MONITORING OF COOLANT TEMPERATURE STRATIFICATION AT PIPING COMPONENTS OF NPP VVER - 440

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1. Introduction

The components of NPP are exposed to load caused by high pressure and operating medium temperature during operation. These loads are characterized by changeable complexion and their effect gradually degrades material of components in consequence of fatigue process initiating damage by fatigue that can limit technical life of technological equipment and determine consideration about possible life extension of NPP units. To be able to identify the operating loads and to quantify their degradation effect on material of NPP components there is need to implement the system aimed at monitoring of real load of components stressed by pressure and temperature field. These systems are part of strategy, so-called aging management. Systems include monitoring of pressures and of temperature fields that are derived from temperature measurements installed directly on the sites with the appearance of temperature fields in wall of construction.

The same technical principle is possible to apply at experiment systems of coolant temperature measurement at circulation loops of primary piping for determination of uncertainty of unit thermal power measurement. Measured results is possible to use for monitoring of pipe aging of circulation loops during transients and steady states in relation to safety systems of nuclear power plant.

2. Temperature stratification

The significant part of temperature measurements in monitoring system is represented by measurements of temperature stratification. It arises in pipings of primary and secondary circuit of NPP at special conditions mainly in horizontal parts of piping connecting objects with constantly or temporarily various medium temperature. At low speed of flow creates layers with various temperature. Temperature stratification is caused by various density of warmer and colder water so that colder water flows at the bottom part of piping section and warmer water at its top part.

Typical technological junction in which temperature stratification arises is surge line, that connects warm branch of main circulation loop with pressuriser (P) with stable temperature difference app. 30°C and during transients 100 and more degrees. Incidences of temperature stratification is possible to identify during transients also at piping of SG feedwater and at main circulation piping (during natural circulation of coolant).

Temperature stratification can cause the significant load of piping in the places of complicated geometry (bends and places of connection to fastening up object), because the walls of pipe became deformed in consequence of various temperatures – top part became longer. It causes auxiliary stresses in the bends and other fittings. In addition, the deformation arises also at circular section. It shows as so-called "pear effect" that causes further tension in the place of piping connection and in the bends.

Measurement of unit thermal power at primary part of technology through temperature difference of coolant at circulation piping is realised by temperature sensors installed in the piping thermowells. For determination of the uncertainty of power measurement from coolant temperature stratification there are dedicated experimental measurement temperature systems which measure temperature difference of coolant of piping section indirectly at its surface. Temperature differences of circulation piping coolant can be caused by insufficient mixing at the plenum chambers, by irregular burn-up of fuel assemblies and by natural stratification at lower flows. Measured results are applicable also for monitoring of temperature stress at various experiments and unit modes.

3. Technical provision of coolant temperature stratification monitoring at circulation piping

Identification of arising and character of coolant temperature stratification can be provided by temperature measurement placed directly at piping.

For measurement inside piping are not advisable conditions in real construction of nuclear units of VVER. Therefore, the measurement is needed to be realised outside piping.

There is necessary to provide suitable accuracy of measurement in respect of measurement of temperature stratification to be applicable for further analyses of loading effects and measurement uncertainty of unit power. Previous installations realised by mechanical pressure of temperature sensor (shell thermocouple) at piping surface seemed to be only a little reliable. At this installation there is not possible to eliminate thermotechnical error that arises by non-defined heat transfer from piping surface to sensor. Experiments indicated that accuracy of measurement in this case considerably depends on force of sensor pushing at measured surface. For these purposes, there was chosen melting method of thermocouples measuring end connection to measured surface for temperature stratification measurements. To eliminate influence of melting procedure at the piping, the thermocouple wires of diameter 0.2mm were welded directly at the piping surface. According to the analyses of so created melting connections interference of piping material is negligible, it doesn’t overreach depth 0.1mm.

Thermocouple wires are from place of weld led in ceramic insulation inserted into protected steel belt that hereby fixes all construction of measurement head at piping and provides taking-out of measurement through heat insulation of piping to terminal box, from which compensation cables are taken-out to thermostatic box. Temperature of cold end of thermocouples is measured by resistance thermometer at compensation box. Measured thermoelectric voltages are led by shielded cable to measurement room, where they are digitalized and computerized. The computer converts measured signals on temperature in °C, filters theirs, saves theirs into files and records theirs at hard disk. Time slopes of measured temperatures are available in a real time or from historic database for chosen period and they can be displayed, described by printer or transferred for further processing.

Few years experience shows that applied method of thermocouple fastening as well as all set of measuring chains meets requirements for accuracy and long term reliability. At the present, 2-5 thermocouples placed equitably heightwise of piping diameter are used commensurate with requirements for respective measuring place.

4. Range and localisation of measurements installed at V1 and V2 of Bohunice

Temperature stratification measurements at units V1 and V2 of Bohunice were installed at surge lines and at SG feedwater nozzles. First measurements were installed in the 1993, 1994 at piping of V-1 and in the 1996 at piping of V-2.

Thermocouples were allocated at one half of external surface from above down. Their location was chosen so that they were able to measure temperature in sections distributive piping section on the same sections with respect to vertical axis of section (picture 1).

Range and location of measurements at 3. and 4. unit of V-2 is for surge line of volume compensation apparent from the picture 2.

Also all SG feedwater nozzles were fitted in by measurement (picture 3).

Before first start up of 2. unit of Mochovce the measurement belts for determination of unit power measurement uncertainty were installed at circulation piping. On basis of some experience from temperature measurements and physicist's estimates the mentioned belts were placed on hot legs of loop 5 and 6 and on cold leg of loop 3. Localisation of measurement is displayed at the picture 4. For hot legs, there was determined the place close to operating measurements used also for measurement of unit power. At cold leg there was used direct piping section between reactor nozzle and place of connection of emergency cooling injection for monitoring of coolant temperature stratification during maturing of this protection.

5. The results of temperature stratification measurement

The results of temperature stratification measurement at surge line of volume compensation show that temperature stratification approves at transient non-stationary mode as start-up and shut-down of unit. Limits and conditions of unit performance allow temperature difference between main circulation piping (MCP) and pressuriser till 140°C at start-up. It expressively influences range of temperature stratification in piping. At start-up, there were measured differences between top temperature and bottom temperature of piping till 100 and even more degrees.

At the shut-down of unit and at expressively changes of power (incidence of emergency protection EP turbine outage), the identification incidences are less expressive and always depend on topical difference between temperature of water in main circulation piping and in pressuriser. At the steady operation, the stratification occurs only in a short range and its incidence at 3. and 4. unit of V-2 is different. It bears on localisation of temperature interface between water effluent from pressuriser and water from primary piping. In case of third unit, the temperature interface is placed closely under pressuriser. That's why only a little of water warmed in pressuriser gets into surge line. It causes increase of top piping surface temperature next to pressuriser.

In case of fourth unit, temperature interface is situated by far closer to main circulation piping. As a matter of fact, surge line of this unit has a higher temperature than temperature of main circulation loop is. In the direction to main circulation piping (MCP) the temperature gradually decreases and equalises with temperature at MCP as late as at place of compensatory piping orifice to MCP. At transients, the difference in location of temperature interface shows as stratification event shift closer to MCP.

The cause of this difference between 3. and 4. unit isn't clearly explained. At the present, some possible interpretations are in a stage of development. However, must be emphasised that although this event seems to be interesting, it doesn't cause increased risk for lifetime of 3. or 4. unit of V-2. Major piping load arises from stratification at transients and it bears on topical situation dependent upon transient management, mainly at start-up of unit.

In respect of PG feedwater nozzles, the stratification events are identified mainly at start-up and shut-down of unit . At this time the temperature differences at piping section reach till 70°C (see picture 5-10).

Improvement of situation and alleviation of stratification incidences at SG feeding piping is expected from reconstruction of feeding heads (realised at V2 at present). This fact was proved true at Dukovany NPP.

Data acquired by measurement of temperature stratification at surge line of pressuriser and at SG feeding piping are according to loading effect divided to categories respecting the size of temperature differences and form of temperature field. Mentioned dividing was realised for purposes of evaluation of loading and piping fatigue damage. These categories come into computer system created by program file PMD, which computes loading at piping by using of finite element method. Hereafter, so computed stresses are evaluated for fatigue by method of rain flow. As a result is a data of accumulated fatigue damage in most loaded places for given period.

The results of computes of fatigue damage caused by stratification effects show that stratification events at piping can influence lifetime of piping and hereby all operational reliability and safety of NPP unit.

6. The results of measurements for determination of unit power uncertainty

During the 1st and the 2nd campaign of Unit 2 of Mochovce there were created graphic temperature curves from experimental measurements. The results show the need to analyse and evaluate data separately for steady and transient states of unit technology.

6.1 Analysis of measured temperature data during steady state in first campaign

Identification of coolant temperature stratification size at piping of circulation loop during steady state is very important mainly from view of determination of temperature unit power measurement uncertainty. The steady states are characteristic by stable temperature ratios, by open loop isolating valve (LIV) and by operation of all reactor coolant pumps (RCP). Graphic courses of several periods are recorded at picture 11 and 12.

The values of TC_V-S parameters representative temperature difference of upside and bottom of piping surface at hot leg of loops 5 and 6 reach values from 0,4°C till 0,75°C at individual power levels till to 100% unit power. During the 1st campaign of unit there weren't recorded any significant temperature differences of piping surface representative coolant temperature stratification. The measured values were at level of uncertainty of experimental temperature measurement.

6.2 Analysis of measured temperature data during transients at the 1st campaign

At transients, together with the changes of temperature and pressure conditions at primary and secondary circuit reactor power and states of RCP and LIV, there is important to identify coolant temperature field for purpose of determination of reactor power measurement uncertainty and size of temperature piping loading. During commissioning several realised experiments initiate transients. For purposes of evaluation there was interesting to analyse measured data in transients during reactor cooling mode at Unit 2 by nature coolant circulation.

Courses of measured values of TC_V-S parameters at loop 5 and 6 are noted at the picture 13 and 14. The test was aimed at verification of reliable start-up of nature circulation after RCP shut-down and determination of power which can be achieved by nature circulation at nominal heating app. 30°C. During test the loops 1, 4, 6 and 3 were gradually shut down by closed LIV. In state of RCP shut down the coolant circulation speed is from 10-40 min commensurate with number of closed LIV. Nature circulation ran in loop 5 without interruption. The difference TC_V-S achieved the maximum value app. 0.75°C during whole test. In respect of 6.loop with closed LIV, the difference between upside and bottom of piping was in maximum 38°C that represents significant gradient of coolant temperature field at shut-down branch of circulation piping. Measured temperature difference hereby characterises the size of piping temperature load.

6.3 Analysis of measured temperature data during steady states at the 2nd campaign

After the 2nd start-up of Unit 2 of Mochovce measurement at cold leg of loop 2 accrued to measurements on 5. and 6. circulation loop. (hereinafter called as 5H, 6H a 3S). Temperature curves on 5H, 6H and 3S till achievement of nominal power are included at pictures 15 -17. The temperature difference heightwise of piping on hot legs achieve values of 5H app. 2.5°C and of 6H app. 1,1°C. These difference values are at steady states similar for whole evaluated period of 5H and 6H. During operation of unit at the 2nd campaign there was on 3S recorded maximum TC_V-S temperature difference with value of 3,3°C.

7.3 Analysis of measured temperature data during transients at the 2nd campaign

During unit shut-down there was provided in cooperation with Mochovce to use circulation loop 5 and 6 for coolant nature circulation. Nature circulation ran separately on 5.and 6. loop. During this time all RCP were shut-down and LIV were open only at respective loop. The measured temperature curves are enclosed at picture 18 and 19. Graphs show measured temperature difference of top and bottom thermocouples TC_V-S at respective leg – for 5H app. 2,5°C and for 6H app.1,4°C. The measurements were evaluated for states of coolant nature circulation at temperature app. 30°C during reactor shut-down.

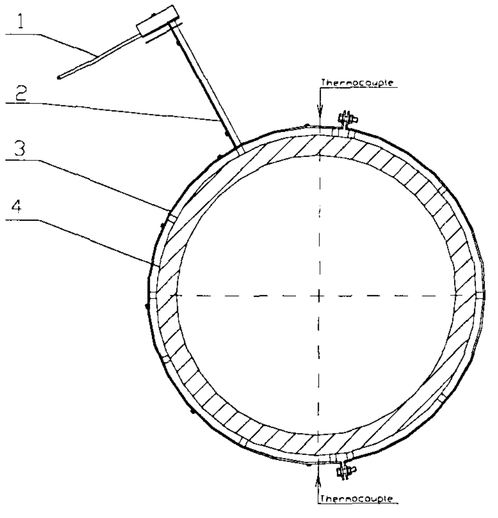
8 Conclusion

Monitoring of temperature stratification demonstrated that stratification events at surge line of volume compensation and at piping of SG feedwater can expressively affect loading and total lifetime of these technological junctions. Therefore stratification events deserve particular attention of NPP user. The results of measurements allowed to consider stress state at piping. By correct interpretation of stratification causes there is possible to optimise management of unit transients so, that stratification influence on equipment lifetime was minimal.

By realisation of experimental measurement at NPP Mochovce there were acquired data indirectly representative coolant temperature stratification at hot and cold legs of circulation loops. The results from measurements are applicable also for other units VVER-440 in Slovakia, Czech republic, Hungary, Bulgaria and countries of former USSR.

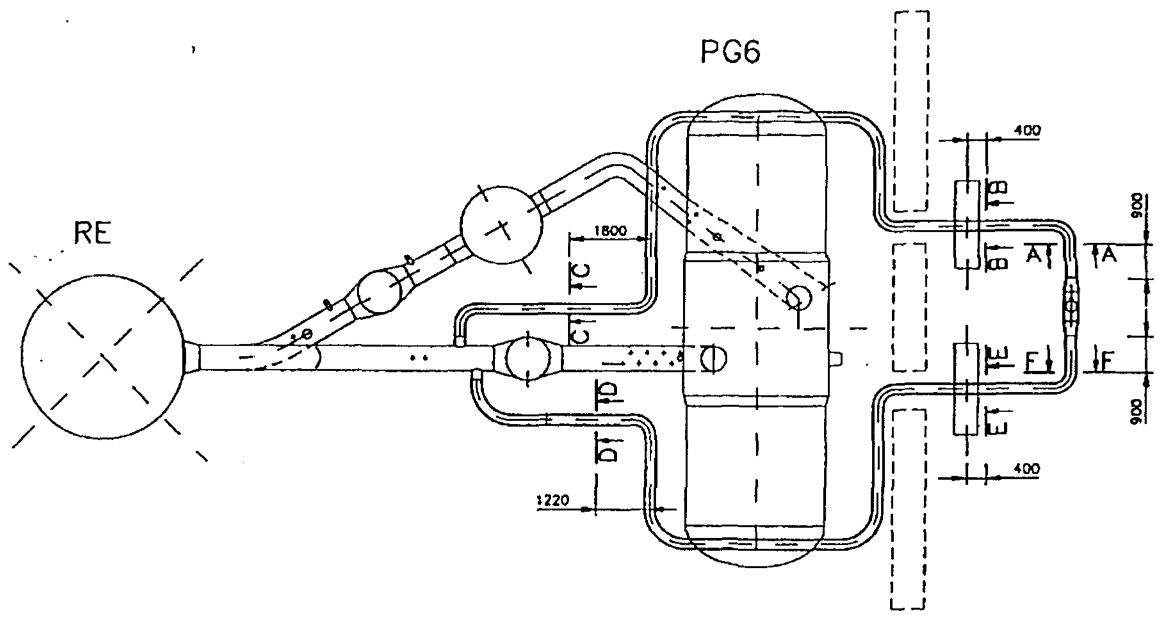
Based on results of measured data analyses during steady state there is possible to note that during the 1st campaign of unit operation weren't found any significant differences between top and bottom part of piping (till 0,75°C). The values of coolant temperature differences between top and bottom part of piping (TC_V-S) are near the accuracy of temperature measurement canals. The temperature differences between top and bottom part of piping (till 3,3°C) found at the 2nd campaign of unit operation will require calculation of corresponded coolant temperature stratification at piping.

Surveillance of gradients of coolant temperature field at transients, which are characteristic by changes of reactor power and RCP and LIV shut-down, has a big account to provision of unit safety operation. The results make possible to determine size of piping temperature loading, accuracy of power measurement, eventually modify courses of experiments and unit modes to minimise gradients and hereby extend primary piping lifetime.

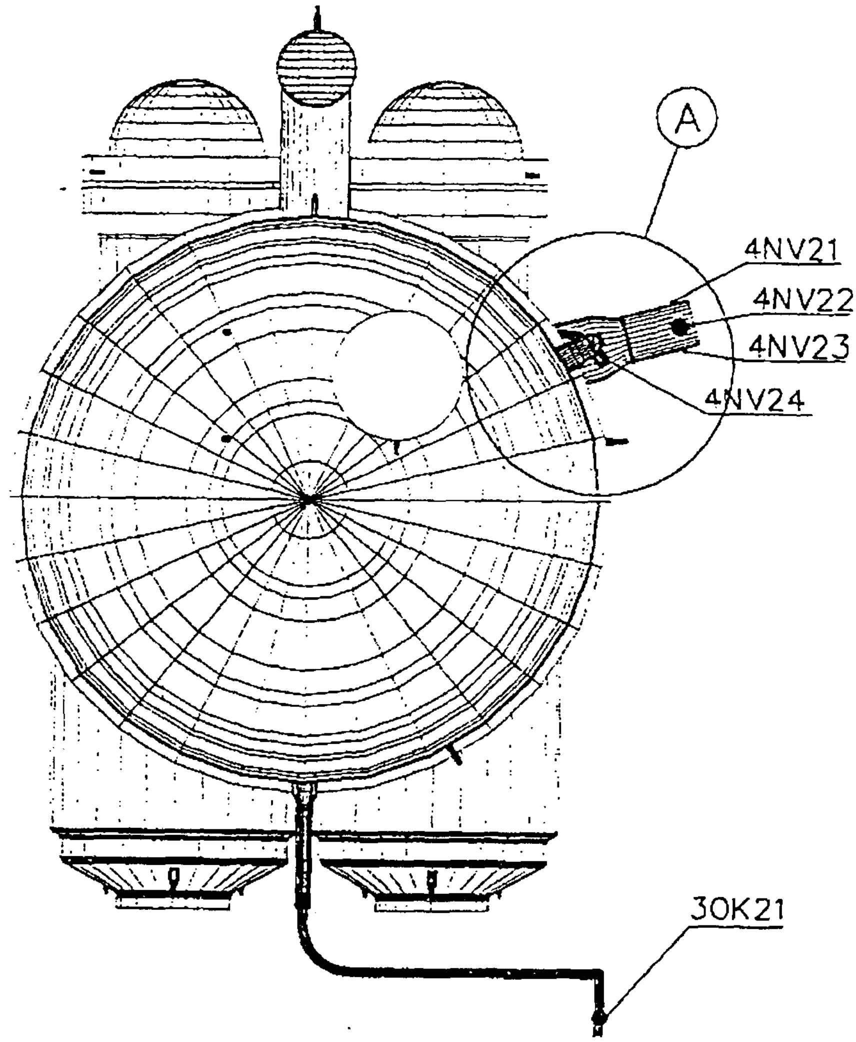


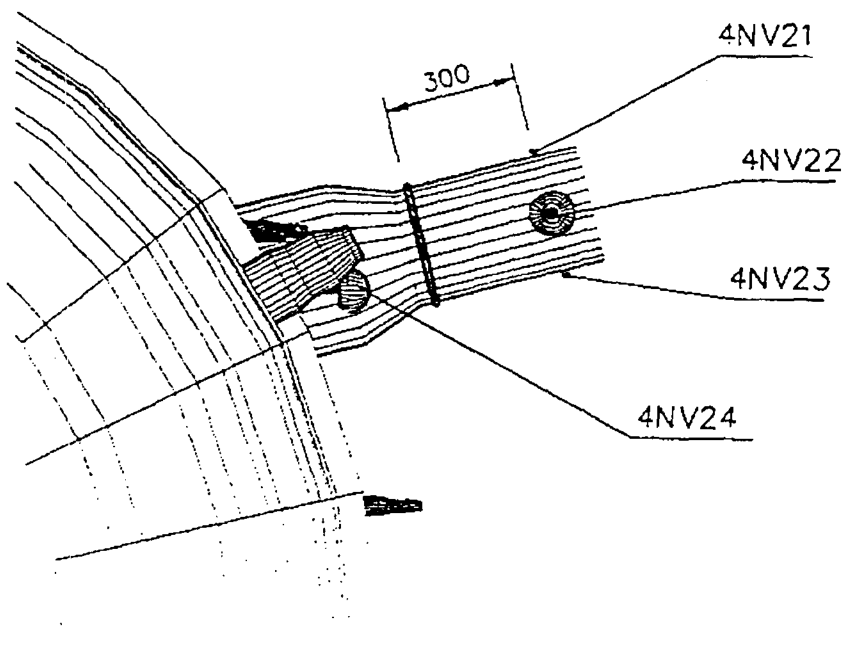
1. Output compensation cables
2. Leading cannal of thermocouples
3. Protective measuring belt of thermocouples
4. Technological piping

Picture 1 Construction of measurement belt

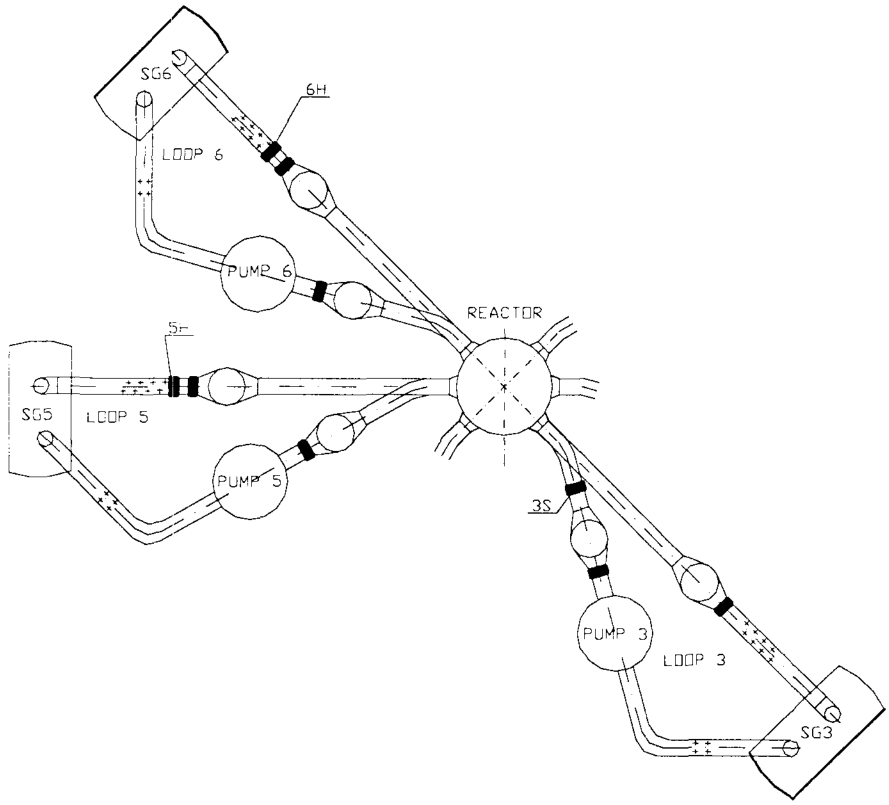


Picture 2 Place of temperature stratification measurements in NPP V2 – surge line

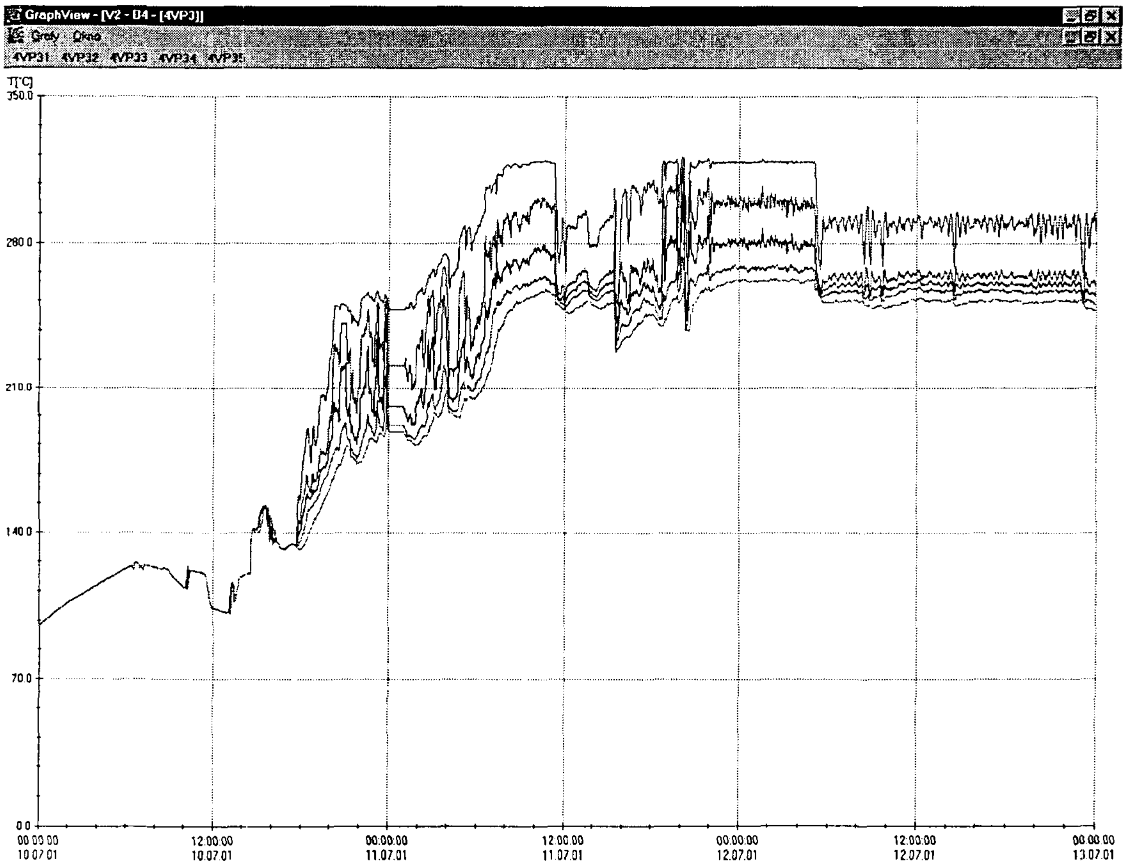




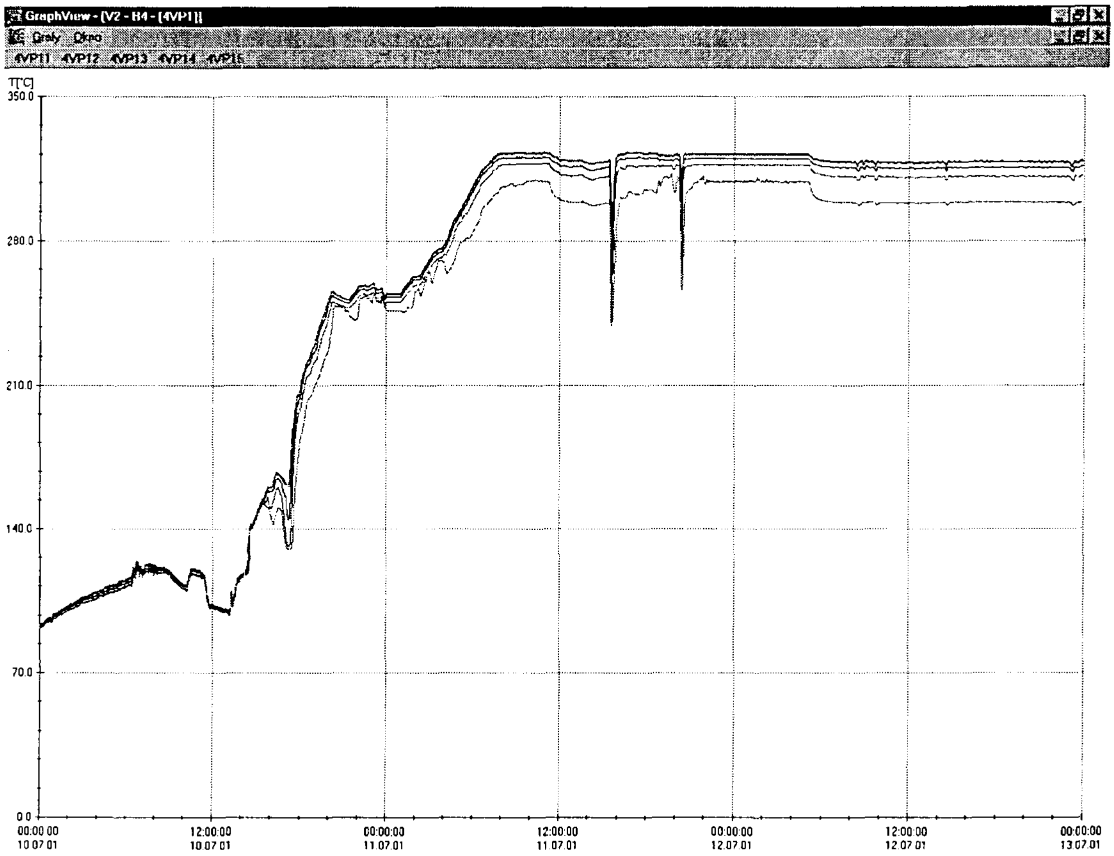
Picture 3 Place of temperature stratification measurements in NPP V2 – piping of SG feedwater



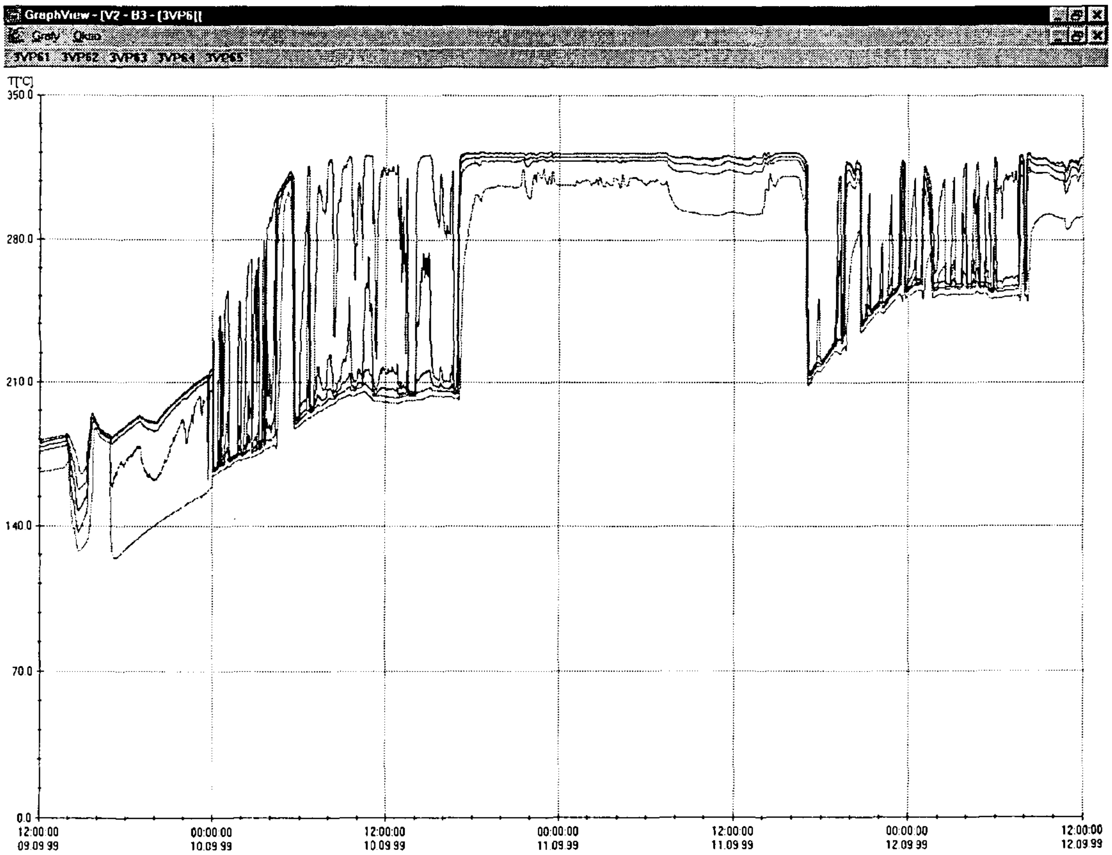
Picture 4 Place of temperature stratification measurements in Unit 2 Mochovce



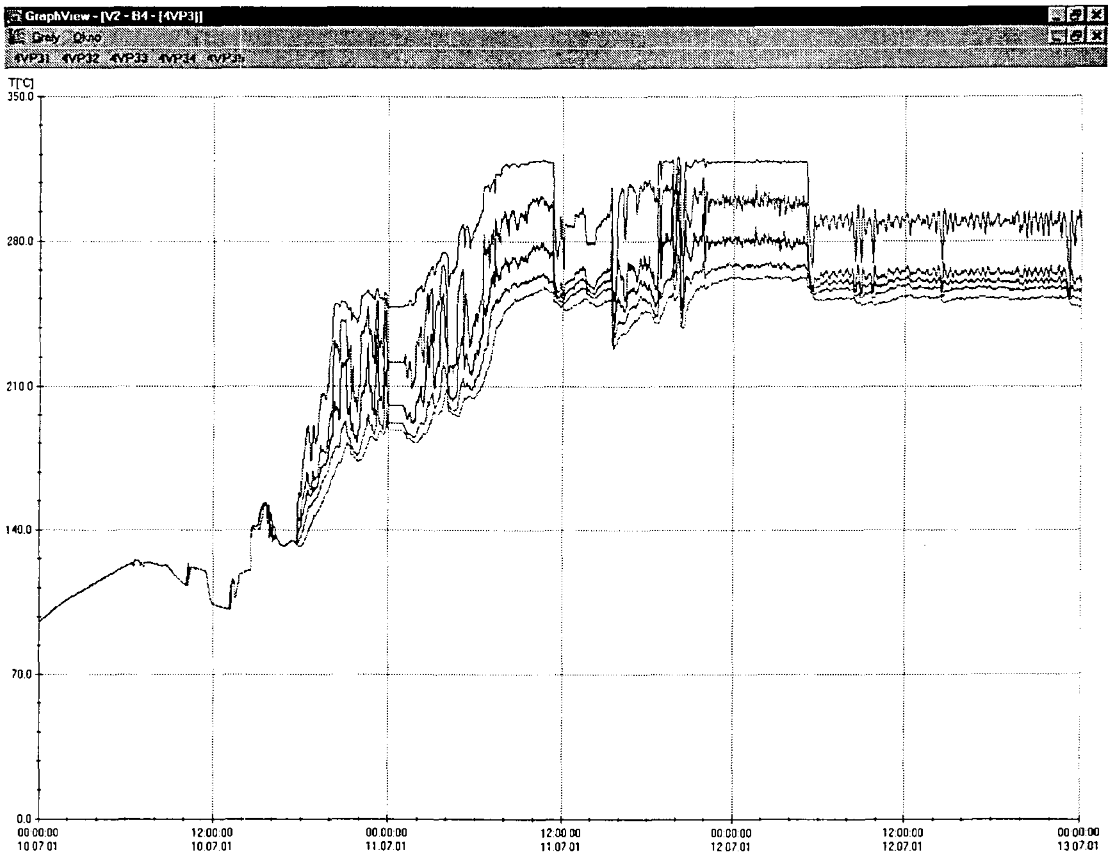
Picture 5



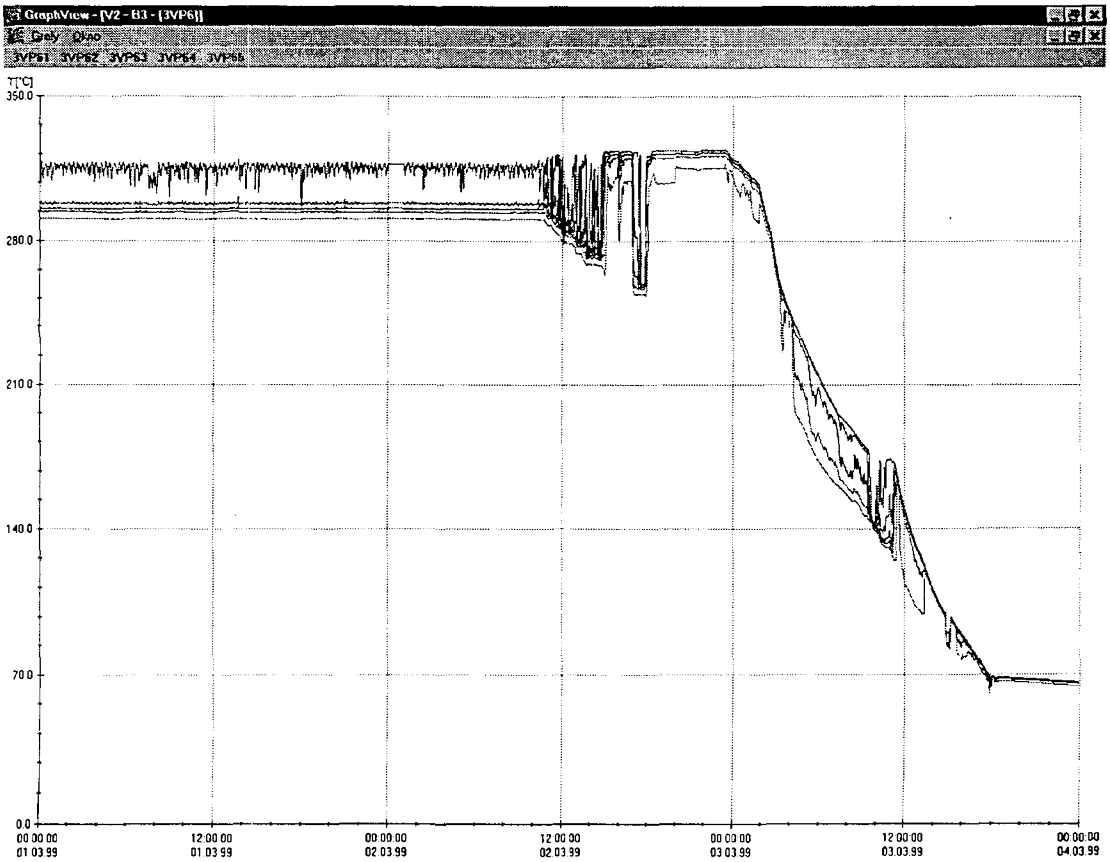
Picture 6



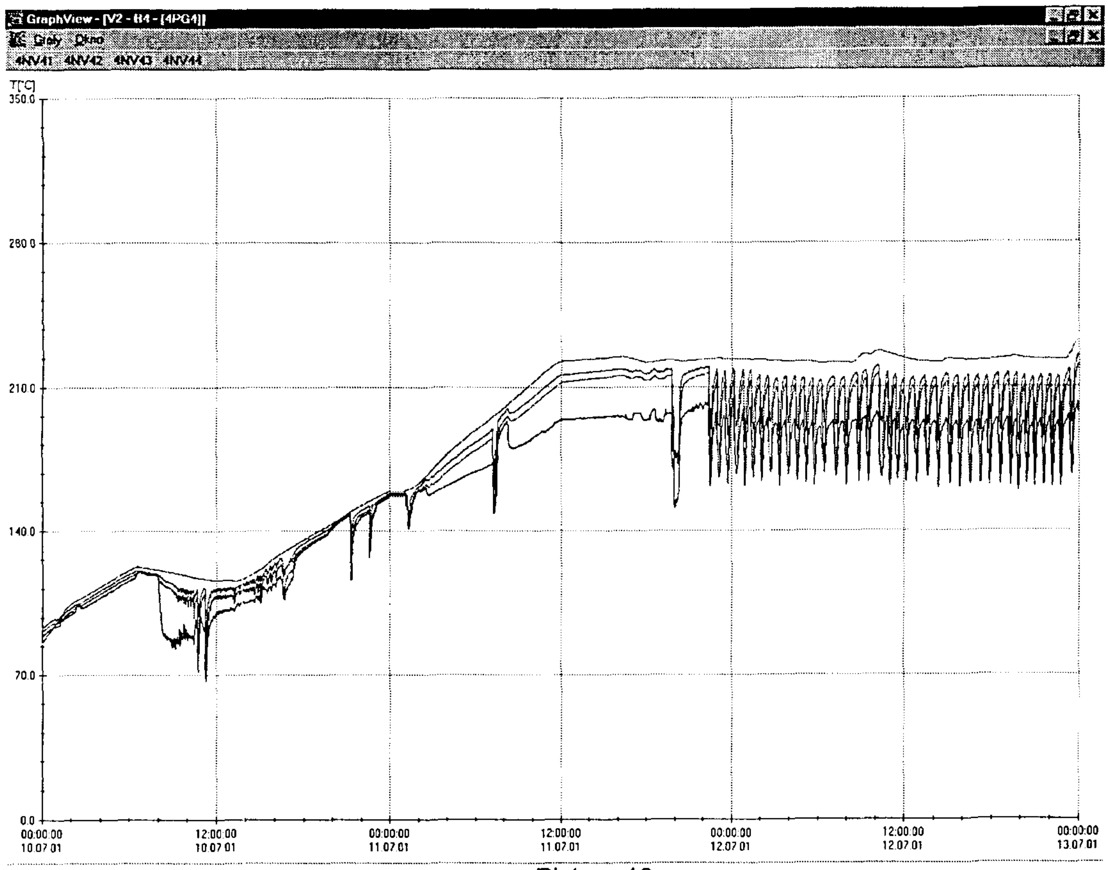
Picture 7



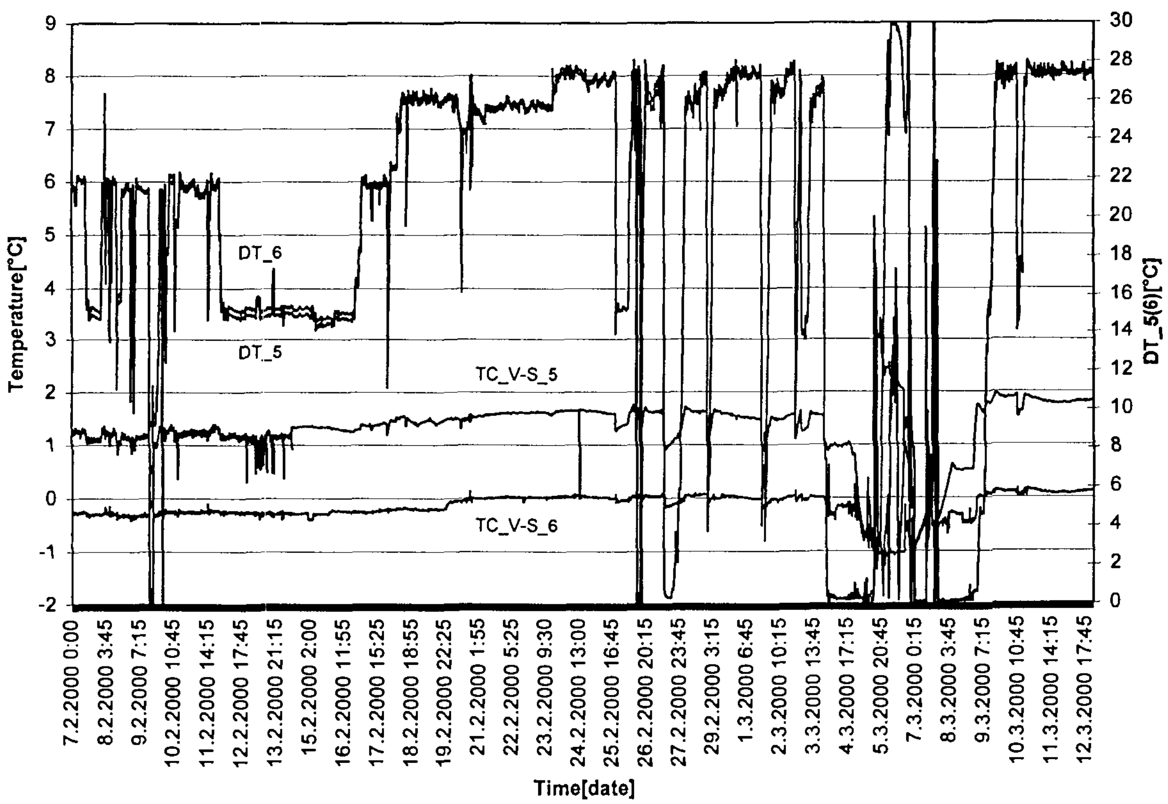
Picture 8



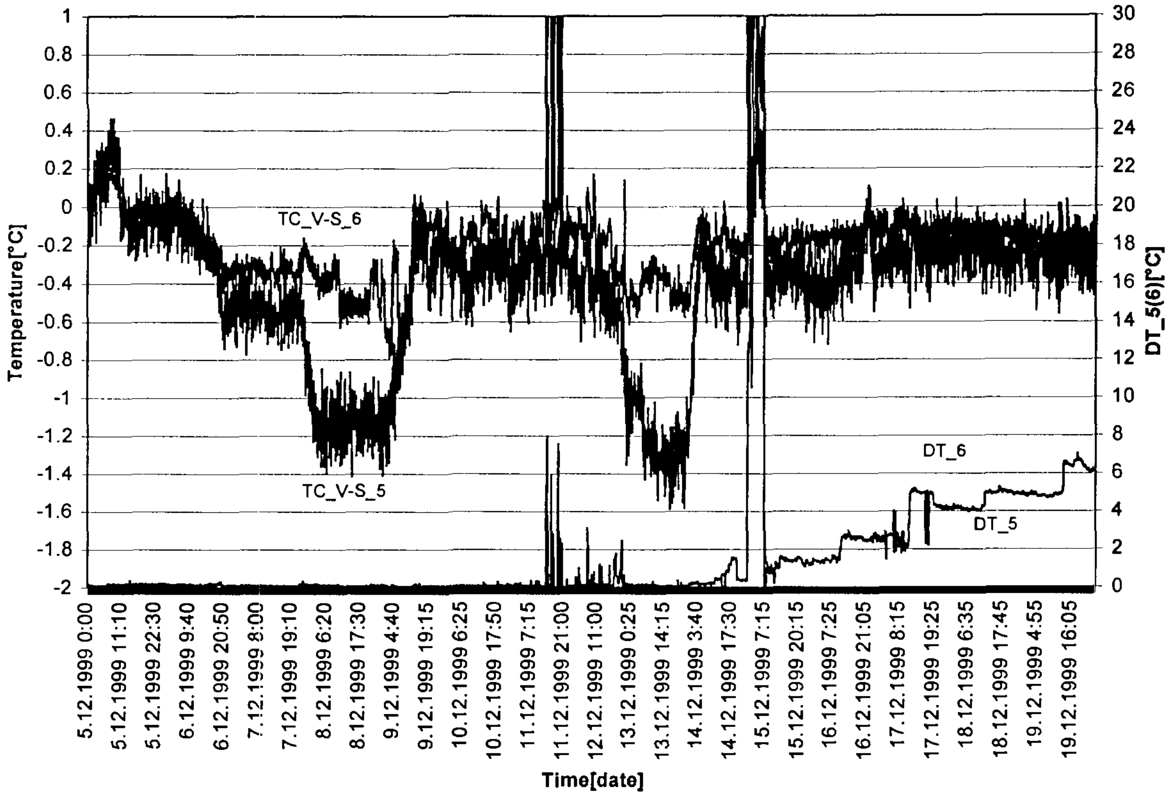
Picture 9



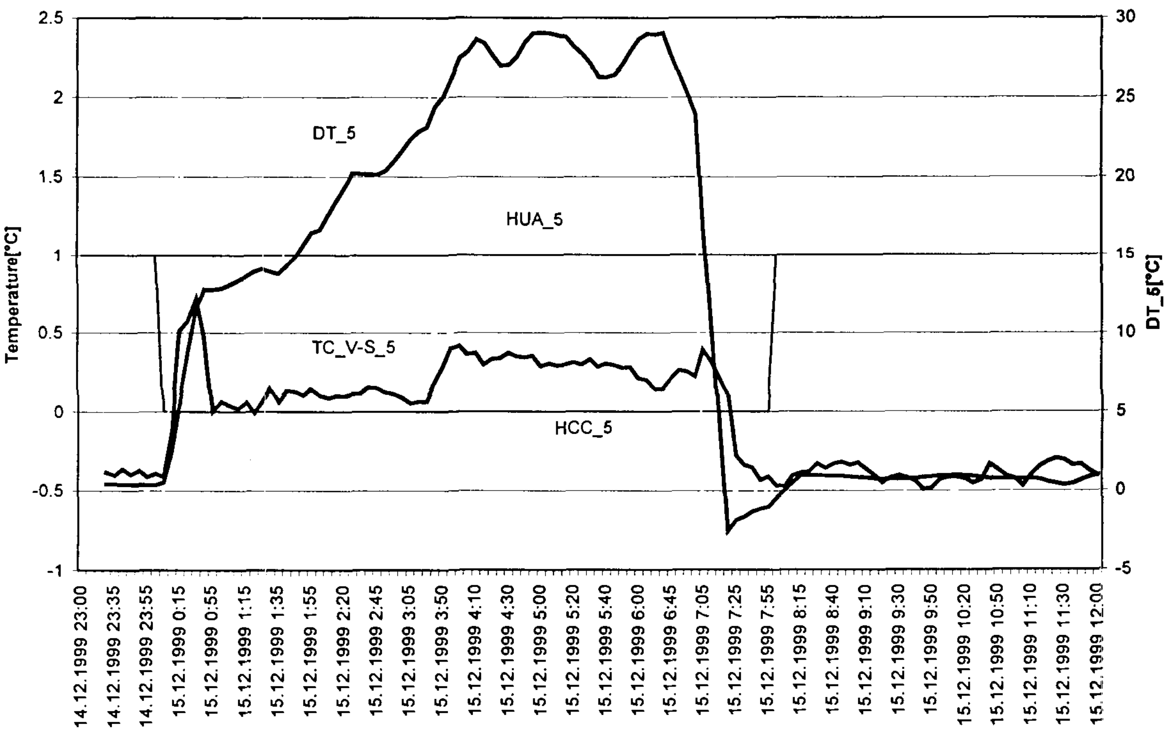
Picture 10



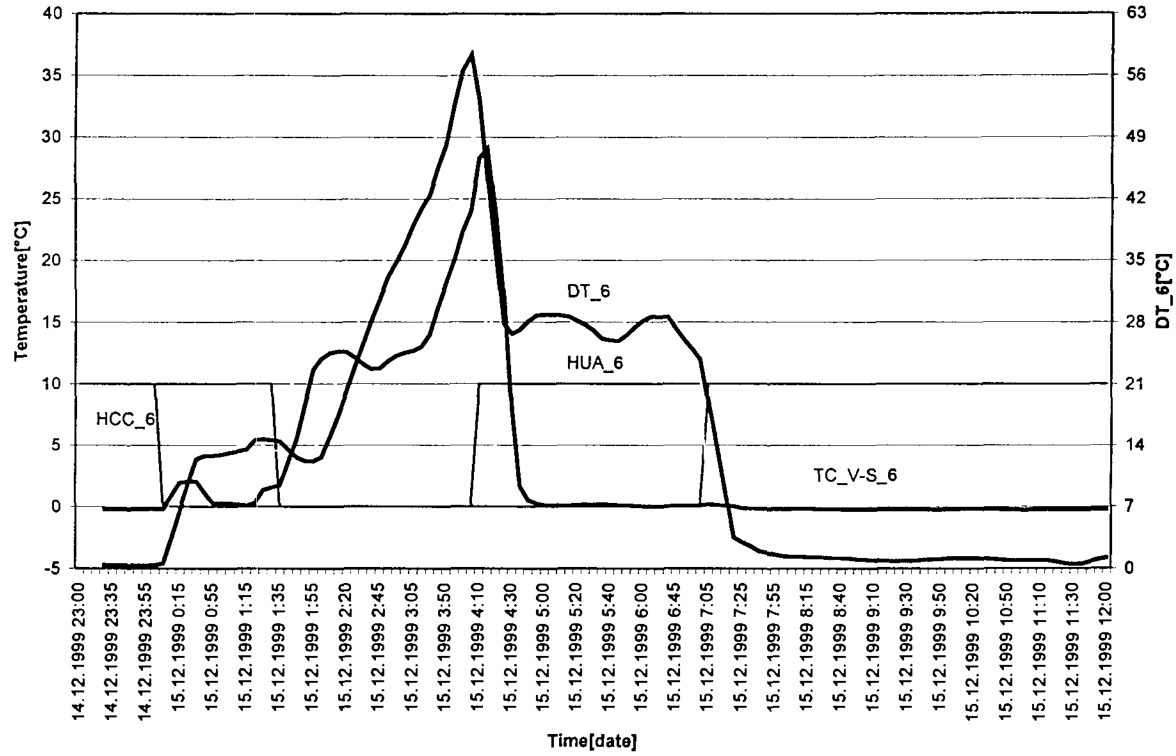
Picture 11 Curves of temp. differences TC_V-S on hot legs Unit 2 Mochovce – nominal power



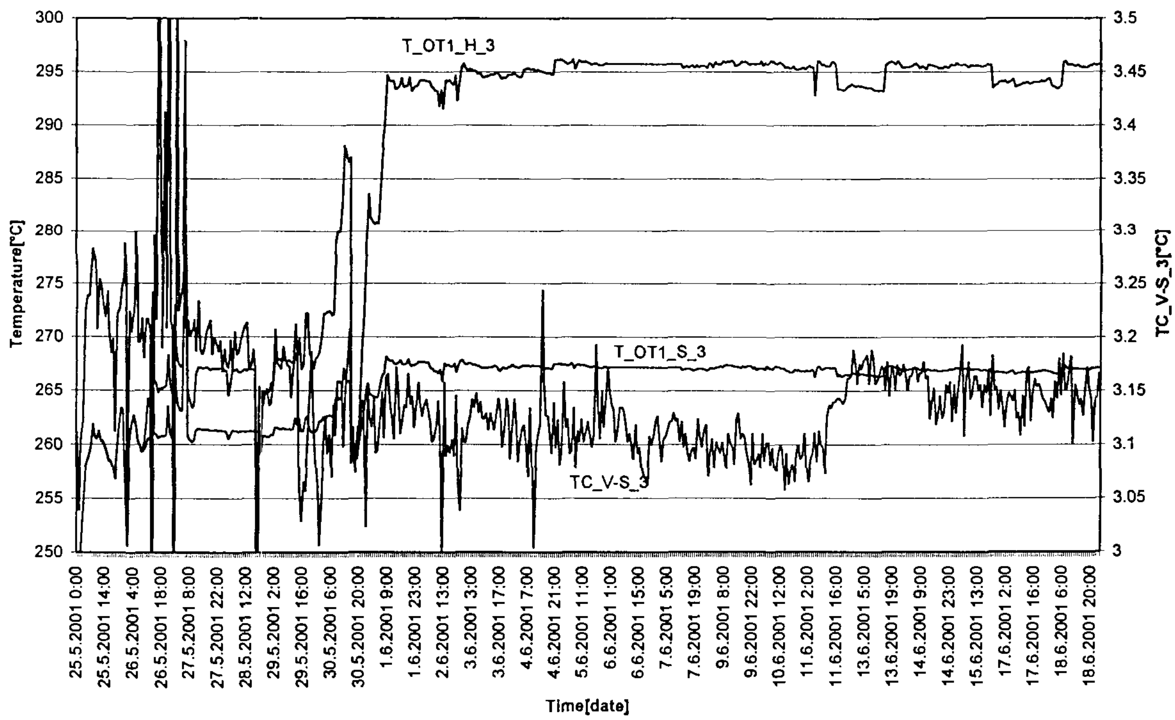
Picture 12 Curves of temp. differences TC_V-S on hot legs Unit 2 Mochovce – 20% of nominal power



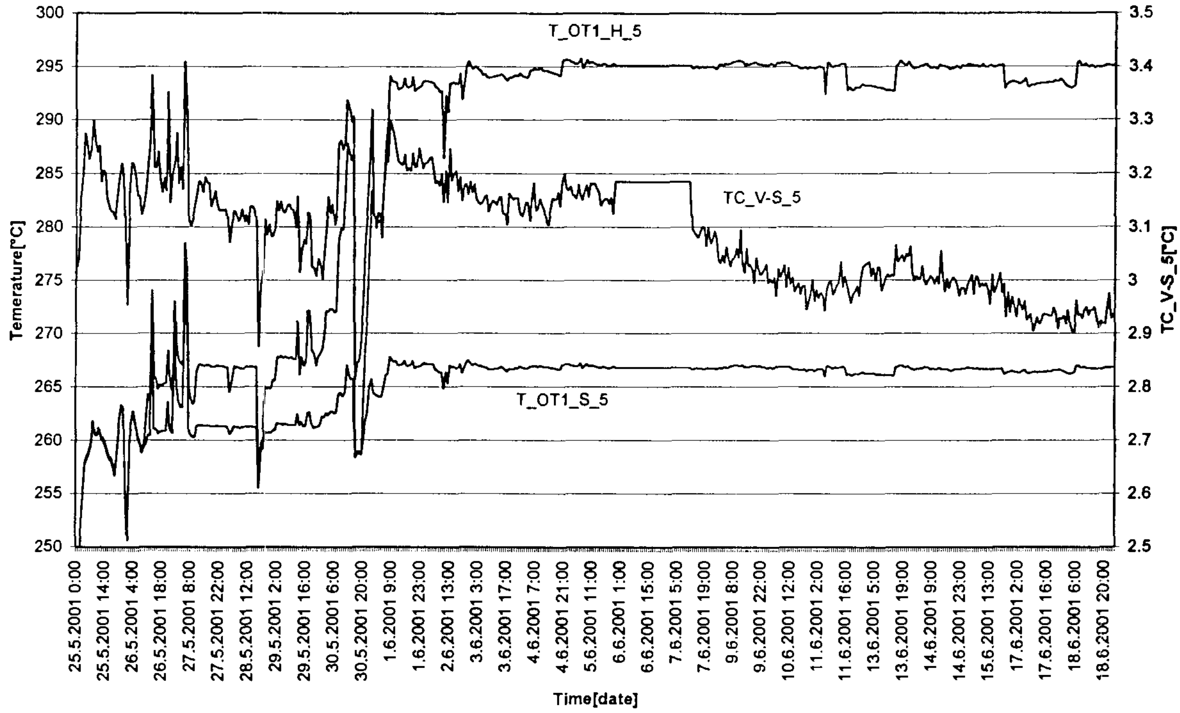
Picture 13 Curves of temperature differences TC_V-S on 5th hot leg – natural circulation



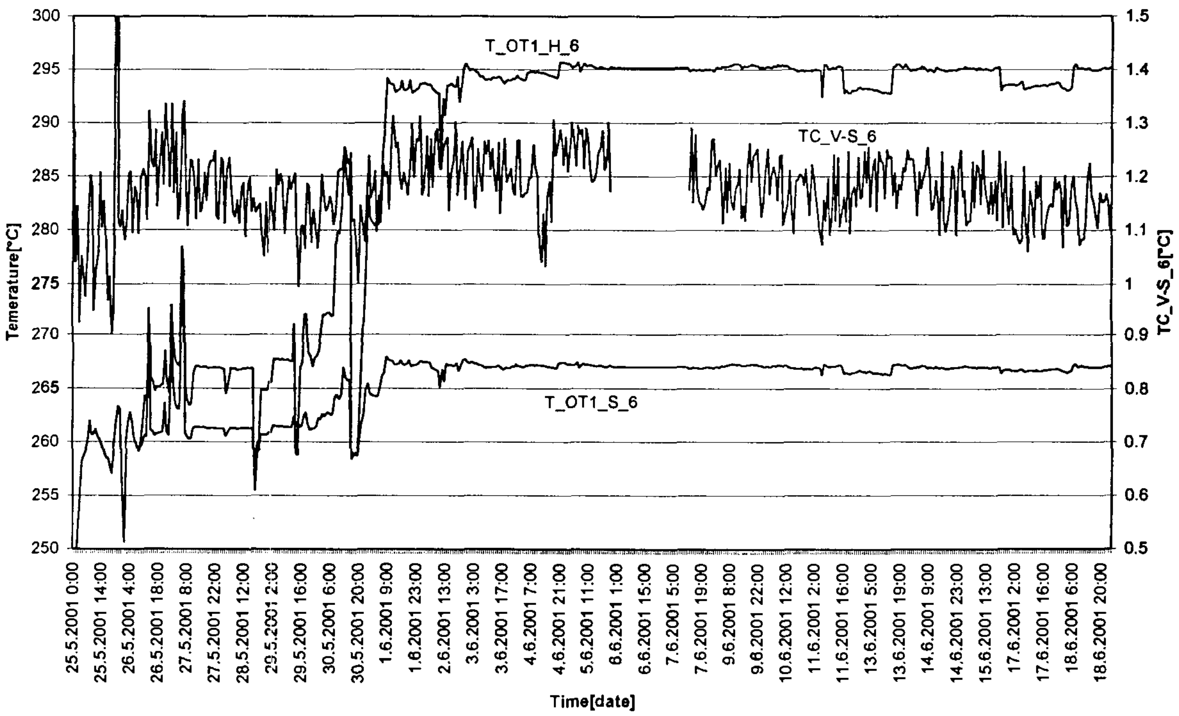
Picture 14 Curves of temperature differences TC_V-S on 6[th] hot leg – natural circulation



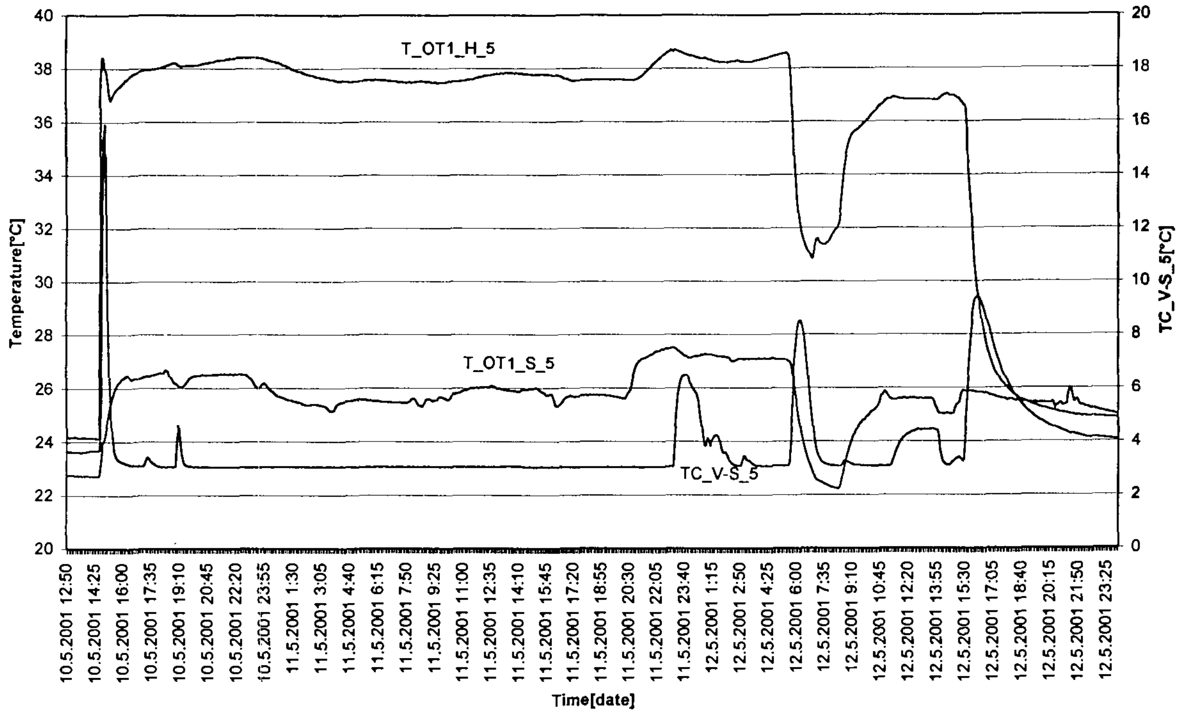
Picture 15 Curves of temperature differences TC_V-S on 3[th] cold leg – nominal power



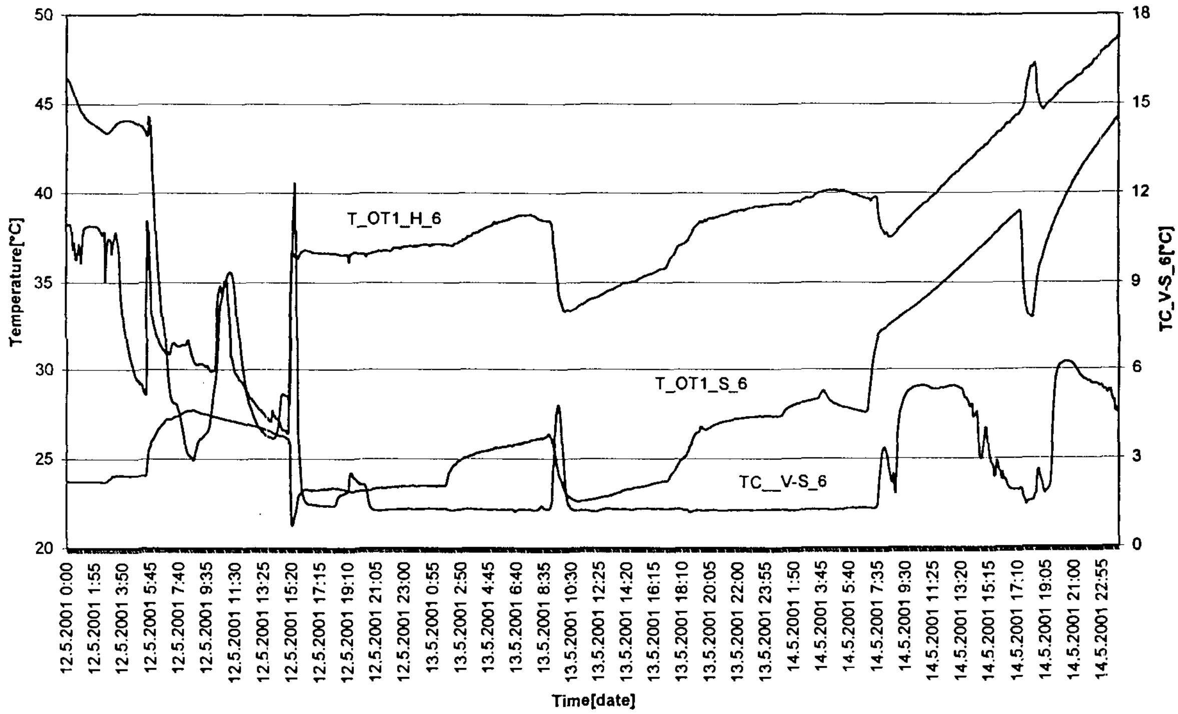
Picture 16 Curves of temperature differences TC_V-S on 5th hot leg – nominal power



Picture 17 Curves of temperature differences TC_V-S on 6th hot leg – nominal power



Picture 18 Curves of temperature differences TC_V-S on 5[th] hot leg – natural circulation



Picture 19 Curves of temperature differences TC_V-S on 6[th] hot leg – natural circulation