RESULTS OF TESTS WITH LARGE SACRIFICIAL AND SELF-CLEANING STRAINERS AND THE INSTALLATION AT RINGHALS 2

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Abstract

The paper describes briefly activities performed by Vattenfall Utveckling AB at Älvkarleby Laboratory as part of the qualification programme for the new ECCS strainers at PWR plant Ringhals 2 based on the "robust solution" with large sacrificial strainers and a self-cleaning "wing-strainer" of same type as used for the five modified Swedish BWR plants.

With the new knowledge gained from several BWR strainer projects following the Barsebäck strainer incident in 1992, the functioning of ECCS strainers for PWR was re-evaluated. The upgrading at Ringhals 2, a 3-loop Westinghouse plant having fibreglass and mineral wool as insulation, was the result of a design study including a lot of experimental work mainly in 1993 and 1994. The new ECC system was installed in 5 days in the summer outage 1995.

In a first study in year 1993 in the large test tank at Älvkarleby Laboratory it was discovered that the earlier design basis for debris settlement was not fulfilled. Recirculating water falling from a large break will not only prevent settling of the fibrous insulation debris but also disintegrate wads and larger pieces to fibres and fines. It could no longer be assumed that the insulation would settle in front of the strainers. This discovery affected the further work within the project group and the work at Älvkarleby Laboratory.

It is presented some test data that have not been published before, e.g. combinations of fibres and particulate material. The test programme included also chemical treated fibrous insulation as well as combinations with carbon powder or oil. Also experiences from combinations of fibres and RMI debris were gained.

Some information from projects later performed for the US market are included. Also it is included some experience on deviations in results when tests are performed in different ways. At the end the modified strainer system for Ringhals 2 is presented.

1. Introduction

With the new knowledge gained from several BWR strainer projects [1, 2] following the Barsebäck strainer incident, the functioning of ECCS strainers for PWR was re-evaluated. The upgrading at Ringhals 2, a 3-loop Westinghouse plant having fibreglass and mineral wool as insulation, was the result of a design study including a lot of experimental work mainly in 1993 and 1994. The new ECC system was installed in the summer outage 1995.

The Ringhals 2 strainer upgrading project has been reported at the workshop in May 1999 and at the NEI Workshop, Baltimore July 2002 [3a, 3b] and has also earlier been described in two NEI articles [4a, 4b] A more general deseription of alternative designs developed by Vattenfall Utveckling AB was presented in another NEI article [4c].

This paper describes mainly activities performed by Vattenfall Utveckling AB at Älvkarleby Laboratory as part of the qualification programme for the new strainers at Ringhals 2.

Possible combination effects of oil and fibre in the water and effects of fibre and carbon powder in the recirculation water were studied in the small one-dimensional test rig.

CFD calculations of flow pattern in the bottom region of the containment were performed and revealed that quite high velocities could be present in areas close to the existing strainers.

Possible air ingestion caused by air pulling vortices was studied in a 1:3.5-scale model. The strainer system was found to perform satisfactorily at all operating conditions. The new ECCS system installed at Ringhals 2 in the summer outage 1995 is a self-cleaning wing strainer combined with horizontally mounted sacrificial strainers.

Self-cleaning is induced by short interruptions in the suction flow. The effectiveness of the cleaning was demonstrated in a full-scale test using fibrous insulation chemically treated to simulate a pressurised water reactor environment. Self-cleaning was also achieved for very thin layers of fibres having small pressure drops.

In Chapter 7 system aspects and information about the modification work of sump screens in Ringhals 2 are briefly covered.

2. Sedimentation, resuspension after disintegration and transport of fibreglass insulation

2.1 The fill up phase

An initial study [5] of the fill-up phase was performed in the 5 m diameter cylindrical stainless steel tank. Steam fragmented insulation (MIT NG2) from steam blasting in Karlshamn thermal power plant was used as well as insulation cut into pieces. A vertical pipe in the centre of the tank simulated a fall of 4.6 m. Figure A, shows first the start conditions of one test – large cut pieces and a water depth of 0.35 m. At a flow rate of 18.6 l/s the tank was filled up to 1.70 m of water during 26 minutes. The second picture, Figure B, shows the disintegrated insulation on the bottom when the tank was emptied.

Figure A. Cut insulation before recirculation fill-up started
(Tank diameter D = 5.0 m)

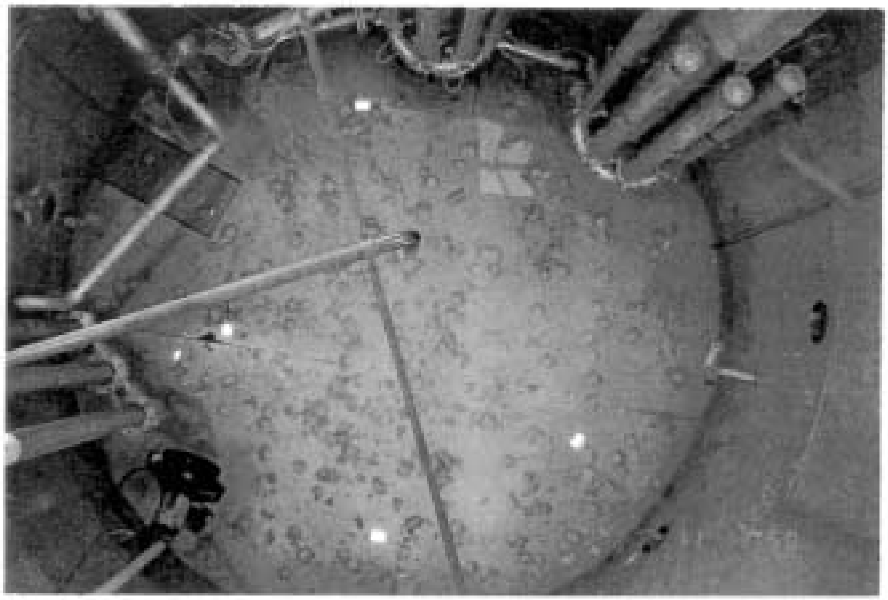
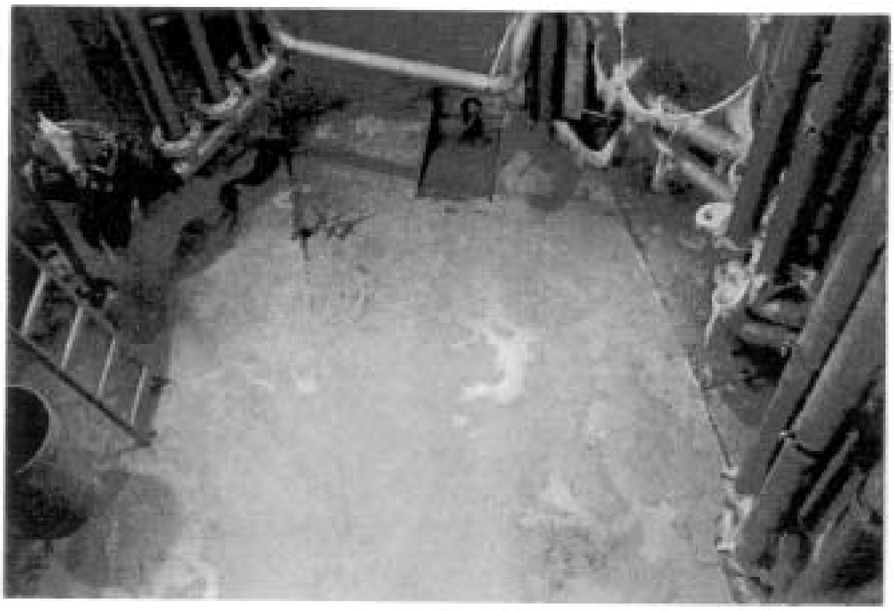


Figure B. After the test, when the tank was emptied
(Time t = 26 min, water depth H = 1.7 m when flow was stopped)

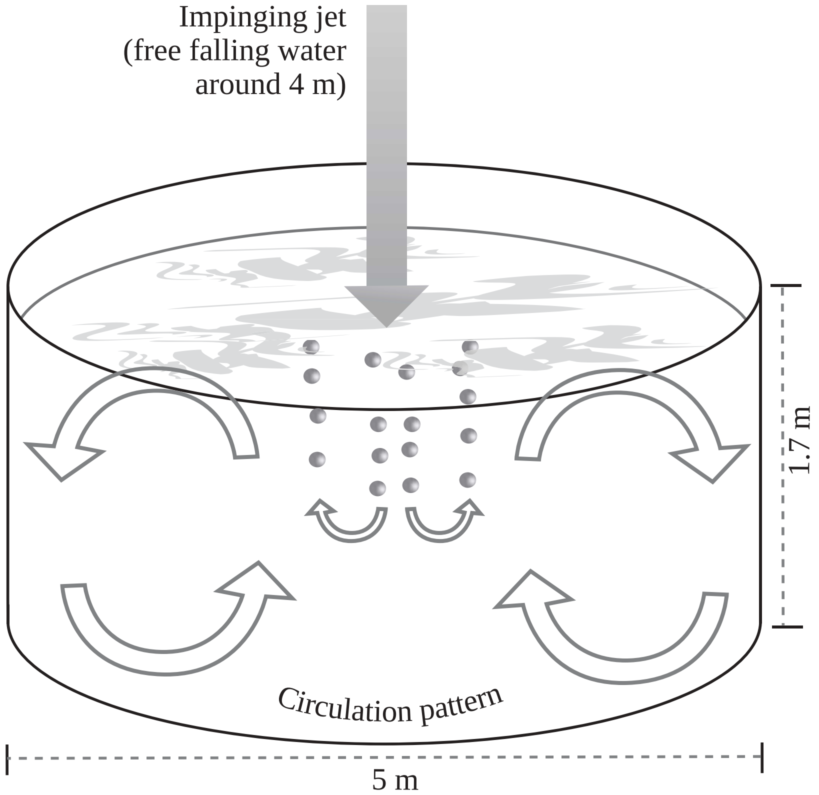


Most of the cubes had been disintegrated into tiny clusters and a lot of single fibres. Clusters fell to bottom within half an hour after the water flow was stopped but fibres remained suspended for hours.

The falling water entrains air and a circulation of the water is started, as shown on the Figure C. Pieces of the fibrous material will be moved up to the surface in the basin where the falling water is tearing apart larger pieces into smaller clusters, individual fibres and fines. This will continue as long as the plume of falling water remains.

Figure C. The falling water entrains air starting a circulation pattern, which will move fibrous insulation debris up to the surface in the basin where the falling water is tearing apart wads and clusters into fines and individual fibres

(Tank diameter D = 5 m, final water depth H = 1.7 m)



Individual fibres tend to be collected parallel to the strainer surface, i.e. perpendicular to the flow through the strainer.

The fibrous mat on the strainer will be very tight $\rightarrow$ high pressure drop.

A similar test using a plane weir, Figure D, elevated 4.6 m above pool bottom instead of a pipe created same type of disintegration. Circulation currents were weaker due to asymmetry and fragmentation was slower. But for long time operation in the circulation mode the final result of disintegration will be about the same. This is supported by results from the bed build up and head loss tests performed in the tank. (I would like to mention that in a high and narrow tank this phenomenon probably will be restrained.)

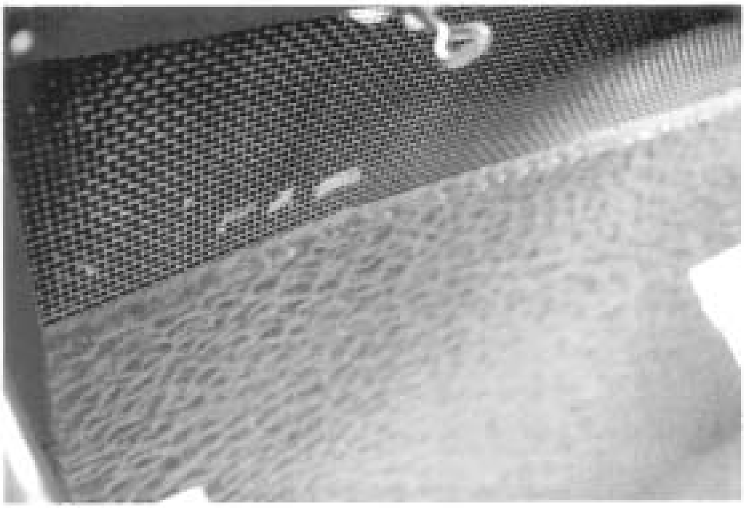
Figure D. Discharge over a horizontal edge (weir), simulating Ringhals 2

Ringhals reported [6] that half of the circulation flow will originate from plane plumes and the flow rate per unit width will be higher than tested. As the flow per surface area was representative of Ringhals 2 containment the test was expected to be very realistic and simulate conditions in the containment.

2.2 Flat mesh strainer head loss test

Steam-fragmented fiber insulation which had been further disintegrated by the falling plume was tested on a flat strainer 4 mm mesh and it caused very high pressure drops, see Figure E. Consequently these tests showed that it could no longer be assumed that the insulation would settle in front of the strainers and cause only minor head losses on the strainers. Also when settlements occur the finer parts will reach the strainers and the fibrous mat on the flat strainer mesh will be very tight.

Figure E. Debris layer on a flat strainer surface (mesh # 4 mm) using steam-fragmented fiber insulation



2.3 Containment pool circulation

The flow of water near the bottom of the containment during recirculation was also studied by 3D computations using CFD code Phoenics. A total flow rate of 800 kg/s was added in different ways and the same amount was withdrawn through the two existing strainers. The water was assumed to be free from impurities (such as insulation fibres). The results [7] indicated that the way water flows down in the containment towards its bottom is very important for the order of magnitude of the water velocities there. In Figure 6, Enclosure 3 results from a simulation of a uniformly distributed rain through the top of the computational domain (1.7 m above the bottom of the containment pool) are shown. Velocities on the order of several cm/s and upwards can be observed already here and according to the experimental results [5] a few cm/s is sufficient to impede sedimentation. In the calculations with concentrated water jets (water falls) flow velocities of the order 0.1 to 1 m/s were calculated in certain areas. Unfortunately a large postulated break location was close to the strainers also.

2.4 Debris bed build up on strainers and head loss increase

Head loss increase across the strainer over time is influenced by bed characteristics such as: debris sizes and distribution; porosity; compressibility; and filtration effects. To build up a debris bed with characteristics similar to actual plants, it is necessary to have not only the same flow velocities (flow per unit area) in the model as in the plants but also to have the correct concentration of material (debris) in the water that is approaching the strainer. Furthermore, for a complete simulation, it is important that the concentration over time is reduced in the same way as in an actual condensation pool. Thus, the turnover rate must be considered for each model.

Sedimentation also plays a roll in the removal of suspended debris from the suppression pool. The flow velocity profile and turbulence level of the pool together with the size, shape and density of the debris contribute to the sedimentation level. It should be noted that small amounts of fiber insulation in the water reaching the strainers combined with large concentrations of particulates (sludge) in the pool water can create a higher pressure drop than a large quantity of fiber on the strainers due to the “deep bed effect” in the latter case.

Also the sequence of the addition of the material to the test pool can be important. From e.g. the tests reported in reference 19 it was an experience that addition of particulate material (Minileit) after a fibrous bed (Rockwool) was formed created a much higher pressure drop compared to parallel addition or if the particulates were added first.

Thin layers of fibers plus particulates on a perforated plate can behave a bit unpredictable when holes close and open up, causing changes in the head loss as the strainer is loaded.

Sedimentation had earlier been studied in flume tests and a settling tank when sedimentation and "piling up" against the vertical, flat mesh strainers was considered an acceptable method. Typical settling velocities for chemical treated fibrous insulation in hot water was 3-14 cm/s and bottom transport started at approximately 5-6 cm/s for cut pieces, about 25 mm side length [22, 23].

Penetration of fibres from various fibrous insulations were studied in tests for Forsmark Sweden and TVO, Finland [18 and 24] and were reported in the "green book" [25]. Those early tests were performed with panel strainers having a hole size of 4 mm instead of 3 mm.

3. Head loss tests

3.1 Strainer pressure drop from fibrous insulation

The main tests for Ringhals 2 were performed in the large open tank and two types of tests were run, first a recirculation test with free falling water combined with the use of one half scale vertical wing strainer of Ringhals 1-type. This test showed that the head loss over the strainer was about the same as had been reached in earlier tests with steam fragmented fibreglass insulation at corresponding velocities.

The loading to reach a pressure drop of 2 m of water is in fact a little less (pint A) than the "pessimistic" curve F7 (Figure 1 in Attachment 1) used for computations of head loss development on BWR strainers using the computer code SILAR (version 1-4). In that code, it is assumed that the insulation material consists of fibres, pearls and fines. Flow through, growth of and pressure drop across the porous bed is computed to either Ergun's or Leva's equations. Details of the mathematical model are described in reference 20. Comparisons between results computed by SILAR and measurements in an experimental model of a 1:2 scale screen system (Ringhals 1) was presented in reference 1, see Figure 2 in Enclosure 3. (The upper two head loss curves in Figure 1 are for cut pieces of fibre glass nuclear grade, whereas the lower data fibre glass of same type). Figures 3 and 4 give some additional information from those early tests 1992-1993 and how it deviated from those earlier available head loss correlations, used in the original designs. The test also showed that the filter cake fell off as four discrete packages when the suction flow was reduced to zero [5].

The second type of tests in the tank was performed at dimensioning conditions for a 2 meter long segment of a horizontal full-scale strainer. Strainer surface area relative to floor area is same in model and plant. Recirculating flow was returned to the tank over a weir as described earlier.

A heat-treated mixture of rock wool and fibreglass insulation was added after a mechanical disintegration. One test run at half flow rate using half strainer area showed an increased pressure drop as a higher percentage of larger fragments are sedimenting and clusters and single fibres are building a more compact filter cake.

3.2 Combinations with particulate material

From our previous investigations for BWR plants it is also known that very thin layers with high concentration of particulate material in the debris bed can cause extremely high pressure drops. That was already reported in the OECD/NEA Workshop 1994 [1]. Thus, a situation where sedimentation of larger clusters occurs and disintegrated insulation (single fibres), in combination with particulates is suspended in the water body can cause the highest pressure drop, i.e. higher than in a "deep bed" situation, see Figure 5 in Enclosure 3 taken from reference 1, as Figure 4 E. This has later been confirmed by other tests, e.g. in US.

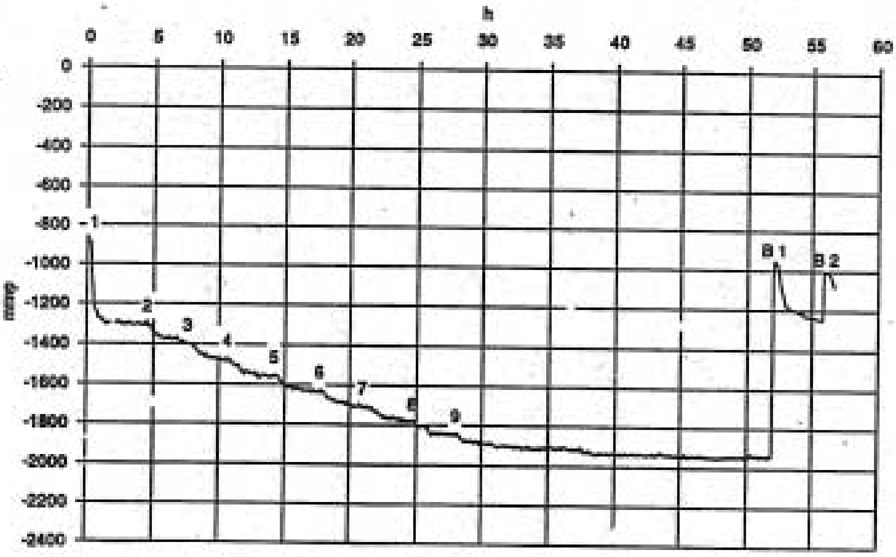
Work was early conducted mainly for Ringhals 1 but verification tests (scale 1:2) also were performed for the specific Barsebäck and Oskarshamn adaptations of the designs. Test of fibres in combination with particulates (calcium silicate) was part of a common programme for the three utilities Vattenfall, OKG and Sydkraft in 1992 and early 1993 before the large sacrificial and self-cleaning (wing-strainers) were installed in the five Swedish BWR's that had to be modified. Slabs of reinforced calcium silicate were water jet eroded to produce the particulates. One example from these tests is given in Figure F(a) and F(b) from reference 13 where the wing strainer was cleaned by back flushing when full suction flow was maintained from the sacrificial strainers.

In a later test for Oskarshamn NPP Units 1 and 2 Transco fibre glass and Gullfiber 6212 was compared [21]. Aging and funmentation (hydrapulper) according to our standard procedure was again used to produce immaterial comparable to the steam fragmented insulation. A vertical wing strainer (D = 250, H = 475, hole size 2.5 mm, 20.2 percent) was used with a flow rate and tank volume was selected to give correct turn-over time compared to the pressure-suppression pool of the plant. The tests showed that head loss for Transco was close to the earlier used F4-curve in Figure 1. Gullfiber had a considerably higher head loss.

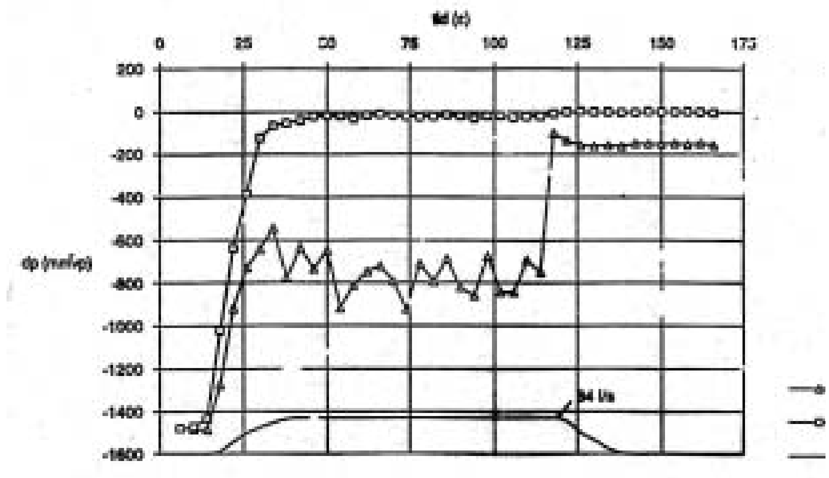
As part of the Proof of Principle (POP) testing programme on three designs a series of tests with one large wing-strainer (0.3 m diameter), located either vertically or horizontally, were performed in 1996 as a joint effort between ABB Atom AB, ABB Combustion Engineering and Vattenfall Utveckling AB, at the Vattenfall Utveckling test facility in Älvkarleby, Sweden.

Figure F(a). Ringhals 1 strainer system some time after cleaning of the wing strainer when a further build up of debris on the wing strainer has occurred

Figure F(b). Intake strainers for ECCS. Pressures recorded at model tests, scale 1:2. Test 4 in phase 2



Differential pressure, P1



Backflush No 1 (B1)

This “passive, self-cleaning wing strainer” was tested with sludge, insulation and recipe material consistent with that requested by the BWR Owner’s Group (BWROG). The purpose of these tests was to record their operability under conditions consistent with tests of other strainers for US BWRs. The sludge, as requested, consisted of Grade 2008 and 9101-N-40 black iron oxide, presoaked according to a procedure.

Different loadings with different ratios particulate material and fibres were tested and can be used for more general head loss correlations. Debris per unit area for a certain approach velocity was simulated as the main parameter and the strainer was operated under specified flow rates in order to collect the debris on the strainer surface. The strainer performance was recorded for each debris type and combination tested. Some tests were run until all particulate material was collected on the strainer

– the black water was cleaned and it was checked by taking water samples. Some results are given in Figures G, H and I(a) and the photo in Figure I(b) taken from reference 14.

It was concluded that the test results can be used in the design of passive, self-cleaning wing strainers for conditions in the Reference Plant.

These tests also demonstrated that self-cleaning first occurred at zero flow. On horizontal strainers, fins are proposed to be located on the lower half of the strainer, preferably at 4:30 and 7:30 positions. This arrangement would allow for cleaning of one-quarter of the system. It is not necessary, and thus not the intention to clean the whole strainer area using this passive, self-cleaning system. Sacrificial areas on the strainer act to clean the pool water and bind the insulation on the strainers.

In the additional testing specified for Cooper NPP, Nebraska results showed that the method to calculate head losses presented in Utility Resolution Guidance (October 1996) gave considerably lower pressure drops than measured in the test [15].

Figure G. Passive self-cleaning wing strainer, altered wing position, segmented length (600, 600, 600 mm)

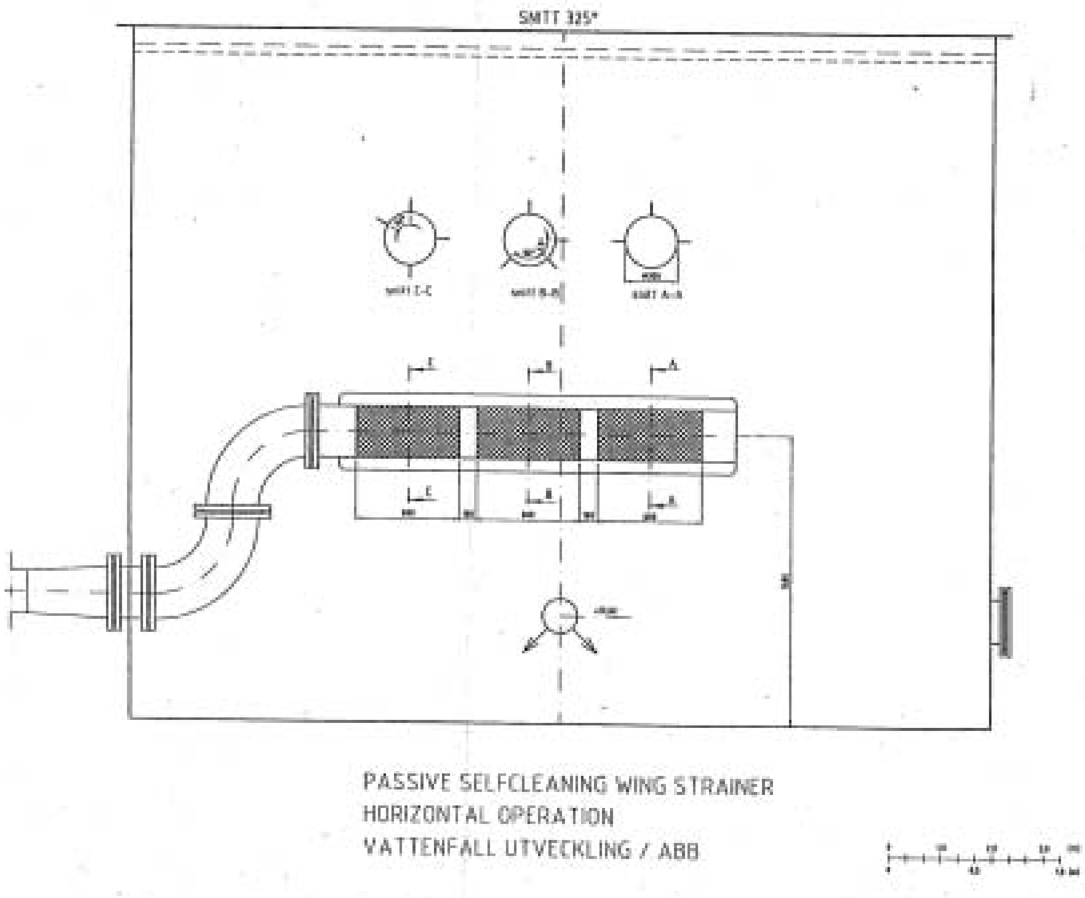


Figure H. Test W42H – Flow rate and pressure drop as a function of time

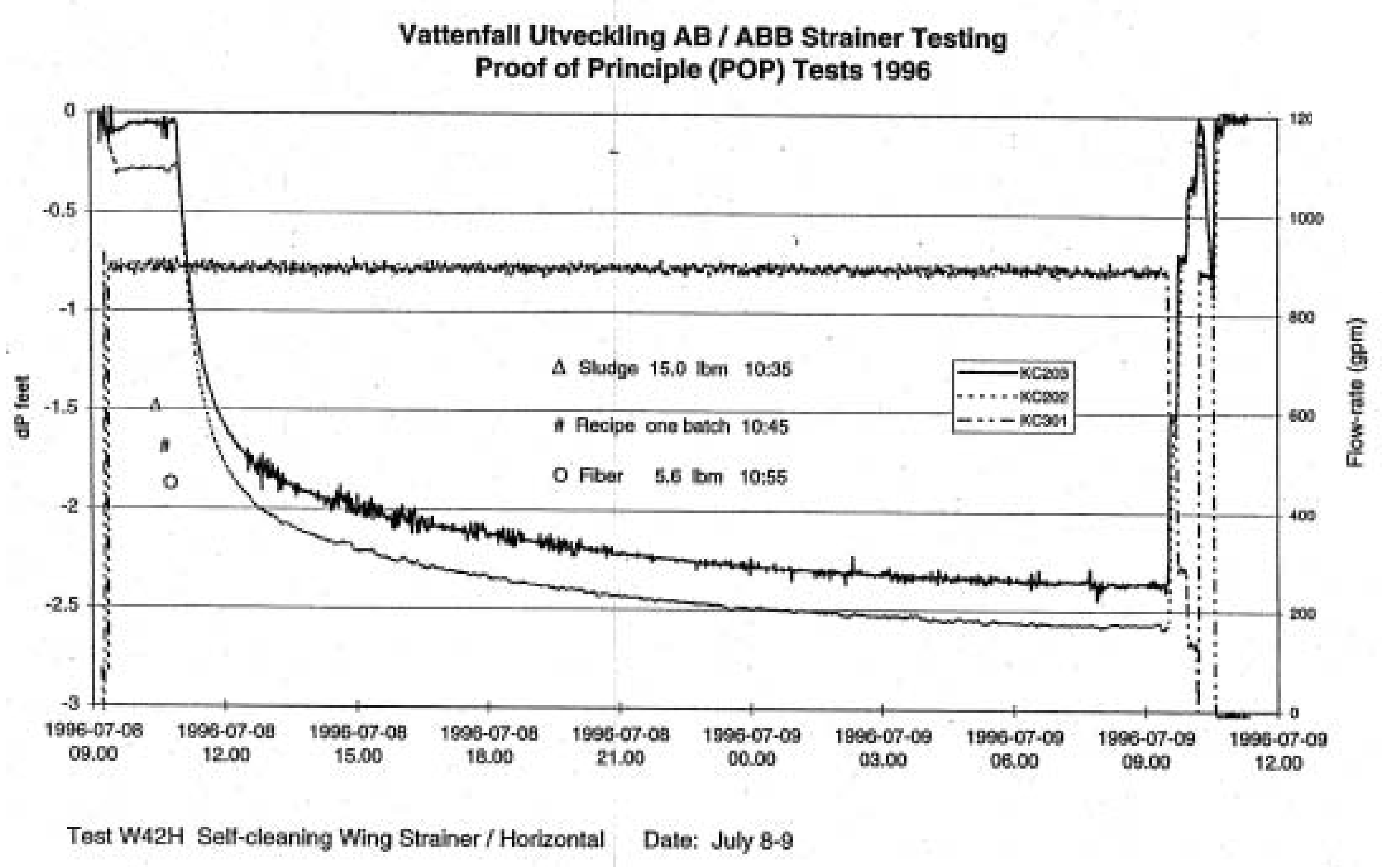
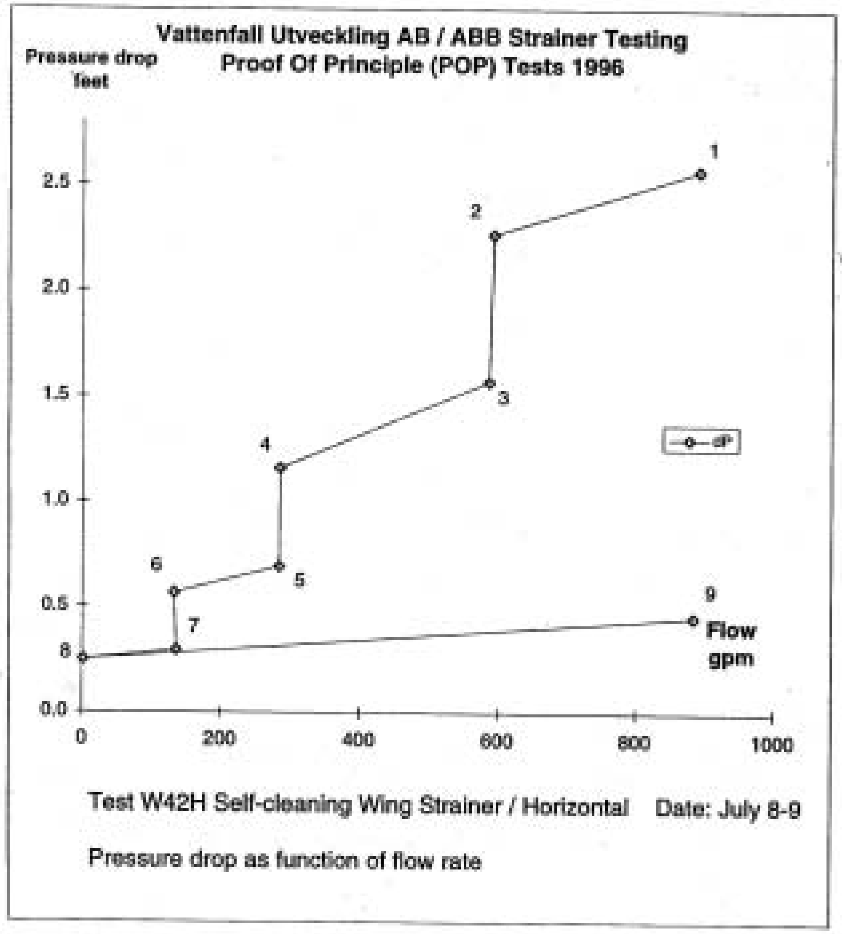
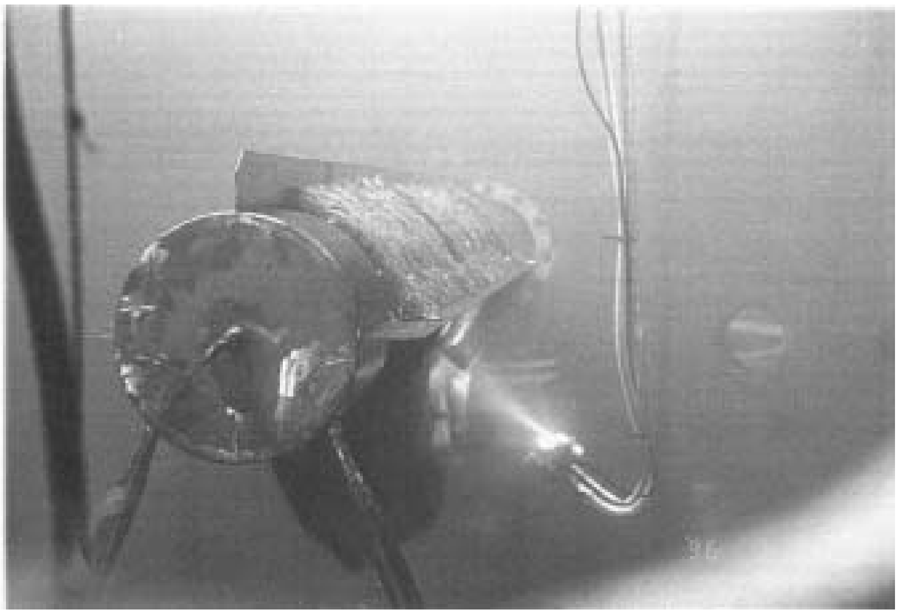


Figure I(a). Test W42H – Pressure drop as a function of flow rate



Point	Time	Flow-rate (%)	dP (ft)
1	09.29	100	2.57
2	09.33	67	2.27
3	09.42	66	1.57
4	09.46	32	1.16
5	09.55	32	0.69
6	09.58	15	0.57
7	10.08	15	0.30
8	10.10	0	0.25
9	10.24	99	0.46

Figure I(b). POP test W62H
Cake is falling off after loading glass of fiber insulation (1.3 kg/m^2) sludge (3.6 kg/m^2) recipe when flow rate is reduced to zero



3.3 Possible effects of oil or carbon powder

These tests for Ringhals 2 were performed in a small one-dimensional model using water with temperature and chemistry representative for conditions at a LOCA. A filter bed of rock wool and fibreglass that had been heat-treated and disintegrated was formed before carbon or oil was added. No extra pressure drop was found for the small but typical concentrations that were tested [10].

3.4 Pressure drop increase during long time recirculation

Long time recirculation tests were carried out at Siemens laboratories in Erlangen as a part of the Steam Generator Replacement Project for Ringhals Unit 2. From these tests during post LOCA representative temperature and chemistry it was known that the pressure drop increased after 120 hours and more. There was no limit to the pressure drop increase.

The pressure drop increase over long time was explained by four factors:

1. The chemicals e.g. NaOH in PWR Post LOCA water is soaking SiO_2 from the glass fibres. Thus the kinematic viscosity of the water increases.
2. The glass fibres are being less resilient as a result of the chemical attack and therefore the filter is being packed denser.
3. Impurities captured by the filter migrate from upstream positions to downstream positions. The same is valid for fibres, when dislocated they always moves downstream, which result in a less porous filter.
4. The increasing pressure drop due to 1, 2 and 3 will create an increased load over the filter bed and this will cause further compression which will then give even higher pressure drop, etc.

3.5 Behaviour of reflective metallic insulation (RMI)

Same type of large tank tests for Ringhals 2 [8] performed with RMI and combinations of RMI and fibrous insulation showed that the RMI will stay at tank bottom and will not be transported to the strainers as the approach velocities are very low for this design. The fibrous insulation will have a minor effect on the movement of RMI and only a few very small metallic pieces were observed in the filter cake. This means that no extra head loss is likely to occur due to a combination of RMI and fibres. The material used was RMI from the high pressure blast tests at Karlstein, Germany.

The transport tests in a flume [8] showed that velocities above 0.09 m/s were needed for moving that material (7 classes). Approach velocities to the vertical strainers lower than 0.04 m/s never could hold any of the blasted pieces, and a more typical “holding value” was 0.1 m/s. Settling tests in a tank showed that all fragmented RMI (all classes) settled at a speed above 0.1 m/s. Hyvärinen (STUK) found sedimentation velocities about 0.04 to 0.08 m/s for the statlest descent mode of flat pieces [26].

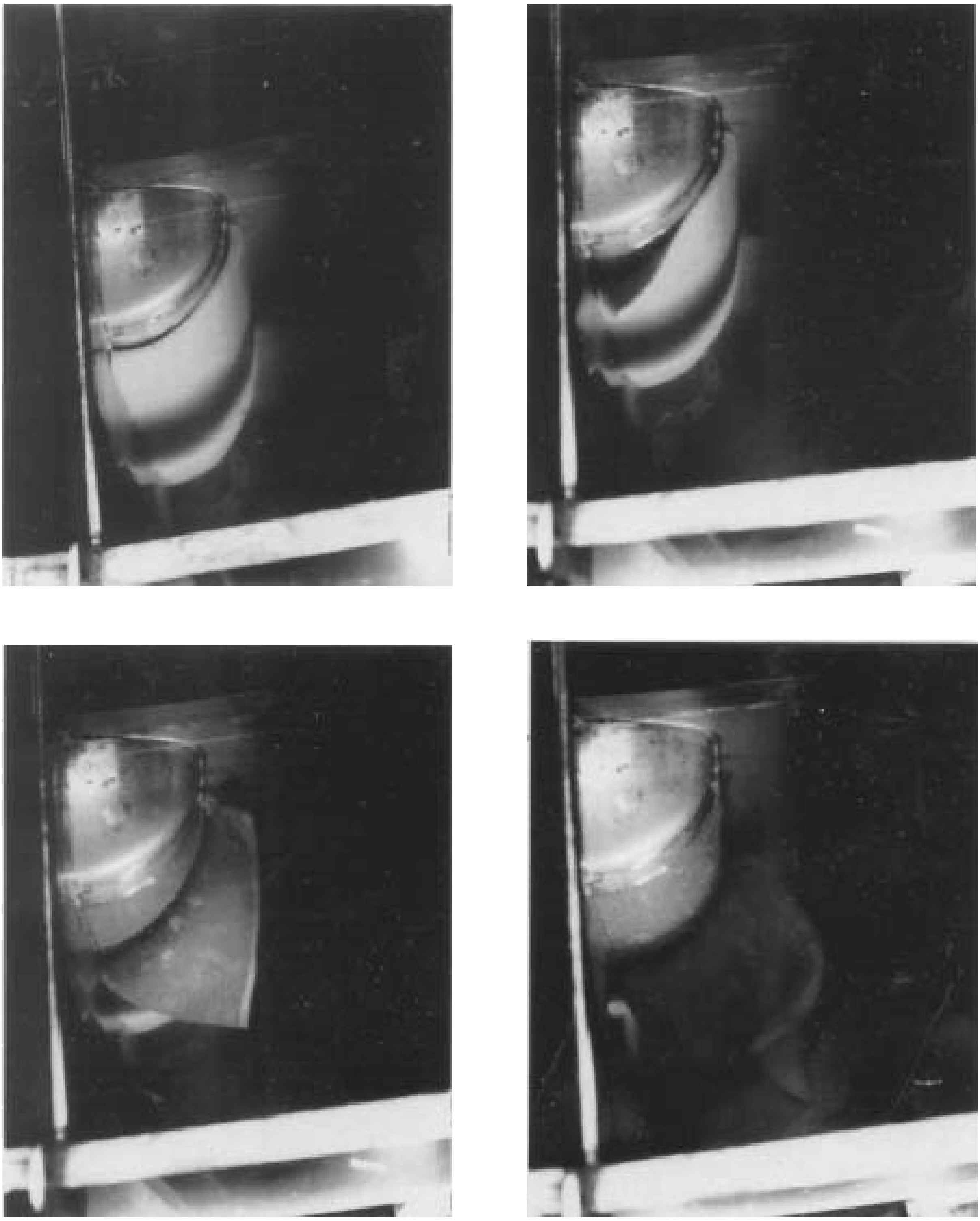
The strainer loading and head loss tests for Ringhals 2 had very low approach velocities (0.01-0.02 m/s) to the strainer, but the tank was also stirred up by the falling water.

4. Test of self-cleaning of the wing strainer

4.1 Ringhals 2 design

The self-cleaning qualities of the wing strainer at Ringhals 2 were verified at full scale using one quadrant of the full-scale strainer. Also in this test serie water chemistry after a LOCA was simulated, but all the five tests were all run at room temperature. Two different mixtures of fibreglass and rock wool were tested and all tests were made for very thin layers with a low pressure drop. Self-cleaning was achieved when layer thickness was more than 12-25 mm. A sequence from the self-cleaning at zero flow is presented in the four photos on Figure J.

Figure J. Self-cleaning occur at PWR plant Ringhals 2 [9b]



4.2 BWR design

In the development work for BWR large sacrificial and self-cleaning strainers it was in numerous tests demonstrated that self-cleaning occur on the wing wtrainer [1, 3, 13, 14, 15 and 16]. Two examples of self-cleaning are already presented in Figures F and I(b) from tests with vertical wing strainer (Ringhals 1) and a horizontal one (from the POP-tests, [16]).

5. Gas accumulation prevention in the system

5.1 Possible air ingestion from vortices

Possible air ingestion caused by air pulling vortices was studied using a reduced scale 1:3.5 hydraulic model [11]. An appropriate area of the Ringhals 2 containment with major obstacles was included in the model.

This relatively large scale was selected for the test due to possible scale effects in modelling vortices. Experiences from similar testing were incorporated, especially those from extensive US studies for NRC concerning reactor containment recirculation sumps of the present PWR type. The sensitivity to extra distortions of the approach flow profiles was also tested as well as exaggerated flow rates (above correct Froude number).

At correct Froude number simulation surface dimples (vortex type 2, [27] occurred frequently and in some cases also vortex type 3 occurred. At full scale (plant) velocities dye cores (type 3) occurred more frequently. At double plant velocities type 5 vorticies (pulling air bubbles) were observed occasionally, before the main current “washed away” the vortex rather than promoted its build up. At extreme low water levels that circulation is stopped by the fins and only very local disturbancies were noticed. Pictures from those tests are shown I Figure 7, Enclosure 3.

Main conclusions were that the proposed design of the new strainer system using long horizontal cylindrical strainers in combination with vertical self-cleaning strainers of Ringhals 1-type was found to perform satisfactorily for all operating conditions considered. The likeness of air ingestion from vortices would be small.

5.2 Boiling in the debris layer

As the water temperature could be close to 100°C at recirculation and Regulatory Guide 1.1 does not allow the use of containment overpressure in the NPSH calculations, the maximum head loss over the strainers must not be higher than the water column above the strainers. Otherwise there will be boiling in the debris layer. The Ringhals 2 strainers are designed to avoid boiling in the debris layer rather than investigating the effects of boiling, i.e. pressure drop over strainer is kept low and measured by the dp-system installed. The design of the recirculation water source i.e. the refuelling water storage tank is also of great importance.

6. Bi-stable wing strainer

This is a new, patented, self-cleaning strainer system, which can be cleaned without either changing the suction flow or back flushing.

In this design a flexible bi-stable wall is installed inside the strainer. The free edge can be closed against either of two opposing arch-shaped walls in the strainer, or in the pipe. As the filter becomes clogged, the pressure difference between one side of strainer and the other increases. When a certain pressure difference is obtained, the bi-stable wall switches from one side of the strainer to the other. The pressure pulse, in combination with the fins, cleans one side, making it ready for when the other side is clogged and the next switch will take place. This strainer is easy to install because it can be mounted on an existing flange.

The principle of the bi-stable strainer (model data D = 375, H = 600 mm) was successfully demonstrated during the POP-tests [16, 17]. Figures K and L are from those tests.

Figure K. Bi-stable strainer during installation for testing at Vattenfall Utveckling AB, Älvkarleby Laboratory

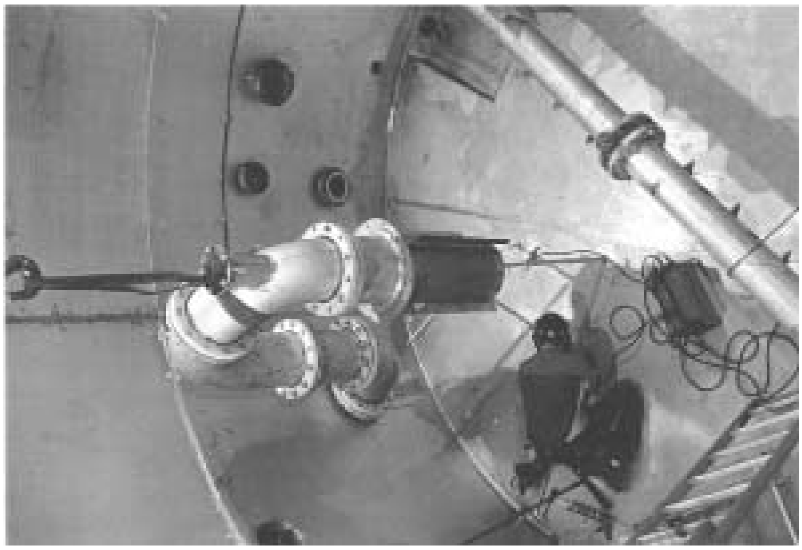
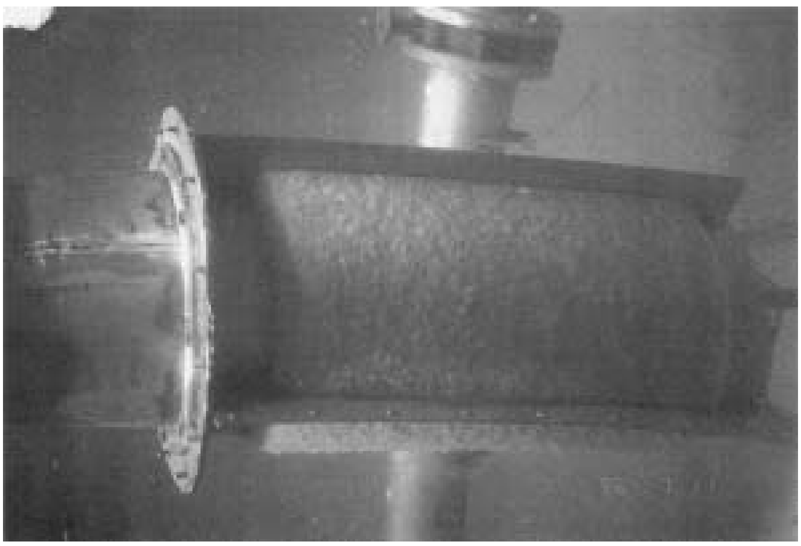


Figure L. Bi-stable strainer during testing



It was also [16] concluded that further development work and testing will be required before the bi-stable strainer is ready to be installed in a plant. The flow rate and NPSH requirements will determine the actual size and spring force. However, the estimated size of the bi-stable strainer, based on a flow rate of 10 000 gpm (630 litres/s), is approximately 4 ft (1.2 m) in height and 2-2.5 ft (0.6-0.75 m) in diameter with 23% porosity.

Later it has been discussed to have the bi-stable wing strainer as a further back-up in the “Swedish robust solution”.

7. Plant modification at Ringhals 2. Large sacrificial and self-cleaning strainers – a robust system

7.1 Basic design requirements and defence in depth philosophy

The basic technical requirements for the ECCS strainers in the USA plants are essentially the same as for the Swedish plants. The strainers shall have capacity to separate from the recirculation flow the amount of debris that is determined by reasonably conservative plant specific analysis. Other basic design criteria such as low internal pressure drop and structural strength are also similar in Sweden and the USA.

The concept chosen for Ringhals 2 is based on a defence in depth philosophy and comprises:

- large passive strainer area;
- differential pressure measurement over the strainer;
- possibility to clean a part of the strainer area.

The large strainer area means that the thickness of the layer of impurities is reduced. It has been demonstrated that debris spreads evenly over the strainer area. The pressure drop over a layer of debris is a function of the thickness of the layer and the water velocity. Therefore the enlargement of the strainer area is the most straightforward way of increasing the strainer capacity. In strainer area should be large enough to. In the short term recirculation, strainer area should be large enough to capture all imputities within the limits of the maximum allowed pressure drop. By using a differential pressure measurement system the operators can get on line indication of differential pressure development.

In the long time recirculation mode, i.e. more than 100 h, the pressure drop is expected to increase. Small dislocations of particles and fibres are packing the debris layer denser on the strainer surface. Therefore a part of the strainer area should be possible to clean. With the chosen strainer design it is possible to clean a large enough area only by turning off the flow to normally no backflush system is needed. Should active backflushing system be preferred, such a concept can be added or a bi-stable strainer can be included.

7.2 General information about Ringhals 2

Ringhals 2 is a 3-loop Westinghouse PWR in operation since 1974. The architect engineer was Gibbs & Hill Inc. There are two 100% emergency core cooling (ECCS) and four 50% Containment Spray (CS) trains. The ECCS flow is 2*240 l/s and the CS flow is 4*125 l/s. In the original design the recirculation trains were taking suction from two cage type sump screens each having an area of 7 m^2. The screens were designed in conformance with NRC Regulatory Guide 1.82, published in June 1974.

At steam generator replacement in 1989 the steam generators were insulated with nuclear grade fibreglass insulation. Insulation tests were performed by Vattenfall and the insulation material supplier. It was found that the capacity of the strainers was insufficient. A new design was developed resulting in an installation of a wire fence type pre-strainers. In addition, an overflow was added to the original screens. This design was based on sinking debris.

The Ringhals 2 containment contains the following types and quantities of insulation materials.

Metal reflective foils	10 720 m^2	Polyurethane	4 m^3
Fiberglass	136 m^3	Reinforced cement (Linpac)	2 m^3
Mineral wool	85 m^3		

7.3 Design review of Ringhals 2 recirculation function in 1993

In light of the knowledge gained as a result of the Barsebäck strainer incident a design review of the Ringhals PWR's recirculation function was made in 1993. As described above, tests and CFD calculations performed at Älvkarleby Laboratory with new and aged insulation material in a containment model showed that insulation debris did not sediment at the bottom of containment during the recirculation phase as previously anticipated, mainly due to the stirring effect of the recirculation water falling down into the water pool. In addition the falling water broke up the insulation debris into finer particles, which would create a higher pressure drop over the strainers than previously anticipated. Thus the design review showed a necessity to improve the recirculation function. With the experience gained during the work with the strainers for the Swedish BWR's, namely the necessity to handle a variation of insulation materials and impurities, it was decided to improve the strainers rather than change insulation material.

7.4 Design basis

The Ringhals 2 requirements on a solution of the ECCS and CS problems were the following:

- The plant shall fulfil the FSAR requirement namely that the strainers shall be able to handle the effects of all the limiting events for the plant plus a single failure.
- The strainer should be able to handle the various combinations of debris.
- Man-machine aspects are important. The operating instructions should be easy and also give the operator's sufficient information and control over the recirculation function.
- The strainers should have a simple and robust design.
- The solution should as far as possible be verified by tests.
- The strainers should be possible to install during a normal refuelling shutdown.

7.5 Limiting events, physical separation and single failure, design- and service loadings

The FSAR safety analyses and probabilistic risk assessment showed that the two limiting events when strainers would be used are large and medium size loss of coolant accidents (LOCA).

The two sump cages were replaced by four pipe strainers one for each ECCS and one for each 2*50% CS train. The capacity of one ECCS plus one CS strainer should be sufficient to handle all debris even if it is assumed that the CS flow may be interrupted depending on the type of initiating event. Thus the design can handle a single active failure in one of the safety trains.

The strainers are designed to sustain the following loads:

Design pressure:	50 kPA (external and internal pressure).
Design temperature:	149°C without pressure loading. 100°C with pressure loading.
Seismic loads:	No. According to the plant limiting events, LOCA and earthquake do not occur in combination as the reactor coolant pressure boundary is seismically qualified.
Missiles and jets:	The strainers are not designed for direct missiles as they are only used after LOCA's and the complete reactor coolant pressure boundary is inside the missile barriers. They are however protected against smaller objects.

7.6 Strainer capacity for fibers, metal foils and impurities

Vattenfall's tests reported at the OECD/NEA Workshop in Stockholm showed that nuclear grade fiber insulation without jacketing could be fragmented at a distance of 35 pipe diameters from a pipe break. As Ringhals 2 has a limited amount of pipe restraints to keep the jet in a fixed position, the strainer capacity is based on fragmentation of all the insulation material inside one complete loop (missile barrier) plus some insulation material, on connecting piping outside the missile barrier such as main steam piping, in total 45 m^3 of fiber glass and 12 m^3 of mineral wool. In addition metal reflective insulation material as well as other debris is considered. To gain sufficient knowledge for this design review, water and steam jet tests of metal reflective insulation as well as transportation and head loss tests were performed.

Among the debris studied could be mentioned lubrication oil for the reactor coolant pumps and carbon from ventilation filters. The special qualities of PWR water resulting from the addition of boric acid and tri-sodium phosphate was also studied.

The head loss characteristics used for the combined effect of debris from mineral wool, fiber glass, metal foils, oil and other impurities was at that time expressed as:

$$\Delta p = 5\,500 * v^{1.5} * t^{1.5} * \nu/\nu 20 \text{ mvp} \qquad \text{(m.o.w)}$$

where: v = velocity in m/s,

t = debris thickness in meters with as installed density,

ν = temperature dependent water viscosity (Δp is in metres of water pillar).

The design was based on the empirical experience that 2/3 or the insulation reaches the pool. Due to the stirring effect of the recirculation water falling down into the pool no sedimentation is assumed.

Tests of metal reflective insulation subjected to steam and water jets were performed in Karlstein. Steam jet tests of fiber insulation were performed in Karlshamn and Studsvik. The tests showed destruction of the insulation material at distances of 15 to 35 pipe diameters from the break. The fragmented material was used for head loss tests.

7.7 Cleaning of the wing strainer

Due to the difficulties of determining the strainer head loss for all combinations of debris during a long recirculation period and to make the design robust it was decided to equip a small part of the strainers with cleaning possibilities. Previous testing of the new Swedish BWR strainer systems supplemented by additional tests of Ringhals 2 strainers at Älvkarleby showed that wing strainers will be cleaned automatically when recirculation is reduced. Thus cleaning of Ringhals 2 strainers is achieved without backflushing or use of moving parts, see also sections 4.1 and 4.2 above.

7.8 Limiting factors for the recirculation function

In most cases the main limiting factors for the BWR recirculation function are the head losses over the suction strainers and the recirculation water level and temperature, which can create low available NPSH for the ECCS and CS pumps. In addition the recirculation pool water level and pool dynamic effects can create air ingestion into the pump suction – compare section 5.1 above. For Ringhals 2 the limiting factor for the recirculation function is the water level in the containment pool or rather the water level above the strainer debris layer. As the water temperature could be close to 100°C at recirculation and regulatory guide 1.1 does not allow the use of containment overpressure in the NPSH calculations the maximum head loss over the strainers must not be higher than the water column above the strainers otherwise there will be boiling in the debris layer. The Ringhals 2 strainers are designed to avoid boiling in the debris layer rather than investigating the effects of boiling.

The design of the recirculation water source i.e. the refuelling water storage tank is of great importance. The maximum allowed refuelling water temperature, maximum 50°C for the Ringhals PWR's, is a main contributor to the maximum recirculation water temperature and the volume of water gives the containment water pool level during recirculation. Another important parameter for the water level is the amount of water trapped in piping system, in compartments and on walls and floors. In Ringhals 2 the minimum water level is 1.6 m above floor level.

7.9 Differential pressure measurement system

A new system for measurement of the strainer differential pressure was tested for various containment water levels and pressure.

In order to give the operators information of the strainer status during recirculation the strainers were equipped with head loss measurement over the debris layer with indication and high pressure drop alarm in the control room. The head loss sensor is of a new patented design enabling a location of the sensor and transmitter in the reactor containment and avoiding sensitive capillaries.

8. Design of the strainer system – the robust solution

The solution is based on the same principle design as the strainers installed in the five Swedish BWR's that were stopped after the Barsebäck incident 1992. It was presented at the OECD/NEA Workshop on the Barsebäck Strainer Incident in Stockholm, 26-27 January 1994 [1], see Figure M.

The new robust strainer system (protected by patents) consists of a number of sacrificial cylindrical strainers connected in parallel to a common manifold pipe. A separate cylindrical strainer is attached to the suction line before it leaves the pool through the containment wall. Fins along the cylindrical, vertical strainer divide the fibre mat. When the strainer flow is reduced, fins split the debris into sections as the fibrous bed expands. The material falls off and remains on the pool bottom without requiring back-wash flow, see the four photos in Figure J.

The horizontal main strainers are shown in Enclosure 1. The area of the main ECCS strainers is 2*50 m^2 and the area of the CS strainers is 2*40 m^2. The self-cleaning strainers are shown in Enclosure 2. Each strainer has an area of about 1.8 m^2. The strainer is protected from falling objects as shown in Figure O.

The hole in the strainer were chosen to have a diameter of 3 mm. Test at Älvkarleby [18] shows that this hole size together with a low approaching water velocity give a very small amount of impurities penetrating the strainers. This is required in order not to jeopardize the ECCS function but is not required for the CS function, which has been shown to be able to handle large amounts of debris.

Two photos from the installation at Ringhals 2 are presented in Figures N and O. The fins of the vertical, partly tapered cylindrical wing strainer can be seen. The sacrificial strainers are protected by a horizontal roof.

Figure M. Modified sump screens in Ringhals 2

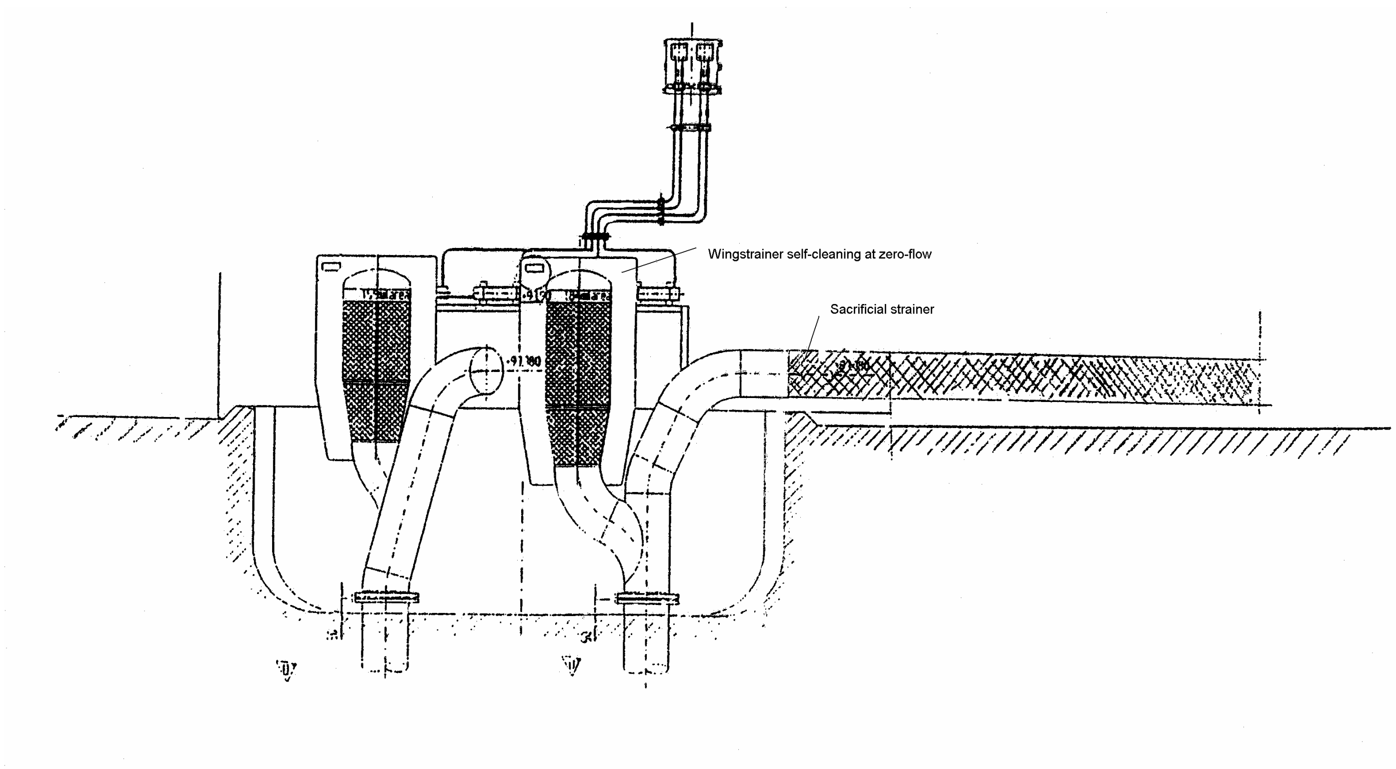


Figure N. Self-cleaning wing strainer at Ringhals 2 NPP

Figure O. The horizontal sacrificial strainers at Ringhals 2

6. Concluding remarks

The large sacrificial and self-cleaning strainers, often named the “Robust Swedish Solution” is a system that so far has proved to be able to handle “all bounding conditions” (the envelope). Although these systems are large, they are easily installed. The strainers are pre-fabricated and easy to transport into the containment. The new strainers at Ringhals 2 were installed in 5 days during the refuelling outage in 1995.

A short summary of the presentation (OH viewgraph picture) is given in Figure 8, Enclosure 3.

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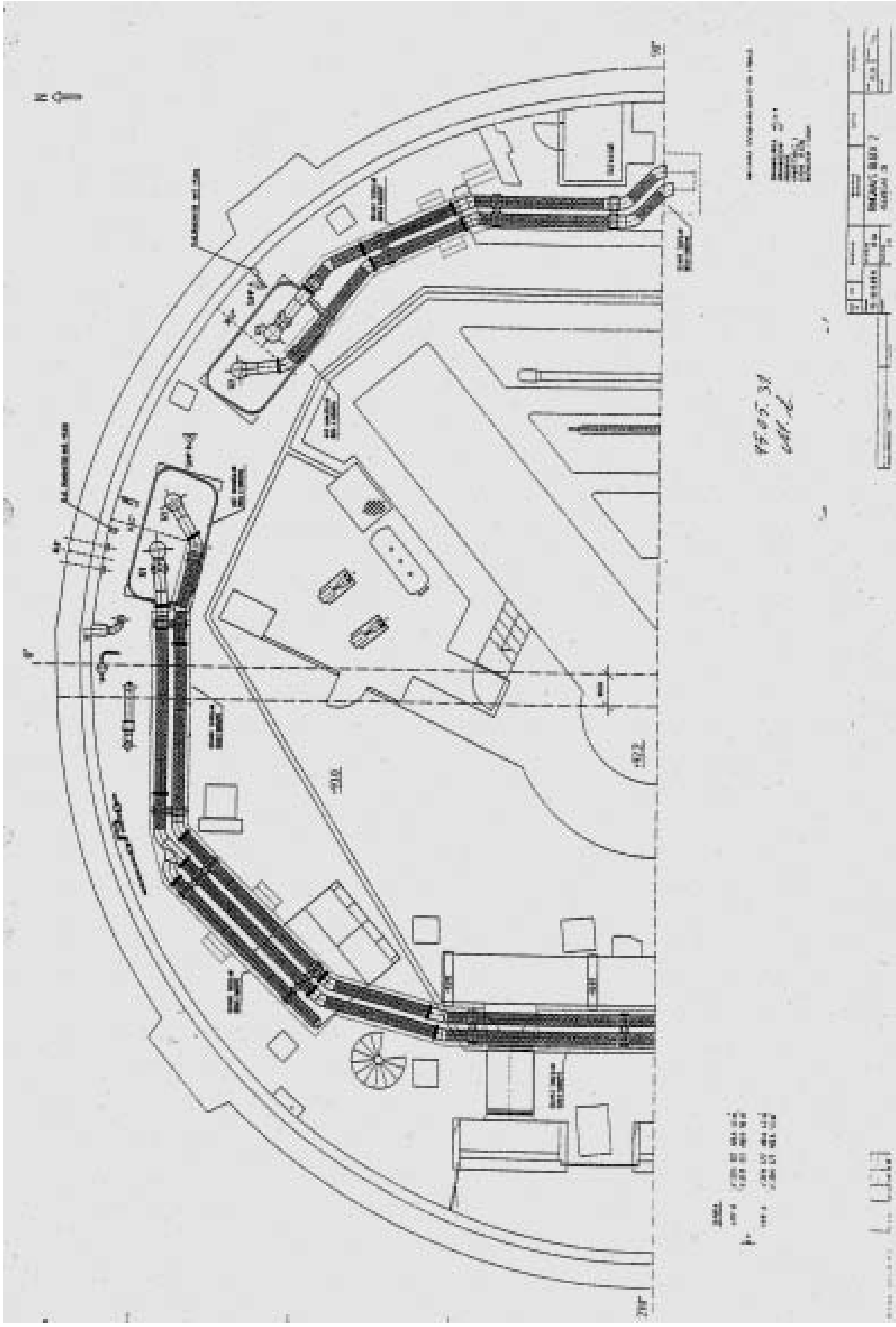
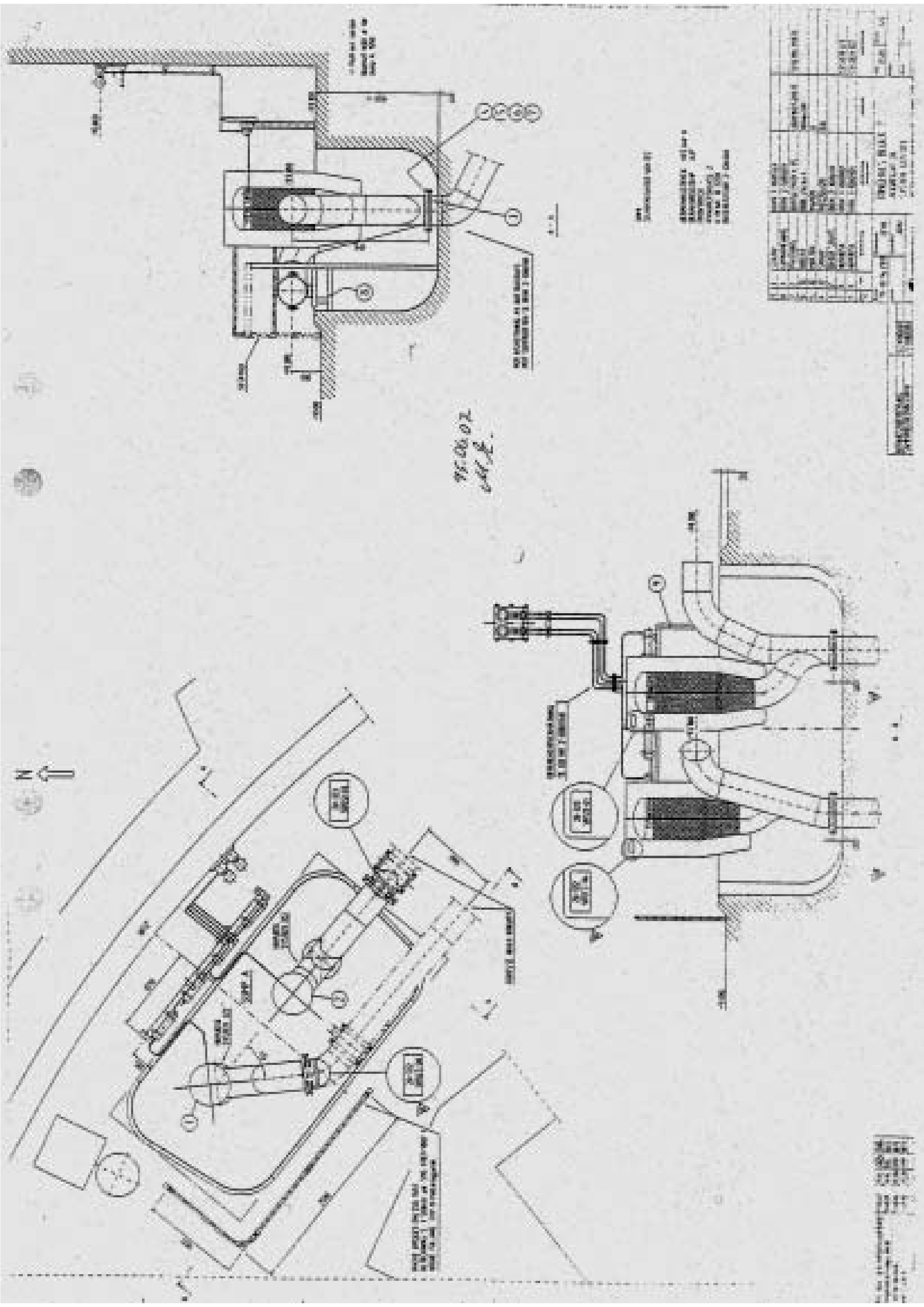
Enclosure 1



Enclosure 2



Enclosure 3

Figure 1. Ringhals 1 Thermal insulation tests

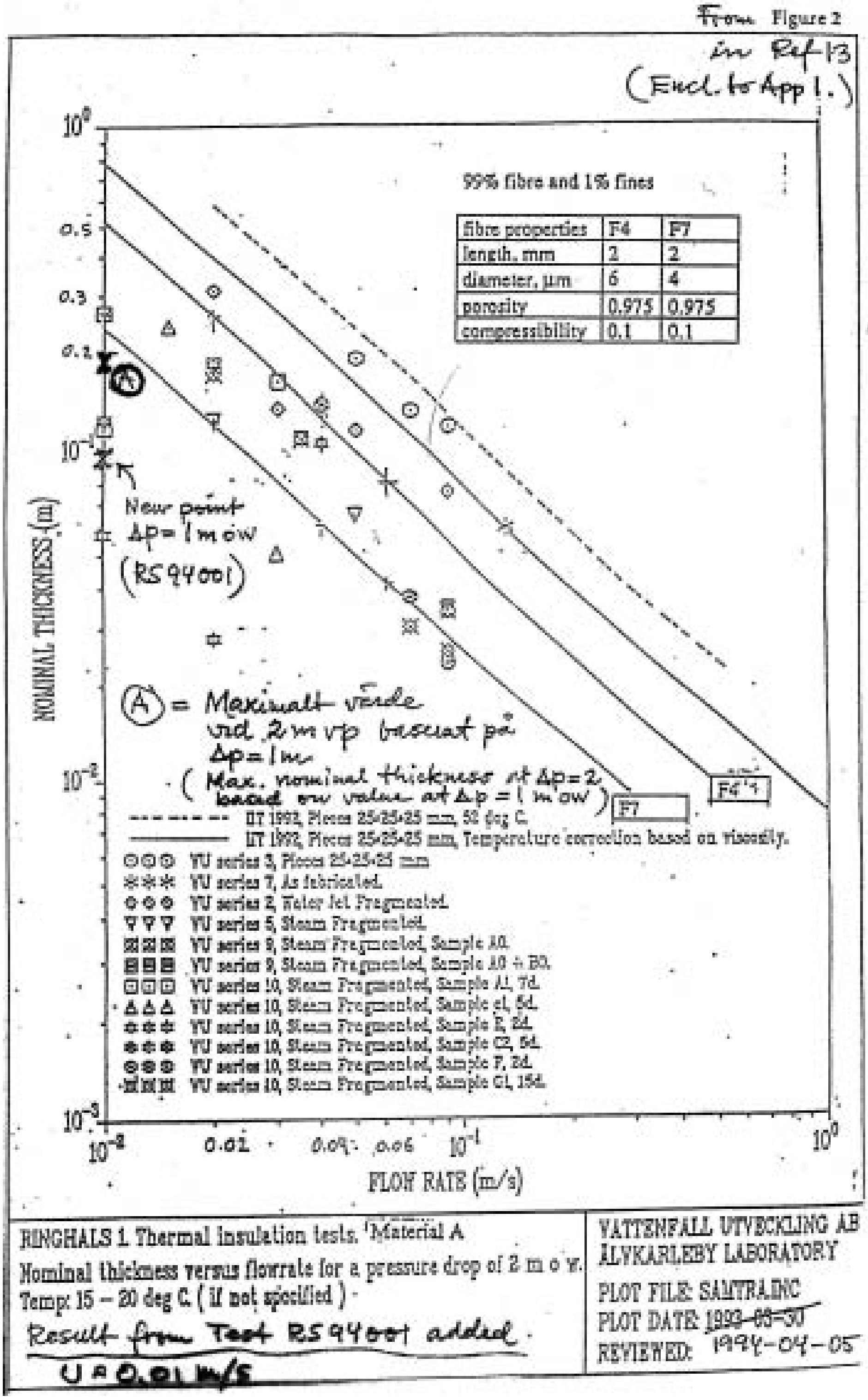


Figure 2. Ringhals 2. Thermal insulation tests

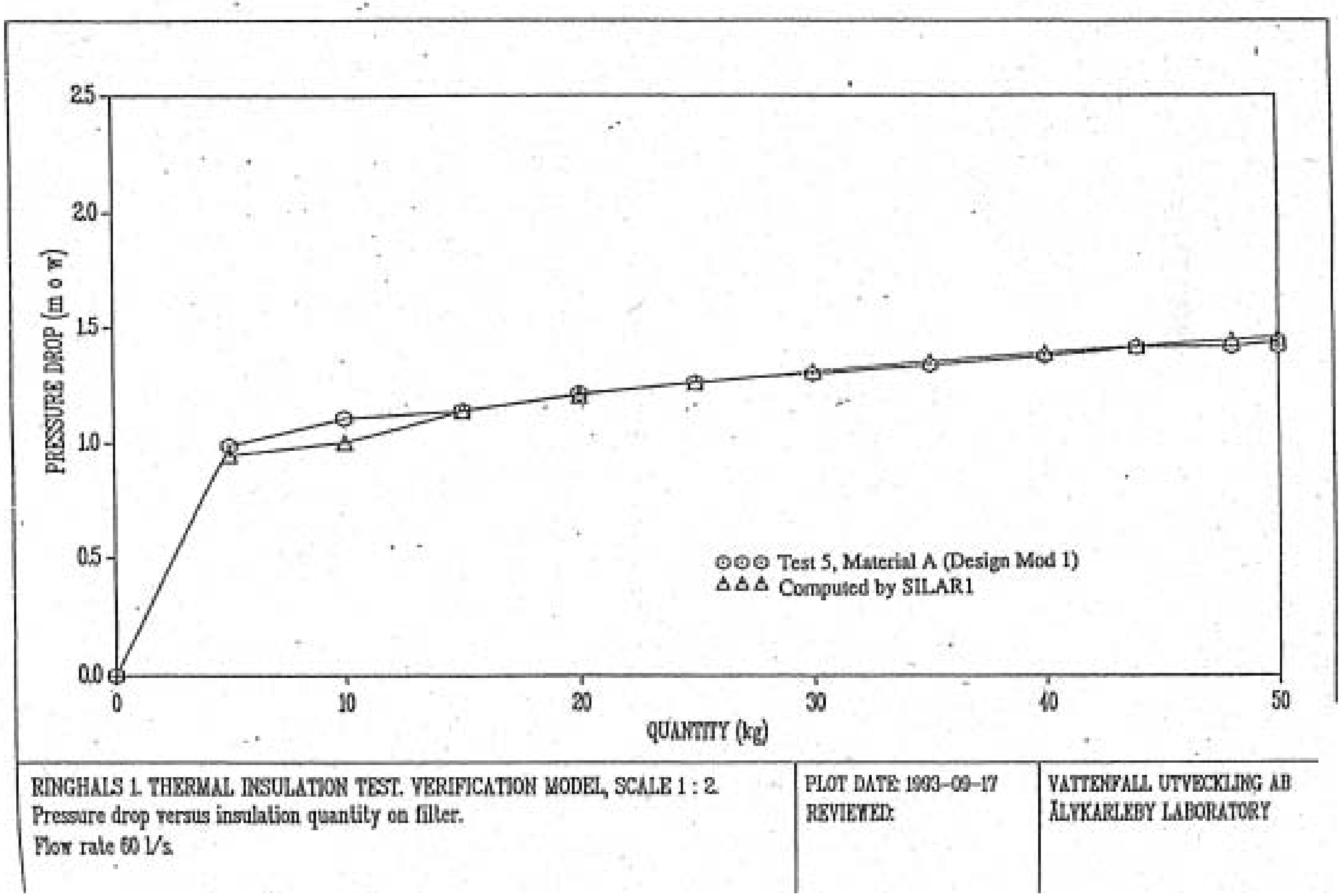


Figure 3. Ringhals 2. Thermal insulation tests

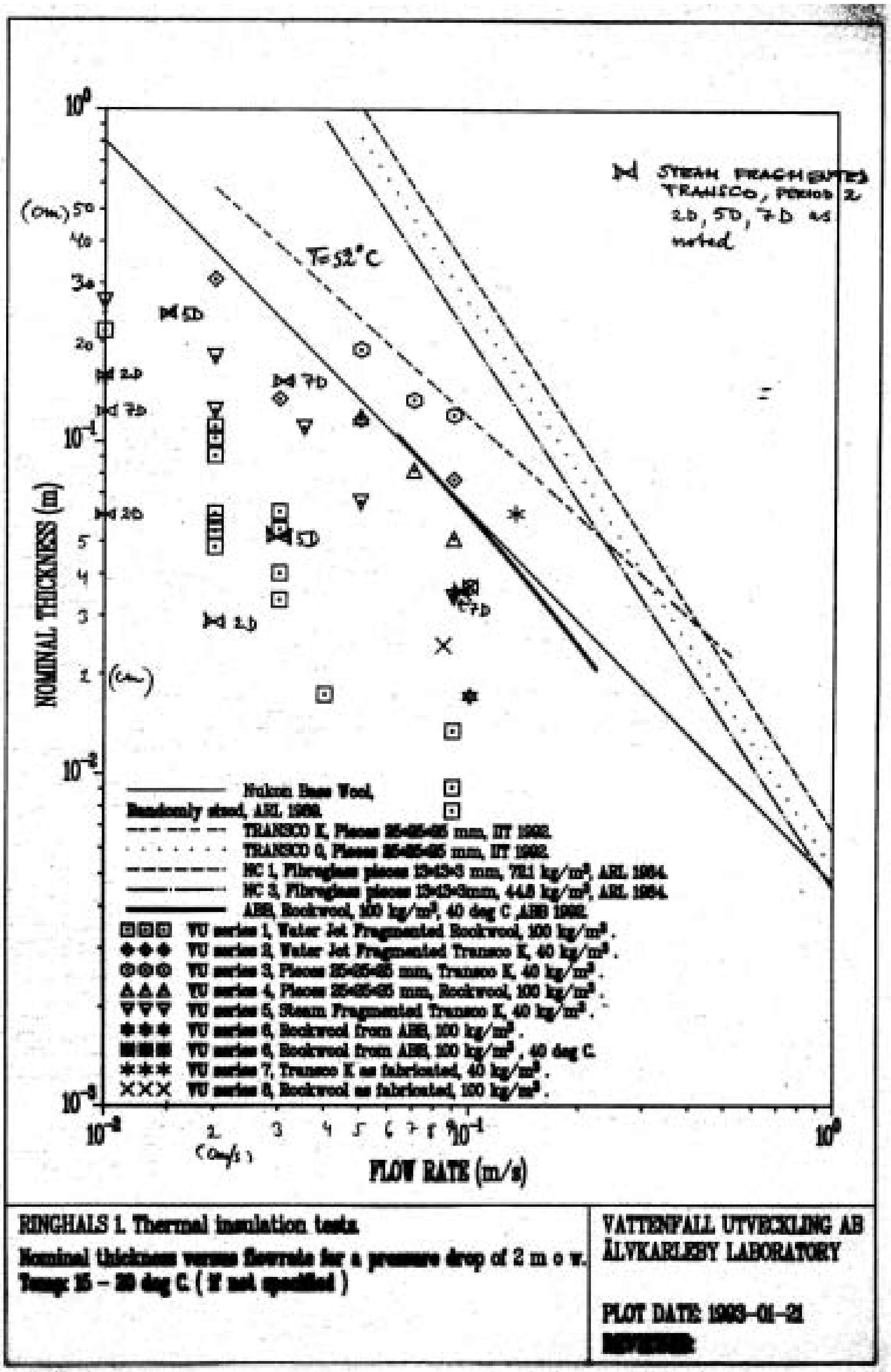


Figure 4. Forsmark 1 and 2

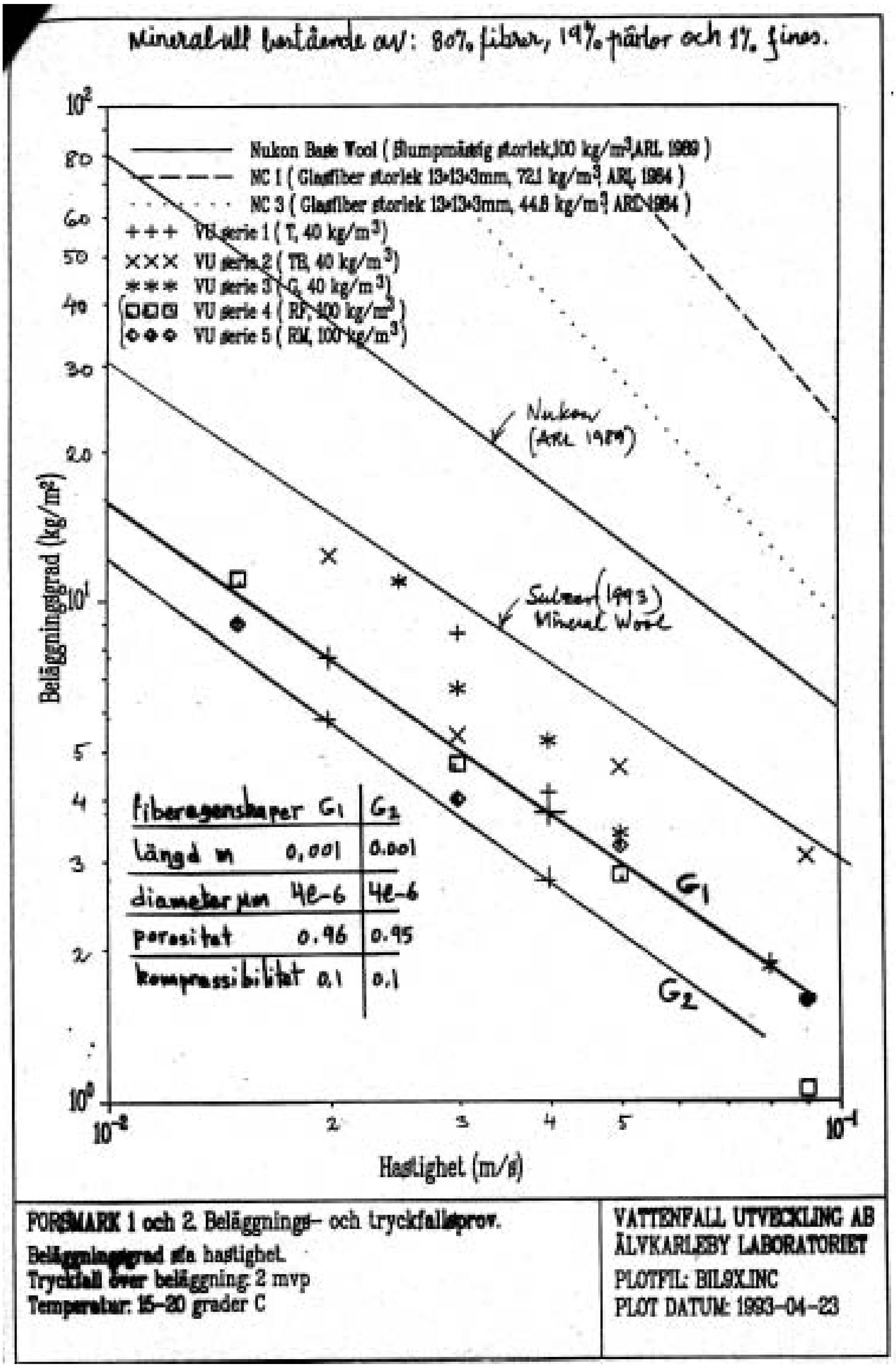


Figure 5. Final pressure drop for various combinations of fines (impurities) and fibres when all material is collected on the striner (perforated plate). The amount of fines in the basin water is held constant (C kg) and the amount of fibres mixed in the water is varying

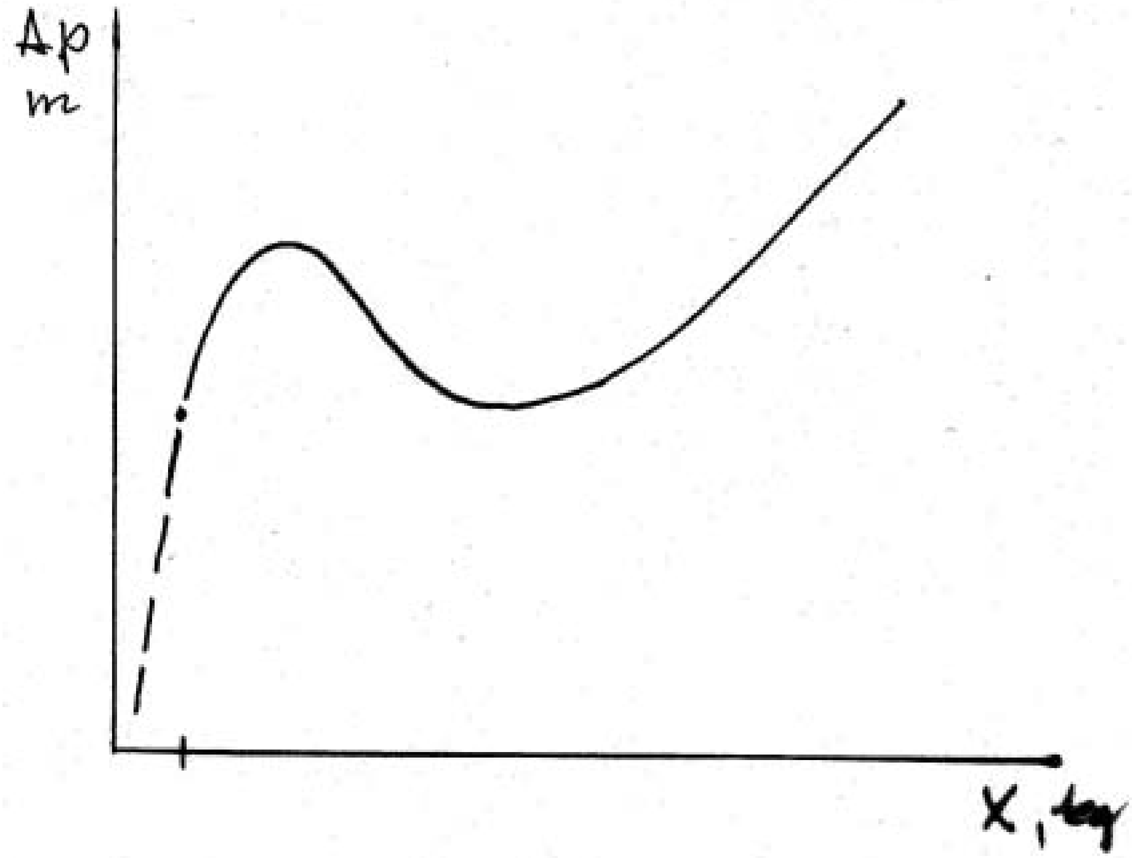


Figure 6. Ringhals 2. Vector plot of velocity

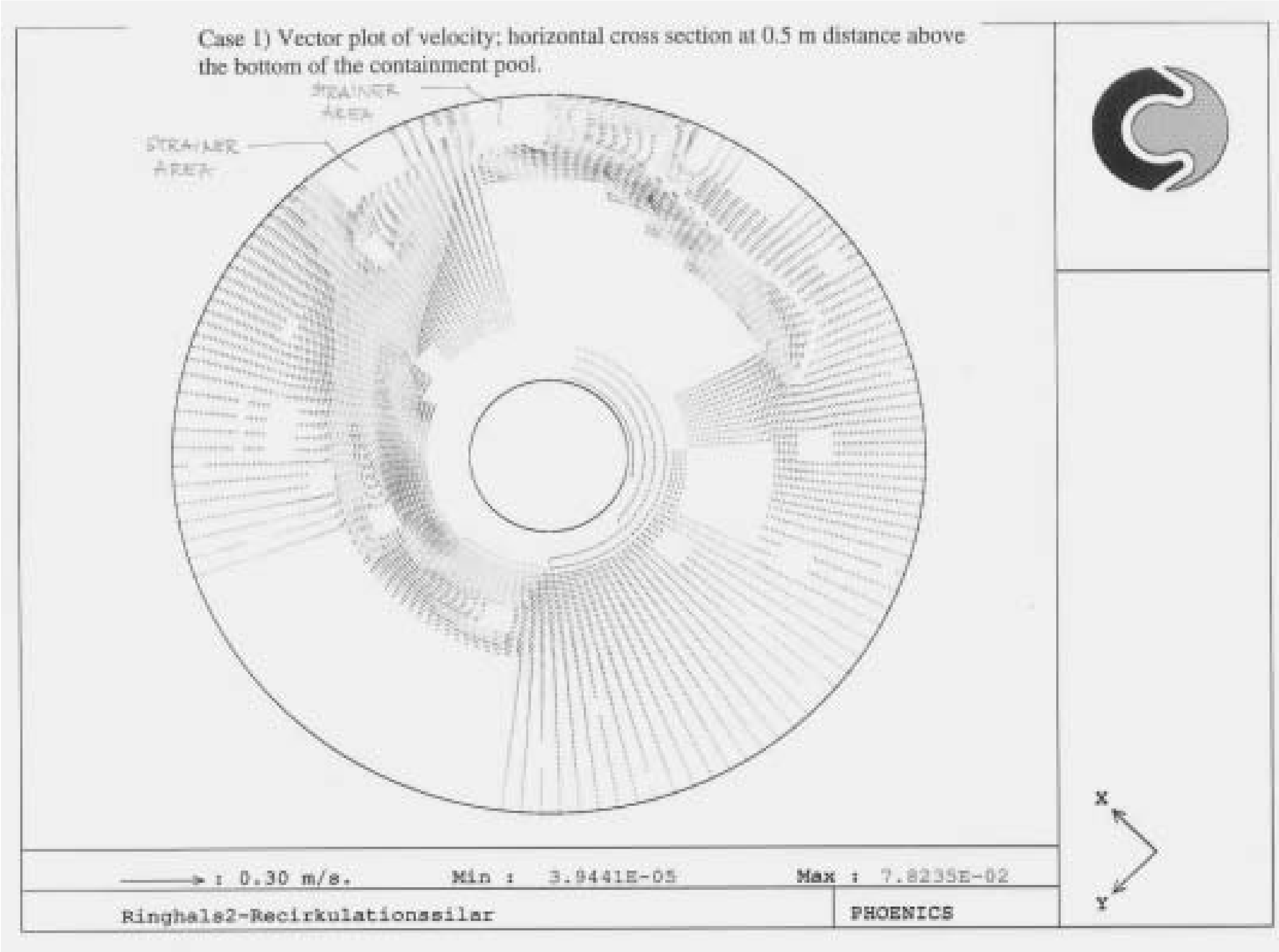


Figure 7(a). From dye studies in the sump area

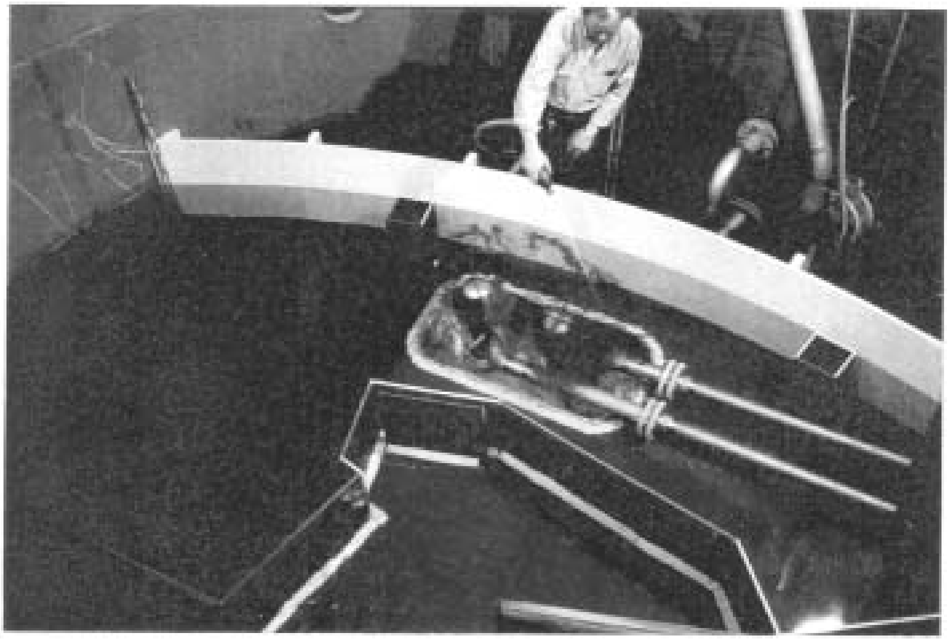


Figure 7(b). Circulating flow and vortex close to one of the vertical self-cleaning strainers

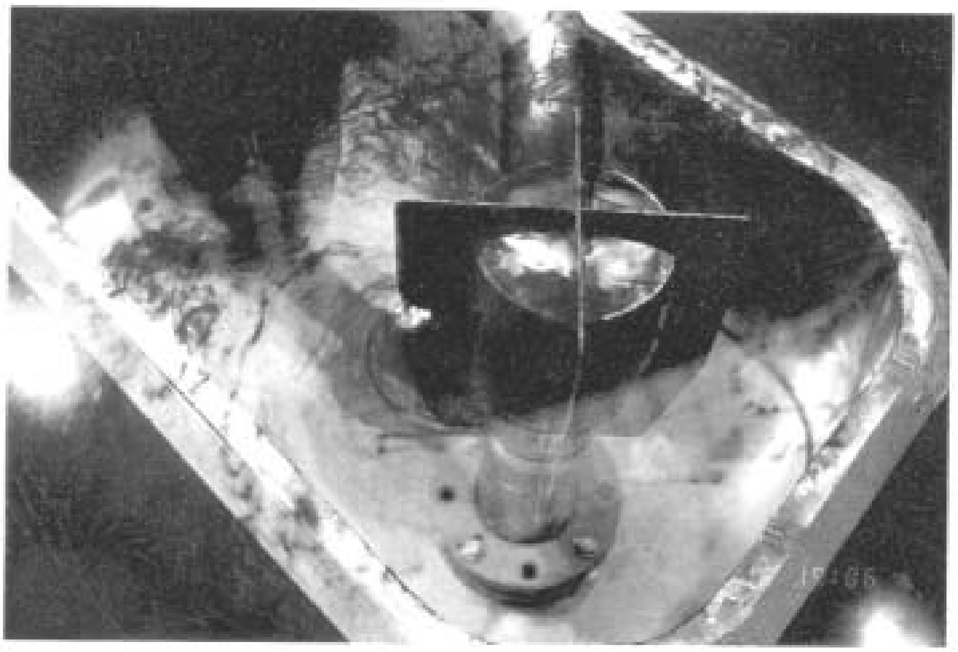
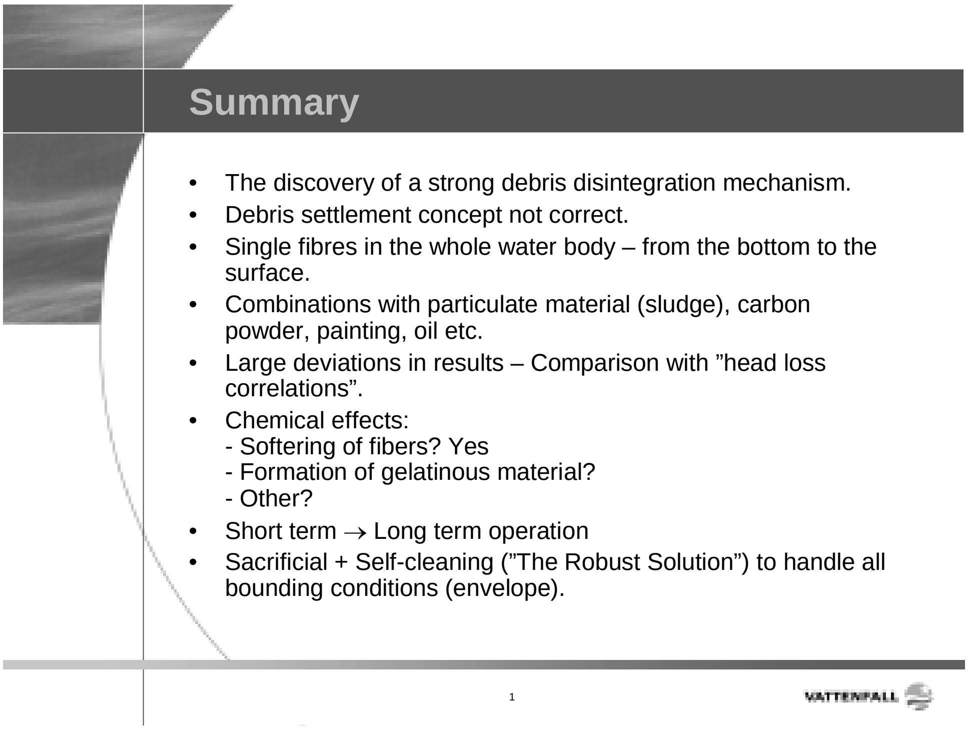


Figure 8. OH viewgraph picture



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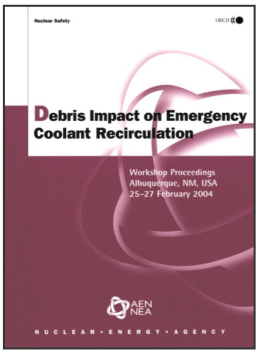

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