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CONDENSATION DRIVEN WATER HAMMER STUDIES FOR FEED WATER DISTRIBUTION PIPE

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1. ABSTRACT

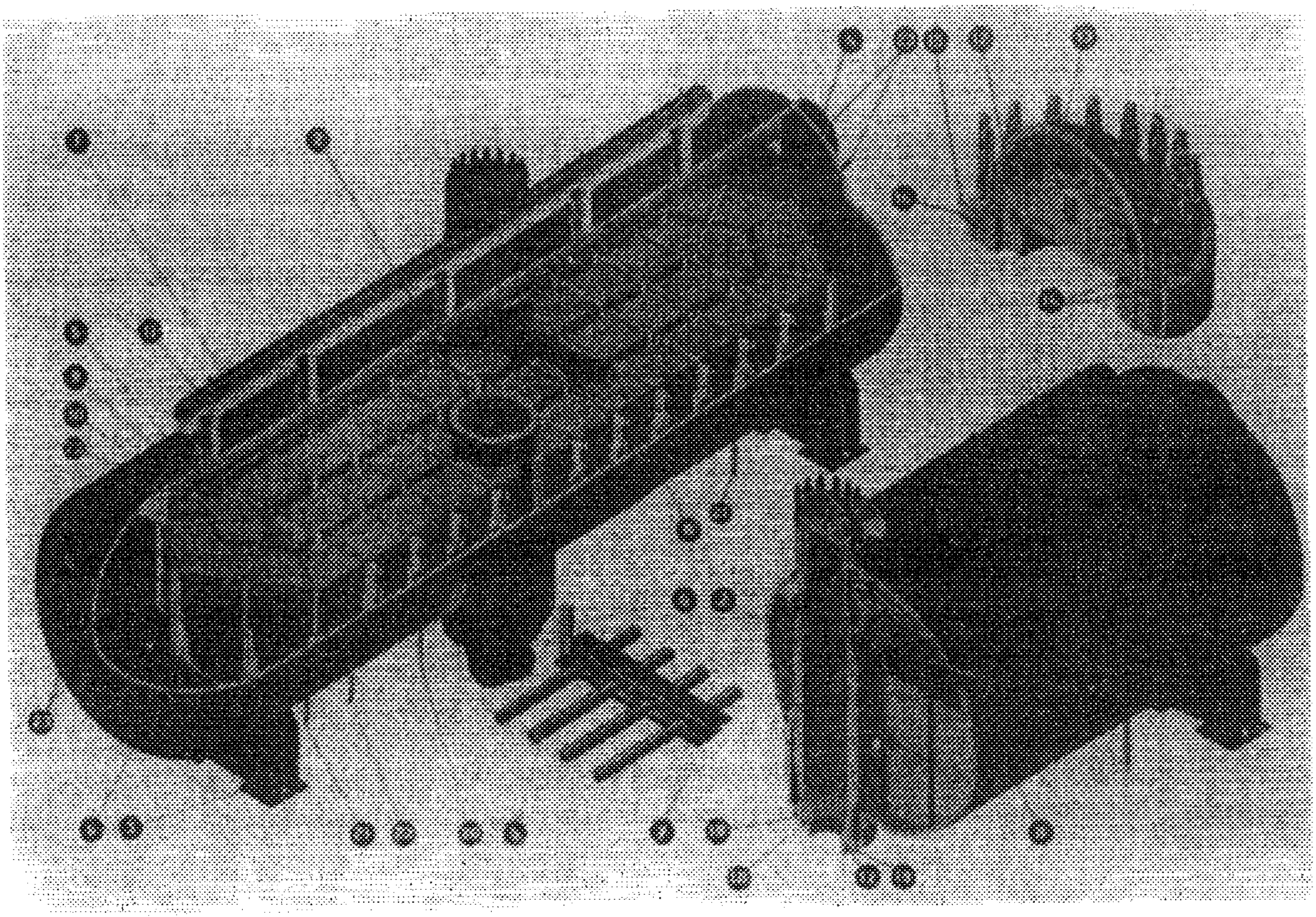
Imatran Voima Oy, IVO, operates two VVER 440 reactors. Unit 1 has been operating since 1977 and unit 2 since 1981. First damages of the feed water distribution (FWD) pipes were observed in 1989. In closer examinations FWD-pipe T-connection turned out to suffer from severe erosion corrosion damages. Similar damages have been found also in other VVER 440 type NPPs. In 1994 the first new FWD-pipe was replaced /1/ and in 1996 extensive water hammer experiments were carried out together with EDO Gidropress in Podolsk. After the first stage of the experiments, Loviisa specific changes for FWD-pipe design was done. In the second stage experiments the changes proved to be successful. In the refuelling outage 1996 the first Loviisa specific FWD-pipe was replaced into the YB56 steam generator in unit 2. The object of this paper is to give a short insight into the design of the new FWD-pipe concentrating on water hammer experiments. Although the water hammer problem of the FWD-pipe is mostly Loviisa specific, the main results of these experiments can be applied for other condensation driven water hammer problems.

2. INTRODUCTION

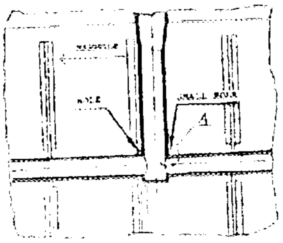
Horizontal steam generators are one of the typical features of Russian designed VVER type nuclear reactors. The VVER-440 and VVER-1000 reactors are the most common Russian designed power plants in commercial operation. In VVER-440 type reactors the original FWD-pipe is made of carbon steel and assembled in the middle of the tube bundle. Originally, both normal and emergency feed water were injected through the same FWD-pipe into the steam generator. In the later designs of VVER-440 steam generators, a separate FWD-pipe for emergency feed water has been assembled. However, in Loviisa Power Plant the emergency feed water is still injected through the main FWD-pipe. The design of the VVER-440 horizontal steam generator is illustrated in Picture 1.

The first damages of the FWD-pipes in Loviisa NPP were observed in 1989. The FWD-pipe T-connection had suffered from severe erosion corrosion failures. Similar damages have been found also in other VVER-440 NPPs. Also the distribution nozzles of the FWD-pipe in the steam generator YB11 were inspected, but no signs of damages or indications of erosion were detected

The first damaged distribution nozzles were found in 1992 in steam generators at both units. The typical damages of the FWD-pipe is illustrated in Picture 2.



Picture 1. Principle of the Loviisa specific horizontal steam generator.



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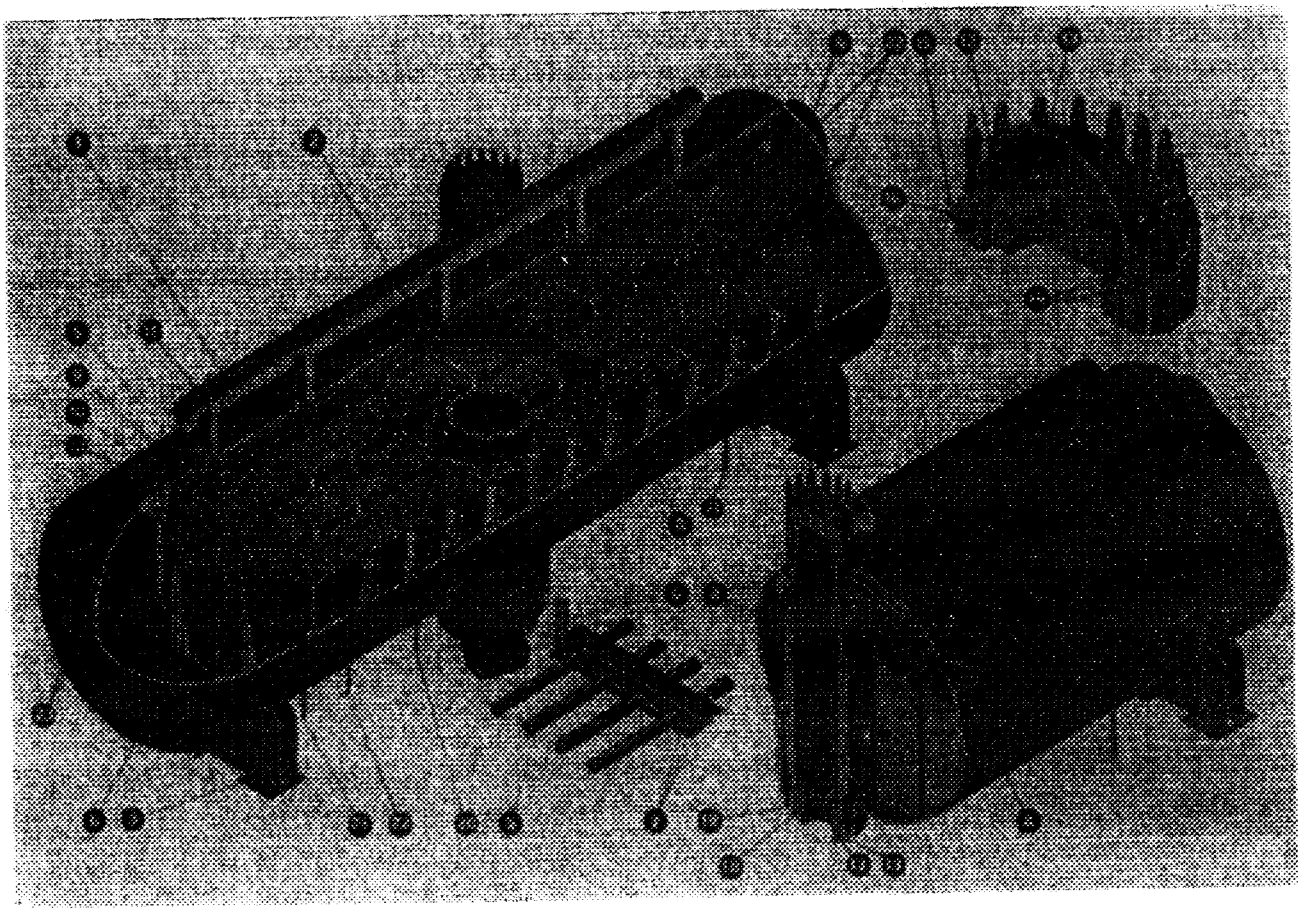

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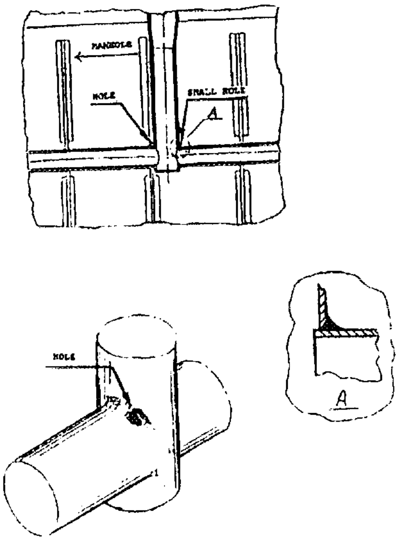


Picture 2. Typical damaged of FWD-pipe T-connection.

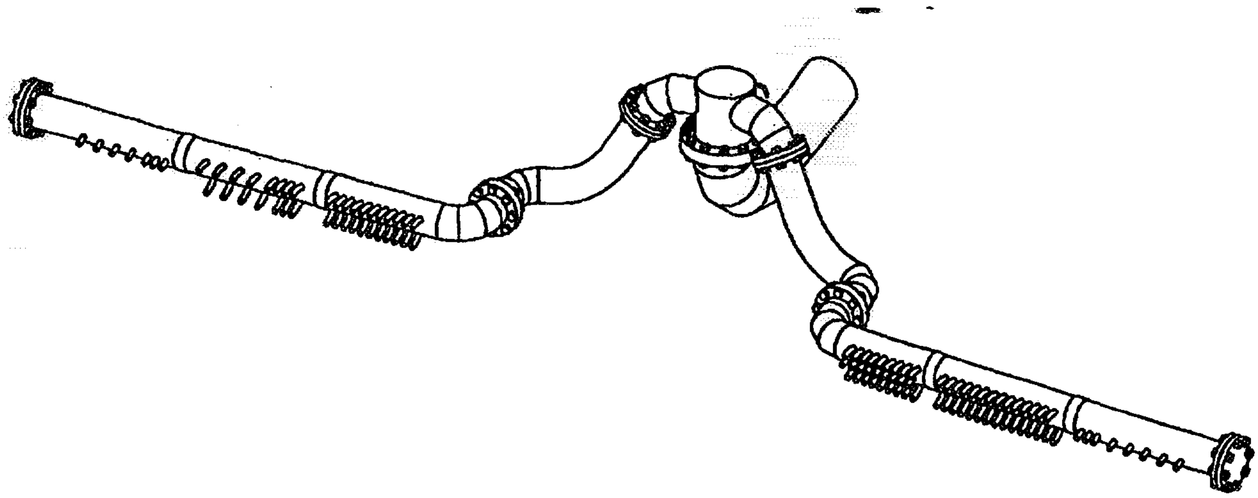
In autumn 1992 different possibilities to repair the damaged FWD-pipes were studied. Since the old distributor is situated inside the tube bundle it was turned out to be more preferable to replace it with a new construction. In 1991 two new feed water distributors, designed by Vitckovice company, had been assembled at Dukovany NPP /2/. Additionally, OKB Gidropress had presented their design for a new FWD-pipe and IVO was also planning its own FWD-pipe construction.

In spring 1994 all the six steam generators of Rovno NPP unit 1 were replaced with FWD-pipes designed by OKB Gidropress. After the assemblage of the new FWD-pipes and a successful experimental program at Rovno NPP Unit 1, a decision was made to install OKB Gidropress designed FWD-pipe in the steam generator YB52 at Loviisa Unit 2 in 1994 refuelling outage. The FWD-pipe is illustrated in Picture 3.

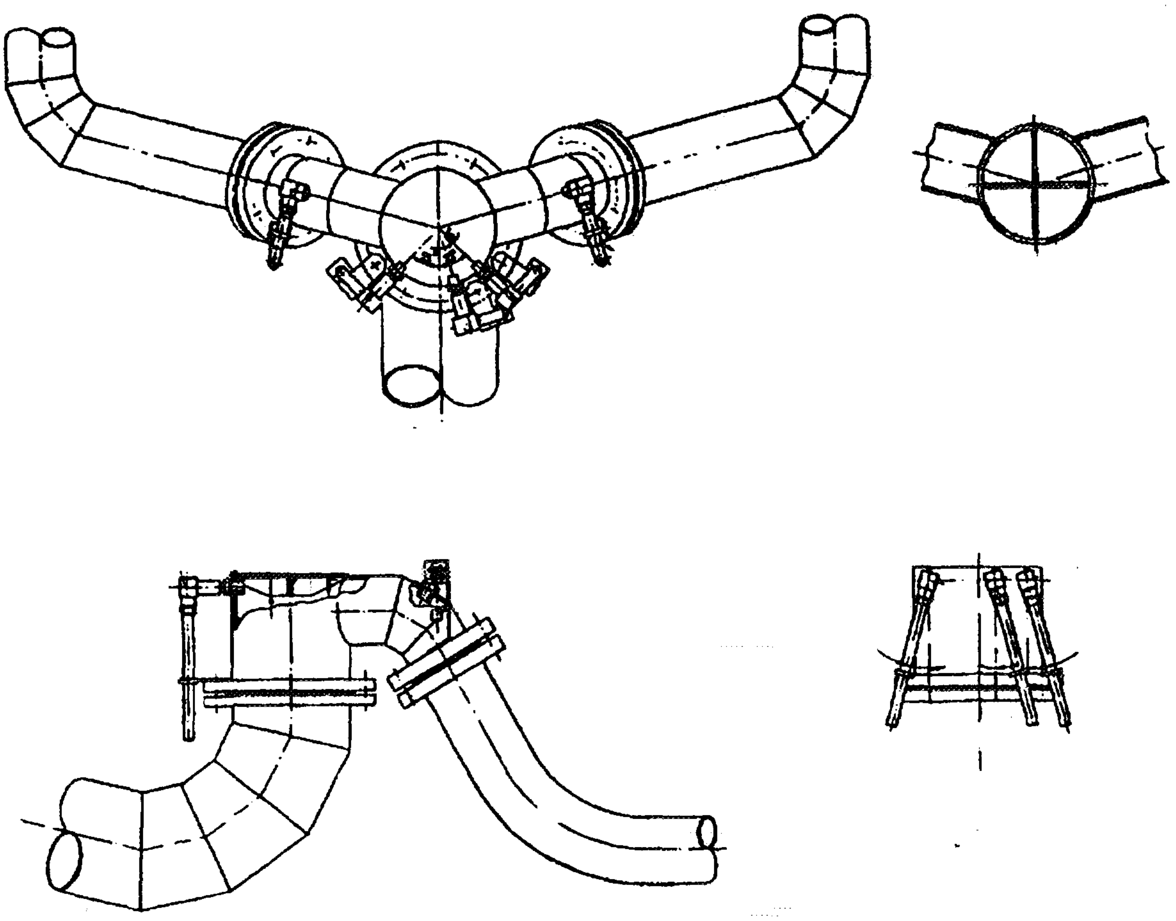
The Finnish regulatory body, STUK, gave conditional permission for the FWD-pipe of new design but requiring IVO to study water hammer phenomenon inside the FWD-pipe and the response of the heat transfer tubes to cold emergency feed water injection. The heat transfer tube response to cold emergency feed water was studied in spring 1995 together with Lappeenranta Technical University using the Pactel test facility. The replaced Gidropress designed FWD-pipe was instrumented to measure possible water hammering. During the start-up phase some selected tests were carried out and clear observations of the water hammer phenomenon were made. It was concluded that the water hammering is provoked when steam bubbles in the partially flooded FWD-pipe are condensated into the cold feed water.

In the refuelling outage 1995 the cover of the T-piece of the Gidropress designed FWD-pipe was reinforced against possible hammering. Furthermore, in the T-piece five venting pipes were assembled to balance pressure difference between the steam generators steam dome and the distributor. The modified design of the T-piece is illustrated in Picture 4. However, in the start-up phase it was deduced that the influence of the assembled venting pipes was almost insignificant. The intensity of pressure peaks seemed to be only slightly, if any, smaller than before the modifications. After these observations large scale experiments on condensation induced water hammers were decided to be carried out.

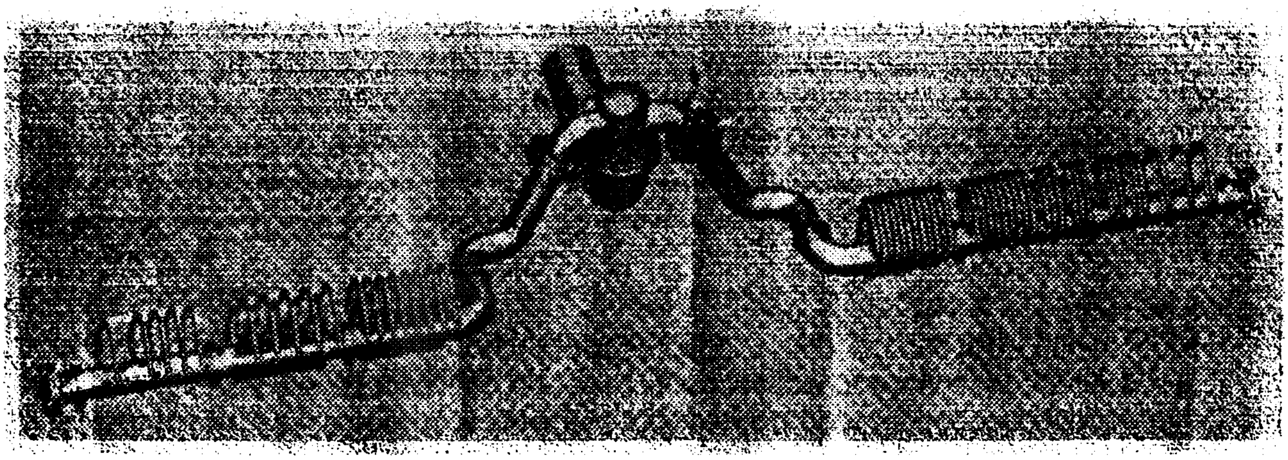
Finally in the early spring and summer 1996 extensive large scale water hammer experiments were carried out together with Gidropress. For the first stage of the experiments the model of YB52 FWD-pipe was studied. The construction was modified by adding 5 additional venting pipes in the descending part. For the second stage experiments the original design was changed decreasing the maximum pressure pulses significantly. After experiments some last modifications were made to the distribution nozzles and to the cover of the T-piece. With new elliptical geometry of the T-piece cover the stress levels will remain below the critical fatigue fracture level also in accident conditions. In 1996 in the annual refuelling outage of Loviisa Unit 2 a Loviisa specific FWD-pipe was assembled into the steam generator unit YB56 /3/. The Loviisa specific FWD-pipe is presented in Picture 5.



Picture 3. FWD-pipe assembled into YB52 in Loviisa Unit 2 in 1994.



Picture 4. Redesigned T-piece, assembled into YB52 in 1995.



Picture 5. Loviisa specific FWD-pipe, assembled in YB56 in Unit 2 in 1996

3. DESCRIPTION OF THE TEST FACILITY

In late summer of 1995 the first negotiations on water hammer experiments were hold with Gidropress were. It was foreseen that thermal-hydraulic analyses will need reliable validation methods, and experiments could not be avoided. A full scale model of one half of the FWD-pipe was to be used to avoid uncertainties related to scaling and interpreting down scaled results. The size of the model was limited by the size of the pressure vessel of the test facility.

The experiments were to be carried out in Gidropress's thermal-hydraulic laboratory in Podolsk, Russia. Gidropress was responsible for manufacturing FWD-pipe model, measuring the main process parameters and operating the facility. IVO was responsible for designing and assembling of the instrumentation of the FWD-pipe model and determining the test matrix.

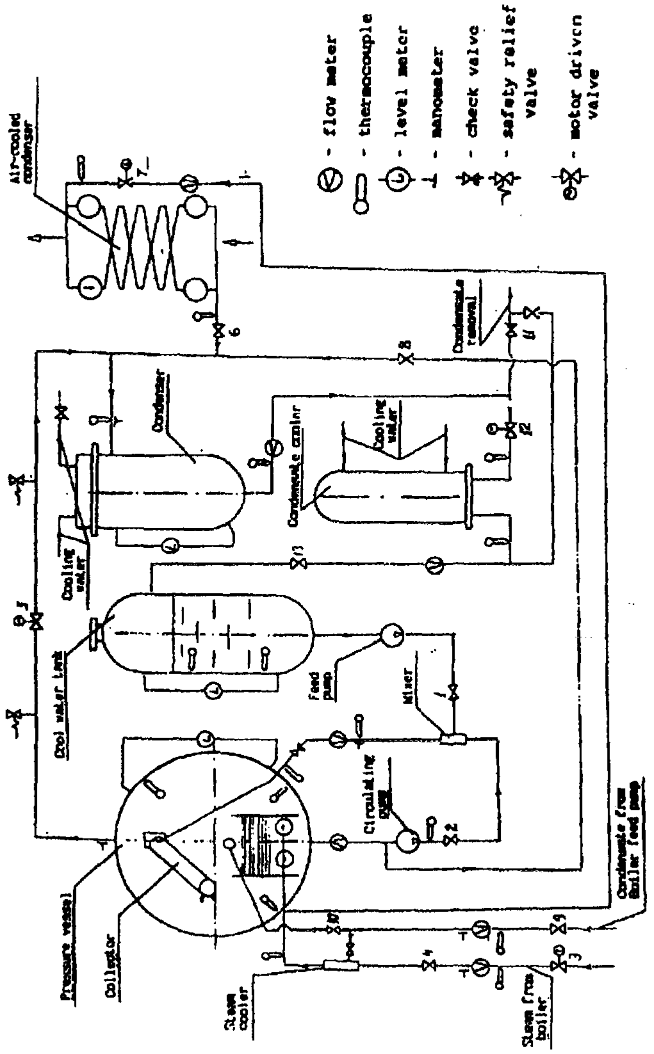
The thermal-hydraulic laboratory of Gidropress was built in 1971. The facility has been used for several thermal-hydraulic large scale experiments. It has been successfully applied for VVER-1000 steam separation experiments and steam drum experiments of RBMK reactors. Recently the facility has been used for researching the residual heat removal system of VVER-1000 type reactors.

The facility has been designed to provide full range parameters for the need of large scale experiments. The schematic diagram of the test facility is illustrated in Picture 6. The FWD-pipe model is shown in Picture 7. Feed water is injected using the pump 4P5-8A from the atmospheric tank. Maximum volume of the tank is 10 m^3. Minimum temperature of the tank is 20 °C. To provide higher temperatures, saturated water is injected from the vessel using pump CEN148 and mixed with cold feed water in the mixing device. The required feed water mass flow rate and the temperature are controlled with manually operated valves 1 and 2. For controlling the pressure in the vessel superheated steam is injected through valves 3 and 4 and mixed with boiler condensate. The mixture is injected into the vessel under water level through the steam distributing device (Picture 7).

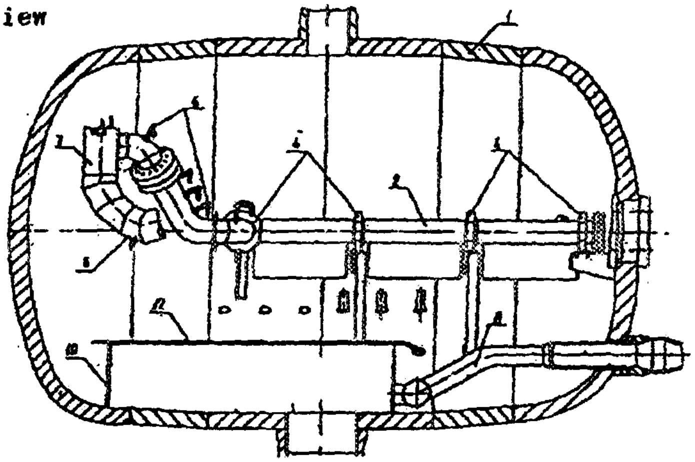
In most experiments a large amount of steam is required for balancing the pressure. Additionally, a relatively small volume of the system requires quick response from the boiler. The approximated demand for steam flow rates was defined by simple hand calculations before experiments. The system pressure as well as other main system parameters were controlled manually. In initial conditions valve 5 is open. In order to limit the pressure drop in vessel valve 5 is closed before the initiation of feed water injection. In some extreme experiments when cold feed water was injected into the vessel with maximum flow rates, the air cooled heat exchanger was operated parallel to the condensers.

The level of the vessel could be controlled by either draining the vessel or injecting additional water in order to check the effect of the water level on water hammering. The vessel is drained by opening valve 8. In order to speed up the water level rise velocity inside the vessel additional condensate can be injected into the vessel by opening valves 9 and 10 with a boiler feed pump.

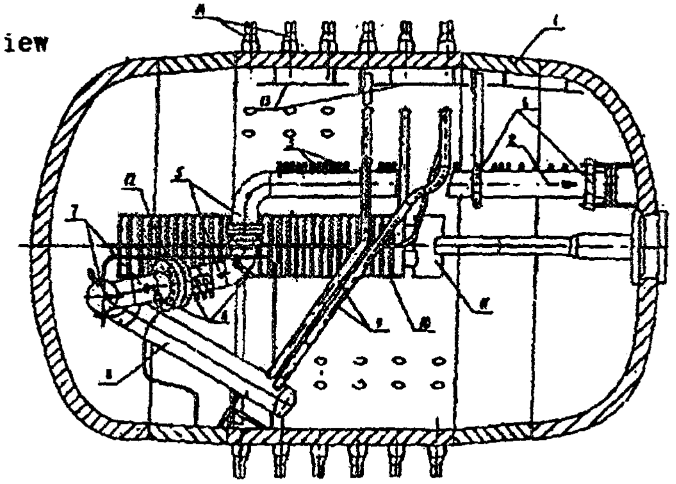
For the operations and controlling the facility five persons were needed. All the controlling was carried out by manually operating valves. The main parameters as pressure in the vessel, feed water mass flow rate and feed water temperature were recorded in 2 Hz frequency.



side view



top view



1 - pressure vessel
2 - distributing pipe
3 - distributing nozzles
4 - supporting rings
5 - downcomer
6 - venting pipes
7 - T-piece
8 - supplying pipe
9 - feed water supply
10 - box with tube bundle
11 - steam supply to collector
12 - condensate supply to collector
13 - thermal shield of pressure vessel
14 - penetrations for transducers

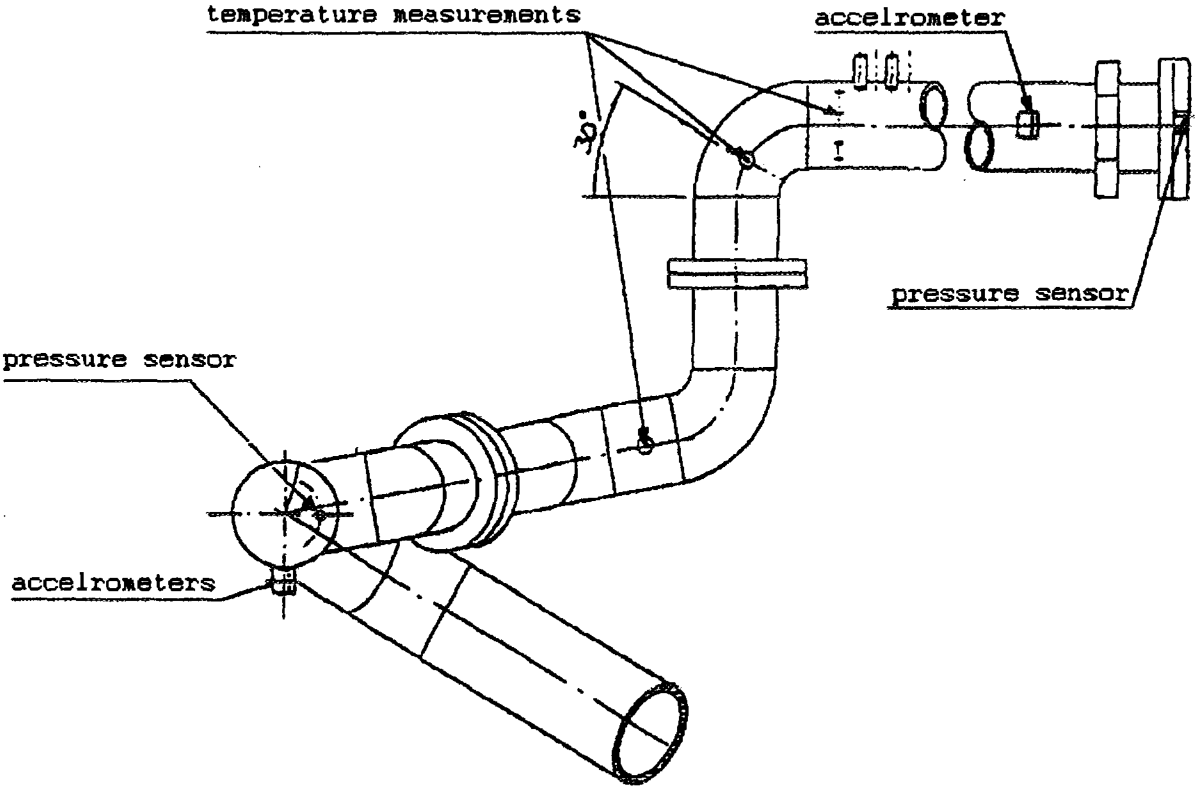
Picture 7. FWD-pipe model

4. INSTRUMENTATION OF MODELLED FEED WATER DISTRIBUTION PIPE

The main objectives of the water hammer experiments were to find out the prevailing parameters leading to water hammers, as well as the sensitivity of hammering to boundary conditions. Additionally, the measured feed water heat-up rate substantiated the earlier analyses of the heat transfer tube lifetime. More specific description of the instrumentation and its design basis is given in /4/. The design basis for the instrumentation was determined by hand calculations. Due to the high pressure wave velocity a high measuring frequency was required for all measurements. The high frequency noise components in every channel were removed using a low-pass filter.

Both the thermal hydraulic behaviour and the FWD-pipe model response due to the water hammering were to be measured. The instrumentation of the facility is shown in Picture 8. The model of the FWD-pipe was instrumented with:

- 2 piezoelectric pressure transducers
- 21 thermocouples
- 4 strain gauges
- 4 accelerometers
- 1 pressure difference transducer for level measurements at T-piece.



Picture 8. Instrumentation FWD-pipe model.

The piezoelectric pressure transducers were mounted at the cover of the T-piece and in the end plate of the FWD-pipe. After the first phase experiments the pressure transducer in the end plate was replaced in the T-piece. The pressure pulses were measured with high 16 kHz frequency sampling rate to detect actual pressure behaviour. This recorded pressure information has been later applied as the imposed loads for structural integrity and lifetime analyses of the T-piece.

The thermocouples were to measure the water level and its heat-up inside the distributor. The sampling rate of all 21 thermocouples was 50 Hz. The temperature distribution was measured at three different locations with one circular and two vertical matrixes. For the second phase experiments one thermocouple from the circular matrix was replaced to measure feed water heat-up rate in the feed water line inside the pressure vessel.

Four strain gages were mounted at locations where their signals would indicate global structural response due to excitation by water hammer pressure pulses. The sampling rate of the strain gages was 2 kHz. The experiments demonstrated that the global structural modes were excited by water hammering. The strain response, however, was not of high magnitude due to the short duration of pressure pulses (i.e. wide excitation band).

Three out of the four unidirectional accelerometers were mounted at the T-piece to measure its response in the three orthogonal axes The fourth accelerometer was placed at the horizontal part of the FWD-model to measure the structure's axial response. The sampling frequency of the accelerometers was 2 kHz.

5. WATER HAMMER EXPERIMENTS IN LOVIISA NPP AND IN PODOLSK

In the refuelling outage of 1994 the first Gidropress designed FWD-pipe was assembled into the steam generator YB52 in Unit 2 of Loviisa power station. The distributor was instrumented to measure possible water hammers. In the experiments, during the start-up phase, indications of possible water hammers were observed. Unfortunately the number of instrumentations was limited by the allowed penetrations in the manhole. Therefore, the measurements did not reveal clearly the prevailing conditions during water hammers or onset mechanisms. However, it seemed obvious that the combination of the feed water mass flow rate and the temperature is the most predominant factor influencing in the intensity of hammering.

The experiments demonstrated that water **hammers may occur when the mass flow rate into the steam generator exceeds 6 kg/s and the temperature difference between steam generator and feed water exceeds 100 °C**. The maximum pressure peak was calculated to correspond approximately 15 bar from the structure responses. Clear discrepancy was detected in some results. **In some experiments water hammering occurred when the temperature difference was relatively low, 40 °C**. Later it was deduced that a cold water plug in the feed water line initiated the hammering, and the phenomenon was upheld regardless of warmer feed water. The hysteresis feature of water hammering was later demonstrated in the experiments in Podolsk.

In summer 1996 extensive water hammer experiments were carried out together with Gidropress. Imatran Voima Oy was responsible for designing the instrumentation, measuring the water hammers and determining the test matrix. Gidropress was responsible for assembling the model of the FWD-pipe, operating the facility and measuring the main process parameters.

The experiments were carried out in three phases. In the first phase a slightly modified Gidropress designed model was studied. The Loviisa specific design was researched in the second stage experiments. In the third stage visual experiments were carried out using both initial model and transparent PVC-model. In the first two stages the experiments were carried out with actual secondary parameters P_{sg}=2-45 bar and T_{fw}=20 - 160 °C and half of the actual FWD-pipe was used for modelling the geometry. In the first stage experiments five venting pipes were assembled in the descending part of the model. The incoming feed water pipe line was volumetrically scaled down 1:2 to model correctly the flow velocities. The test matrix of the first stage is illustrated in Table 1.

Table 1. Test matrix in the first stage.

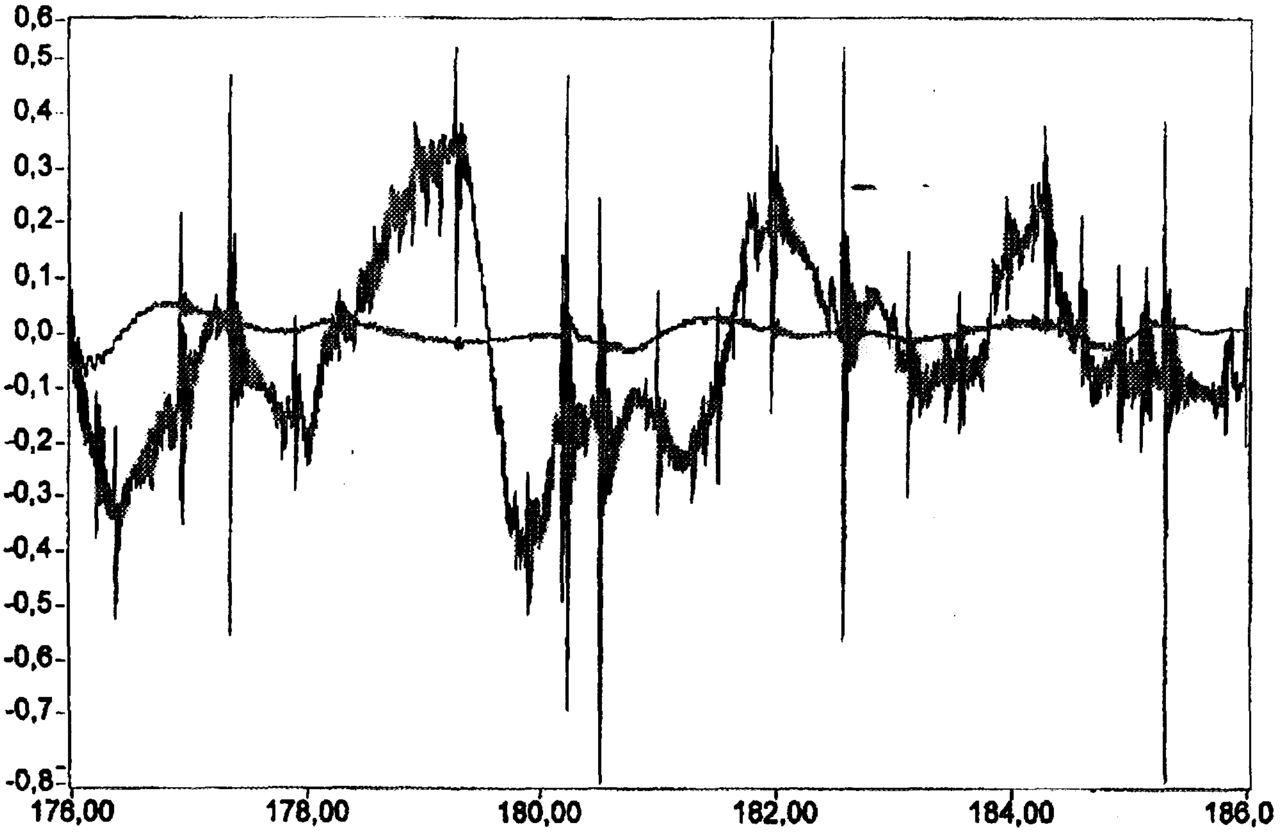
pressure [bar]	mass flow rate [kg/s]	temperature [°C]
45	3,6,9,12,15	20,100,164
7	3,6,9,12,15	100,164
2	3,6,9,12,15	20

The first experiments demonstrated that water hammers are strongly dependent on the combination of prevailing mass flow rate and temperature difference between water and steam. Maximum pressure peaks were found out to be about **65 bar** at mass flow rate 6 kg/s (12 kg in the actual steam generator). Additionally, it was found out that the behaviour of hammering included hysteresis features. Furthermore, the hammering faded always away when the horizontal part of the distributor was flooded.

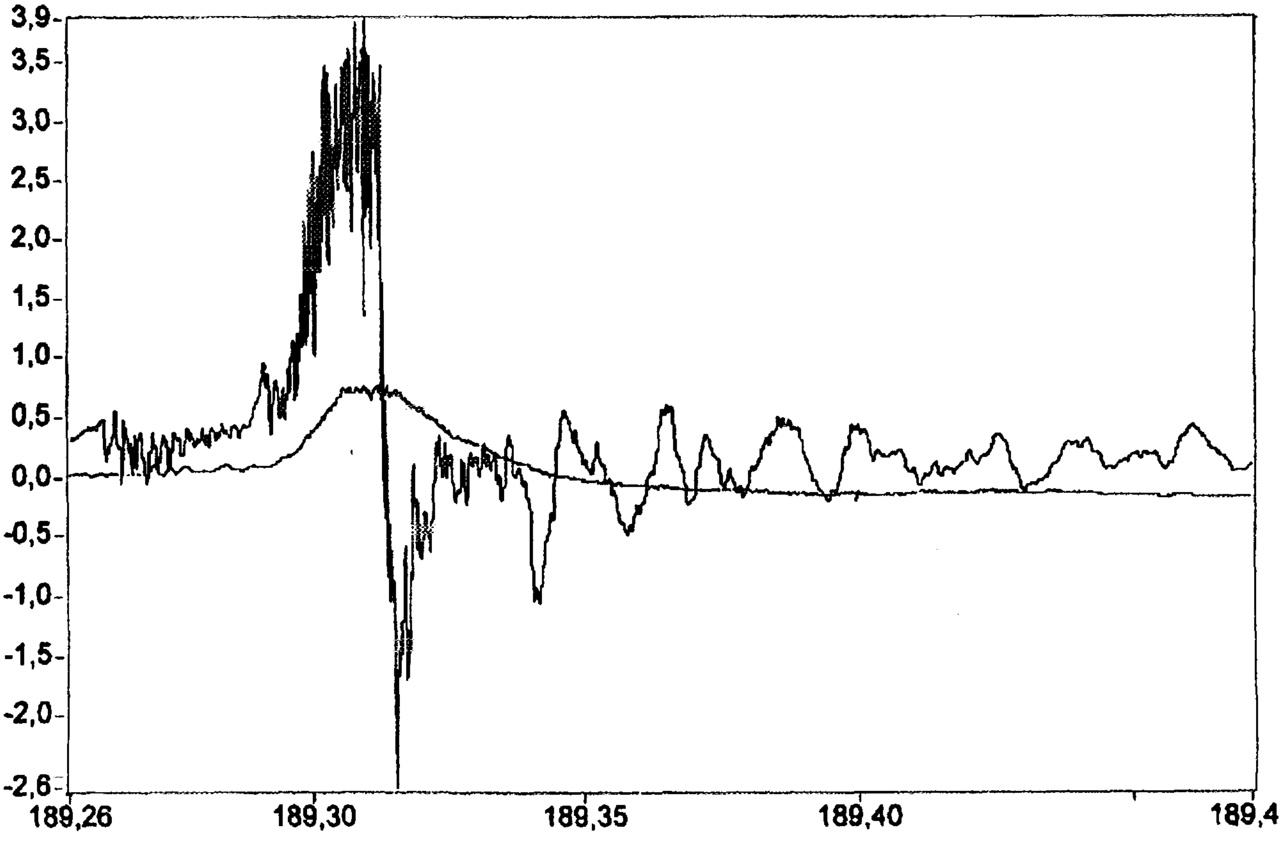
Picture 9 illustrates typical pressure peak behaviour in both T-piece and in the end-plate. In Picture 10 a single pulse is shown in more detail. The data is taken directly from the recorded files. One should note that positive values mean under pressure and negative values overpressure. Prior to the pressure peak condensation of the steam exists leading to accelerating pressure drop. Simultaneously in the horizontal part water waves prevents the steam flow from compensating the condensation. The strings of water plugs start to penetrate upwards leading to series of rapid pressure pulses. The whole duration of the peak from condensation till a stabilised phase takes roughly 50 milliseconds. Single pressure peak consists of series of minor pulses. The duration time of a single pulse is typically about one millisecond.

The maximum pressure peaks of the experiments are presented in Pictures 11 and12. It can be observed that the pressure peaks are strongly dependent on both feed water mass flow rate and its temperature. It should be noted that the temperature is measured outside the test facility and the heat-up rate in the facility is differs from the actual one.

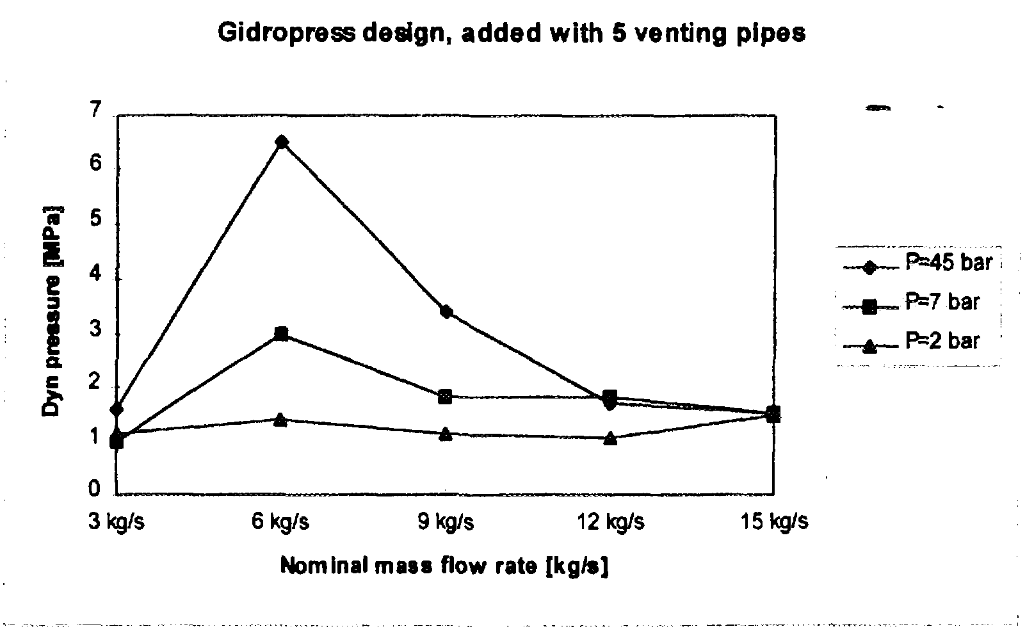
After the first stage experiments, stress analysis for the FWD-pipe was carried out. According to those calculations the weakest part, the T-joint, may hold against such water hammers only for a limited time, order of few minutes.



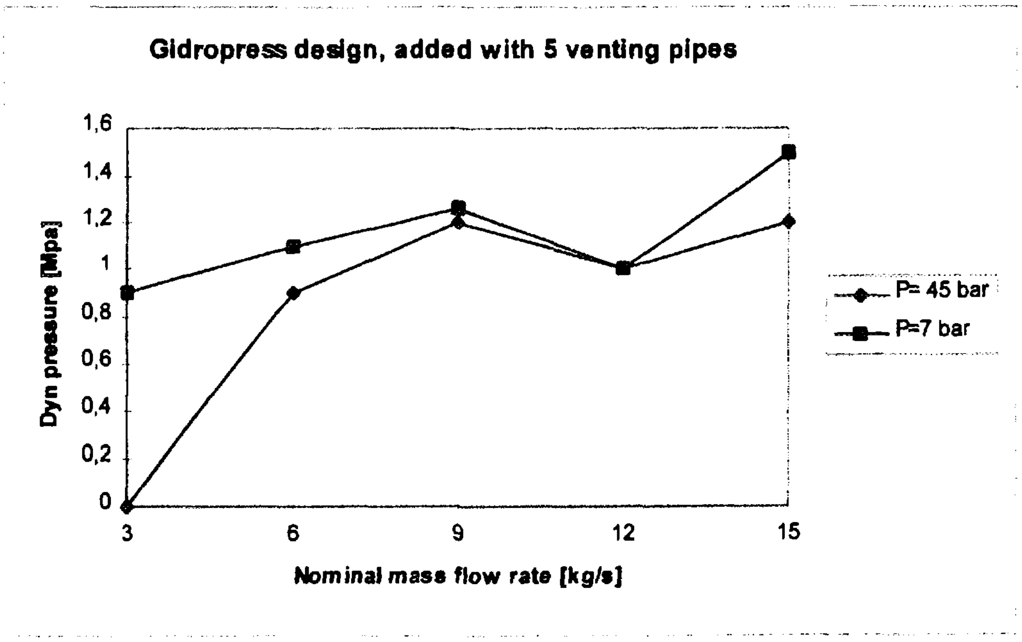
Picture 9. Typical water hammering ($\dot{m}$=6 kg/s and T=20 °C)



Picture 10. Single water hammer ($\dot{m}$=6 kg/s and T=20 °C)



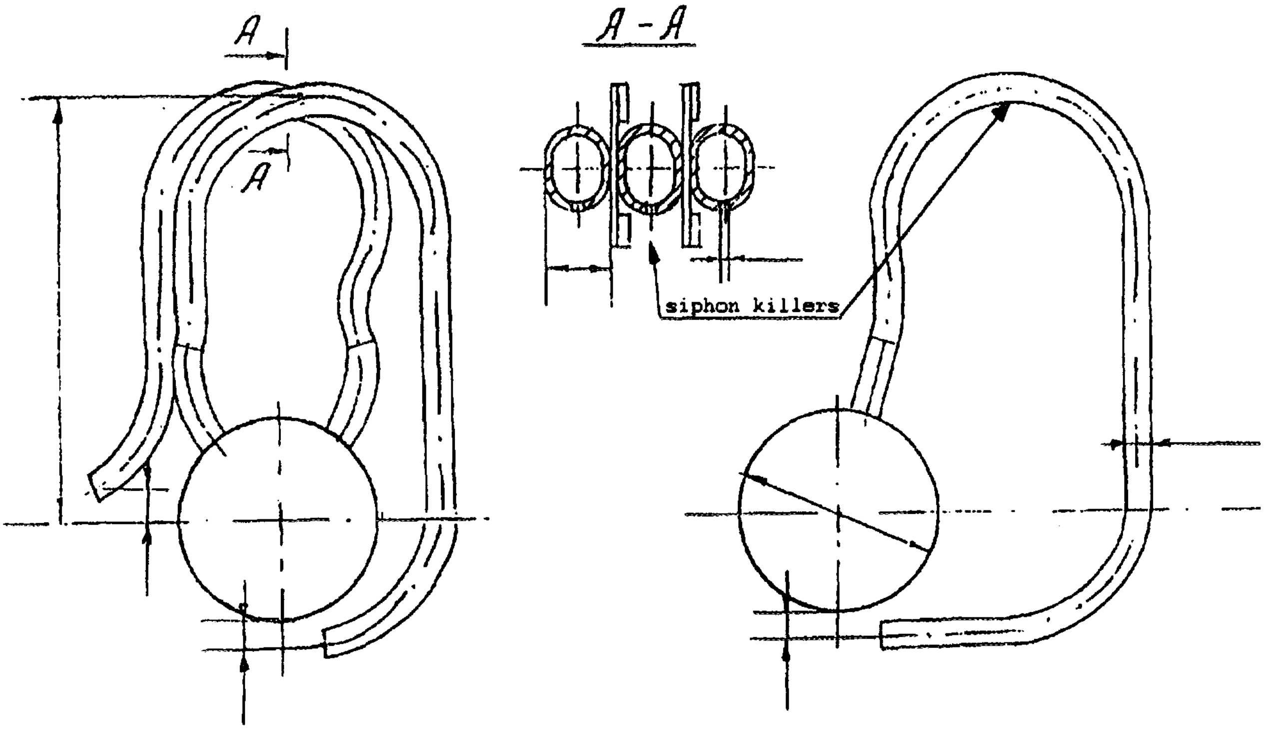
Picture 11. Maximum pressure peaks T_{fw}= 20 °C.



Picture 12. Maximum pressure peaks T_{fw}=100 °C

For the second stage experiments the design of the FWD-pipe was changed. The principle of the new design is shown in Picture 13. The most important changes were the new construction of the feed water nozzles and the removal of the venting pipes in the descending part.

With the new design the horizontal part of the pipe remains filled with water limiting the heat transfer area between water and steam. In addition, in the new distributing nozzles small holes were drilled to equalize the distribution between nozzles at low mass flow rates. In turn these siphon cutting holes prevent the level in the descending part from oscillating. In the T-piece flange a throttling device was assembled to choke down the kinetic energy of possible slugs. Additionally, a slug breaker was assembled in the T-joint. However, this device did not influence much the peak intensity. The test matrix of the second stage is presented in Table 2. After the experiments, some final modifications were made for assemblage purposes.



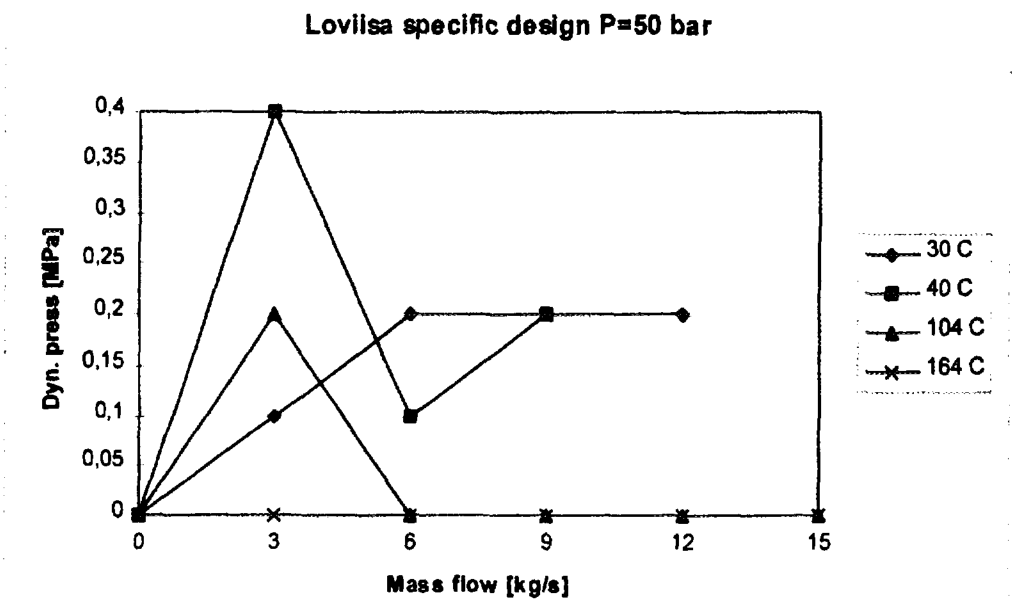
Picture 13. Principle of the new construction.

Table 2. Test matrix in the second stage.

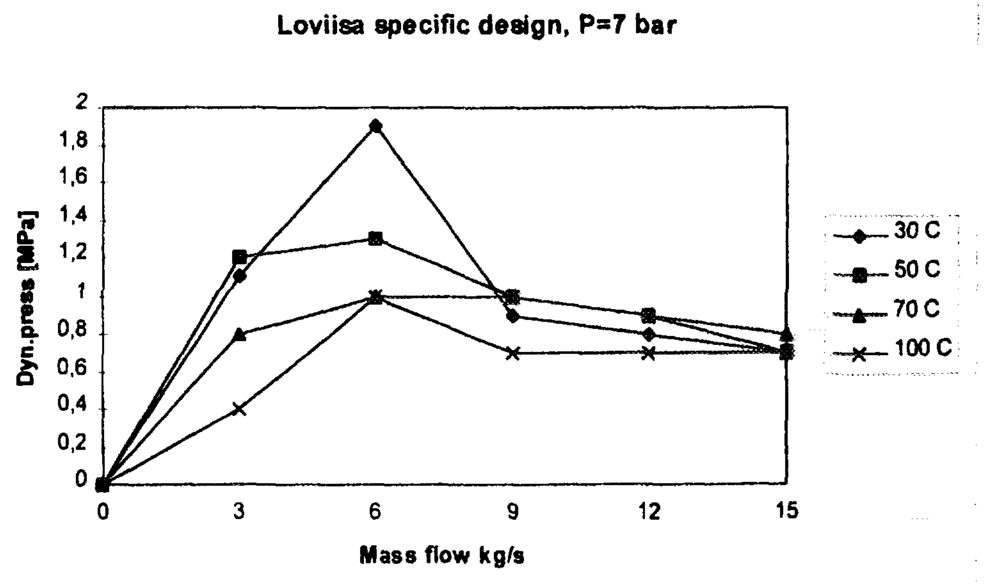
pressure [bar]	mass flow rate [kg/s]	temperature [°C]
50*	3,6,9,12,15	20,40,104,164
30	3,6,9,12,15	30
7	3,6,9,12,15	30,50,70,100

*Note the following experiments were not carried out:
T=30 °C, m=15 kg/s and
T=40 °C, m=12 kg/s and 15 kg/s

The redesign of the FWD-pipe proved to be successful. Maximum pressure peaks at P_{sg}=45 bar were limited to correspond to 4 bar. The maximum pressure peak at P_{sg}=7 bar was reduced from 30 bar down to 19 bar. The main result of the second stage experiments is presented in Pictures 14 and 15.



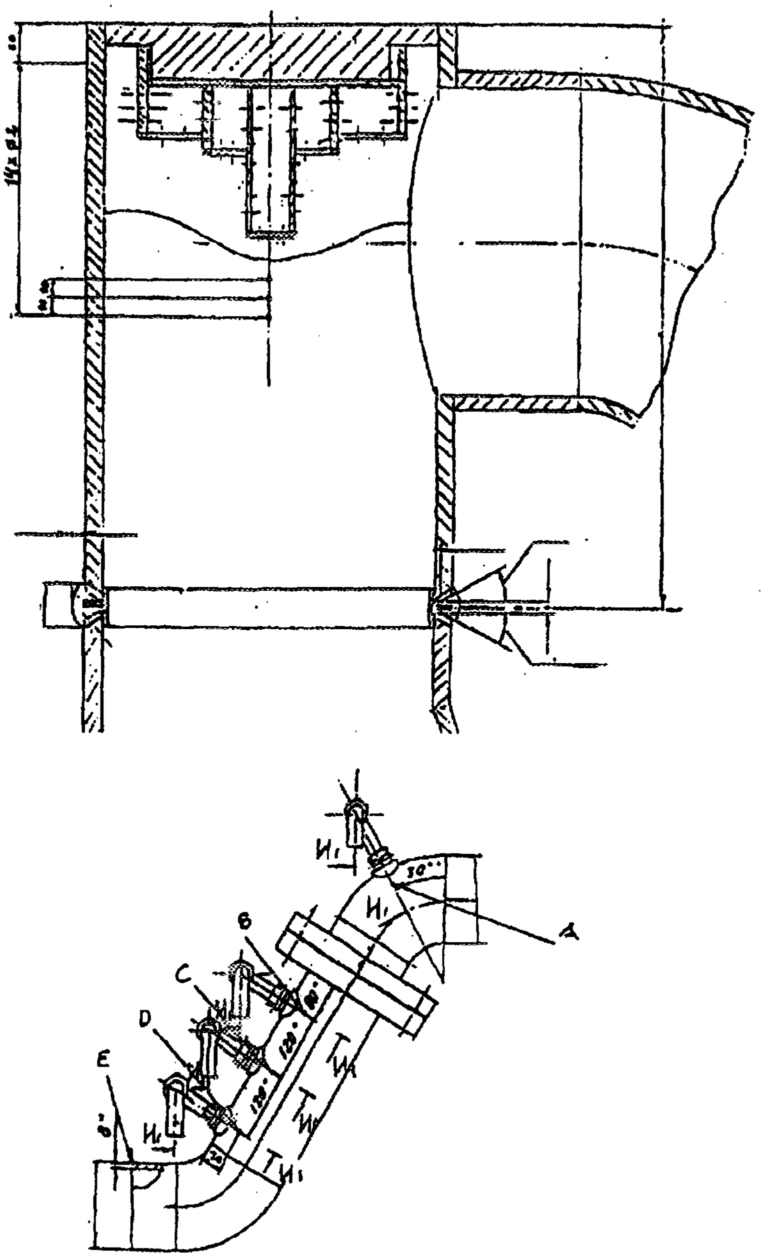
Picture 14. Maximum pressure peaks P_{sg}=50 bar.



Picture 15. Maximum pressure peaks P_{sg}=7 bar.

In the third stage of the experiments the FWD-pipe behaviour was visually inspected at atmospheric pressure. In the T-piece 15 holes (d=2 mm) were drilled to reveal the level behaviour. Furthermore 5 holes (d=2 mm) were drilled in the descending part for revealing level behaviour. The placings of the drilled holes is presented in Picture 16. Table 3 illustrates the main results and observations.

The final visual experiments have been carried out in Loviisa NPP. For this purpose a transparent plastic model was manufactured. The study dealt with both YB52 and Loviisa spesific construction. The T-piece, the descending part and the 10 first nozzles of the redesigned construction were modelled. The object of this study was to research visually the phenomenon inside the pipeline at atmospheric pressure.



Picture 16. Placing of the holes in the visual experiments.

Table 3. Major results of the visual experiments in Podolsk

Mass flow rate	Observations		
[kg/s]	T-Piece level [mm]	Descending part level	Operating nozzles [%]
3	62	C	50
6	82	C,(B fluctuating)	70
9	112	C,(B fluctuating)	100
12	full	C,(A fluctuating) (B no flow)	100
15	level hitting the top	all but not B	100

The results presented in Table 3 reveals that the level in the descending part remains all the time above the level of the bending of the distribution nozzles. Another important observation was that the level remained stabile in the descending part and did not start to oscillate after flow perturbations. With low mass flow rates only nozzles were operating and the level in the descending part remained more or less stabile. During these experiments large scale level oscillation could not be observed. The results presented in Table 3 is discussed in more detail later.

6. WATER HAMMER PHENOMENON INSIDE THE FWD-PIPE

In industrial applications water hammers are usually a consequence of abrupt flow rate changes. A rapid closure of a valve or a flow perturbation influencing promptly the fluid velocity may lead to extensive pressure peaks. Typical characters of water hammers are a short disturbance time, constant sound of speed and a low Mach number. In principle, condensation induced water hammering can be divided into two regions, namely, initiating mechanisms leading to water hammering and pressure wave propagation in fluid. With simple hand calculations the water hammer magnitude can be easily predicted. The maximum pressure peak and its duration time can be calculated from the well known equations (1) and (2), respectively:

$$\Delta P = c \cdot \rho \cdot \Delta v \qquad (1)$$

$$\Delta t = \frac{2 \cdot \Delta l}{c} \qquad (2)$$

where

ΔP = pressure peak magnitude

c = modified sound velocity, typically 1000 m/s -1500 m/s (includes both fluid and structure)

ρ = density of the fluid

Δl = length of the water slug.

In condensation driven water hammers the water plug is accelerated by pressure difference due to the condensation between water and steam. A typical feature in condensation driven water hammers is the flow perturbation initiating rapid condensation which in turn influences the mixing of the temperatures at the fluid phase interface. In wavy flow mode the strings of the water slugs are formed from the waves which are accelerated by the pressure difference. When the slugs finally hits the dead end volumes or flow obstacles, sufficient water hammers will be generated as one can deduce from the equation (1). The velocity for a frictionless, one dimensional water slug can be determined from the equation (3).

$$v = \sqrt{\frac{2 \cdot S \cdot dp}{\Delta l \cdot \rho}} \qquad (3)$$

where

v = end velocity for the slug

S = acceleration length

dp = driving pressure difference over the water slug

Δl = length of the water slug

ρ = density of the fluid

The equations (1) and (3) show that sufficient pressure peaks are generated with low pressure difference and in short distance. The experiments in Podolsk demonstrated that the maximum pressure peaks occur with maximum subcooling. Furthermore, the pressure peaks are strongly dependent on the mass flow rate. Maximum water hammers were observed when the mass flow rate into the test facility was 5-6 kg/s. Undoubtedly the predominant factor for condensation driven hammering is the condensation heat transfer coefficient which, in turn, is dependent on the flow mode and the subcooling rate of the water. The first stage experiments revealed the most important initiating mechanisms to water hammering:

- water mass flow rate
- temperature difference between steam and water
- water level in the vessel

Later the visual experiments with PVC-model confirmed the earlier observations deduced with actual parameters. The water hammers seem to be initiated by three different mechanisms:

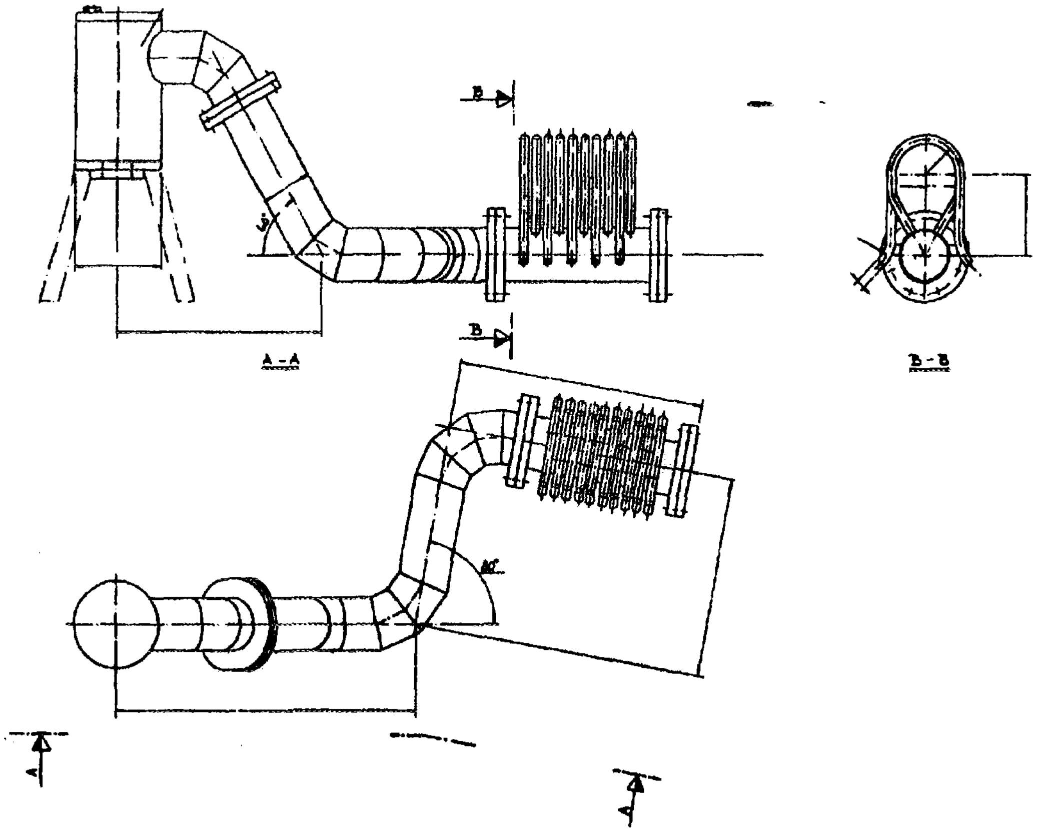
- the flow mode transition in the distribution part from stratified flow to wavy or stratified wavy
- flow rate perturbation
- collapse of an annular vortex in the horizontal part
- condensation in the T-piece.

6.1 Flow phenomenon leading to water hammering in Gidropress designed FWD-pipe

Although the condensation driven water hammering phenomena normally depends on the prevailing boundary conditions and geometry, the main results and observations of these experiments can be used for other applications too. Onset mechanisms of the water hammer could be detected from the results of the first stage experiments and the correct mitigative changes for the FWD-pipe could be made. In order to get better understanding for the flow mechanisms and their influence on the condensation, selected visual experiments were carried out. For this purpose a transparent PVC-model was manufactured. The PVC-test facility illustrated in Picture 17. Although the facility is designed to model a Loviisa specific FWD-pipe, it can be applied for studies of the Gidropress design by removing the end plate. The facility is a full scale model with one half of the distributor modelling T-piece, the descending and horizontal parts including 10 nozzles.

Flow modes in the descending and horizontal part as a function of the mass flow were demonstrated In the PVC-facility. At relatively slow velocities, up to 0.5 kg/s, the phases are well separated and flow remains stratified. When the mass flow rate is roughly 1 kg/s the annular vortex flow begins to exist between the bendings. The annular vortex is created when the flow direction is changed in the first bending giving circulating trajectory for water layer. After the second bend the vortex is dumped due to the opposite directed bending. After the second bend the water layer is slightly inclined due to the centrifugal forces. In the annular vortex flow mode flow dispersion could be detected ,setting off from the annulus toward the centreline.

When the mass flow rate is increased up to 6 kg/s, the stratified flow becomes wavy . The flow mode between the bends include the mode of the annular vortex flow and wavy flow. In this mode the annular vortex may collapse forming water slugs. In the annular vortex flow mode hammering is initiated if the condensation is large enough to create pressure difference accelerating the slugs. When the steam bubbles in the FWD-pipe are cocondensed, string of water slugs are pushed by the pressure difference between steam dome and FWD-pipe. Different flow modes are illustrated in Picture 18. Although these phenomena could not be seen from the temperature measurements in Podolsk experiments, they most probably exist at least in some extent.



Picture 17. PVC-facility used for visual experiments in Loviisa.

The main results showed that the water hammering and the water slugs are normally created in the horizontal parts of the FWD-pipe, typically at mass flow rates 3-9 kg/s due to the annulat vortex flow mode. With higher flow rates it seems evident that the slugs are created in the region of the distribution nozzles or in the T-piece. At higher pressure the intensive hammering always faded away when the water level in the test vessel was raised above the FWD-pipe. This is obviously a consequence of the decreased heat transfer are in the horizontal part of the FWD-pipe.

The preliminary hand calculations predicted that the transition from stratified mode to wavy flow mode may exist at the SG mass flow rate round 6 kg/s. Furthermore, it was assumed that the hammering decreases when the horizontal part is flooded limiting heat transfer area between phases. The flooding criteria for a pipe can be calculated from the equation (4) /5/.

$$\dot{m} = \pi \cdot \rho \sqrt{g \cdot R^5} \qquad (4)$$

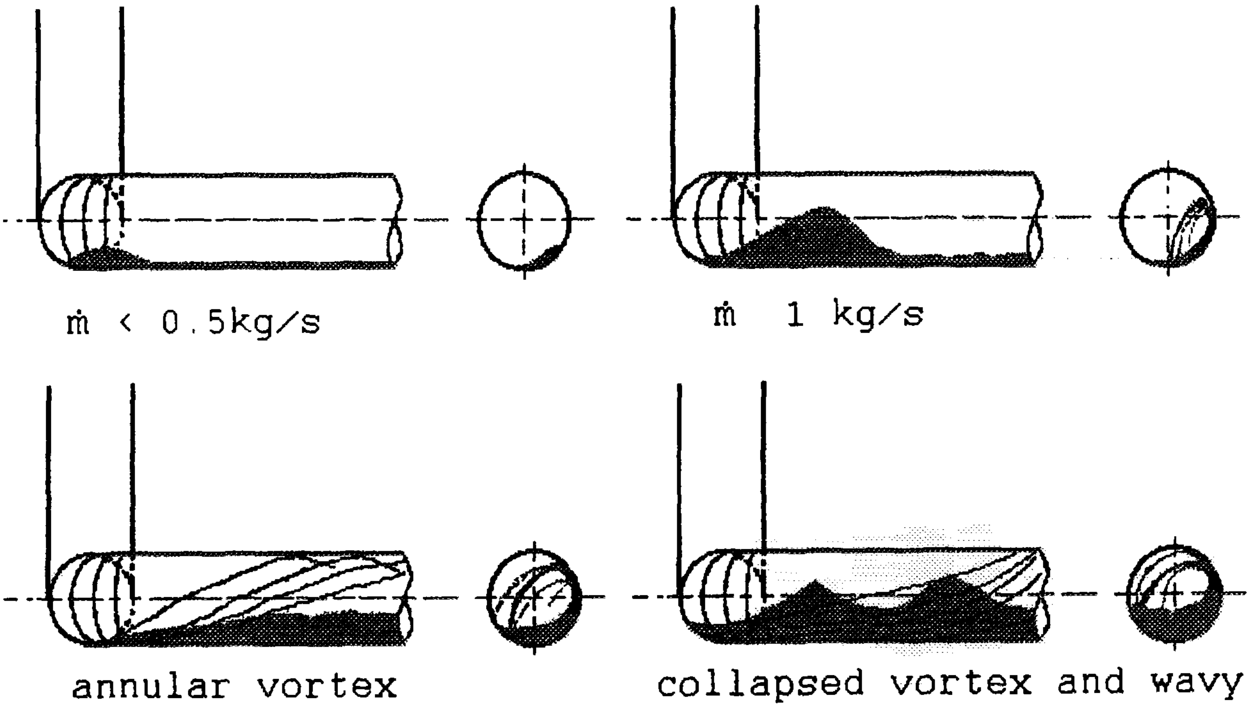
where

$\dot{m}$ = mass flow rate

ρ = fluid density

g = gravitational acceleration

R = radius of the pipe



Picture 18. Different flow modes in YB52 FWD-pipe construction.

According to the equation (4) the horizontal part of the FWD-pipe is filled with water if the mass flow rate corresponds to 13 kg. This feature was demonstrated in all the experiments and is shown in the Table 3. When the mass flow rate into the facility is about 13 kg/s, the water almost fills the T-piece and the horizontal part of the tube before distribution nozzles. This feature limits the heat transfer reducing the condensation. However, condensation in the descending part occurs, but it can be compensated with the venting pipes. The capacity of the venting pipes is enough for compensating relatively low condensation at high pressures. Some hammering was detected with mass flow rates of 13-14 kg/s, though. The T-piece is not fully filled with water and some condensation may take place in this small steam volume.

In some additional experiments, the effect of the flow perturbation, was clearly demonstrated. Abrupt shut off of 6 kg/s mass flow rate generated maximum water hammer order of 70 bar. Additionally if the mass flow rate was promptly increased an intense water hammer response could be seen.

At low pressures the hammering frequency seemed to increase. On the other hand the magnitude of the hammering was limited due to the lower subcooling of the feed water. The wavy flow mode is a consequence of lower steam density. Additionally, the venting pipes were not capable of compensating the condensation. With a vessel pressure of 2 bar the controlling of the facility was extremely difficult.

6.2 Water hammer mechanisms in Loviisa specific FWD-pipe

The new nozzles were designed for the Loviisa specific design (YB56) to limit the condensation heat transfer area. Additionally the 5 venting nozzles was left in the T-piece balancing the possible condensation. Furthermore, a throttling device was assembled in the T-joint flanges to choke down kinetic energy of the slugs.

The possibility of the water level oscillation of the descending part part was discussed provoking continous water hammering. Additionally, it was pointed out that this siphon pipe effect occurs also in the case of abrupt decrease or disconnection of feed water flow. To avoid both these phenomena small holes were drilled in the upmost part of the inner curve of the nozzles. The effect of the holes was demonstrated in visual experiments both in Podolsk and with the PVC-facility.

The oscillation of the descending part water level is obviously limited by the small holes in the distribution nozzles. Moreover, the holes in the nozzles balance the pressure difference at low mass flow rates and prevent the siphon pipe effect leading to a more even flow distribution between nozzles. Without the siphon cutting holes, only a limited number of the nozzles would be operating or more or less continuous flow oscillation of the nozzles would be developed. These features might, in turn, increase a condensation provoking a continuos water hammering.

The venting pipes in the T-piece were needed for two reasons. When injecting cold feed water at high pressures, the venting pipes are capable of compensating the condensation. Additionally, if the feed water flow into the collector is disconnected, under-pressure in the T-piece is formed leading to steam flow from the steam dome. When cold feed water is injected into the steam generator steam bubble is collapsed sucking new steam into the T-piece leading to continuous hammering. With venting pipes the pressure is balanced between T-piece and steam dome, and steam back flow from distrubution nozzles does not exist. This mecahanism was demonstrated with the PVC-facility. At lower pressure the capacity of the venting pipes seems to be inadequate but the water hammer magnitude is still tolerable.

7. CONCLUSIONS

The first damages of the feed water distribution (FWD) pipes were observed in 1989. The FWD-pipe T-connection had suffered from severe erosion corrosion failures. Similar damages have been found also in other VVER 440 NPPs.

In spring 1994 all six steam generators of Rovno NPP unit 1 were replaced by FWD-pipes designed by OKB Gidropress. Later in summer 1994 an OKB Gidropress designed FWD-pipe was assembled into steam generator YB52 at Loviisa Unit 2. The Finnish regulatory body, STUK, gave conditional permission for the FWD-pipe of new design requiring IVO to study water hammer phenomena inside the FWD-pipe and the heat transfer tube's response to cold emergency feed water injection. During the first year's operation several water hammerings were detected in start-up conditions.

In the refuelling outage 1995 the cover of the T-piece was reinforced against possible hammering during the start-up phase. Additionally, five venting pipes in the T-piece were assembled. However, in the start-up phase water hammering was clearly observed. The influence of the assembled venting pipes was almost insignificant. After these observations large scale experiments on condensation induced water hammers were decided to be carried out.

In summer 1996 extensive water hammer experiments were carried out together with Gidropress. The experiment was carried out in three stages. In the first stage a modified model was studied and in the second phase a Loviisa specific FWD-pipe version was studied. In the third phase visual experiments were carried out. In the first two phases the experiment were carried out with actual secondary parameters and one half of the actual FWD-pipe was used for water hammer studies. The third stage experiments were carried out in atmospheric pressure for visualising the phenomenon.

In the first stage experiments the model of the YB52 FWD-pipe was used. The maximum pressure peak was found to be about 65 bar. According to strength calculation the life-time for the T-piece was analysed to be order of few minutes. For the second stage experiments the construction of the FWD-pipe was redesigned. The changes proved to be successful. The maximum pressure peak was decreased down to 19 bars. However, the construction of the T-piece was redesigned to better tolerate better possible water hammers. In 1996 in the annual refuelling outage of Loviisa Unit 2 a redesigned FWD-pipe was assembled into the steam generator unit YB56. The remaining FWD-pipes of old design and the FWD-pipe in the YB52 will be changed during the next 4 years.

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