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TEMPERATURE ETALON FOR VVER-440 REACTORS

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Abstract

Description, properties and benefits resulting from the use of temperature etalon in VVER-440 reactors are shown in the paper presented. The reactor temperature etalon is a measurement system for accurate measurement of coolant temperature at reactor inlet and outlet. The accuracy of the measurement of temperature is 0,18°C, the accuracy of the measurement of temperature difference is 0,14°C, both at the credibility level of 0,95. With regard to metrology, temperature sensors in the reactor temperature etalon are related to etalons in higher levels. The reactor temperature etalon checks the accuracy of measurement in each measurement cycle. It serves for the metrology assurance of standard temperature measurements in reactor. Up to now, it has been installed at 12 units with VVER-440 reactors in Slovakia, Czech Republic and Bulgaria.

1. Introduction

Thermal reactor output and power distribution in the core are maintained by means of temperature measurements in reactor. For each reactor, the limiting values of temperature difference in both reactor and fuel assemblies for stabilized power modes are thus specified and maintained. These limiting values are specified in such a way that core safety is assured in the case of assumed design basis accidents. It is then assumed that the accuracy of the said measurements is relatively high at the beginning of fuel cycle and in the course of it (1°C corresponds approximately to 3% of power) and is constant.

Based on the above mentioned, it can be said that two requirements exist in relation to the accuracy of temperature measurements from the time point of view. Firstly, relative high accuracy prior to unit start-up to power and possibility of its control, and secondly, possibility to control accuracy during the whole cycle. According to [1], the accuracy of measurements of reactor coolant temperature with thermocouples should be better than 1°C.

Analyses of standard reactor temperature measurements carried out at the end of seventies showed [2] that their accuracy [3] does not meet fully the increasing requirements on operational safety and economics. Systematic steps were sought with which it would be possible to improve the existing standard temperature measurements so that they meet the above mentioned requirements on accuracy. Based on the analyses of advantages and deficiencies in standard reactor temperature measurements and on the existing measurement equipment in the field of temperatures, a systematic approach was proposed for enhancing their accuracy and checking the accuracy during time [4,5]. The systematic steps consisted in that a relatively accurate measurement system for the measurement of temperatures and temperature differences in reactor [6] was proposed which should serve as a reactor temperature etalon. This temperature etalon measures the temperature and temperature difference in reactor with a relatively high accuracy (0,18°C and 0,14°C for $p=0,95$) and is related metrologically to etalons at higher levels [7,8,9]. The temperature etalon in each measurement cycle checks its accuracy for the measurement of temperature and temperature difference. By means of the reactor temperature etalon, it is possible to calibrate complete measurement circuits of standard temperature measurements in reactor under real conditions during quasi-isothermal and operational conditions, which can then achieve extreme accuracy of measurement in the range of ± 1°C. The evidence of the above mentioned statement is based on the results of a long-term comparison of pairs of measurement circuits with resistance thermometers and with thermocouples situated at one measurement point in various reactors, and on the properties of thermocouples themselves [5].

2. Description and properties of the reactor temperature etalon

The reactor temperature etalon was implemented at 12 reactors during eighties and nineties within the period of approximately 16 years. The technical level and terminology for temperature etalons have changed and developed during the 16 years (abbreviation UMDT has been used for a long time). The description and properties shown below are related to recent variants of reactor temperature etalon.

2.1 Principal scheme of measurement

The principal scheme of measurement of the reactor temperature etalon is shown in Fig. 1 [10]. The shown connection of sensors, complete trains, measurement and evaluation devices makes it possible to carry out – besides standard functions for collection and processing of temperature data – also the monitoring of accuracy of the measured data and diagnostic controls. The reactor temperature etalon according to the proposed solution enables multiple measurements of temperatures and temperature differences by means of two independent physical methods. It also makes possible to measure - by means of analog-digital transducer for voltage measurement - the loop resistance of measurement circuits and the isolation resistance of the reactor temperature etalon. Redundant and diverse measurements and the way of connection make it possible to carry out automatic checks of the magnitude of random errors in the measurement of temperature and temperature difference and to check the presence of systematic errors in the measurement of temperature and temperature difference in each measurement cycle. The used method of measurement of loop resistance in measurement circuits and of isolation resistance in systems enables to identify the presence and point of fault.

According to the scheme of measurement in Fig. 1, each combined sensor of temperature (KST) *1* consists of two resistance thermometers (OT) – OT1 and OT2 *2* and of three thermometers (TČ). Out of these thermocouples, TČ2 *3* is designed to measure temperature, TČ1 and TČ3 *4* to supply power and measure OT. Resistance thermometers OT1 and OT2 are supplied by current source *9* via normal resistance ***10.*** Comparative joints of TČ1, TČ2 and TČ3 are situated in isothermal box ***5,*** where temperature is measured by resistance thermometer ***6.*** Switch-over contact *7*, switch-off contact ***8*** and switch-on contact *13*, are controlled by control element *16*. Together with resistor *11* and loading resistor *14*, they serve for finding the values of spurious voltage, loop resistance in measurement circuits, isolation resistance in the system, and for identifying presence and point of fault in measurement circuits.

2.2 Accuracy of measurement

The method of temperature measurement by means of OT according to Fig. 1. with individual static characteristics, in four-cable alignment, with direct current power supply, in which microprocessor equipment is used for the measurement and evaluation, provides broad possibilities for minimizing both systematic and random errors in the measurement of reactor coolant temperature and temperature difference.

In order to achieve a minimum error of measurement in the reactor temperature etalon, an analysis of the impact of potential partial errors on the resulting error in the measurement of temperature and temperature difference [5] was carried out. Based on this analysis, partial errors were minimized with the objective to achieve minimum errors in the measurement of temperature and temperature difference. Partial errors were minimized with regard to the magnitude of their impact on the resulting error and to the technically and economically demanding character of the minimization of the particular partial error.

The resulting design accuracy of the temperature etalon is 0,18°C for temperature and 0,14°C for temperature difference with the credibility of 0,95.

A significant property of the measurement according to Fig. 1 is that by an adequate selection of the magnitude of normal resistance *10* it can be ensured that a possible occurring shift of zero in A/Č transducer, res. any systematic error in A/Č transducer, have a negligible impact on accuracy in the measurement of temperature and temperature difference [5].

2.3 Automatic check of measurement accuracy

The reactor temperature etalon checks accuracy in the measurement of temperature and temperature difference in each measurement cycle.

By the term monitoring of accuracy in the measurement of temperature and temperature difference, the monitoring of random error component in the measurement of temperature and temperature difference, the monitoring of presence of systematic error component in the measurement of temperature, and the monitoring of presence of systematic error component in the measurement of temperature difference are understood.

2.3.1 Method for monitoring the random error component in measurement

The calculation of random error component in the measurement with OT is based on double measurement of temperature by means of OT in each measurement point. The magnitude of the random error component, as expressed by square root deviation in each measurement cycle, is determined from differences of temperatures measured with OT1 and OT2 according to the equation:

$$s_{MOT} = \sqrt{\frac{1}{11}\sum_{j=1}^{12}\left(\Delta t_{MOTj} - \bar{\Delta t}_{MOT}\right)^2} \qquad \text{...(1)}$$

where: $\Delta t_{MOTj} = (t_{OT1} - t_{OT2})$ difference of temperatures measured with OT1 and OT2 in j- KST, [°C]

$\bar{\Delta t}_{MOT} = \frac{1}{12}\sum_{j=1}^{12}\Delta t_{MOTj}$ average value of differences between temperatures OT1 and OT2 in legs, [°C]

2.3.2 Method for monitoring the presence of systematic errors

Determination of the presence of systematic error component in the measurement of temperatures and temperature differences measured by means of OT is based on the scheme of measurement in Fig. 1 and on the fact that the accuracy of measurement with TČ calibrated under real conditions approaches the accuracy of measurement with OT [5].

The principle of monitoring the presence of systematic error consists in that any systematic error occurring in any element in the scheme in Fig. 1 has different impact on the measurement with OT, than on the measurement with TČ. If the difference between the measurements with OT and TČ is known at the beginning of unit start-up, it is then possible to monitor the presence of systematic errors in the course of unit operation by monitoring this difference. This consideration will be expressed in mathematical terms below.

At the beginning of fuel cycle, following the first achievement of the rated power level, initial differences between OT and TČ in the measurements of reactor coolant temperature $(\delta_t)_0$ and in the measurements of reactor coolant temperature difference $(\delta_{\Delta t})_0$ will be determined according to the equations:

$$(\delta_t)_0 = \frac{1}{6}\sum_{i=1}^{6}(t_{RTC} - t_{ROT})_i \qquad \text{...(2)}$$

where: $t_{RTC,i}$ - temperature of coolant in i- loop measured by TČ, [°C]

t_{ROTi} - temperature of coolant in i- loop measured by OT, [°C]

$$(\delta_{\Delta t})_0 = \frac{1}{6}\sum_{i=1}^{6}(\Delta t_{RTC} - \Delta t_{ROT})_i \quad \text{...} \quad (3)$$

where: $\Delta t_{RTC,i}$ - temperature difference of coolant in reactor, measured by TČ in i- loop, [°C]

Δt_{ROTi} - temperature difference of coolant in reactor, measured by OT in i- loop, [°C]

During the subsequent course of the whole fuel cycle, the presence of systematic errors in reactor coolant temperature and temperature difference is monitored by monitoring changes in actual differences versus the initial ones, between OT and TČ, according to the following equations:

$$\delta_t = \frac{1}{6}\sum_{i=1}^{6}(t_{RTC} - t_{ROT})_i - (\delta_t)_0 \quad \text{...} \quad (4)$$

$$\delta_{\Delta t} = \frac{1}{6}\sum_{i=1}^{6}(\Delta t_{RTC} - \Delta t_{ROT})_i - (\delta_{\Delta t})_0 \quad \text{...} (5)$$

2.4 Diagnostic inspection

The reactor temperature etalon according to Fig. 1 is equipped also with an option of diagnostic controls.

2.4.1 Diagnostic control for the presence and point of fault

In the case that during the automatic control of accuracy according to point 2.3 it is found that the accuracy of measurement does not comply (meaning that one of the parameters of accuracy exceeds the allowable limits), res. a suspicion exists that in the reactor temperature etalon a fault occurred in measurement circuits, it is possible to diagnose the presence and point of the fault.

The algorithm for revealing the presence and point of fault is based on the knowledge of various combinations of loop resistance in measurement circuits measured directly by the measurement and evaluation device in the temperature etalon [10]. The loop resistance is calculated directly from the measured voltage, from which temperature is determined, and from the additional voltage obtained by loading the measured voltage by loading resistor ***14*** using the switch-on contact ***13*** in Fig. 1.

2.4.2 Diagnostic control for the measurement of isolation resistance

The isolation resistance of the system is obtained from the voltage measured at the resistor ***11***, to which the current source ***9*** is connected by the switch-on contact *7* according to Fig. 1.

2.4.3 Diagnostic control for obtaining spurious thermovoltage

Spurious thermovoltages needed to be known for the possibility to eliminate them, are obtained by opening the switch-off contact ***8*** in Fig. 1.

3. The way of implementation and verification of properties of the reactor temperature etalon at units

The reactor temperature etalon has been implemented in the course of two decades at 12 units with VVER-440 reactors in Slovakia, Czech Republic and Bulgaria. During this gradual implementation of the temperature etalon at 12 units, the etalon has been upgraded gradually. The latest version of the temperature etalon implemented at two Mochovce units – that will be described below – represents the most advanced type.

During the use of 12 temperature etalons of reactor, the first of which have been in use for more than 20 years, also their properties have been verified in detail.

3.1 Description of the most advanced type of the reactor temperature etalon implemented

The most advanced type of the reactor temperature etalon at Mochovce units 1 and 2 implemented, according to the detailed design [11], represents a version with the most advanced components for establishing measurement trains and mainly measurement and evaluation devices. It was installed at unit 1 in 1998 prior to unit commissioning, at unit 2 in 1999. The KST was installed in circulation piping according to Fig. 2, at V-213 units according to Fig. 3. In the measurement channels, the most advanced cabling is used with the emphasis on resistance against EMI. The cabling is led into the measurement and evaluation device of the etalon situated in the room for operational measurements in the computer complex at higher level (VKVÚ) at both units. All the functions of the equipment according to Fig. 1 are coordinated by two personal computers (PC) which at the same time communicate mutually and with VKVÚ by means of network connections. The core of the equipment is a measurement central complex Hewlett-Packard containing a group of multiplexers and an A/D transducer having high discrimination capacity with a maximum suppression of interference signals and with adequate speed. By means of the complex, such accuracy of measurements is achieved which exceeds significantly the accuracy of operational measurement systems. The realization of the measurement and evaluation device with the arrangement of its individual components is shown in Fig. 4. A more detailed description of the technical solution of the etalon at Mochovce units is shown in associated technical documentation [12].

The measurement and evaluation device enables to monitor at a display the performance of the measurement and evaluation PC. The measurement PC provides the measurement of data, their conversion to physical parameters and recording in temporary databases. The data are then transferred by network into the evaluation PC where they are evaluated, recorded and processed together with other operational measurements obtained from VKVÚ by data transfer in network. The form of output from the temperature etalon on which temperature data are shown together with the corresponding parameters of accuracy (• random error of measurement of coolant temperature and temperature difference; • systematic error of temperature measurement; • systematic error of temperature difference measurement) together with a statement whether the accuracy of measurement complies with, is shown in Fig. 5.

If all the parameters of accuracy are in the allowed ranges the message: „ACCURACY OF MEASUREMENT COMPLIES“ is displayed on the display in green color. If any of the parameters of accuracy exceeds the allowed limits, it is highlighted in red and simultaneously it is displayed in red color on display: „ACCURACY OF MEASUREMENT DOES NOT COMPLY“.

3.2 Verification of properties of the reactor temperature etalon under real conditions

The properties of the reactor temperature etalon were verified in first realizations under laboratory conditions; later on during long-term at 12 units built. Among the most important properties, the accuracy of measurement, and the automatic control of accuracy and diagnostic control belong.

3.2.1 Verification of the measurement accuracy

The correctness of the design accuracy of the reactor temperature etalon shown in section 2.2 was verified by finding the actual accuracy of the reactor temperature etalon under real conditions. The actual accuracy of temperature etalons was obtained in the following way:

a) Long-term monitoring of parameters of measurement accuracy of the reactor temperature etalon under real conditions as shown in sections 2.3.1 and 2.3.2 at a number of units. The results are shown in [5,13,18,19,20].

b) Review by the Czechoslovak Institute for Metrology (ČSMÚ) at Bohunice unit 4. During this review, a check of combined sensors of temperature, measurement trains, power supply current, normal resistance and measurement and evaluation device were done. The results are shown in [17].

c) Comparison of temperatures from the reactor temperature etalon with those obtained from indirect measurements of temperature in loops during quasi-isothermal conditions by means of measuring the pressure of saturated steam in secondary system. This method of indirect measurement of temperature is known [18]; the results from comparison at Bohunice unit 4 are shown in [19].

d) Comparison of temperatures from the reactor temperature etalon with those from noise thermometry. Noise thermometry is an absolute, very precise method for temperature measurement [20]. Sensor of noise thermometry and KST of the temperature etalon were located besides each other in cold and hot legs of the loop No. 1 at Bohunice unit 2. The obtained results are shown in [21].

The conclusions from the verification according to points a) to d) are unambiguous. The actual accuracy of the measurement of coolant temperature and temperature difference by the temperature etalon is better than the design accuracy.

3.2.2 Verification of the automatic accuracy control

The verification of the automatic accuracy control of the reactor temperature etalon was done under both laboratory and real conditions.

The verification under laboratory conditions was carried out in such a way that the reactor temperature etalon was fabricated completely under laboratory conditions, KST were situated in two different furnaces with their temperatures set to those in hot and cold legs, and then potential measurement errors in various magnitudes and combinations were simulated and their impact on the accuracy parameters was obtained. The results are shown in [22]. The conclusion from the verification is that any error of measurement occurring in the reactor temperature etalon and affecting the accuracy of the measurement of temperature and temperature difference, will be significantly registered at least at a single accuracy parameter.

The verification of the reactor temperature etalon has been done under real conditions, on the occasion of occurrences of real errors at units. This verification also confirmed that the three accuracy parameter used are representative ones for the accuracy control of measurement of the temperature etalon, that automatic control of accuracy is a reliable tool for monitoring the accuracy of measurement of temperature and temperature difference by the reactor temperature etalon.

3.2.3 Verification of diagnostic control

The verification of diagnostic control during the monitoring of occurrence and point of fault was done under both laboratory and real conditions during simulations of various potential faults in the measurement circuits of the reactor temperature etalon (open and short circuits at various points). The results of verification have confirmed that the above mentioned diagnostic control reliably reveals the occurrence of faults in measurement circuits and in the case of a fault occurrence, the control finds its point (e.g., in the case of an open circuit in thermocouple in KST, it finds the number of KST, the number of TČ and which of its electrodes is damaged).

Diagnostic controls for the measurement of isolation resistance of the complete temperature etalon and for the revealing of spurious thermal voltage were verified by comparison with other measurement devices, and the results were positive.

4. Benefits from the use of reactor temperature etalon at units

The ways of using the temperature etalons at 12 units are different. At 10 units, they have been used as non-standard systems that should serve for precising and controlling the accuracy of the standard reactor temperature measurements. At two units (Bohunice V-1), they are additionally used as standard operational systems for maintaining reactor thermal power level. The benefits from the utilization are undisputed, mainly as follows:

- Metrology relations are ensured. It has a positive impact on the enhancement of accuracy of the standard reactor temperature measurements (assemblies + loops) prior to unit start-up to power [5,13, 23]. At the two Bohunice V-1 units, systematic errors in the measurement of reactor temperature difference with the magnitudes of 0,3°C at unit 1 and 0,6°C at unit 2 were found and remedied. The remedy of these errors at unit 2 made it possible to uprate the reactor thermal power level by 28,5 MW [23]. At four Dukovany units and at two Bohunice units (units 3 and 4), the magnitudes of systematic errors in the measurement of coolant reactor temperature difference were found in the range up to 0,5°C [13] (systematic error in temperature difference of 0,1°C corresponds to approximately 5 MW of reactor thermal power).
- Possibility to monitor continually the accuracy of the standard reactor temperature measurements during fuel cycle is obtained. Knowledge of the measurement accuracy in the standard reactor temperature measurements is favorable for explaining anomaly conditions, which can occur during reactor control. Among the most typical anomalous conditions, the following can be shown: differences between the measured and calculated thermal power distributions in fuel assemblies that can limit the reactor thermal output, differences between the maintained and actual reactor thermal output, unexpected values of reactor bypass coefficient, etc. Knowledge of accuracy of the standard reactor temperature measurements is important also from the point of their conditions during fuel cycle for the needs of maintenance. Benefits from the accuracy monitoring of the standard temperature measurements are shown in other papers in the symposium.

Advantages of temperature etalon utilization and its features are in attachment 1.

5. Conclusions

The use of reactor temperature etalons at 12 units with VVER-440 reactors confirmed their positive impact on the accuracy of standard reactor temperature measurements. The actual measurement accuracy of coolant temperature and temperature difference by the reactor temperature etalon at units is better than the design accuracy for the measurement of reactor coolant temperature (0,18°C) and temperature difference (0,14°C). The automatic control of measurement accuracy in each measurement cycle gives at display an explicit color information whether the measurement accuracy is satisfactory. Its reliability is also high (except for the first installations of the reactor temperature etalon in which the measurement and evaluation part was not reliable satisfactory). Diagnostic codes enable to monitor the occurrence and points of faults.

Sensors of the reactor temperature etalon are related metrologically to etalons at higher levels, they serve for metrology provision of the standard reactor temperature measurements. The utilization of the temperature etalon for the calibration of standard reactor temperature measurements during quasi-isothermal and power conditions enables to obtain maximum achievable accuracy from the existing standard reactor temperature measurements, and enables to control their accuracy during reactor fuel cycle.

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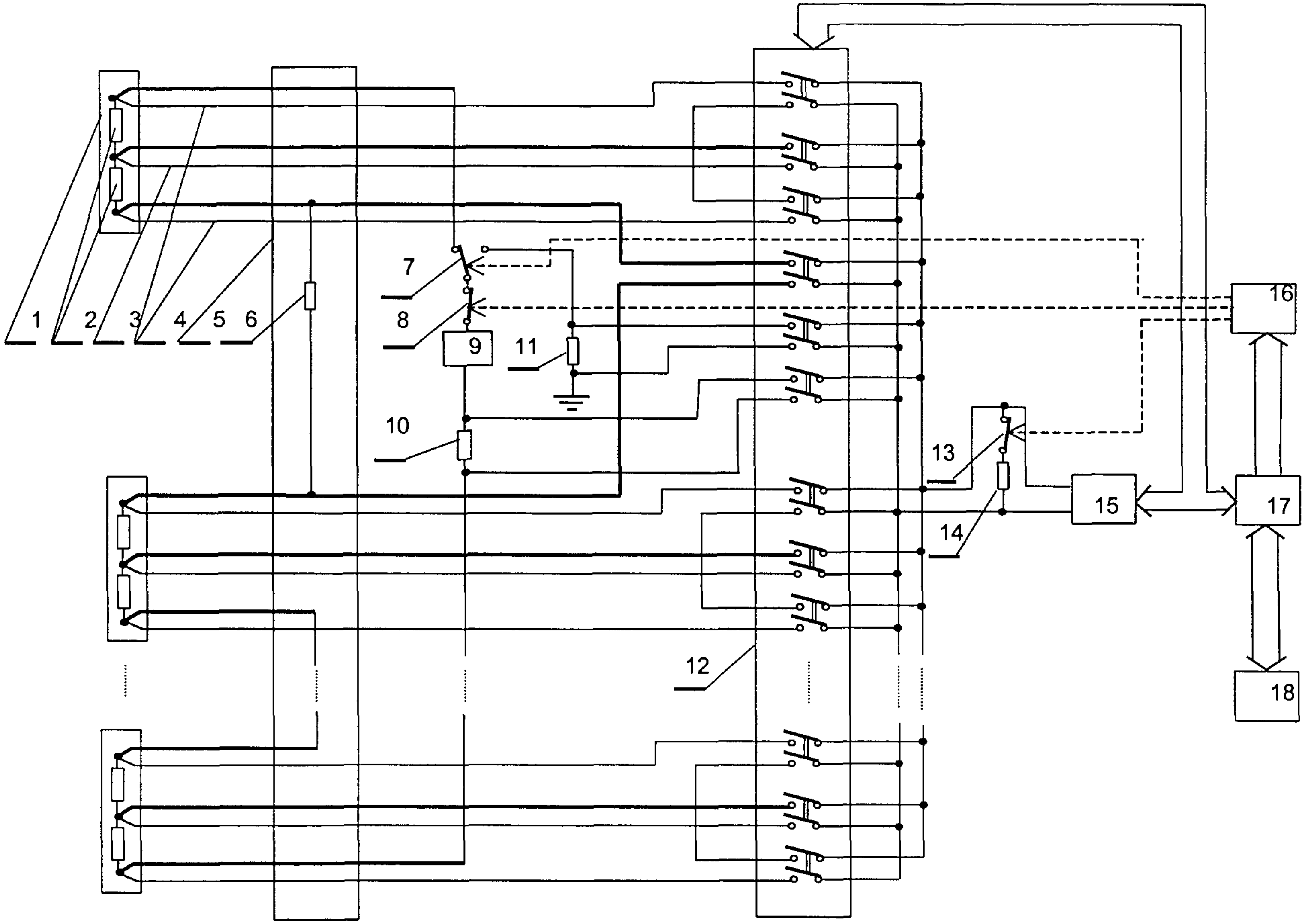
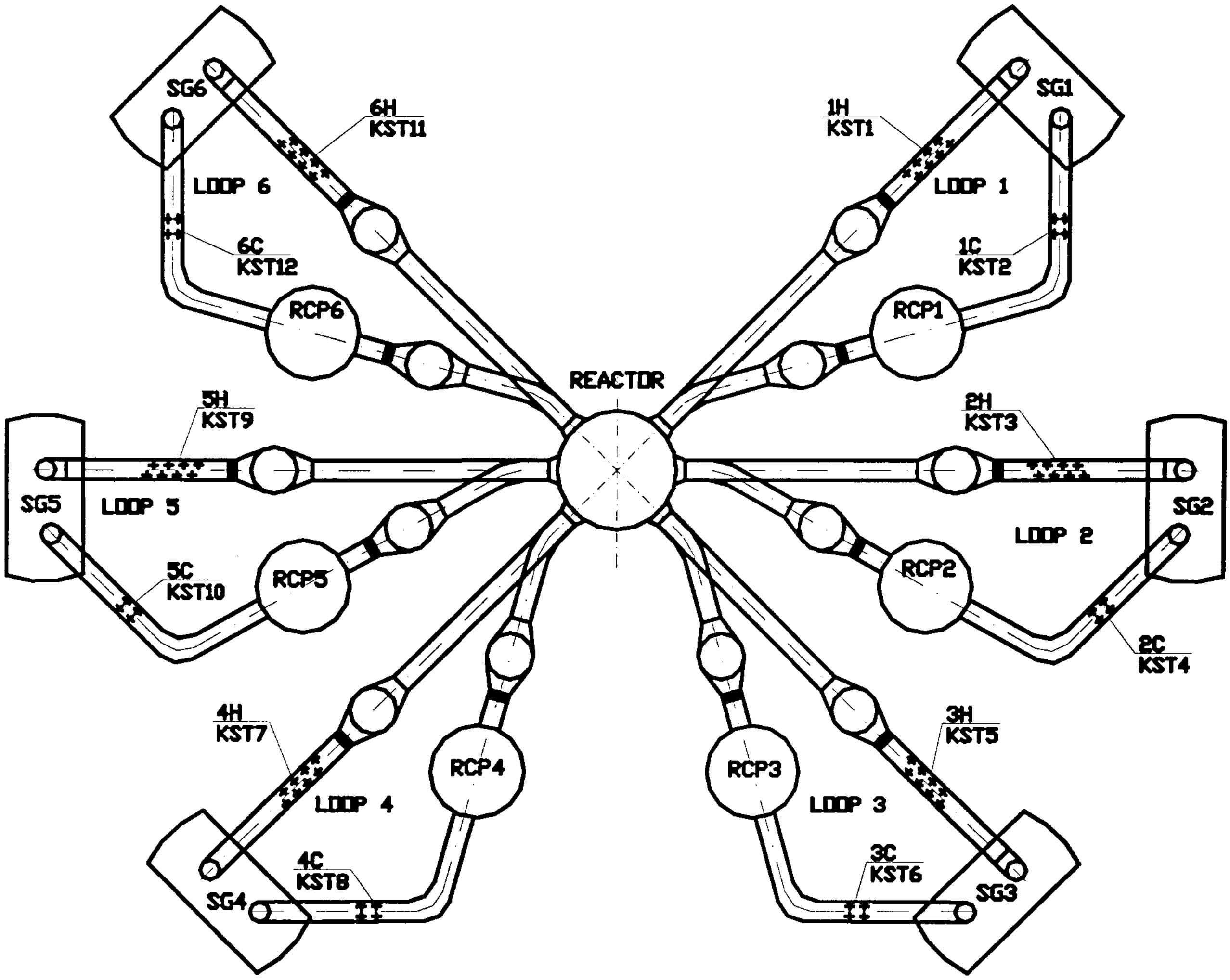


Fig. 1 Principal scheme of measurement of the reactor temperature etalon

Explanation:

1 – KST; 2 – OT1, OT2; 3 – measurement TČ2; 4 – power supply for TČ1 and TČ3; 5 – isothermal box; 6 – OT; 7 – switch-over contact; 8 – switch-off contact; 9 – current source; 10- normal resistance; 11 – resistance; 12 – multiplexor ; 13 – switch-on contact; 14 – loading resistor; 15 – analog-digital transducer; 16 – control element; 17 – computer; 18 – indication and recording device



LEGEND: PGi- steam generator in loop i-

HCČi- reactor coolant pump in loop i-

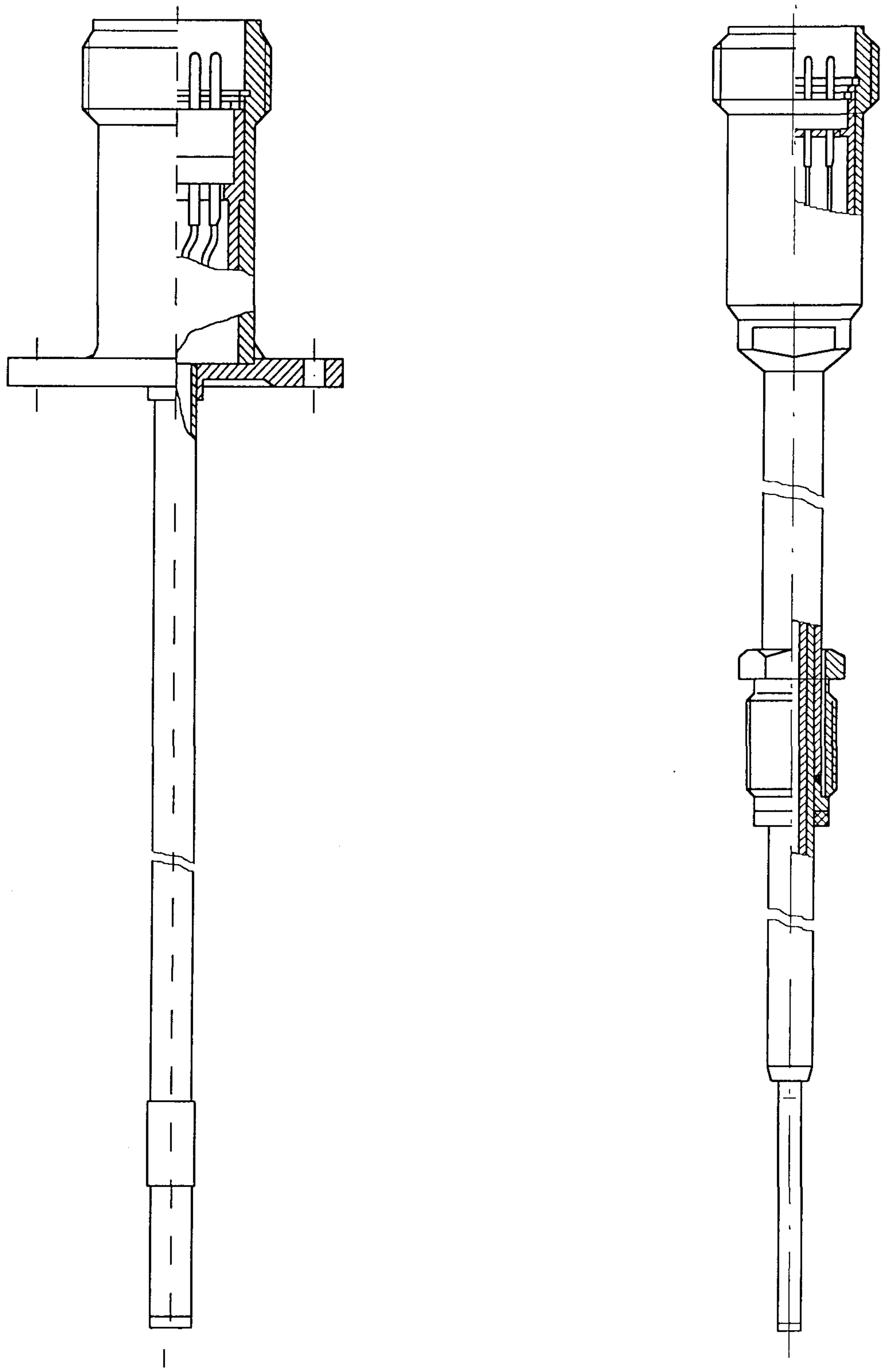
\+ - location of wells for temperature measurement

2H / KST3 location of combined sensors;

in upper part, the loop number and leg type (hot, cold) are designated

in lower part, the leg number is designated in which combined sensor of temperature is situated (it is simultaneously the number of combined sensor of temperature)

Fig.2: Scheme of KST distribution in circulation loops, type V-213



Type KST-1 (V-230)

Type KST-2 (V-213)

Fig. 3: Form of KST in the realization for V-213 and V-230 reactors

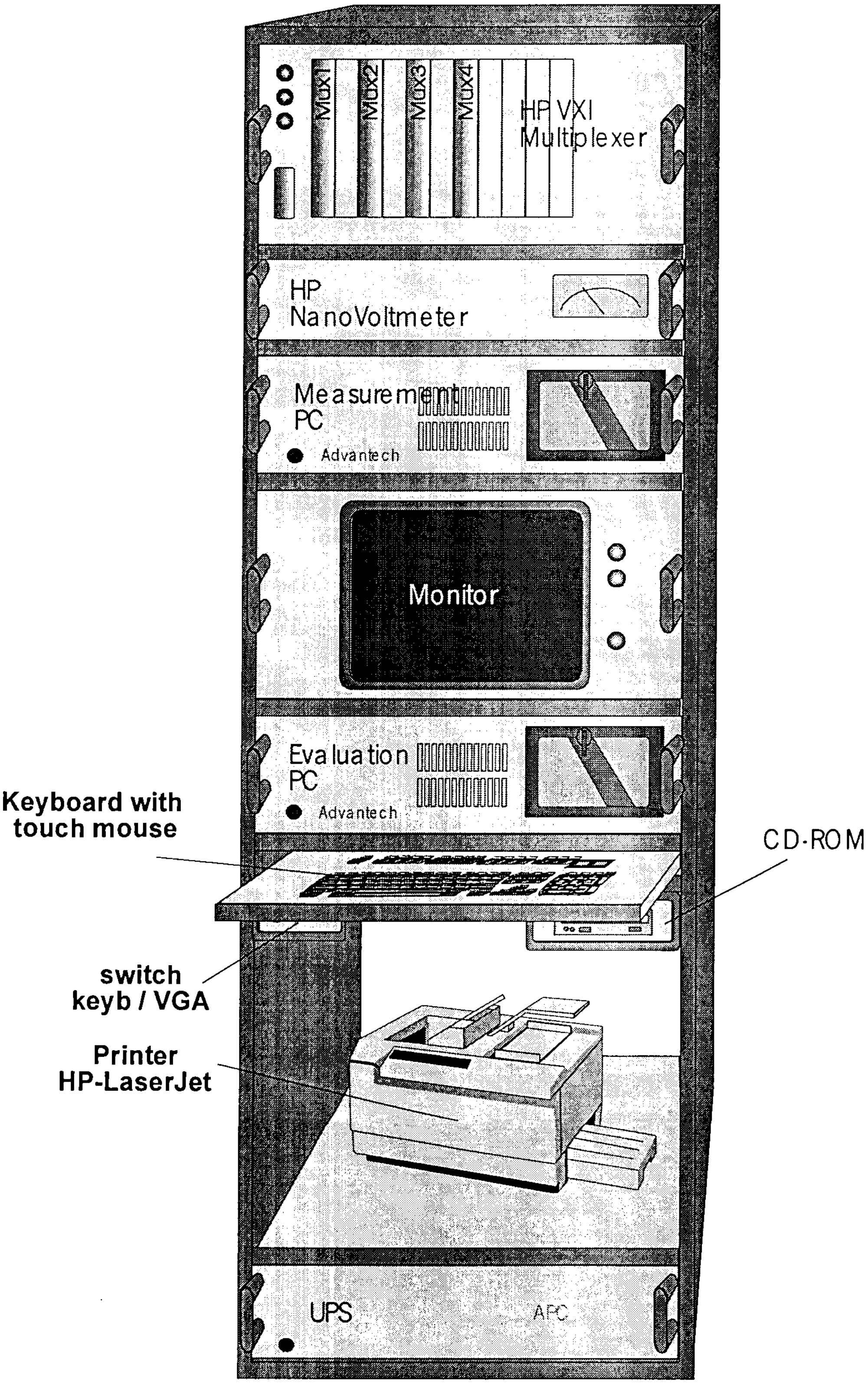
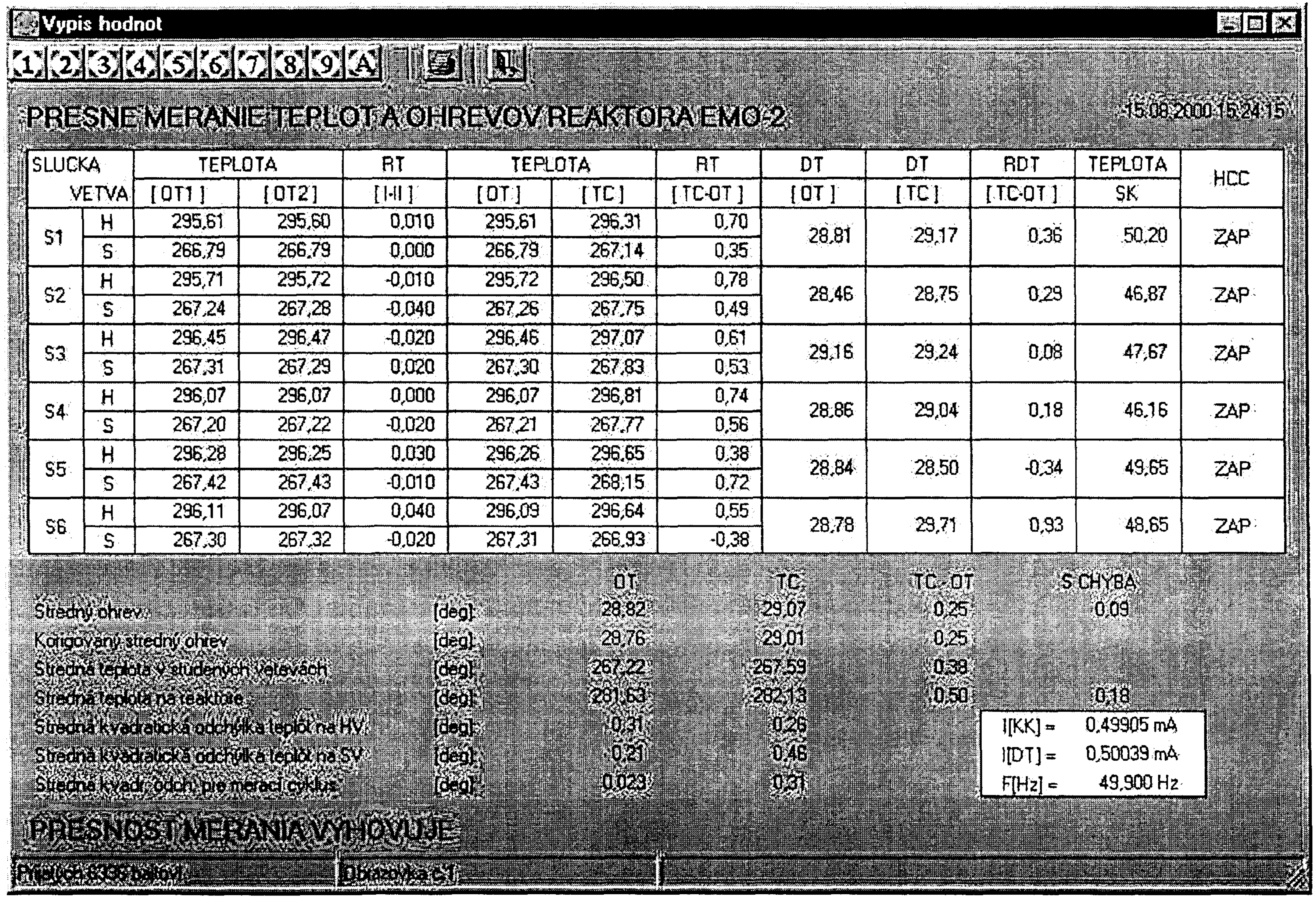


Fig. 4: View on the measurement and evaluation device of the reactor temperature etalon



PRESNE MERANIE TEPLOT A OHREVOV REAKTORA EMO-2

15.08.2000 15:24:15

SLUCKA		TEPLOTA		RT	TEPLOTA		RT	DT	DT	RDT	TEPLOTA	HCC
	VETVA	[OT1]	[OT2]	[I-II]	[OT]	[TC]	[TC-OT]	[OT]	[TC]	[TC-OT]	SK	
S1	H	295,61	295,60	0,010	295,61	296,31	0,70	28,81	29,17	0,36	50,20	ZAP
	S	266,79	266,79	0,000	266,79	267,14	0,35					
S2	H	295,71	295,72	-0,010	295,72	296,50	0,78	28,46	28,75	0,29	46,87	ZAP
	S	267,24	267,28	-0,040	267,26	267,75	0,49					
S3	H	296,45	296,47	-0,020	296,46	297,07	0,61	29,16	29,24	0,08	47,67	ZAP
	S	267,31	267,29	0,020	267,30	267,83	0,53					
S4	H	296,07	296,07	0,000	296,07	296,81	0,74	28,86	29,04	0,18	46,16	ZAP
	S	267,20	267,22	-0,020	267,21	267,77	0,56					
S5	H	296,28	296,25	0,030	296,26	296,65	0,38	28,84	28,50	-0,34	49,65	ZAP
	S	267,42	267,43	-0,010	267,43	268,15	0,72					
S6	H	296,11	296,07	0,040	296,09	296,64	0,55	28,78	29,71	0,93	48,65	ZAP
	S	267,30	267,32	-0,020	267,31	266,93	-0,38					

		OT	TC	TC - OT	S CHYBA
Stredný ohrev	[deg]	28,82	29,07	0,25	0,09
Korigovaný stredný ohrev	[deg]	28,76	29,01	0,25	
Stredná teplota v studených vetevách	[deg]	267,22	267,59	0,38	
Stredná teplota na reaktore	[deg]	281,63	282,13	0,50	0,18
Stredná kvadratická odchýlka teplôt na HV	[deg]	0,31	0,26		
Stredná kvadratická odchýlka teplôt na SV	[deg]	0,21	0,46		
Stredná kvadr. odch. pre merací cyklus	[deg]	0,023	0,31		

I[KK] = 0,49905 mA
I[DT] = 0,50039 mA
F[Hz] = 49,900 Hz

PRESNOST MERANIA VYHOVUJE

Prijatých 8396 bajtov | Obrazovka č.1

Fig. 5: Form of output of reactor temperature etalon