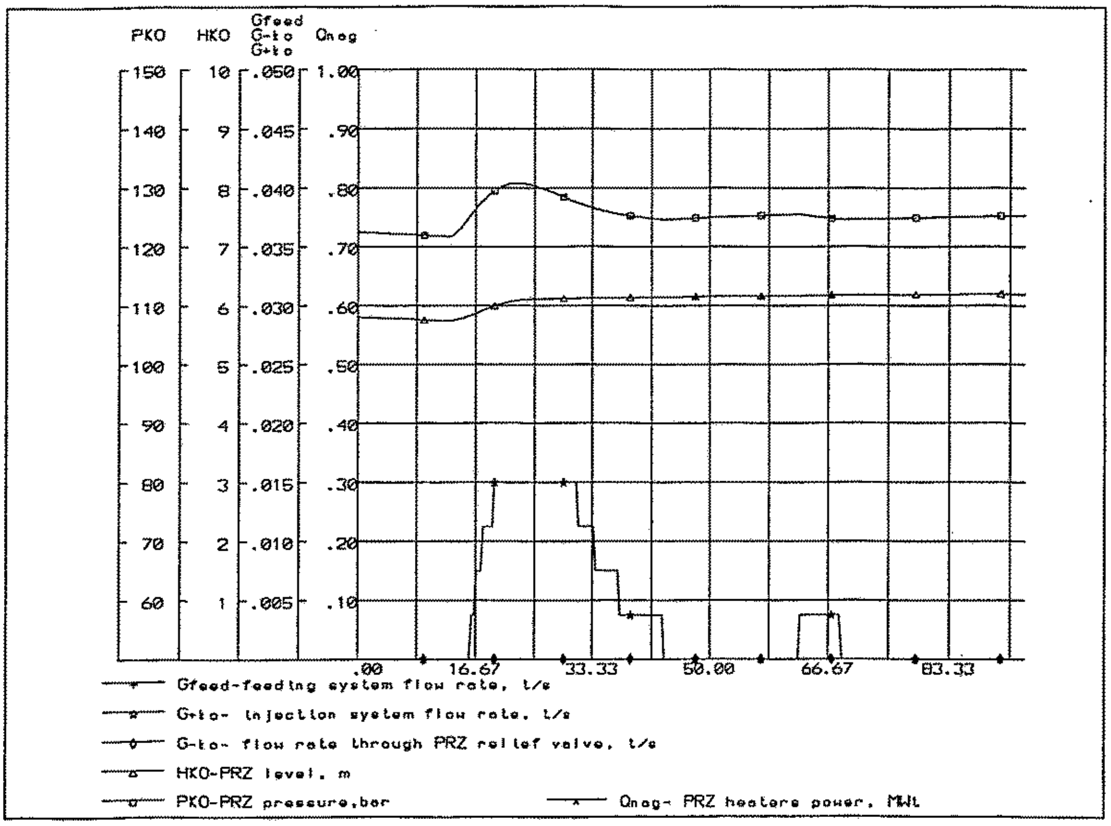

fig 48.

Primary circuit parameters.

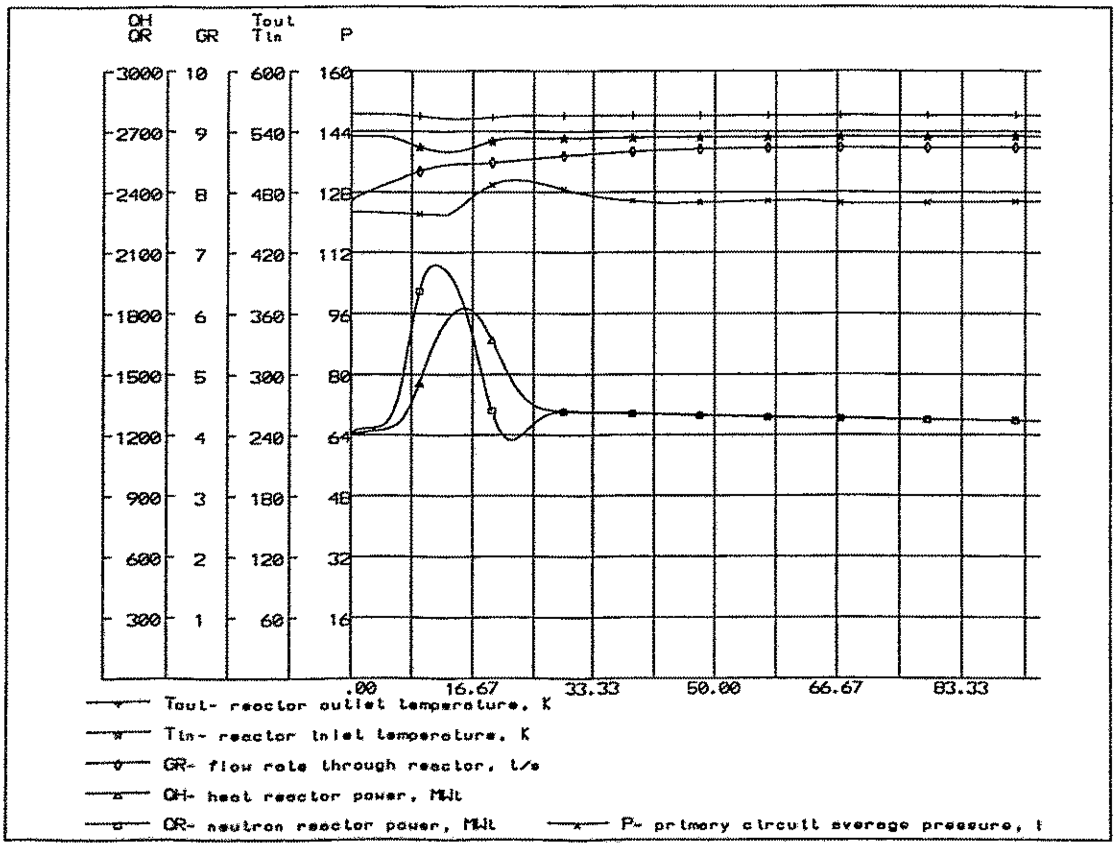

fig 49.

VVER-440. Transient name: 1 of 6 loops connection (v46_9).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, ("real" mixing).

Core parameters

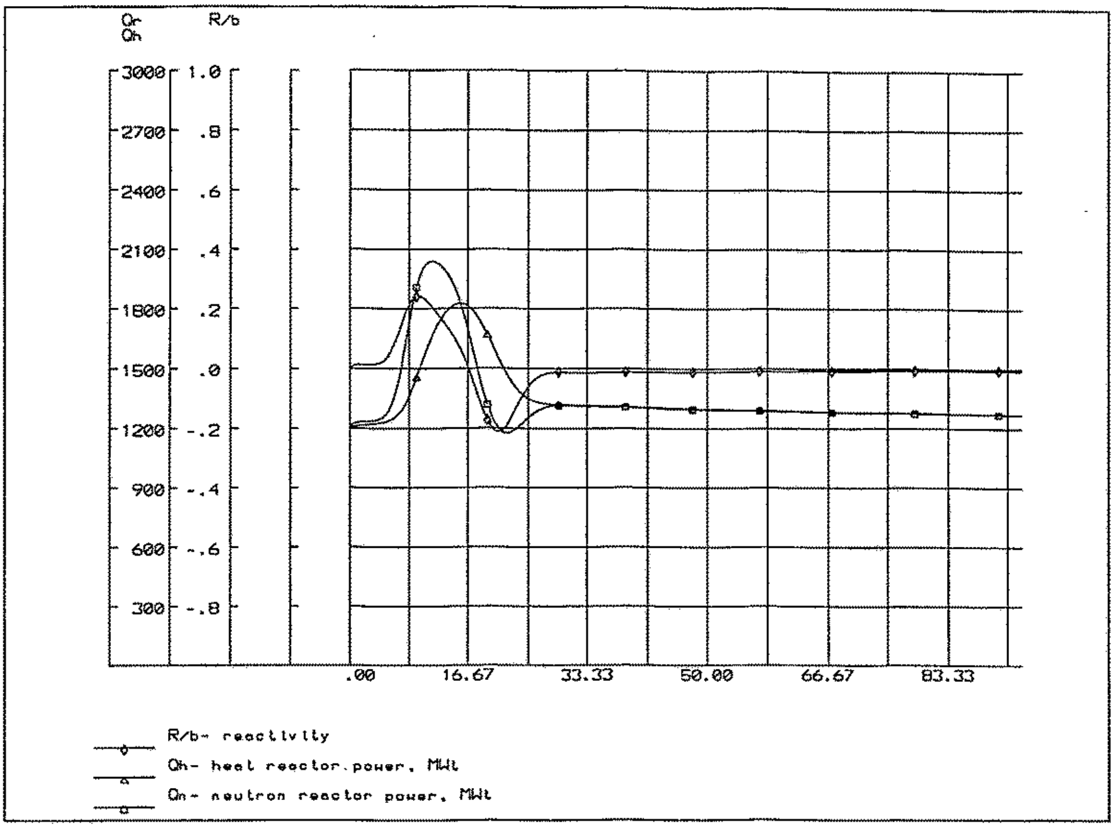

fig 50.

Fuel temperature distribution (hot channel)

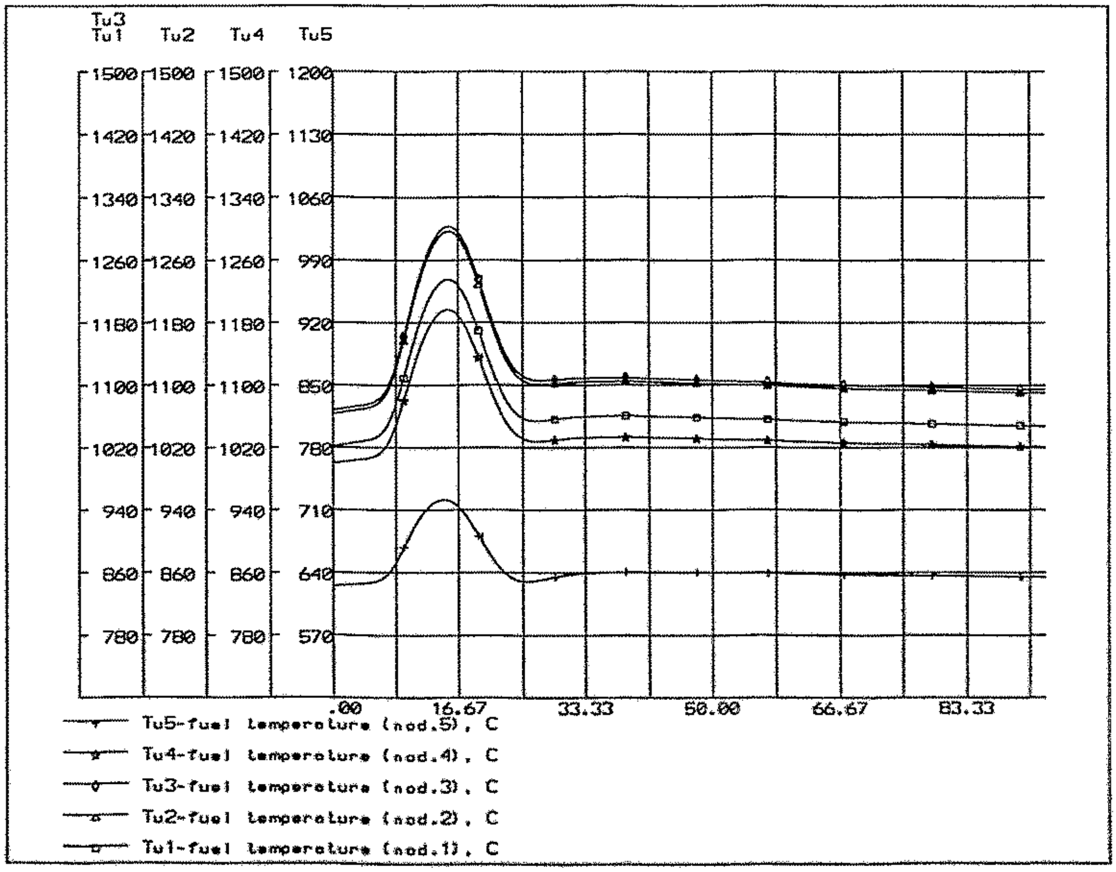

fig 51.

VVER-440. Transient name: 1 of 4 loops connection (v43_1).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (ideal mixing)

Pressurizer parameters

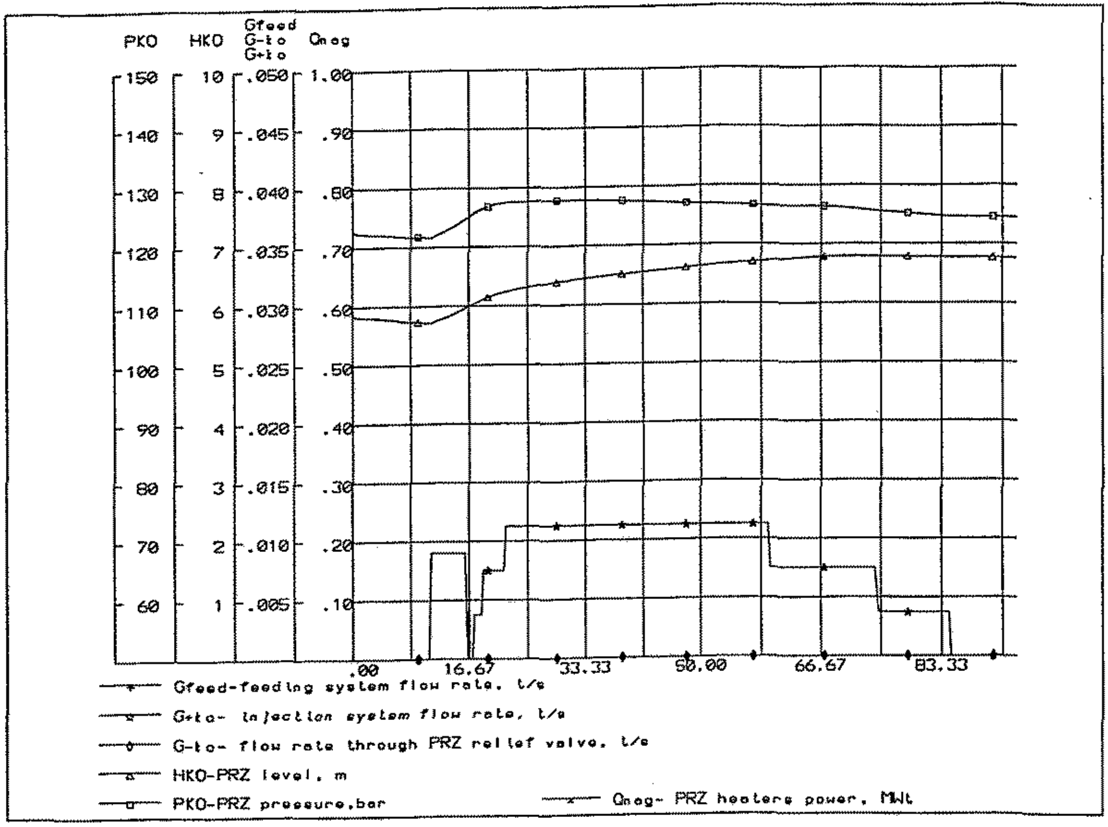

fig 52.

Primary circuit parameters.

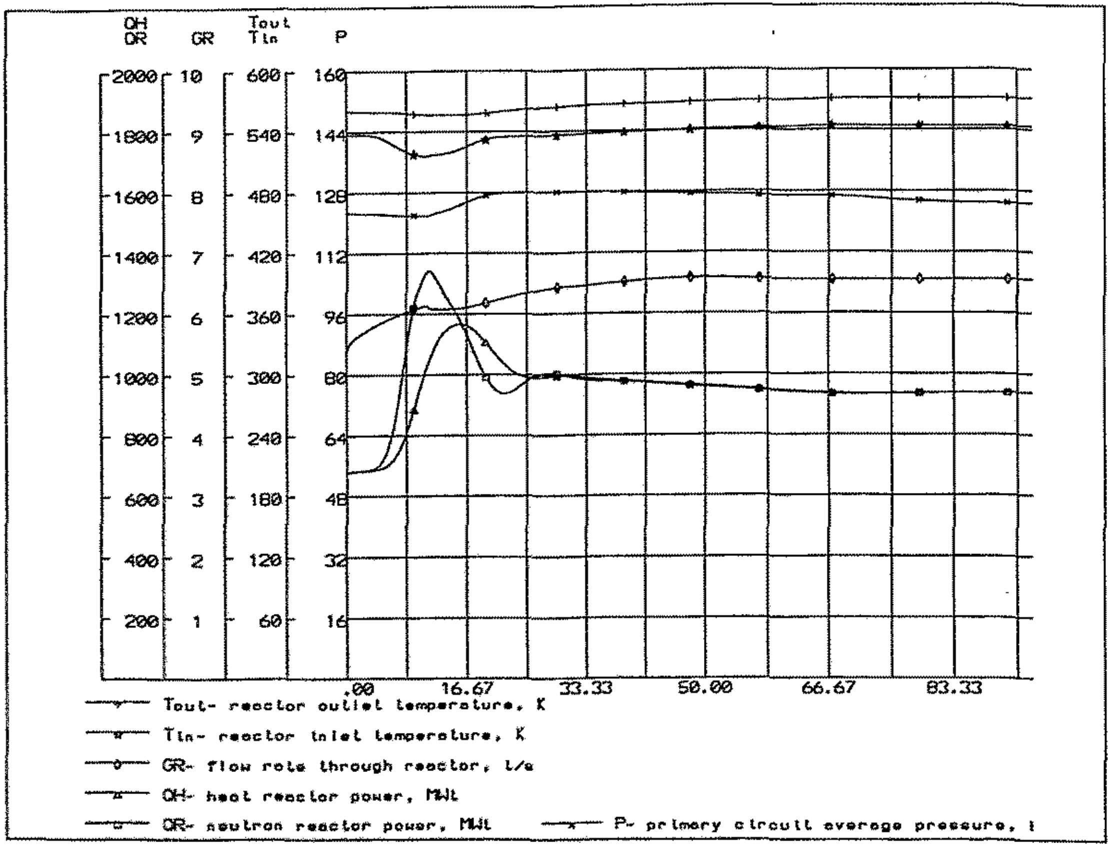

fig 53.

VVER-440. Transient name: 1 of 4 loops connection (v43_1).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (ideal mixing).

Core parameters

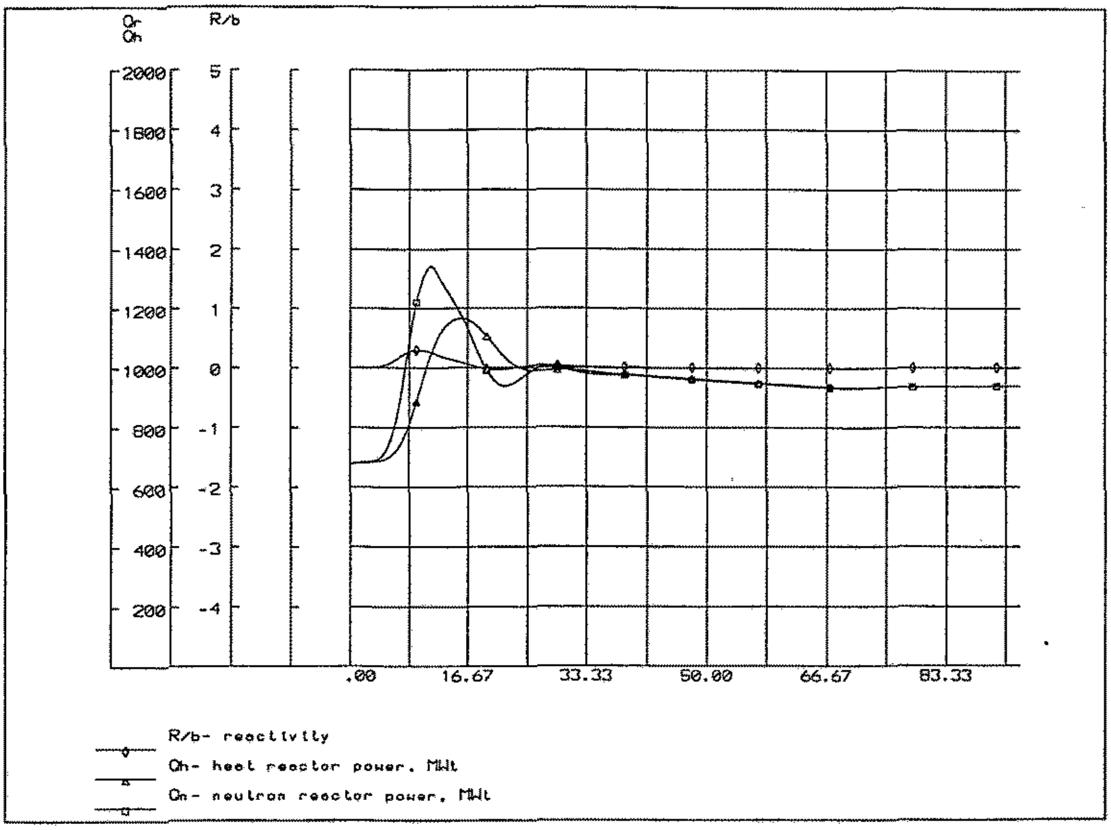

fig 54

Fuel temperature distribution (hot channel).

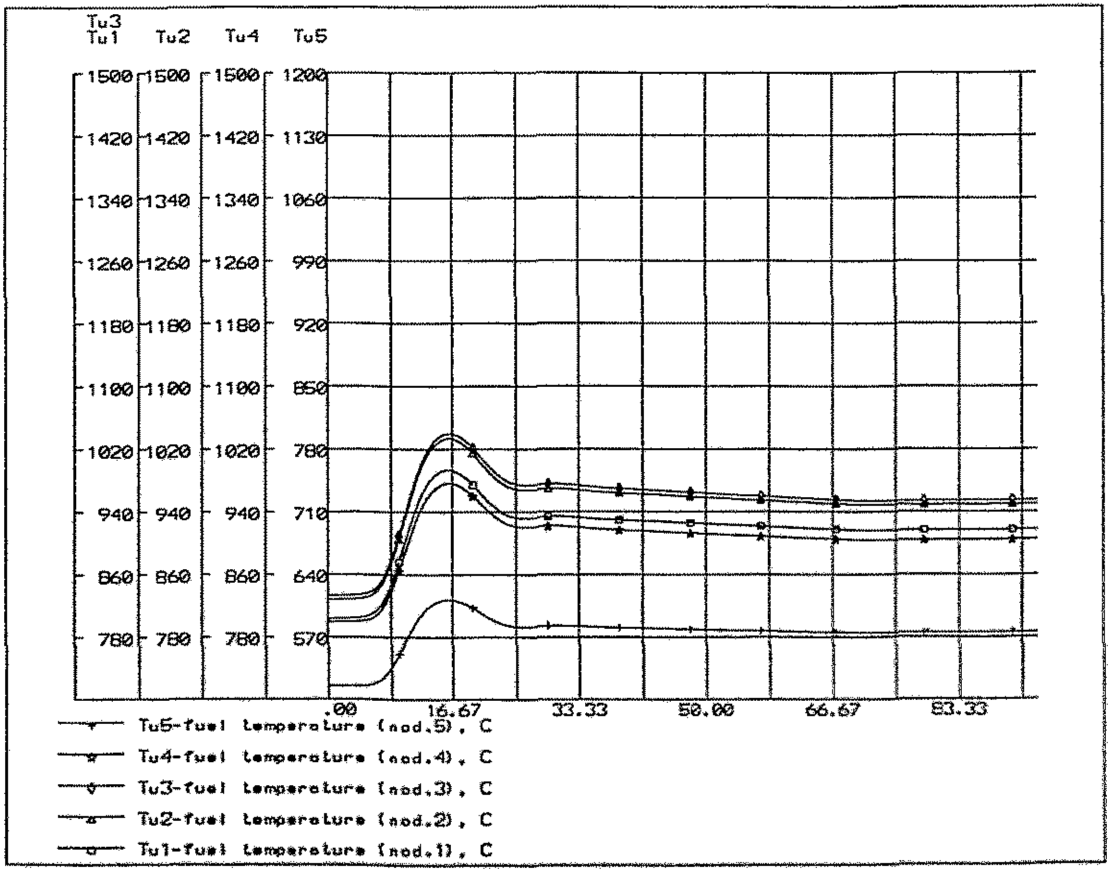

fig 55.

VVER-440. Transient name: 1 of 4 loops connection (v43_2).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (no mixing)

Pressurizer parameters

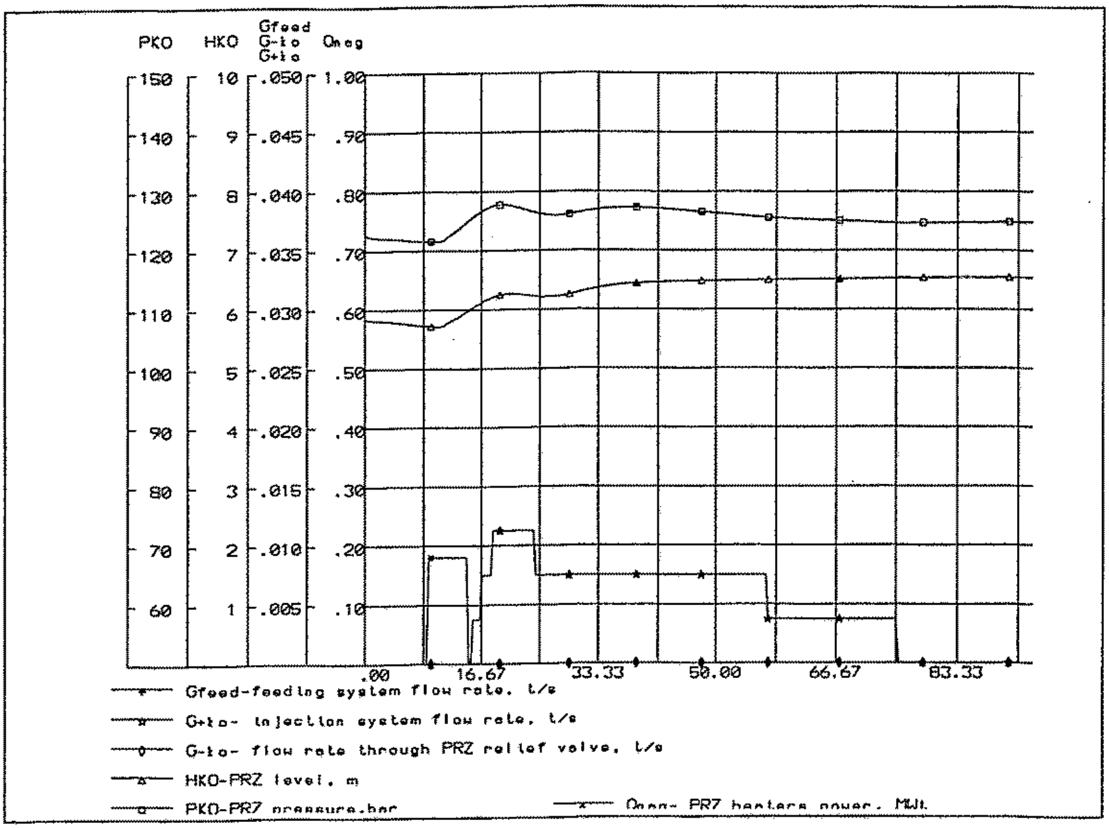

fig 56.

Primary circuit parameters.

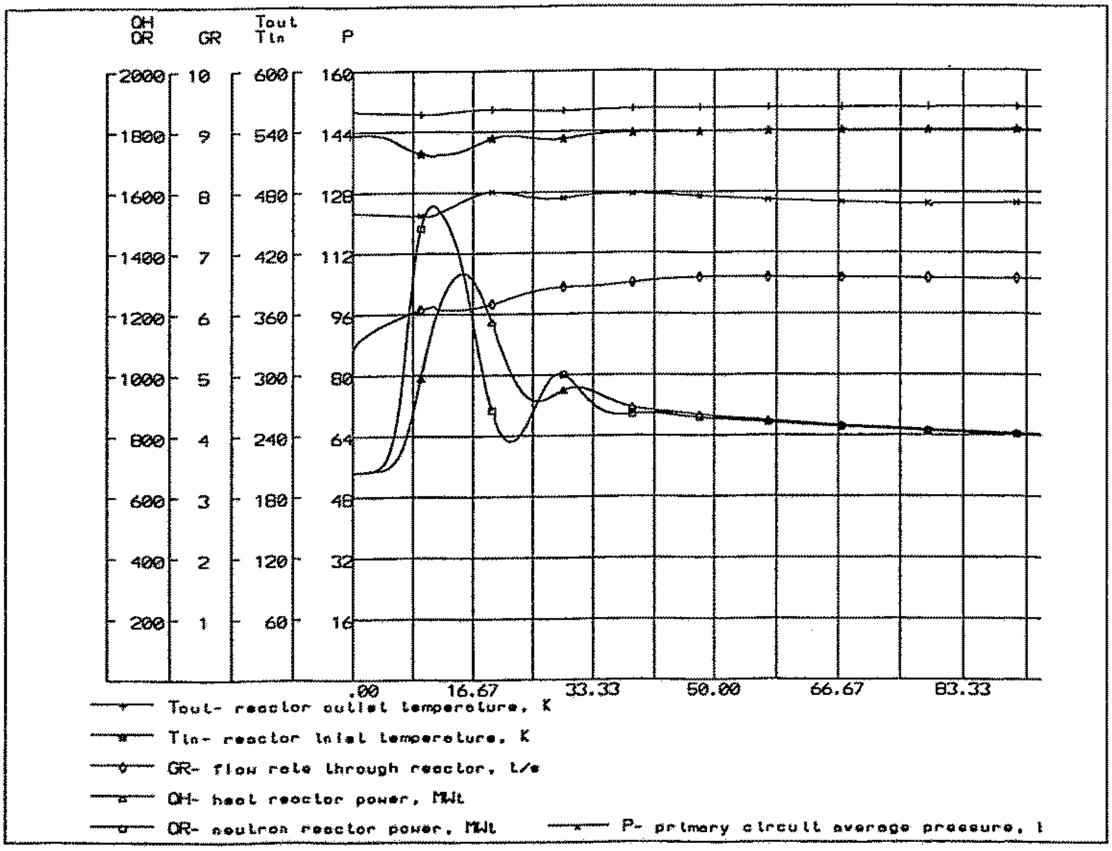

fig 57.

VVER-440. Transient name: 1 of 4 loops connection (v43_2).

Initial power level - 1210 MWt, at the beginning of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (no mixing).

Core parameters

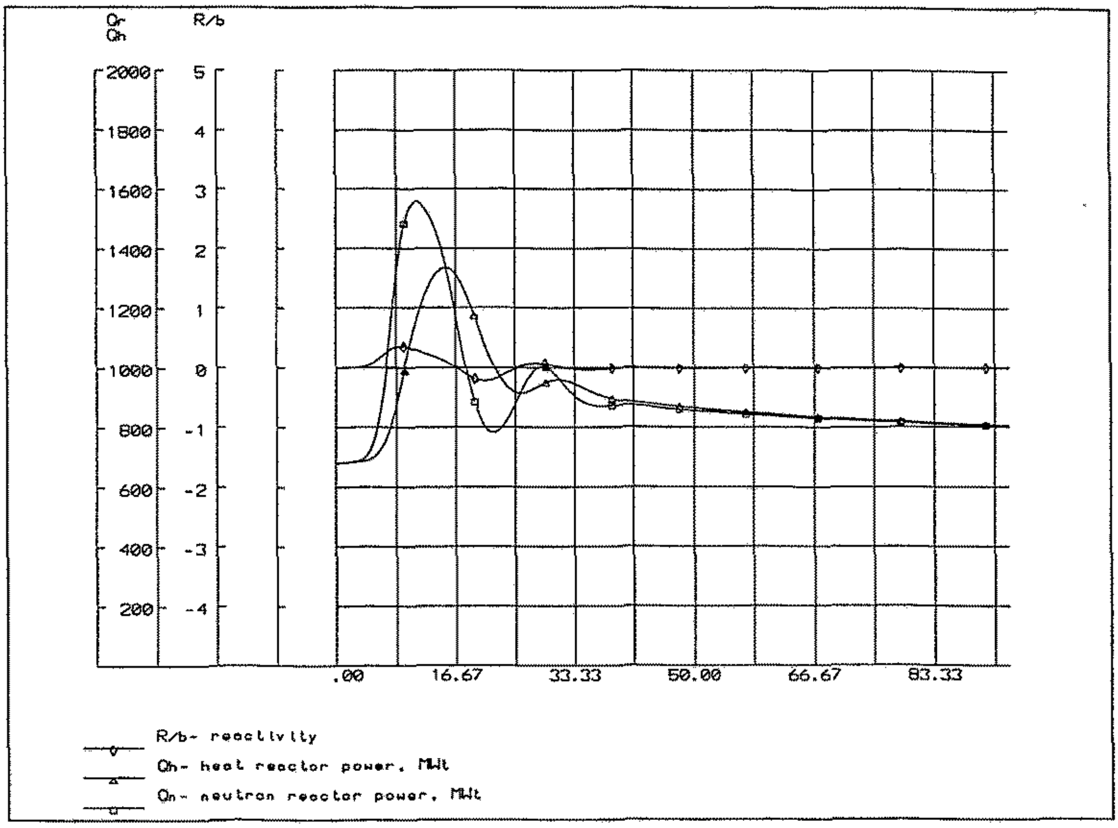

fig 58

Fuel temperature distribution (hot channel).

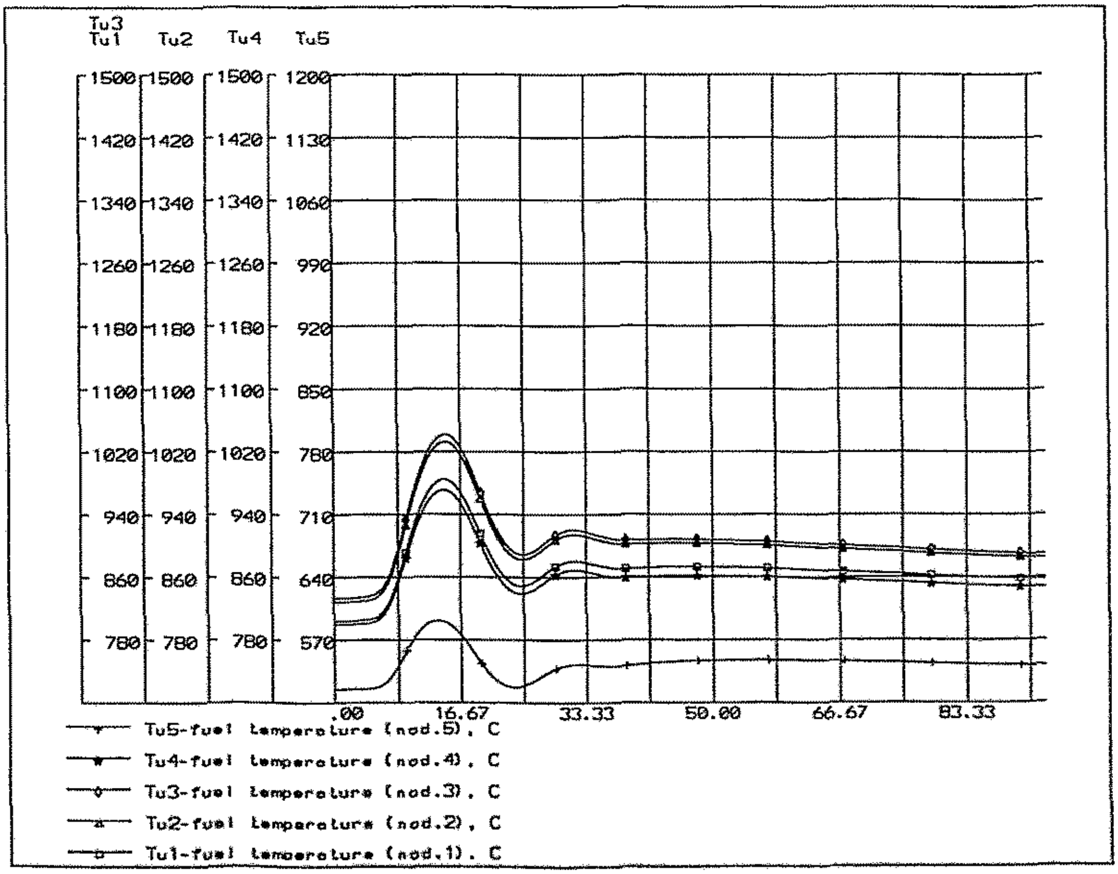

fig 59.

VVER-440. Transient name: 1 of 4 loops connection (v43_3).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (ideal mixing)

Pressurizer parameters

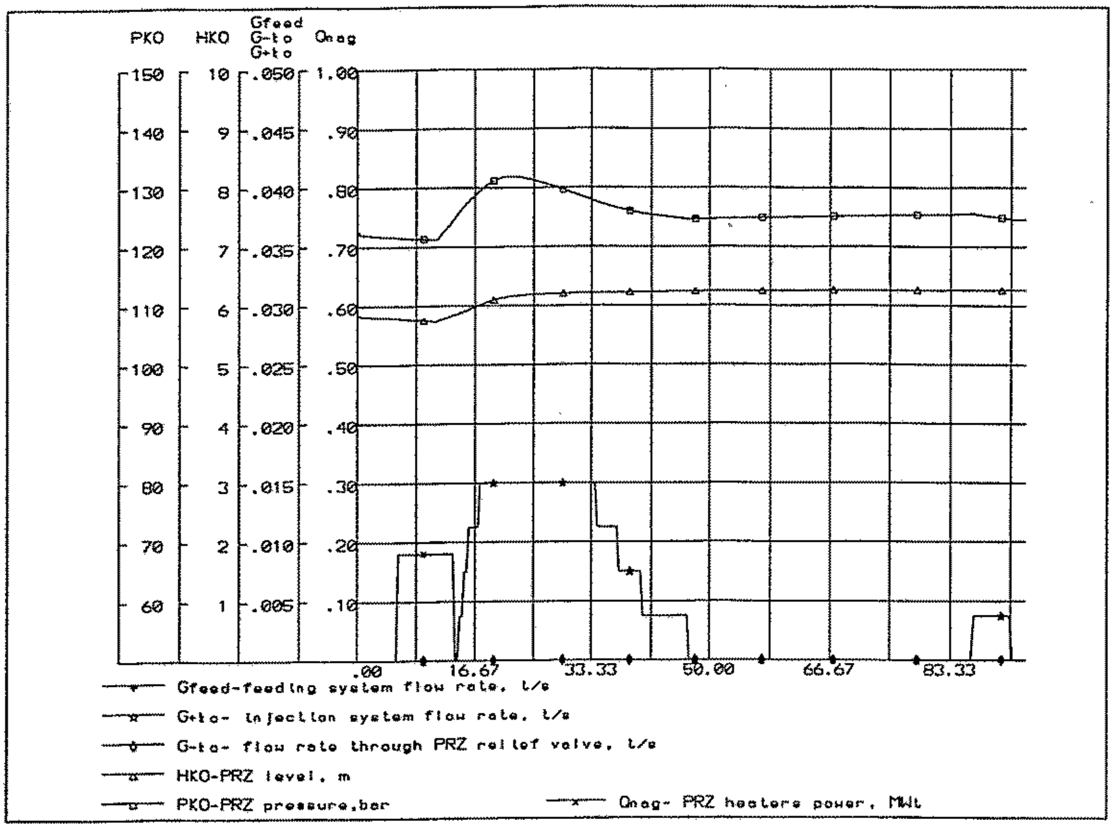

fig 60.

Primary circuit parameters.

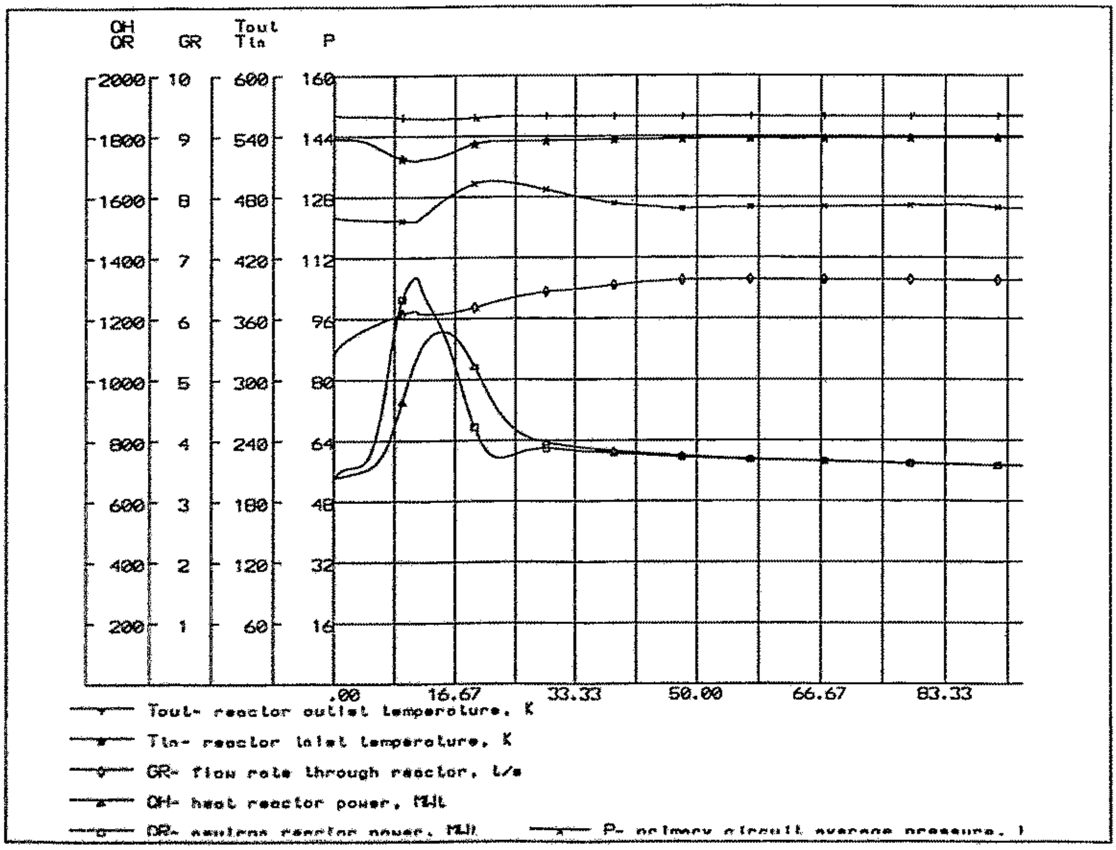

fig 61.

VVER-440. Transient name: 1 of 4 loops connection (v43_3).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (ideal mixing).

Core parameters

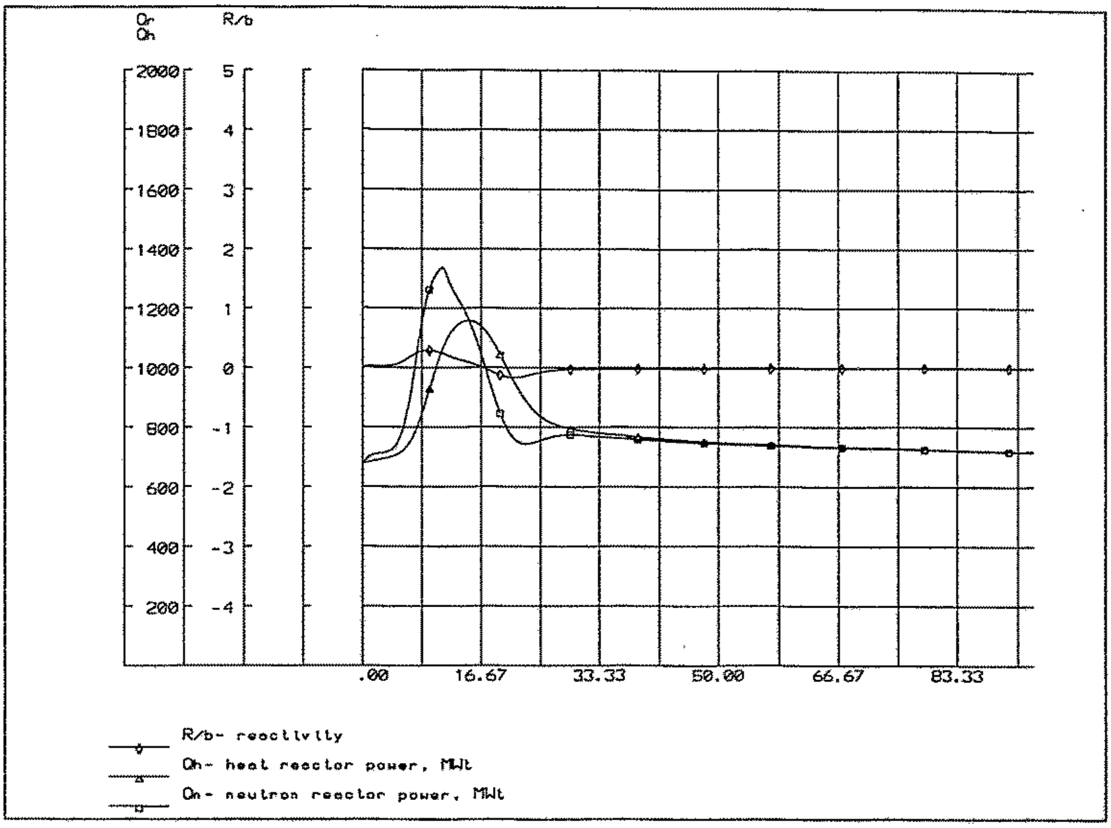

fig 62.

Fuel temperature distribution (hot channel).

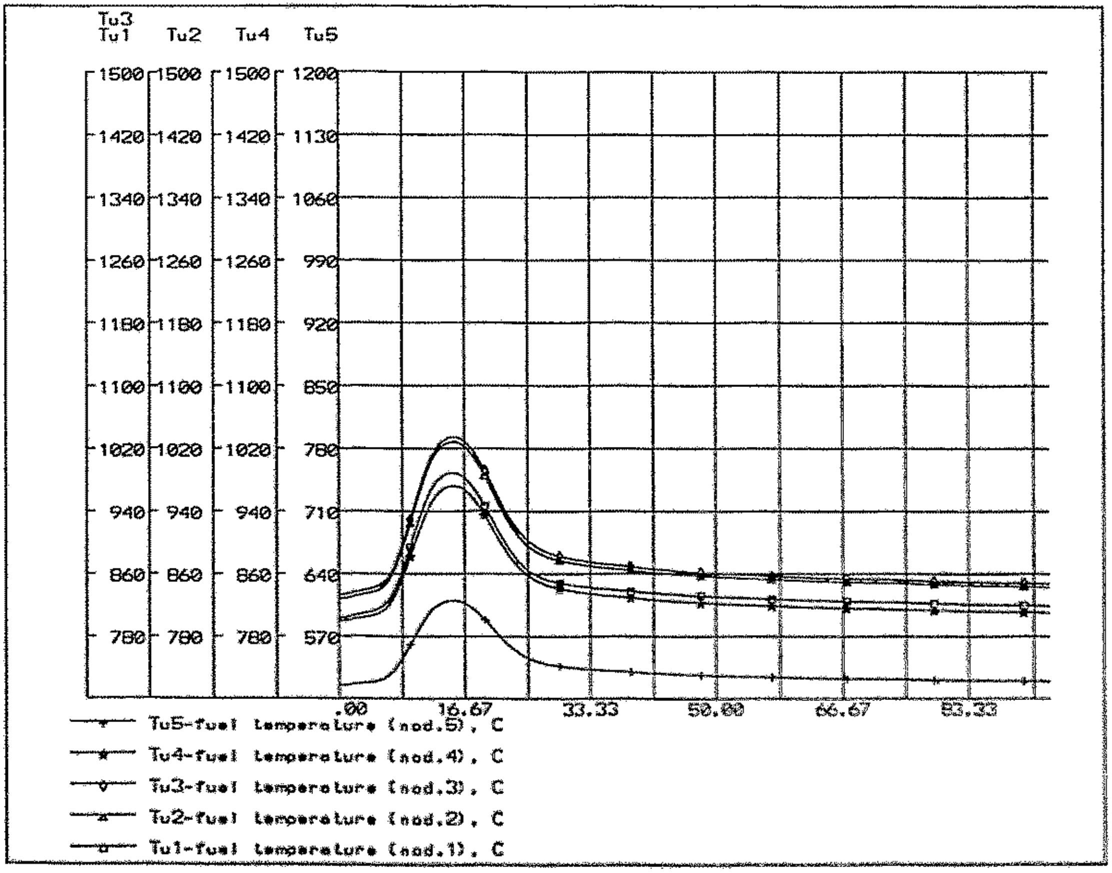

fig 63.

VVER-440. Transient name: 1 of 4 loops connection (v43_4).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.

Disconnected loop parameters: T=373 K, Cb=0.0 g/kg. (no mixing)

Pressurizer parameters

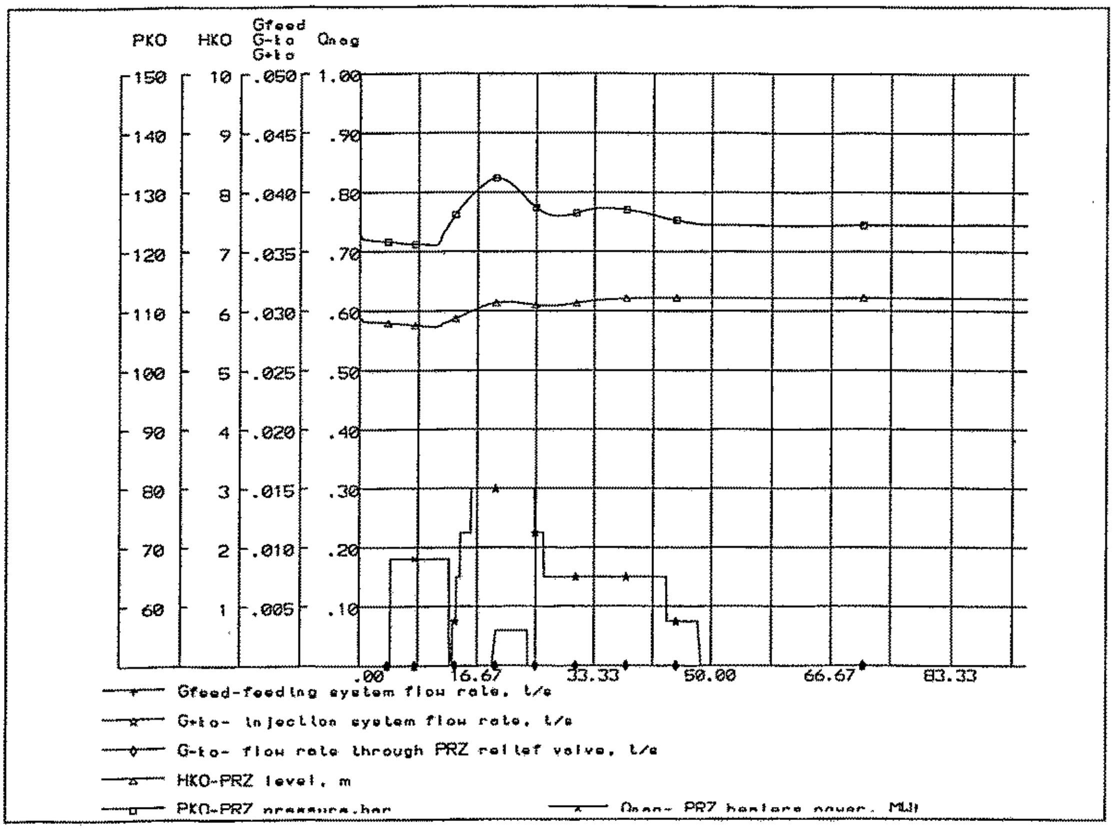

fig 64.

Primary circuit parameters.

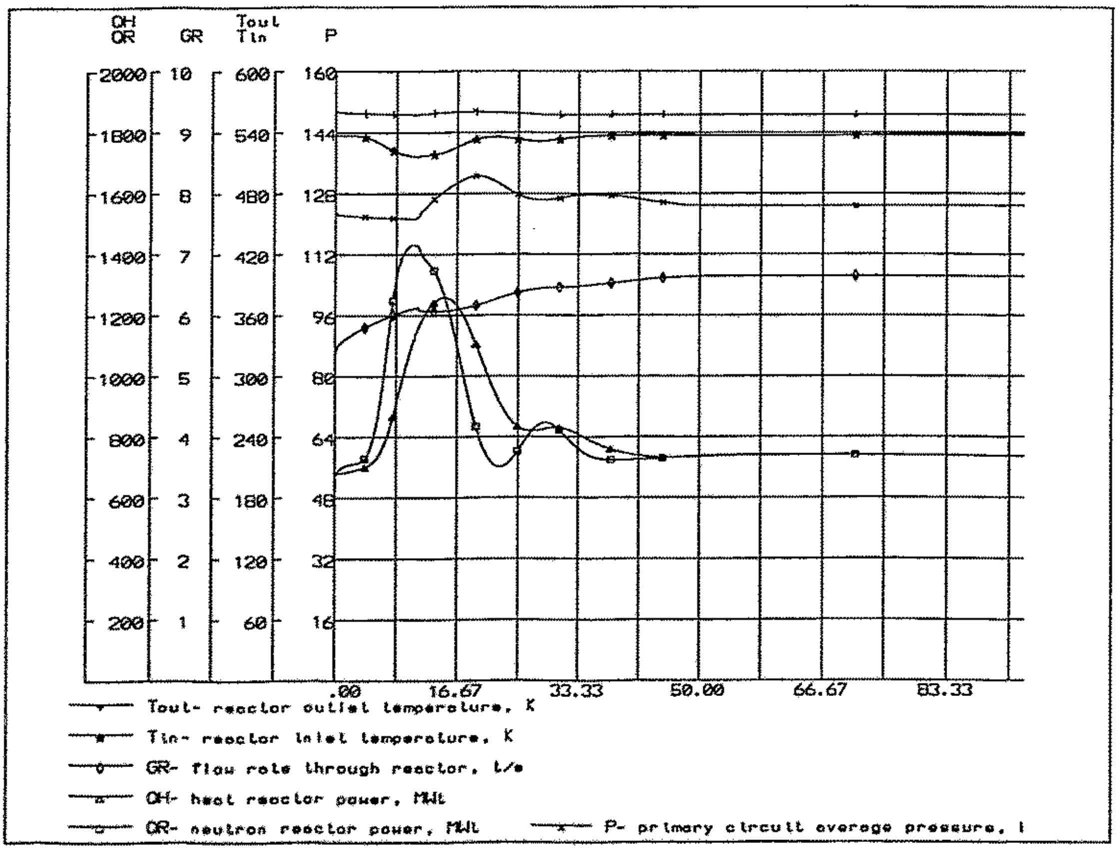

fig 65.

VVER-440. Transient name: 1 of 4 loops connection (v43_4).

Initial power level - 1210 MWt, at the end of fuel cycle. Scram is fault.
Disconnected loop parameters: T=373 K, Cb=0.0 g/kg, (no mixing).

Core parameters

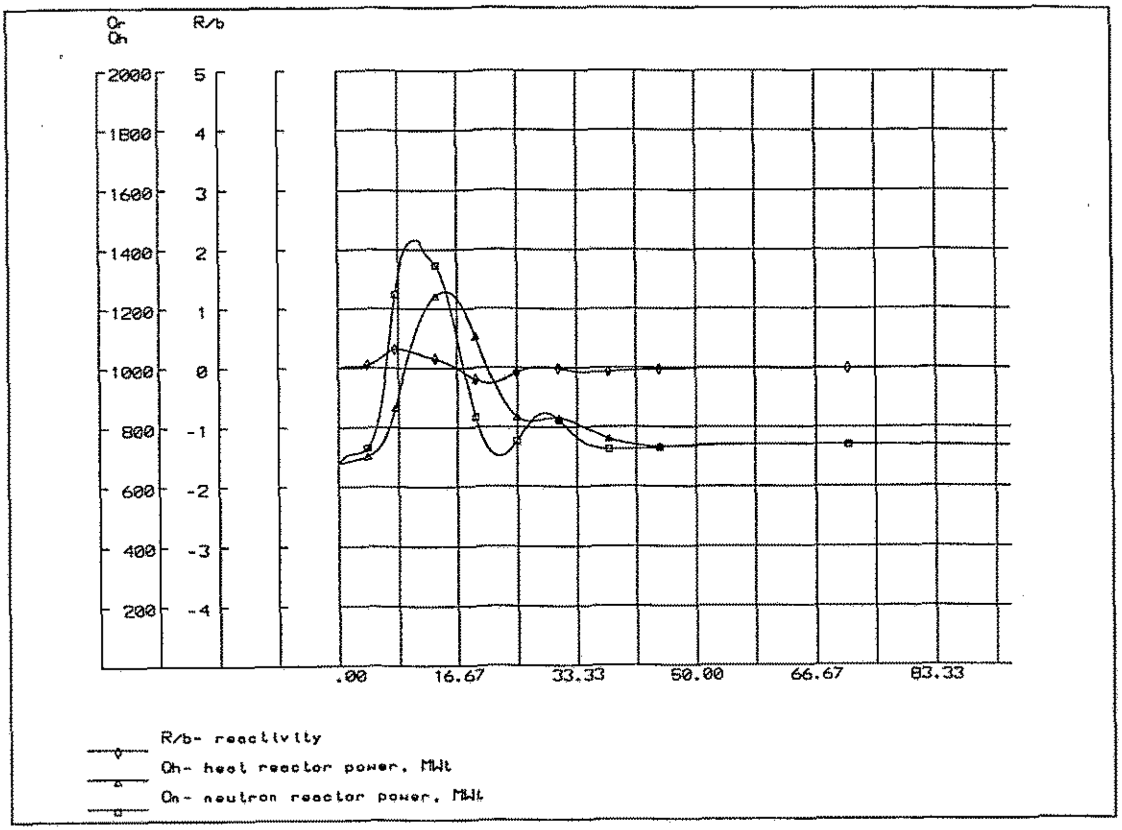

fig 66

Fuel temperature distribution (hot channel).

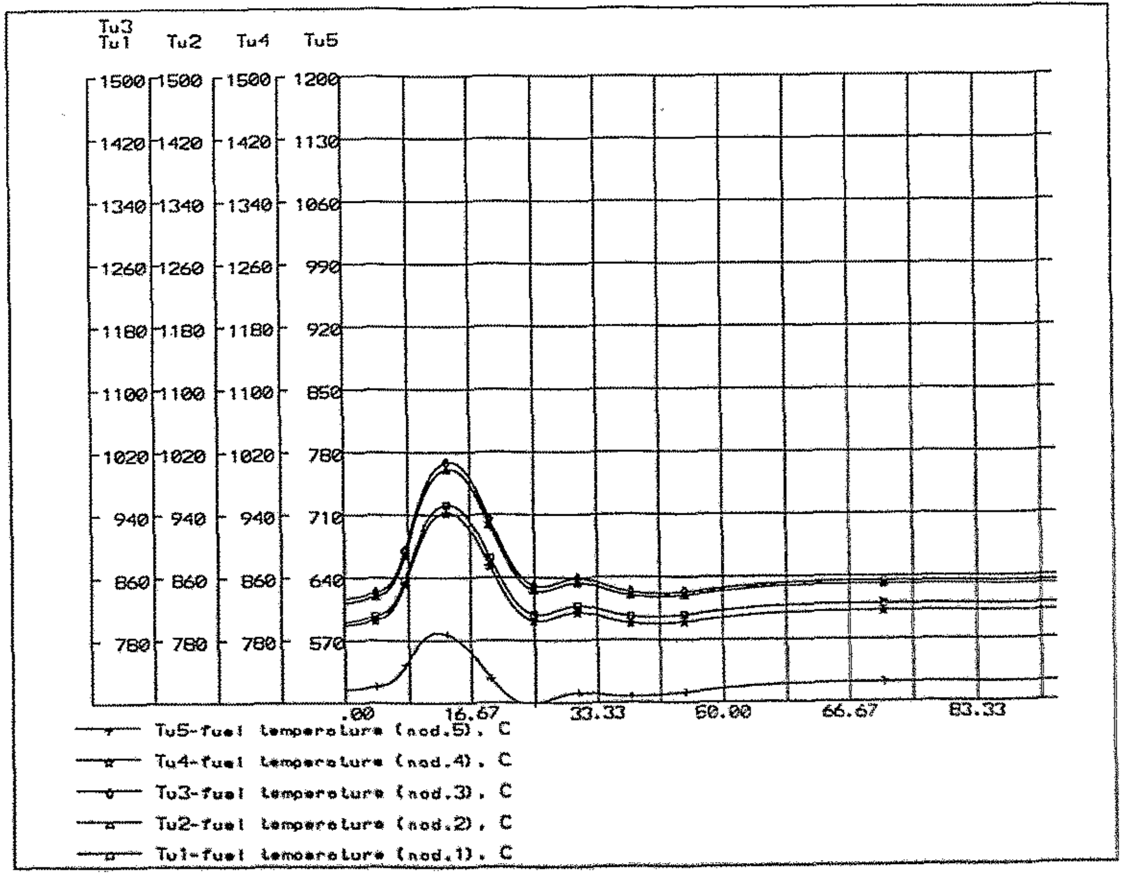

fig 67.

2. Analysis of the transient "Steam generator tube rupture"

2.1. Description of the transient

NPP works under nominal conditions (the main parameters of the initial conditions obtained using the SiTAP code are shown in table 2.1). After breakage of a tube in one of the steam generators (SG), due to a water leak from the primary circuit to the secondary side, level of radioactivity in the secondary circuit will be increased. The release occurs through both ends of the tube, the leak place is located at a distance of 1.7 m from the hot SG collector. After reaching a J^{131} concentration in the water of the secondary circuit of $1 * 10^{-7}$ Cu/l, a signal to the control room is produced (time of reaching this concentration ranges from 17 to 40 sec.)

The operator (acting according to the rules) transfers the Regulator of Automatic Power Support (RAP) to a mode of maintenance of constant reactor neutron power. At the same time, he changes RAPs "setpoint of limited regulated power (RLP)" to the value 83% of nominal power. The operator also sends a signal on stopping of the Main Pump (MP) on the accidental loop. After receiving this signal, with a delay of 0.7 sec, closing of Main Isolating Valve (MIV) on the same loop is started. Then, the operator (through approximatly two minutes) closes a Feed Water Valve (FWV) (closing duration - 6 seconds) on the accidental SG. After closing it completly, the signal on Main Isolating Steam Valve (MISV) closing is produced (duration - 15 sec). Increasing of pressure in the accidental SG is limited by the operation of the Steam Dump System (BRU-A, BRU-K). The process is completed by the operator (after some time of operation of the Steam Dump System) after compulsory reduction of pressure in the disconnected part of the loop.

2.2 Initial and boundary conditions.

<u>The primary circuit:</u>

-	reactor heat power	1375 MW_{th}
-	pressure	122.9 bar
-	coolant temperature at core inlet/outlet	537.7/568.3 K
-	coolant mass flow rate through one loop	1682 t/s
-	pressure difference on main pumps	4.29 bar
-	pressurizer level	5.7 m

<u>The secondary circuit:</u>

-	pressure SG	47.3 bar
-	pressure before turbine valve	44 bar
-	mass flow rate	0.13233 t/s
-	feed water enthalpy	968 kJ/kg
-	SG tube size	16 * 1.4 mm
-	*steam mass flow rate through turbine*	*0.794 t/s*

2.3. Input data

A description of the SiTAP main input data is contained in table 2.1., a description of the main geometric characteristics is given in table 2.2. Automatic systems characteristics are shown in tables 2.3 and 2.4.

Description of initial data for calculation of "SG tube rupture" transients

Table 2.1

Nr.	Description	Value
	Initial conditions	
1	Full reactor power, MW	1375.00
2	Neutron reactor power,MW	1375.00
3	Primary circuit average pressure, bar	122.90
4	Pressurizer pressure, bar	122.60
5	Reactor pressure drop, bar	3.01
6	Core pressure drop, bar	2.07
7	Coolant flow rate through reactor, t/s	8.73
8	Coolant temperature (reactor inlet), K	538.00
9	Coolant temperature (reactor outlet), K	568.20
10	Average fuel temperature, K	980.00
12	Boron concentration in reactor vessel, g/kg	1.53
13	Boron concentration in nominal loop, g/kg	1.53
14	Hot legs average temperature, K	568.30
15	SG core average temperature, K	546.40
16	Cold legs average temperature, K	537.90
17	Coolant flow rate through 1 loop, t/s	1.56
18	1 SG secondary side pressure, bar	47.50
19	1 SG steam mass flow, t/s	0.135
20	1 SG feed water mass flow, t/s	0.133

Continuation of table 2.1: Neutronic characteristics		
1	Core state conditions	Fresh fuel
2	Reactivity coefficients -by fuel temperature ($d\rho/dt_f$), 1/K -by coolant temperature ($d\rho/dt_c$), 1/K -by coolant density ($d\rho/dg_c$), $(m^3/kg)^{-1}$ -by boron concentration ($d\rho/dc_b$), $(g/kg)^{-1}$ -by pressure ($d\rho/dp$), 1/bar -by power ($d\rho/dQ$), 1/MW	 $-0.34*10^{-4}$ $-1.66*10^{-4}$ 0. $-2.19*10^{-2}$ 0. 0.

Description of NPPs main geometric characteristics

Table 2.2

Nr.	Description	Value
1	Total primary circuit volume (include PRZ), m^3	194.70
2	Hot legs volume, m^3	4.64
3	SG core volume, m^3	6.80
4	Cold legs volume, m^3	4.44
5	Upper plenum volume, m^3	20.40
6	lower plenum volume, m^3	36.50
7	Reactor core volume, m^3	8.00
8	Pressurizer total volume /water volume, m^3	44.00/26.00
9	SG secondary side volume, m^3	74.50
10	Reactor volume, m^3	67.60
11	Loop vertical projections height, m -hot leg -SG core -cold leg -downcomer	 -1.39 0.0 2.79 7.58
12	Hydraulic diameters, m -hot leg -SG core (single tube) -cold leg -downcomer	 0.492 0.0132 0.492 0.250

Continuation of table 2.2

13	Heights, m	
	-core	2.5
	-upper plenum	4.0
	-lower plenum	2.1
14	Plenum characteristics:	
	-upper	
	-cross section, m^2	0.9
	-hydraulic diameter, m	0.917
	-effective length, m	4.29
	-effecive heat transf. area, m^2	166.7
	-lower	
	-cross section, m^2	6.45
	-hydraulic diameter, m	0.678
	-effective length, m	4.0
	-effecitve heat transf. area, m^2	93.6
15	Core bypass characteristics:	
	-cross section, m^2	0.256
	-hydraulic diameter, m	0.0056
	-length, m	2.5
16	Fuel assembly characteristics	
	-cross section, m^2	0.00884
	-hydraulic diameter, m	0.086
	-fuel mass, t	0.136
	-lenght, m	2.5
	-number of rods	126

Automatic control systems characteristics

Table 2.3

Setpoint description	Value
SG feeding regulator	
Control Law	proportional - integrated
Number of signals -Feed water flow rate signal weight -Steam flow rate signal weight -SG water level	3 0.25 0.25 0.25
Reactor scram system ("AZ-1")	
Period of reactor less than	10.0 sec
Reactor neutron power greater than	112% N_{nom}
Primary circuit pressure less than	93.2 MPa
Primary circuit pressure greater than	134.4 MPa
Core pressure drop greater than	0.568 MPa
Secondary circuit pressure greater than	6.3 MPa
Speed of pressure decrease in secondary side greater than	0.2 MPa/s
Reactor protection system ("AZ-2")	
Period of reactor less than	*20.0 sec*
Reactor neutron power greater than	105% N_{nom}
Primary circuit pressure less than	11.28 MPa
Primary circuit pressure greater than	13.15 MPa
Maximal coolant temperature greater than	578.6 K
Secondary circuit pressure greater than	5.3 MPa

SG feeding system

Table 2.4

Setpoint description	**Setpoint value**	**Action**
SG water volume greater than	52.4 m^3	Close FWV (5 sec)
SG water volume less than	49.9 m^3	Open FWV closed
SG water volume less than	44.2 m^3	Start Auxiliary Feeding Pumps (G=0.131 t/s, delay 0.0)
SG water volume less than	38.9 m^3	Start Emergency Feeding Pumps (G=0.139 t/s, delay = 45sec)
SG water volume greater than	51.3 m^3	Close Turbine Control Valve

Secondary circuit valves

Table 2.5

Name	Cross section area, m^2	Open/close speed, m^2/s	Setpoint to open, bar	Setpoint to close, bar
"BRU-K"				
group N1	0.025	0.012	51.0	48.0
group N2	0.025	0.012	51.0	48.0
group N3	0.025	0.012	51.5	48.5
group N4	0.025	0.012	51.5	48.5
"BRU-K"				
group N1	0.012	0.001	53.0	48.0
group N2	0.012	0.001	53.0	48.0
SG Relief Valve				
group N1	0.0142	0.0467	57.88	49.05
group N2	0.0142	0.0467	58.86	51.0

2.4 Results of calculation

For the analysis of the transient "SG tube rupture" two possible variants of the operator action are considered.

Variant A After reception of à signal concerning an increasing in radioactivity in the secondary circuit, the operator sends a signal on MIV closing (using the step-by-step program). The total time of MIV closing, in this case, will be 298 sec.

Variant B Operator closes MIV with maximum speed allowed by its drive. The total time of closing is 90 sec.

2.4.1. Results of Variant A

The expiration of water from the first circuit causes a slow decrease in pressure in PRZ and in its water level. The system of Primary Circuit Pressure Maintenance (PCPM) aims to compensate this fall by the inclusion (on 10 sec) of PRZ heaters, and then of the High Pressure Feeding Pumps (on 52 sec). However, these actions only slow down the speed of pressure fall.

Slow closing of the MIV does not permit fast locating of leakage quickly, and after 66 seconds activation of "AZ-2" occurs. After 98 sec, Reactor Scram System is activated by the signal "Fall of pressure in core below a permissible limit ". In addition, the transient of an emergency block shutdown begins. The analysis is terminated at the moment of complete MIV close.

In the secondary circuit, insertion of the primary circuit coolant causes a pressure increase in the defective SG. After MISV and FWV close, the pressure increase is limited by the periodic work of "BRU". Results of the analysis of this transient are shown in fig. 68-72.

2.4.2. Results of Variant B

Analysis of this variant has shown, that the fast MIV closing permits location of the leakage before plant shutdown signal for a fast stop of a reactor. After MGV complete close plant reaches a stationary state at a new power level. Results of calculation of this mode are shown on fig. 73 -77.

FIGURES

Part II

Fig. 68 - 76

VVER-440. ***Transient:*** *" Leak from primary to the secondary circuit"(Duration of MGV closing - 298 sec)*

Primary circuit parameters.

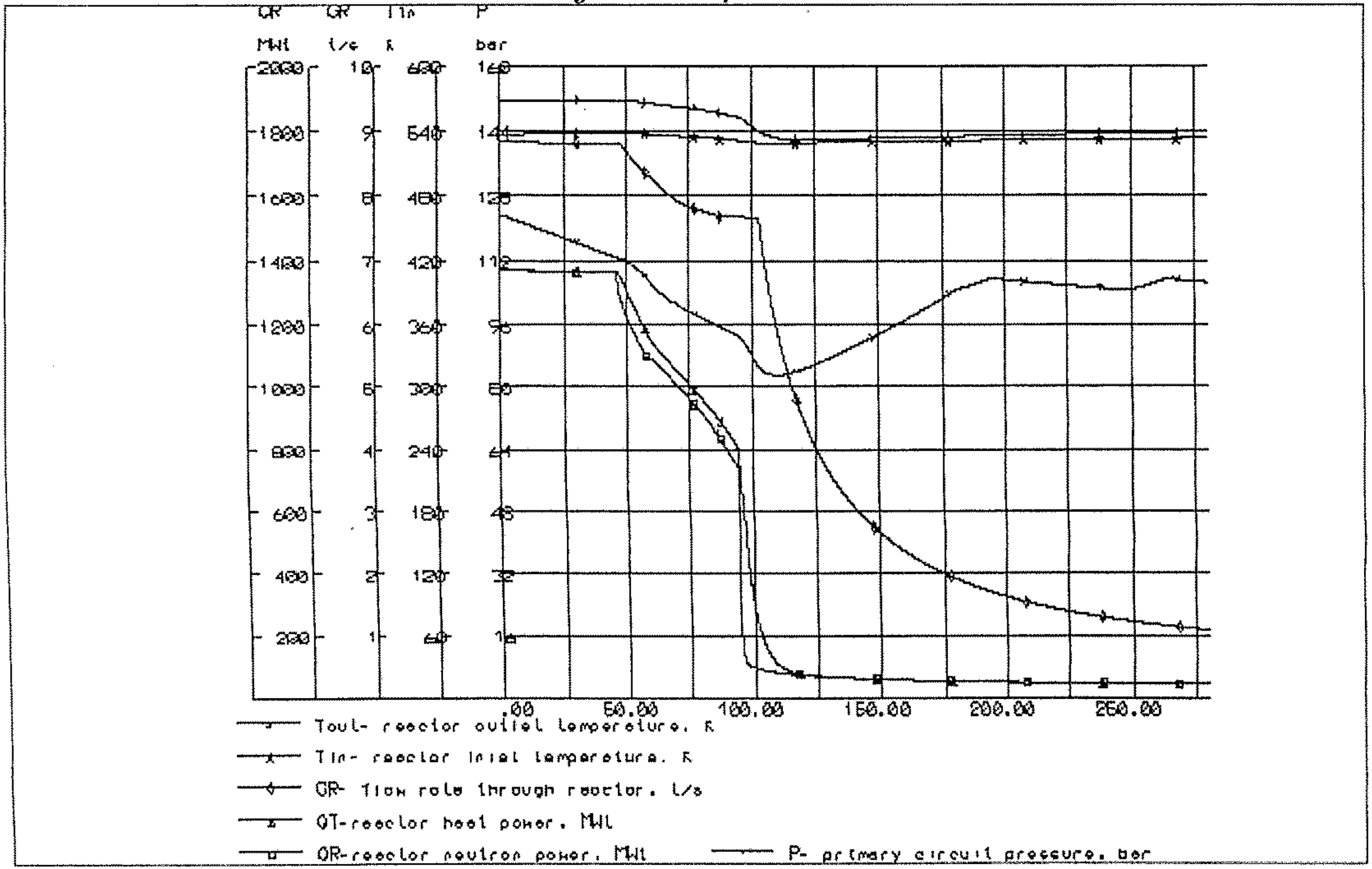

fig . 68

VVER-440. ***Transient:*** *" Leak from primary to the secondary circuit"(Duration of MGV closing - 298 sec)*

PRZ parameters.

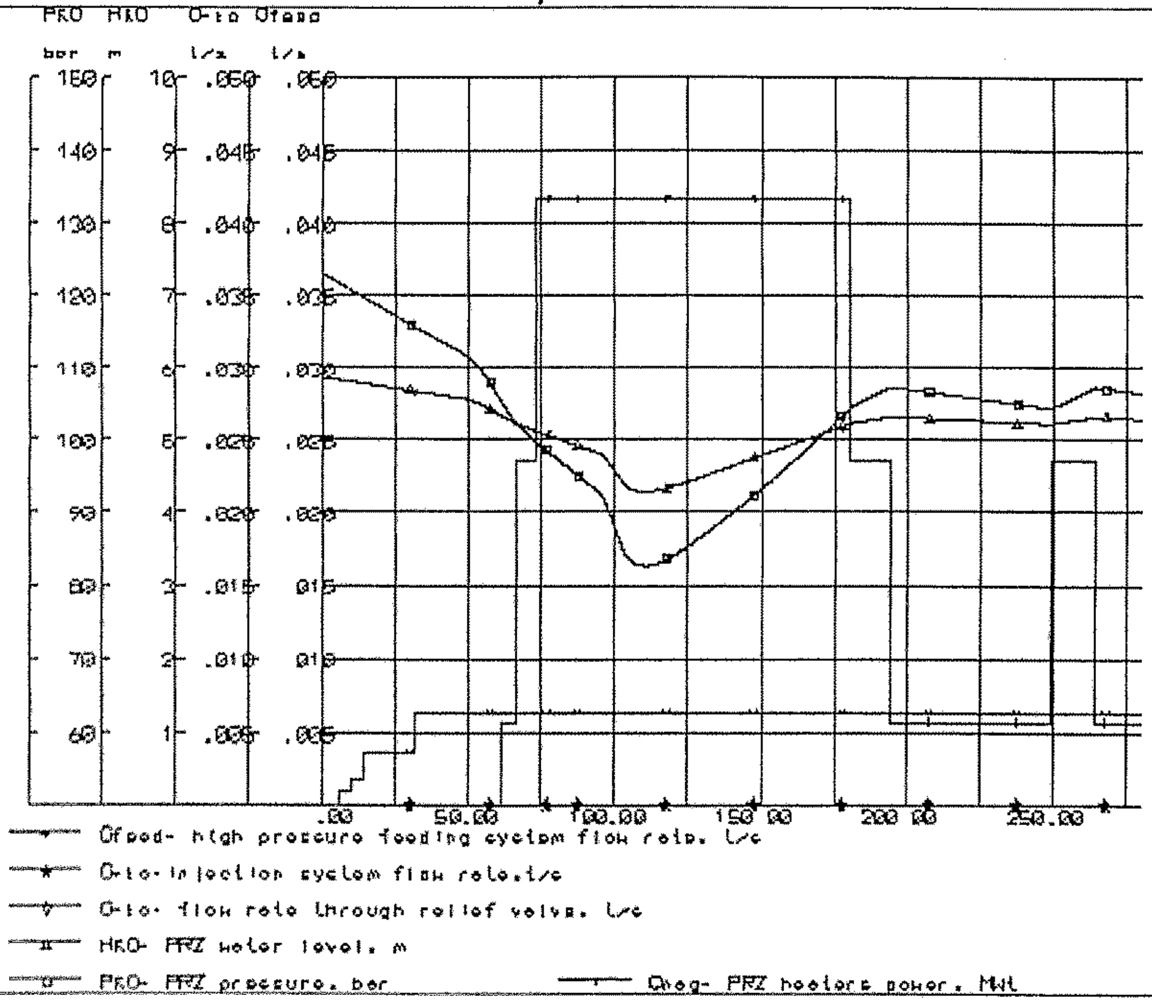

fig 69

VVER-440. **Transient:** *" Leak from primary to the secondary circuit"(Duration of MGV closing - 298 sec)*
Accidental SG parameters.

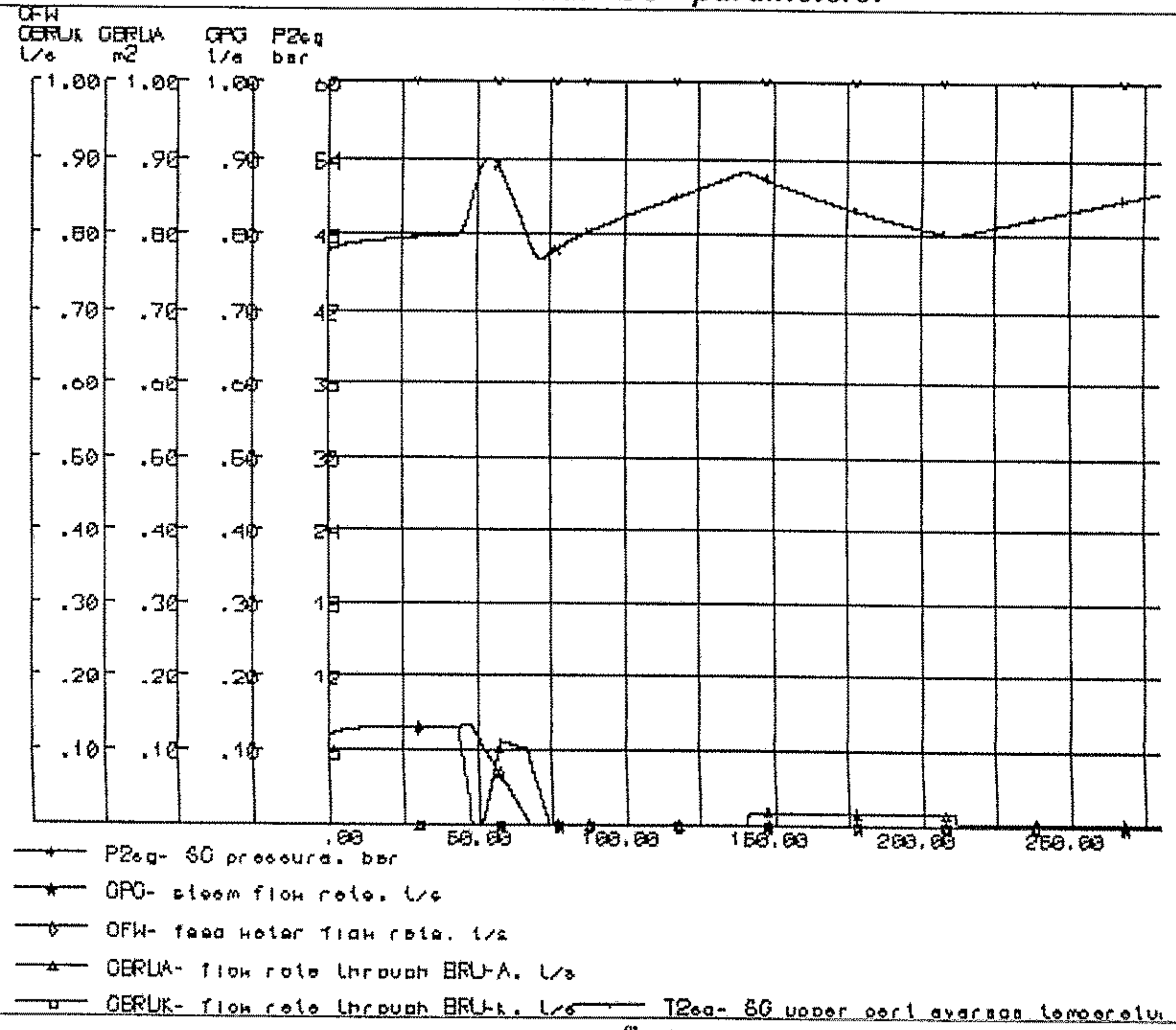

fig 70

VVER-440. Transient: *" Leak from primary to the secondary circuit"(Duration of MGV closing - 298 sec)*

Normal SG parameters.

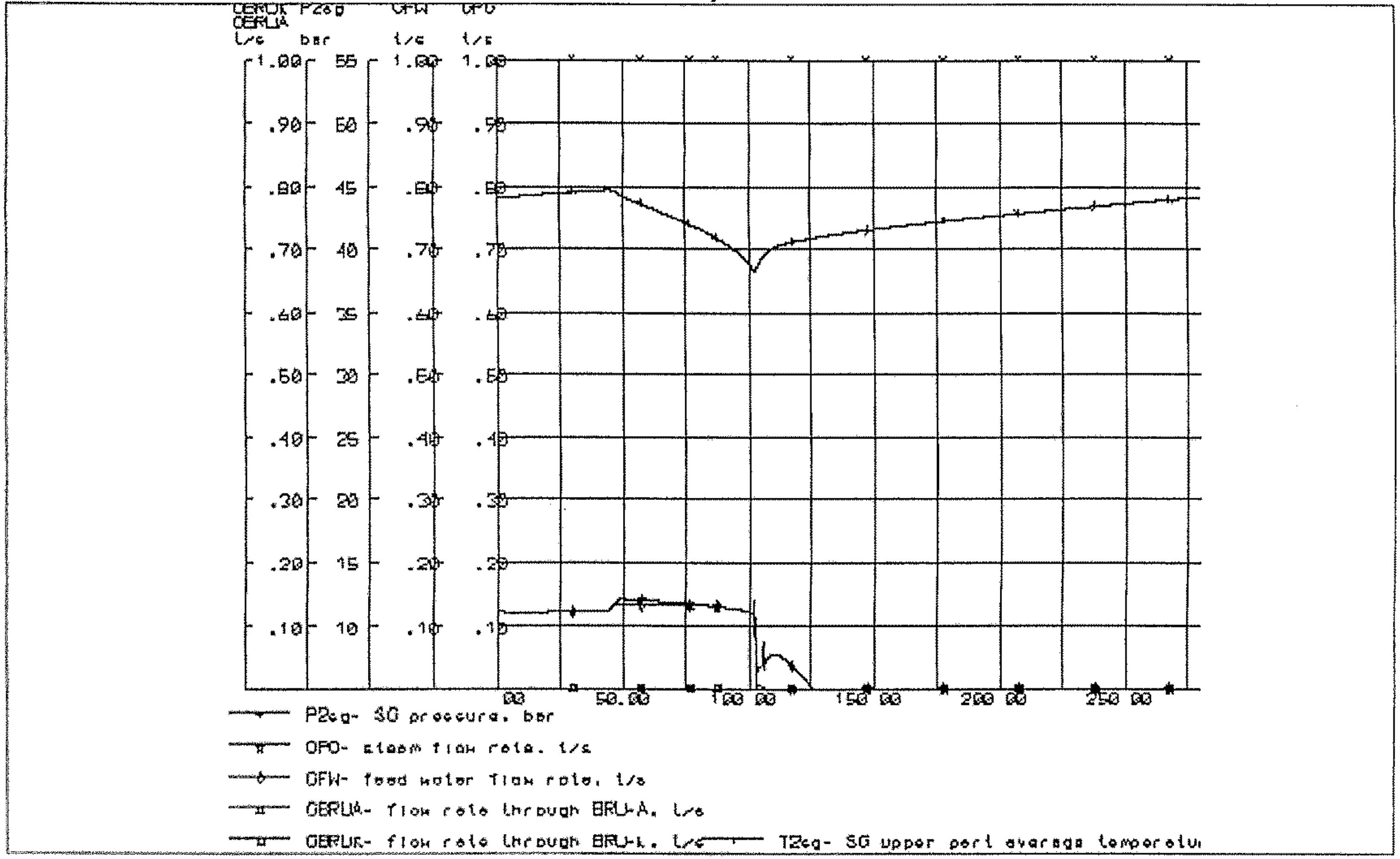

fig 71

VVER-440. Transient: " Leak from primary to the secondary circuit"(Duration of MGV closing - 298 sec)

Main Pumps parameters.

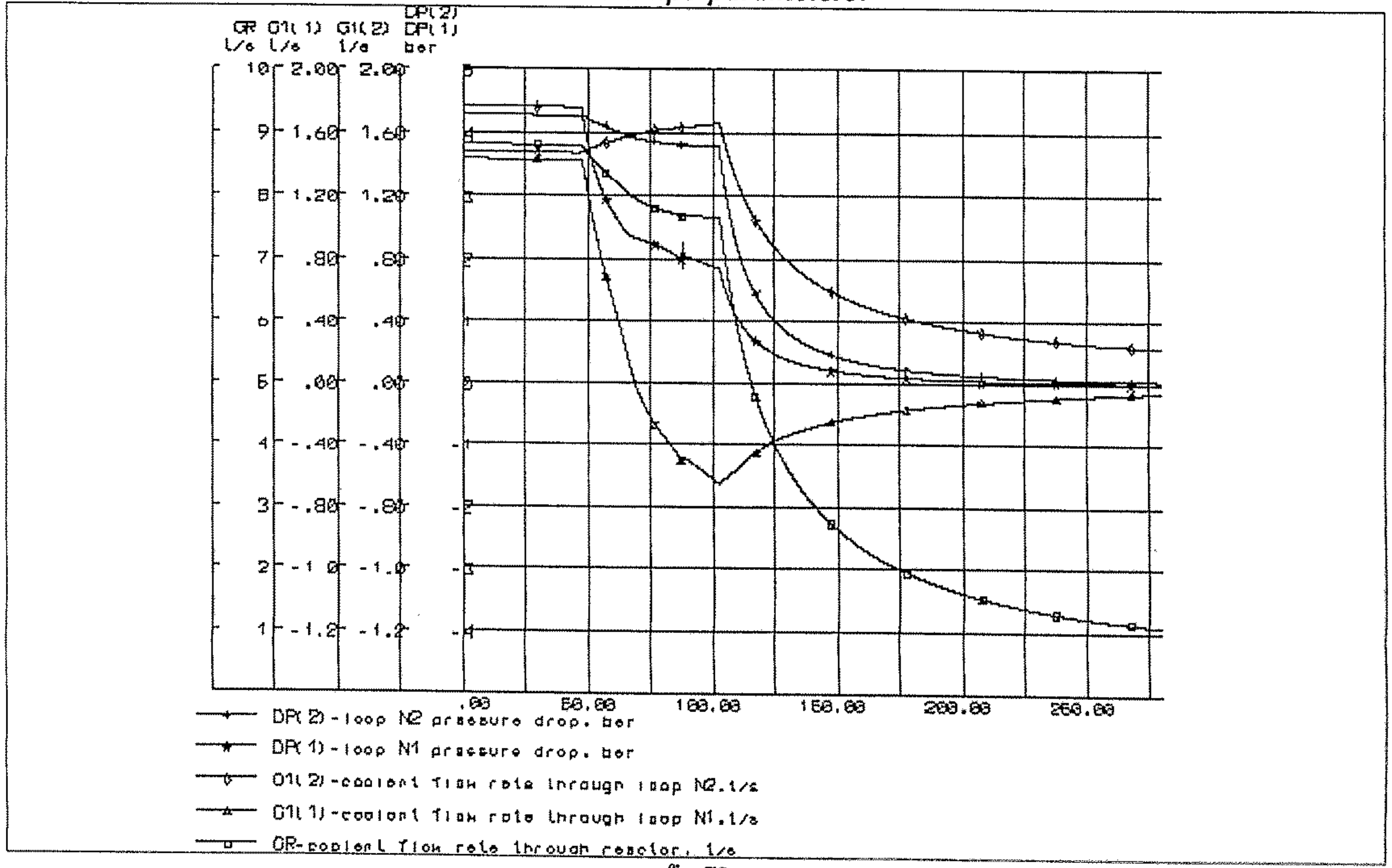

fig 72

VVER-440. ***Transient:*** *" Leak from primary to the secondary circuit"(Duration of MGV closing - 90 sec)*

Primary circuit parameters.

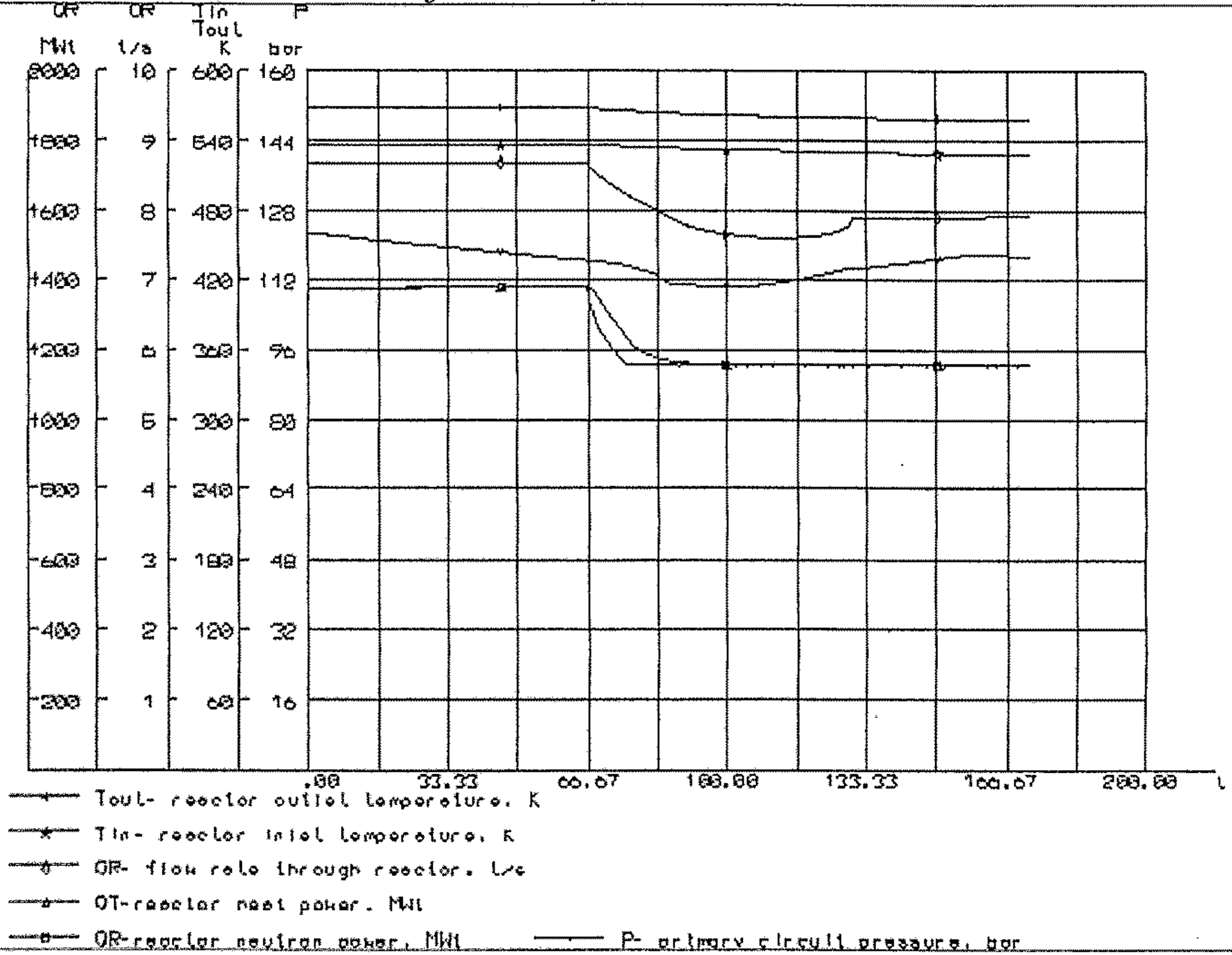

fig 73

VVER-440. Transient: " Leak from primary to the secondary circuit"(Duration of MGV closing - 90 sec)

PRZ parameters.

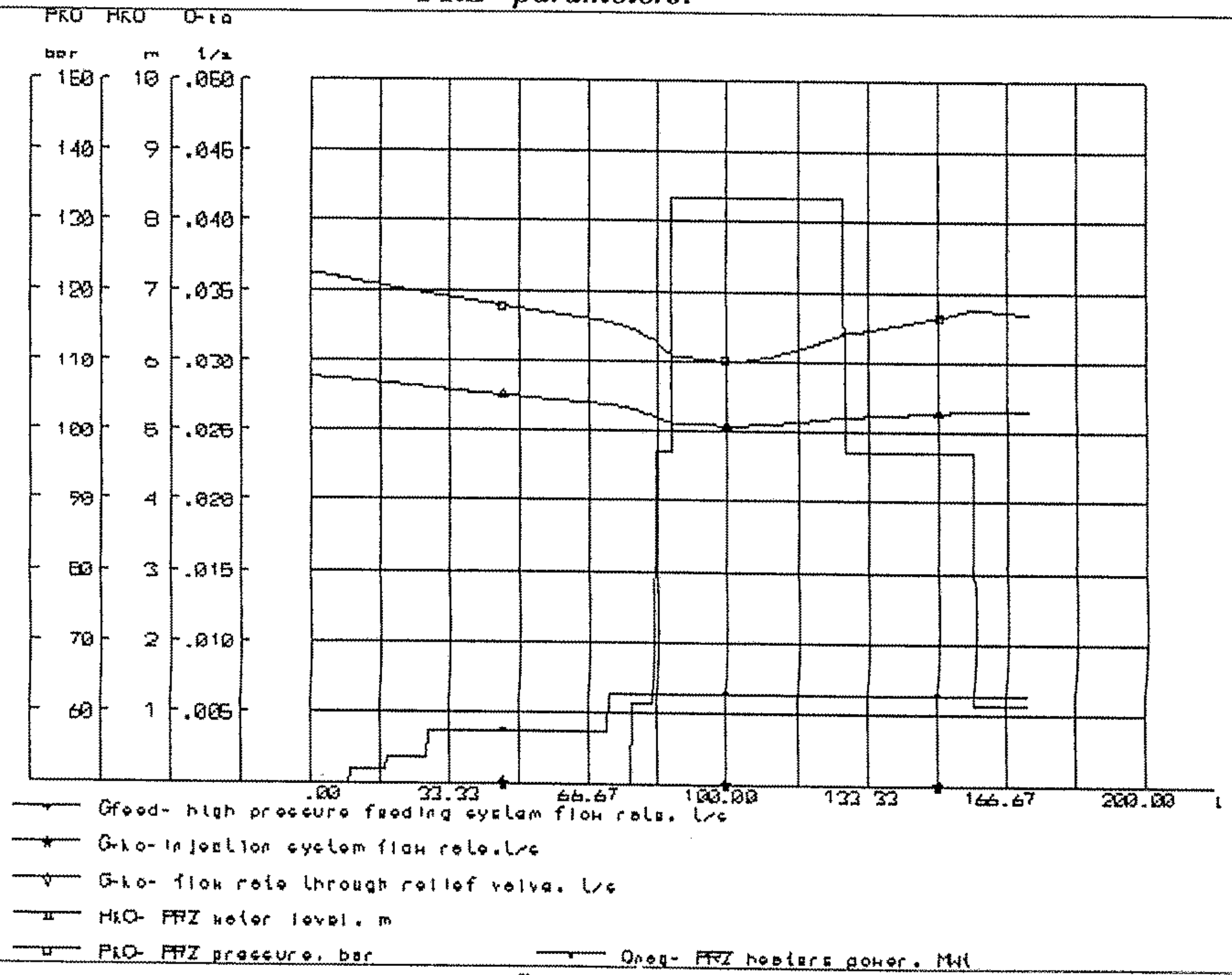

fig 74

VVER-440. Transient: *" Leak from primary to the secondary circuit"(Duration of MGV closing - 90 sec)*

Accidental SG parameters.

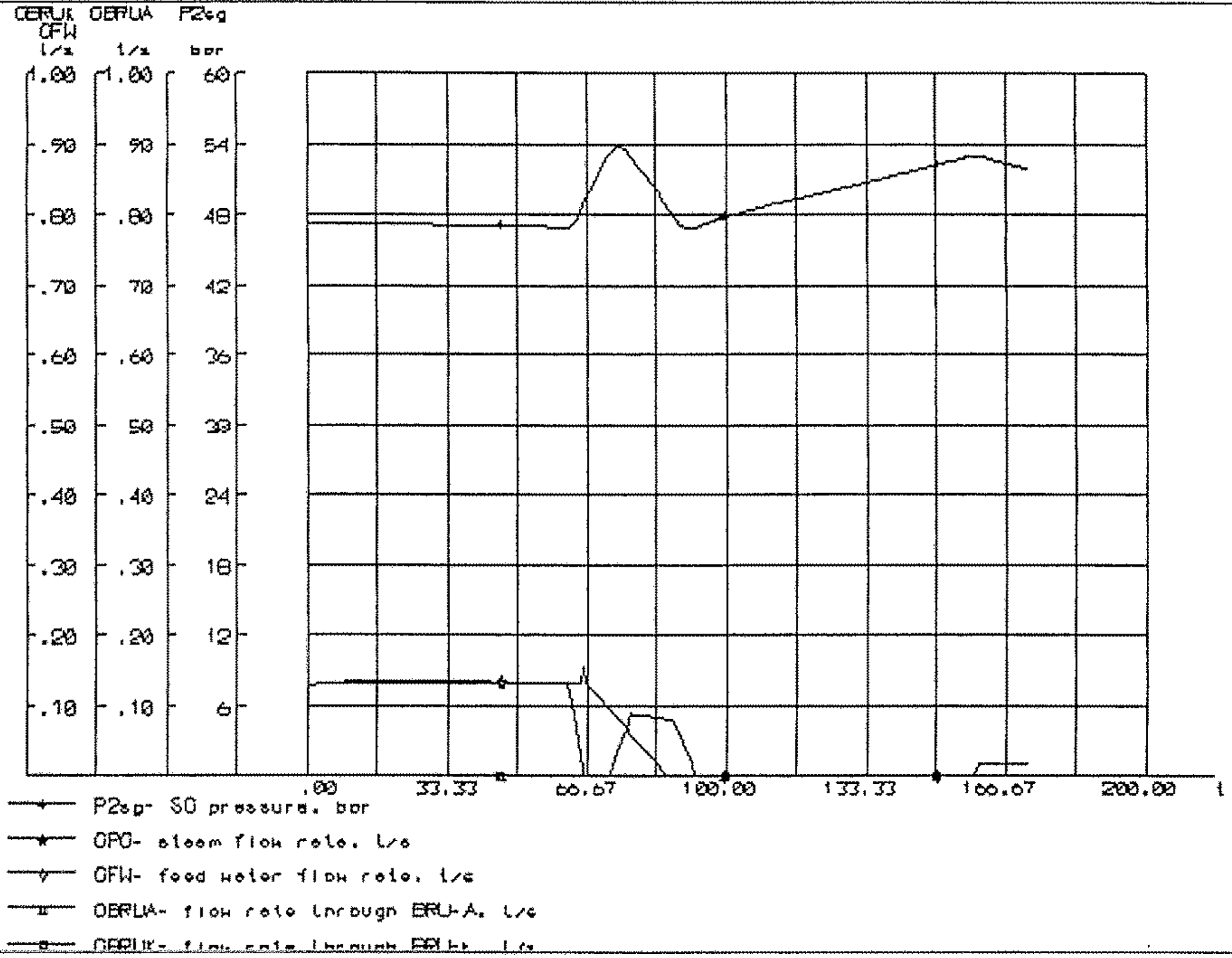

fig 75

VVER-440. Transient: *" Leak from primary to the secondary circuit"(Duration of MGV closing - 90 sec)*

Normal SG parameters.

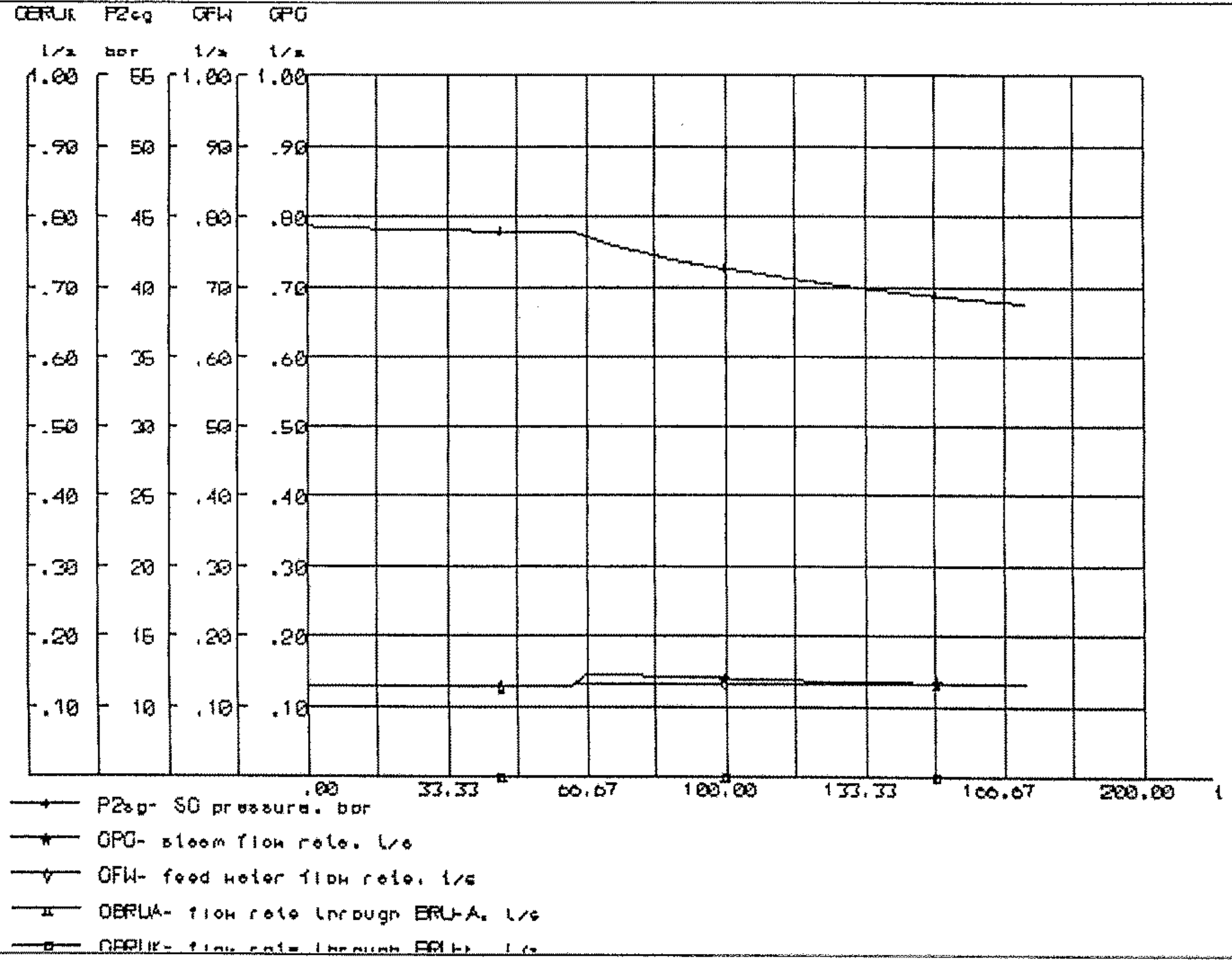

fig 76

Acknowledgement

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