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1. Introduction

At 0539 h on July 28th, 1992 (at the nuclear power plant in Barsebäck, Sweden) a reactor safety valve opened at 30 bar and 2% power during start up after the annual outage. Following reactor scram, the high pressure core spray and the containment spray system initiated automatically. The steam blow down from the safety valve continued for about 20 minutes and damaged insulation on pipes and other components in the drywell. Approximately 2 m^3 of mineral wool insulation was transported to the suppression pool due to the steam jet and the containment spray system. Another 2 m^3 remained in the drywell. According to the plant safety report (SAR), a maximum of 0.3 m^3 of insulation material should be transported the suppression pool. At 0648 h the Residual Heat Removal system was initiated by the shift operators. Soon after, the signal for high pressure drop across one of the strainers of the Containment Spray System alarmed in the control room. At 0652 h a signal alarmed for another strainer. At 0736 h two pumps for the Containment Spray System were stopped, because of indications of cavitation. Since the Containment Spray System was not needed anymore, the strainers were backflushed by the operators after the completion of other activities at 0807 h, and the reactor was shut down without further complications. According to the safety report, the time to plugging and subsequent back flushing of the strainers should last more than 10 hours. A post analysis of the Barsebäck event shows that for a case of a double ended pipe rupture, plugging of the strainers can occur within 20 minutes which yields difficulties in the case of the reactor running at 100% power. As a result of this incident, the Swedish authority required an extensive safety review and demonstration of safe long-term residual heat removal.

On Dec. 14, 1992 [1], the Swiss Safety Inspectorate for Nuclear Power Plants (HSK) required the nuclear power plants Leibstadt and Mühleberg [2] to perform *plant specific ECCS strainer plugging analyses* following the Reg. Guide 1.82, Rev. 1 [3] and provided suggestions for other medium-term measures. The result of the analysis for KKL is presented in this report.

In the case of a Loss of Coolant Accident (LOCA), the core must be covered with water, and the residual decay heat must be removed. This can be achieved with cooling water from different sources. In this report we limit our considerations to the Emergency Core Cooling System (ECCS) with the suppression pool as the coolant source. Accident management measures are not considered in this examination. The criteria is operation of the minimum available ECCS pumps (from TSL [8]) for the removal of long term residual decay heat, according to the original plant design basis.

2. Solution Steps for the Analysis of ECCS Strainer Plugging

The goal of the analysis is to re-examine whether the pressure drop Δp across the strainers exceeds the allowable value Δp_{allow} as a result of deposit accumulation, i.e. deposit from the released insulation material after a pipe rupture. Pressure drop exceeding Δp_{allow} leads to cavitation of the pump and subsequent loss of its functional capability. The solution steps to solve this problem are summarized in the following.

In **Section 3** the maximum possible volume of the released insulation material which can be deposited on the strainers is determined.

In **Section 4** the Emergency Core Cooling Systems are described. We are interested at this point in the flow velocity through the strainers, the surface area of the strainers and the allowable value for the pressure drop Δp_{allow} due to deposit accumulation at the strainers.

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layer thickness at the strainer is calculated.

In **Section 5** measured values are given for pressure drop Δp due to the flow penetrating the deposited insulation material. Values depend on the flow velocity and the deposited thickness.

In **Section 6** the pressure drop Δp is determined from the flow velocity and the thickness of deposits calculated in Section 4 using to the measured values in Section 5. This is compared with the allowable values Δp_{allow} from Section 4.

3. Release of Insulation Material

3.1. Thermal Insulation in the Reactor Building; Location, Construction and Quantity

3.1.1. Insulation Material within the Bio-shield

The RPV is insulated against heat loss by concentrically arranged steel sheets (convection insulation). In this compartment there is no loose insulation material such as mineral wool or fiber-glass.

3.1.2. Insulation Material in the Compartment between Bio-shield and Drywell

According to NUREG-0897 [4] the release of insulation should be considered only for pipes with diameter larger than 10" . The conservative assumptions used in determining the amount of insulation material released take into account contributions by the smaller insulated pipes. Therefore only the Main Steam, the Feedwater, Recirculation, and RHR-System are considered.
The insulation consists of a cylindrical, closed metal case in the form of a half shell (**Fig. 1**), which contains the mineral wool mat and is attached with snap-ons to the pipes. The outer cover is made from 1 mm austenitic metal sheet, and the inner cover from 0.1 mm thick austenitic rippled metal sheet. The insulated main steam pipe YB 10 is shown in **Fig. 2**.
The quantity of mineral wool and metal sheet per meter-length, which depend on inner diameter and thickness of the metal case, are shown in **Fig. 3** and **4**. The values for the mentioned pipes are marked on this graph.

3.1.3. Insulation Material in the Compartment between Drywell and Containment

In this compartment, the Main Steam, Feedwater, and RHR Pipes are separated spatially from the water supply in the suppression pool by the steam tunnel. Other pipes are not considered.

3.2. Release of Insulation Material

A release of insulation material as a result of the opening of a safety/pressure relief valve cannot occur at KKL, since the steam is lead through closed pipes to the suppression pool and is relieved into pool through "Spargers."
Insulation shreds or fibers can be therefore released only as a result of a pipe rupture. There are three different mechanisms for the destruction of insulation due to pipe rupture: first, direct jet impingment; second, through pipe whip; or third, through impact of pipe missiles. The jet impingment provides the major contribution to the plugging of the strainers, whilst the other mechanisms can be neglected.

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3.2.1. Effect of the Steam Jet: NUREG 0897 Rev. 1

The zone affected by the steam jet is shown in **Fig. 5**. The jet is assumed to be in the form of a right-angled cone, divided longitudinally by three parallel planes into three regions, Regions I to III. In Region I the insulation with its steel sheet case is destroyed, and the whole mineral wool content is released. Region II depends strongly on the type of insulation used (see **Fig. 6**). In region III the insulation is displaced in as-fabricated sections. It is recommended in NUREG 0897 to use a zone in the form of a half sphere for the analysis of the steam jet effect instead of a cone. A large difference from the cone model is not expected. The steam jet is assumed to work in opposite directions along the pipe axis from the rupture location.

3.2.2. Effect of the Steam Jet: Interpretation of ABB Västeras

In **Fig. 5** the isobaric pressures are plotted for a pipe pressurized at 155 bar. ABB assumed for the boiling water reactor with a pressure of 70 bar, a cone with a length of five times the diameter for regions I + II. However, insulated pipes within the range of 5 to 7 times the diameter must also be condidered using engineering methods to assess the destruction of insulation. This additional step be conservative so that in the end one does not gain an essential advantage over the method outlined in section 3.2.1. This method was used in all the Swedish nuclear power plants, and released quantities of mineral wool from 3 to 7 m^3 were calculated.

3.2.3. Effect of the Steam Jet: Consideration of the Limiting Values for KKL

The upper limit VDW_{max} for the released volume of the insulation material in the Drywell can be found from the half-sphere model with a radius of 7 times the diameter of the ruptured pipe.
The volume of insulation for the lower limit VDW_{mi} is found similarly by using three times the pipe diameter. This corresponds to Region I in Fig. 5. In both cases half spheres extending in both directions from the rupture point were assumed.

3.3. Range of Postulated Ruptured Locations for Maximum Release

The following criteria are to be considered from NUREG-0897:

- the working of the steam jet is the predominant cause of released insulation fragments, pipe whip impact from fractured pipe sections are secondary.
- the criteria for the selection of pipe break locations should coincide with the specific safety analysis report.
- the rupture must require long term core cooling.

These requirements are conservatively taken into account by identifying the limiting break section from the Main Steam, Feedwater, and Recirculation Pipes which would release maximum insulation material <u>on a double-ended break</u>. Excluded are the probability and leak-before-break considerations. With rough approximations, three cross-sections were identified (see **Fig. 7**). For these rupture locations, as in the following, the volume of the released insulation material is found by the conservative half-sphere model with radius of 7 times the pipe diameter (see also **Table. 1**).

3.3.1. Rupture Location ①: Main Steam Pipe (Angle 315°, Height +11500)

The first break location is taken to be in line YB14 near the <u>weld</u> after the <u>pipe whip</u> restraint just before the steam table (see **Fig. 8**). All four Main Steam, both Feedwater, the

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11). The released mineral wool volume for break location ① is:

$$VDW_1 = 10.03m^3 \quad (1)$$

3.3.2. Break Location ②: Main Steam Pipe (Angle 290°57', Height +4300)

The second break location was chosen in line YB14 in the vertical section below the bend before the RPV nozzle. A Feedwater Pipe is affected as well as two Main Steam Pipes (see **Fig. 12-14**). The released mineral wool volume for break location ② is:

$$VDW_2 = 9.89m^3 \quad (2)$$

3.3.3. Break Location ③: Recirculation Pipe (Angle 335°, Height -3020)

The third break location is taken to be in line YU12 so that the complete recirculation pump casing and a section of the RHR-Pipe are affected by the steam jet (see **Fig. 15** and **16**). The released mineral wool volume for break location ③ is:

$$VDW_3 = 5.81m^3 \quad (3)$$

3.4. Quantity of the Released Insulation Material in Drywell

The half-sphere model with a radius of 7 times the diameter of the particular ruptured pipe was employed to find the maximum volume of the released mineral wool in the Drywell, and it is calculated to be at break location ①, which gives:

$$VDW_{max} = VDW_1 = 10.03m^3 \quad (4)$$

The minimum volume of the released mineral wool for the Main Steam Pipe break was found using the optimistic model in which the material is released within a radius of 3 times the pipe diameter from the break location:

$$VDW_{min} = 6 \cdot D_{FD} \cdot V'_{FD} = 6 \cdot 0.65 \cdot m \cdot 0.3 \cdot \frac{m^3}{m} = 1.17m^3 \quad (5)$$

D_{FD} Diameter of the Main Steam Pipe
V'_{FD} Insulation volume per length for the Main Steam Pipe

3.5. Transport of the Loose Insulation Material into the Suppression Pool

The largest uncertainty is found in this section of the analysis. Streams of turbulent steam due to the expected pressure difference between Drywell and Suppression Pool are primarily responsible for the transport fo the material.
Possibilities of retention of the released material in the Drywell are discussed and to an extent considered in the following section.

The metal case prevents all fragments of the mineal wool insulation from being released. (This is also shown in **Fig. 6**). The volume of the released material has been reduced by 20%, since it can be assumed with certainty that 20% of the insulation remains in fragments of the metal case. (See **Fig. 6**).

About 20% of the material was likewise retained by flow restrictions at Barsebäck. Therefore a retention of of 10% of the material on restrictions was assumed for Leibstadt.

Therefore the quantity of the loose insulation material, which would reach the Suppression Pool, is reduced by 50%. The limit for the insulation volume which can reach the Suppression Pool is calculated as follows:

$$VDAK_{max} = VDW_{max} \cdot 0.5 = 10.03 * 0.5 = 5.02 \cdot m^3 \quad (6)$$

$$VDAK_{min} = VDW_{min} \cdot 0.5 = 1.17 \cdot m^3 * 0.5 = 0.59 \cdot m^3 \quad (7)$$

It seems from the graph in **Fig. 4** that a large quantity of the steel sheet would be released. It was assumed that the steel sheet would either not reach the Suppression Pool or would sink quickly (if it could) to the bottom of the Pool, and will not contribute to the clogging of strainers.

3.6. Spatial and Time Dependent Distribution in the Suppression Pool

3.6.1. Possible Reduction of the Mineral Wool in the Suppression Pool

For the spatial distribution it was considered that the released insulation material would be evenly distributed in the Drywell, and consequently in the Suppression Pool as well.
No further retention possibilities in the Containment, such as deposit accumulation during pool swell were considered.
A considerable scatter in the sedimentation time for mineral wool shreds and fibers in the Suppression Pool was obtained. A quantitative approximation is difficult. It was noticed for example that large shreds sink faster than a few fibers, and aged material sank faster than new. It is therefore not clear that the danger of clogging decreases when, for example the start-up of the ECCS pumps is delayed.
One can try to determine a time dependent deposit accumulation at the strainer. In this case, one considers the quantity of the recirculated coolant and the corresponding quantity of mineral wool, which is then distributed over the strainer area.
In the worst case a larger density of floating material could exist near a given strainer and therefore clog the strainer relatively quickly.

3.6.2. Consideration of the Limiting Value for KKL

A conservative approach has been taken to account for the above factors. It was assumed that **all** the material which reaches the Suppression Pool is distributed evenly on the strainer surfaces which are in operation. The time dependency is not accounted for.

4. Emergency Core Cooling System (ECCS)

4.1. System

The Emergency Core Cooling System delivers the essential water for cooling the reactor core and removing residual heat. These functions are necessary after a Loss of Coolant Accident. The pressure relief in the primary system follows very quickly after the loss of coolant (double-ended break of a Recirculation Pipe or a Main Steam Pipe). The following Emergency Core Cooling Systems are available at Leibstadt:

1 HPCS= High Pressure Core Spray
1 LPCS= Low Pressure Core Spray

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The water for the ECCS is supplied from the Suppression Pool. The HPCS is an exception. It is normally supplied from the condensate storage tank KAKO (Kaltkondensatbehälter in German) until the KAKO-level is "low" and is then automatically switched to the Suppression Pool.

The strainers are mounted before the pump suction nozzles for mechanical protection of the ECCS/SEHR pumps. Each pump has a strainer, with the exception of the SEHR A- and B-Pumps which have a common suction pipe and therefore only one strainer.

4.2. Strainer

Detailed requirements for the strainers are given in **Table 2** and **Fig. 17**. The location of the strainers can be identified from drawings [4] and [5]. In discussing the flow velocity the following cases were analysed:

- Flow velocity through the effective open surface of the strainers; this case yields the minimum pressure loss at the strainer surface under the undeposited condition. The open surface corresponds to the effective open surface of the wire mesh over the opening of the perforated sheet.
- Flow velocity calculated assuming the total surface of the strainer; the pressure drop due to the deposit of insulation material is calculated with this velocity. One can assume that the water flows evenly through the deposit, and that the flow is only constricted near the strainer surface just before the holes. The wire mesh on the perforated sheet can additionally affect percolation to the free surface. The deposit thickness is likewise determined using the total surface area, since the material is evenly deposited on the whole strainer surface.
- Flow velocity in the pipe after the strainer; this value is employed for the calculation of the minimum water level by which air cannot be entrained.

4.3. Net Positiv Suction Head (NPSH)

All the ECCS pumps are centrifugal pumps with the number of stages dependent on the required head. Centrifugal pumps require a stable suction pressure. This suction pressure at the middle of the pump corresponds to the so called *minimum Net Positive Suction Head* ($NPSH_{min}$). If the minimum NPSH is not maintained, the pumps will cavitate and lose their functional capability. The calculation of the NPSH is described in **Fig. 18** and the results are shown in **Table. 4**.

4.4. Suction Conditions for the ECCS Pumps

In the letter to HSK [4] on 8.9.1983, *"Sicheres Ansaugen der Not- und Nachkühlpumpen"*, (Safety Suction of the Emergency and RHR-Pumps), a detailed and overall summary of the specifications for the ECCS Pumps used in this study is presented.
The effective suction conditions for the RHR-Pump "A" are shown in **Fig. 19** for which important aspects are summarized in the following:

❶ The normal water level in the Suppression Pool during operation.
❷ The minimum LOCA-Level. According to the SAR Section 6.2.6, the surface of the water pool may not sink below a level of 0.61m above the highest Drywell-Wetwell openings, even during a LOCA.
❸ The level for the minimum coverage of the suction nozzles to avoid turbulence. The level cannot be reached for example for the given nozzle locations if condition ❷ is maintained.
❹ Water level at the first functional test.
❺ Pressure measured at the suction nozzle of the pumps at a water temperature of

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❻ The existing NPSH at the pump suction for the minmum level specified for the LOCA at a water temperature of 100°C in the Suppression Pool.

❼ Minimum $NPSH_{min}$ according to the pump acceptance report. This value takes into account the maximum water temperature occurring in the suppression pool.

❽ Obtained by adding the pressure drop from the strainer to the pump suction to the minimum NPSH ❽. This is the water level by which the pumps begin to cavitate.

4.5. Allowed Degree of Clogging, i.e. Pressure Drop Δp_{zul}

The existing NPSH is specified for 100°C **(Fig. 19)**. However, the ECCS pumps are designed for maximum temperature from 60°C to about 85°C.
For this study the difference between $NPSH_{min}$ and the available NPSH at a minimum LOCA water level, the normal Containment pressure and the Suppression Pool-water temperature of 60°C to 85°C is important. To prevent cavitation this pressure difference should not be overridden due to additional pressure drops as a result of deposit accumulation (insulation material) at the strainer surface.
The existing NPSH for the above described conditions together with the $NPSH_{min}$ and the resulting allowable pressure difference ΔP_{allow} are shown in **Table 4**.

4.6. Availability of the ECCS and Allowable Maximum Deposit Thickness of the Insulation Material at the Strainers

The Technical Specification TSL [8], provides tabulated allowed times for the case of two systems being out of operation. The worst case is found in Table 3.5.A.2 [6] in row 3. Only the HPCS and the SEHR system are available in this case, whereby the latter has only one common strainer. The strainer surface AS_{min} for this worst case calculated in accordance with the specifications from Table 2 is 4.63 m².

If the strainer area is considered as a plane, conservative values are obtained. The conservatism increases proportionally with the ratio of deposit thickness to diameter. This is not relevant for the dimensions which interest us here. The maximum and minimum deposit thicknesses of the insulation at the strainer are:

$$d_{max} = \frac{VDAK_{max}}{AS_{min}} = \frac{5.02 \cdot m^3}{4.63 \cdot m^2} = 1.08 \cdot m \qquad (9)$$

$$d_{min} = \frac{VDAK_{min}}{AS_{min}} = \frac{0.59 \cdot m^3}{4.63 \cdot m^2} = 0.13 \cdot m \qquad (10)$$

5. Pressure Drop Δp over the Strainer Surface as a Function of Flow Velocity v and Thickness of the Deposit

5.1. $\Delta p(v,d)$: Requirements of Nureg 0897, Rev. 1

On page 3-.59 in Nureg Report 0897, Rev. 1, a function for the pressure drop due to shredded mineral wool insulation deposit is specified (see the equation (10) below). This function was obtained by a curve-fit through measured values:

$$\Delta p(v,d) = 123 \cdot v^{1.51} \cdot d^{1.36} \qquad (10)$$

$\Delta p(v,d)$ Pressure drop in ft H_2O

v Flow Velocity in ft/s

d Thickness of insulation deposit in its original unshredded condition in ft

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$$\Delta p(v,d) = 152.594 \cdot v^{1.51} \cdot d^{1.36} \tag{11}$$

See note dated 8/17/93

$\Delta p(v,d)$	Pressure drop in bar
v	Flow Velocity in m/s
d	Thickness of insulation deposit in its original unshredded condition in m

Two further functions for different fiber glass materials are shown in the NUREG, to demonstrate how the values are material dependent. It is therefore pointed out that the clogging analysis should be carried out with the plant specific values.

5.2 Δp(v,d): Measured in Experiments at Sulzer

The SULZER THERMTEC [9] experiments were carried out using a test cylinder (see **Fig. 21**). Awire-mesh strainer is located at the bottom part of the test cylinder. This is a simulation of the suction strainer surface, loaded with mineral wool. The test showed that the aged mineral wool (in this case approx. 20 yrs old) yielded the largest pressure drop. The wool was stirred in water to simulate the effect of the steam jet. Cold water at 15°C yields likewise a higher pressure drop, because the viscosity of water at low temperature is higher. The experiment was always started with the <u>largest</u> flows so that a compaction of the deposit was already present for the <u>smaller</u> flows. The procedure results again in conservative values for the pressure drop. In **Fig. 22** the measured results are shown graphically. These values lie approximately 2 to 3 times higher than the values according to NUREG equation (11). Through curve-fit from the Sulzer measured values, we found the following constants for equation (12):

$$\Delta p(v,d) = 141 \cdot v^{1.13} \cdot d^{1.14} \tag{12}$$

For $v = 0.2$ m/s & $d = 0.1$ m, Eq (11) corrected gives 0.79 bar & Eq (12) gives 2.63 bar

$\Delta p(v,d)$	Pressure drop in bar
v	Flow Velocity in m/s
d	Thickness of the insulation material in the original unshredded condition in m

5.3 Pressure Drop over an Extended Time Period

Currently experiments by SULZER THERMTEC are underway to examine the time dependent behavior. Initial results have shown that time dependency exists, although the values in [9] have not yet been exceeded.

6. Strainer Clogging

6.1. Cavitation Limit

The curves for constant Δp obtained from corresponding measured values [9] are plotted in **Fig. 23**. We assign the allowable pressure drop Δp_{allow} as the cavitation limit. Cavitation does not occur for all the points under this curve.

The minimum value (RHR C Pump) taken from the last column in Table 4 is considered to be the allowable pressure drop. According to Safety Guide 1 [18], the higher pressure in the containment during a LOCA may not be used to increase the NPSH.

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$$\Delta p(v,d) = 152.594 \cdot v^{1.51} \cdot d^{1.36} \quad (11)$$

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6.2. Δp for the Existing Strainers

Because the flow velocities through the strainers are all roughly the same, $v = 0.25$ m/s, and the deposit thickness is assumed to be evenly distributed on the total available strainer surface, only one system need be analysed.
The pressure drop for the maximum and minimum deposit thickness is presented in **Fig. 24.** It is clear that both values are way over the cavitation limit.
Both deposit thicknesses cannot be achieved in reality because the ECCS pumps will cavitate and fail before the maximum deposit thickness is reached.

6.3. Required Suction Strainer Surface for $\Delta p < \Delta p_{zul}$

We assume again for simplicity that the strainer surface is a plane. If we assume that all the strainers are proportionally enlarged, then the points for a given amount of insulation lie on a straight line through the origin of the graph for different strainer surface areas. This is because the flow velocity and the deposited thickness are inversely proportional to the strainer surface area. Therefore the required strainer surface is inversely proportional to the distance from the origin of the graph.
The exisiting strainer has a surface of 2 m². The required areas to meet the cavitation limits can be calculated from the distance to the origin. The values are plotted in **Fig. 25**.

7. Conclusion

The quantity of the released insulation material in the form of shreds or fibers which can be deposited on the strainer of the ECCS has been determined using conservative methods and assumptions.
The Technical Specification TSL defines the minimum availability of the ECCS System and so the minimum existing strainer surface and/or the deposit thickness of the insulation material can be determined.
In experiments performed by the SULZER the upper limit for the pressure drop due to mineral wool deposit was obtained.
Using these assumptions it is found that the current strainer area of 2 to 2.5 m² is too small and should be increased by a factor of about 6 to avoid cavitation.

Measures for flushing the strainers or the use of alternate coolant sources are not considered in this report.

8. References

[1] "Aktionen nach Barsebäck / Mittelfristige Massnahmen", Brief der HSK vom 14. Dezember 1992.

[2] "Water sources for long-term recirculation cooling following a Loss-Of-Coolant Accident", Regulatory Guide 1.82, Revision 1. U.S. Nuclear Regulatory Commission, November 1985.

[3] "Containment Emergency Sump Performance. Technical Findings Related to Unresolved Safety Issue A-43", A.W. Serkiz, USNRC, NUREG-0897 Rev. 1, März 1985.

[4] "Piping Details. Containment 0°-180°. Plan at -7030", Comprimo BV Amsterdam, Zeichnungsnr. 746-014-SH30/53.

[5] ""Piping Details. Containment 180°-360°. Plan at -7030", Comprimo BV Amsterdam, Zeichnungsnr. 746-015-SH30/44.

[6] "Sicheres Ansaugen der Not- und Nachkühlpumpen", W. Aeberli, KKL-Brief an die HSK, 27. Januar 1984

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[8] "Tests zur Ermittlung des Druckabfalls über die Isolationsmaterial-Schichten",A. Kilbowizc , SULZER-THERMTEC, Versuchs-Bericht 392/40530.

[9] "Aktionen nach Barsebäck / Pendenz-263", Brief der HSK vom 2. Februar 1993.

[10] VDI Wärmeatlas, 5. erweiterte Auflage, Verlag des Vereins Deutscher Ingenieure.

[11] "Fotobuch; Situation Drywell -1.5 m / +0.5m / +10m / +12m", M. Bühler , Abt. M, KKL, 1992.

[12] "Piping Details. Drywell, Section A-A." Comprimo BV Amsterdam, Zeichnungsnr. 746-014-SH14/98.

[13] "Additional Piping Drywell Plan at -elev. +11500", Comprimo BV Amsterdam, Zeichnungsnr. 746-011-SH7/98.

[14] "Additional Piping Drywell Plan at -elev. +9400", Comprimo BV Amsterdam, Zeichnungsnr. 746-011-SH8/98.

[15] "Additional Piping Drywell Plan at -elev. +7300", Comprimo BV Amsterdam, Zeichnungsnr. 746-011-SH9/98.

[16] "Piping Details. Drywell, Section B-B." Comprimo BV Amsterdam, Zeichnungsnr. 746-014-SH15/98.

[17] "Additional Piping Drywell Plan at -elev. -3400", Comprimo BV Amsterdam, Zeichnungsnr. 746-011-SH13/98.

[18] "Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal System Pumps", Safety Guide 1, 11.2.79.

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9. Table

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Bruchstelle	Rohrleitung	Kommentar	Länge[m]	Dämmdicke d [mm]	Kassetteninnendurchmesser Di [mm]	Spez. Volumen V' [m³/m]	Volumen [m³]
1	Frischdampf						
	YB12-Z001	waagrecht	4.00	120	670	0.30	1.19
	YB14-Z001	waagrecht	6.50	120	670	0.30	1.94
	YB11-Z001	waagrecht	7.50	120	670	0.30	2.23
	YB13-Z001	waagrecht	4.00	120	670	0.30	1.19
							6.55
	Speisewasser						
	YB72-Z005	senkrecht	6.00	100	330	0.14	0.81
	YB72-Z002	waagrecht	6.50	100	530	0.20	1.29
	YB71-Z002	waagrecht	2.00	100	530	0.20	0.40
							2.49
	Umwälzsystem + RHR						
	YU12-Z008	waagrecht	0.80	110	330	0.15	0.12
	YU12-Z007	waagrecht	0.80	110	330	0.15	0.12
	TH10-Z010	waagrecht	2.80	120	580	0.26	0.74
							0.98
						TOTAL	10.03
2	Frischdampf						
	YB14-Z001	senkrecht	7.50	120	670	0.30	2.23
	YB12-Z001	senkrecht	2.00	120	670	0.30	0.60
	YB12-Z001	waagrecht	8.50	120	670	0.30	2.53
	YB14-Z001	waagrecht	4.20	120	670	0.30	1.25
							6.61
	Speisewasser						
	YB72-Z007	waagrecht	12.00	100	500	0.19	2.26
	YB72-Z004	senkrecht	6.00	100	330	0.14	0.81
	YB72-Z005	senkrecht	1.50	100	330	0.14	0.20
							3.28
						TOTAL	9.89
3	Umwälzsystem + RHR						
	YU12-Z001	waagrecht	3.00	120	575	0.26	0.79
	YU12-Z001	waagrecht	3.30	150	640	0.37	1.23
	YU12-Z001	senkrecht	4.50	120	575	0.26	1.18
	YU12-D001	Pumpe	3.00	100	1700	0.57	1.70
	TH10-Z001		3.50	120	580	0.26	0.92
						TOTAL	5.81

Tab. 1: Calculation of the quantity of the released mineral wool for pipe rupture locations 1 to 3, with the half-sphere steam jet model with a radius of 7 times the diameter of the ruptured pipe.

System	LPCS	HPCS	RHR			SEHR
	Low Pressure Core Spray System	High Pressure Core Spray System	Residual Heat Removal System			Special Emergency Heat Removal System
	Niederdruckkernsprüh-system	Hochdruckkernsprüh-system	Nachzerfallswärmeabfuhrsystem			Notfallkühlsystem
P & ID	KKL Z03776	Comprimo 813-107/9, 1 von 17	Comprimo 613-105, 1 von 6			Comprimo 613-142, 1 von 5
AK-Nr.	TK10N001	TJ10N001	TH11N001	TH12N001	TH13N001	TF10N001
Azimut	141°	217°30'	38°	322°	349°30'	229°
Höhe	-5'400	-5'400	-5'400	-5'400	-5'400	-5'400
Max Durchfluss [m³/sec]*	0.37	0.48	0.53	0.53	0.53	0.54
Zeichnungsnr.: Korb	SUL-103.160.479	SUL-103.160.479	SUL-103.160.479			SUL-103.160.489
Zeichnungsnr.: Scheibe	SUL-103.160.568	SUL-103.160.568	SUL-103.160.568			SUL-103.160.579
NW Rohrleitung [mm]	500	500	500	500	500	600
Korb Durchmesser [mm]	780	780	780	780	780	880
Korb-Länge [mm]	632	632	632	632	632	722
Korb-Oberfläche [m²]	2.028	2.028	2.028	2.028	2.028	2.608
Anz Löcher Mantel	1'681	1'681	1'681	1'681	1'681	2'162
Anz. Löcher Deckel	347	347	347	347	347	511
Löcher Durchm. [mm]	25.00	25.00	25.00	25.00	25.00	25.00
Gesamte Lochfläche [m²]	1.00	1.00	1.00	1.00	1.00	1.31
Drahtgeflecht :						
Zwischenabstand. [mm]	2.00	2.00	2.00	2.00	2.00	2.00
Drahtdurchmesser [mm]	0.56	0.56	0.56	0.56	0.56	0.56
Reduktion der Fläche %	38.96	38.96	38.96	38.96	38.96	38.96
Freie Oberfläche [m²] **	0.61	0.61	0.61	0.61	0.61	0.80
Fliessgesch. [m/sec]						
In der Rohrleitung	1.90	2.42	2.70	2.69	2.69	1.91
Korb-Oberfläche	0.18	0.23	0.26	0.26	0.26	0.21
Freie Oberfläche	0.61	0.78	0.87	0.87	0.87	0.67

* Runout Menge der Pumpen

** Ueber den Lochprojektionen

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Temperatur [°C]	Dampfdruck [bar]	Dichte [kg/m³]	Dynamische Viskosität [kg/m s]
0.01	0.006112	999.80	0.0017914
10.00	0.012271	999.70	0.0013077
20.00	0.023368	998.30	0.0010027
30.00	0.042417	995.70	0.0007977
40.00	0.073749	992.20	0.0006531
50.00	0.12335	988.00	0.0005471
60.00	0.19919	983.10	0.0004668
70.00	0.31151	977.70	0.0004044
80.00	0.47359	971.60	0.0003550
90.00	0.70108	965.10	0.0003150
100.00	1.01325	958.10	0.0002822

Tab. 3: Physical parameters for saturated water, material value from saturated water, VDI-

ECCS und SEHR PUMPEN

Pumpe/ System	Betrieb. punkt [m³/h]	NPSH 3% [m Ws]	Runout [m³/h]	NPSH Limit [m Ws]	DAK Temp [°C]	Pvap [bar]	NPSH vorh [m Ws]	Stat. zulauf [H* m]	Zulässiger Druck-verlust [bar]
RHR A	1648.00	3.75	1908.10	5.80	85	0.62	9.929	5.7	0.57
RHR B	1648.00	3.70	1900.00	5.80	85	0.62	9.929	5.7	0.60
RHR C	1648.00	3.80	1900.00	5.80	85	0.62	8.939	5.7	0.50
LPCS	1418.40	3.65	1342.60	5.20	60	0.19	8.242	5.7	1.09
HPCS	1418.40	3.50	1710.60	5.68	60	0.19	10.625	5.7	1.10
SEHR A	1533.00	3.90	1930.80	5.70	85	0.62	10.528	7.2	0.69
SEHR B	1533.00	3.90	1940.00	5.70	85	0.62	10.528	7.2	0.69

Pumpenabnahme bei KSB (Betrieb. punkt – NPSH Limit) / Saugverhältnisse im KKL (NPSH) (DAK Temp – Zulässiger Druckverlust)

H* = Zulaufhöhe ab Mitte Saugkorb bis Eintritt 1. Saugrad (s')

Ws = Wassersäule

NPSH = Net Positiv Suction Head

Pvap = Dampfdruck

Tab. 4: Comparison of the existing NPSH at a minimum LOCA water level, the normal containment pressure and Suppression Pool water temperature from 60 to 85°C to $NPSH_{min}$ and the resulting pressure difference Δp_{allow}.

10. Figures

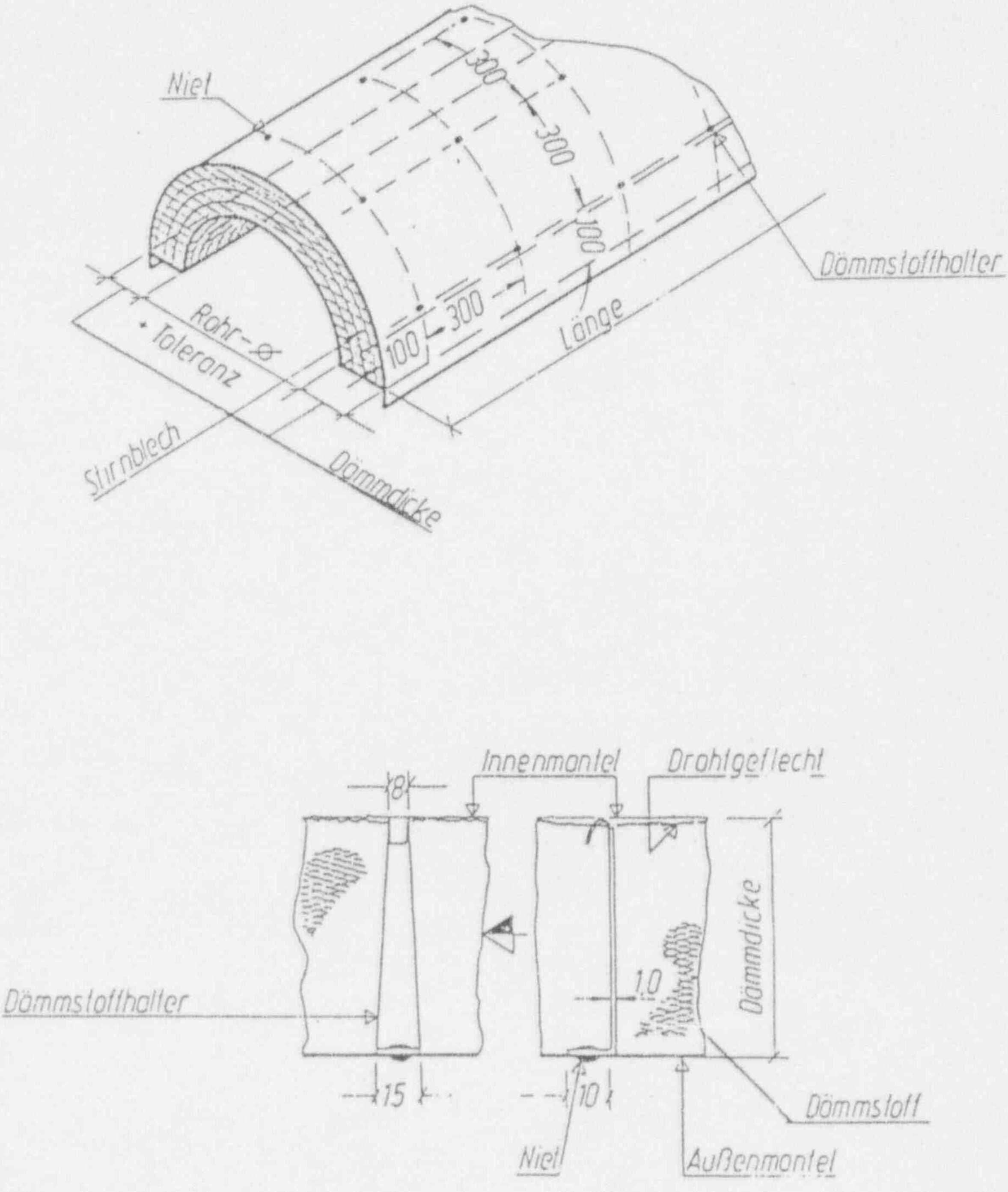

Figure 1: Structure of the metal clad insulation from, G + H drawings 901/81-00-009. Thickness of the austenitic outer cover = 1mm. Thickness of the austenitic inner rippled steel sheet = 0.1 mm. Insulation material: mineral wool.

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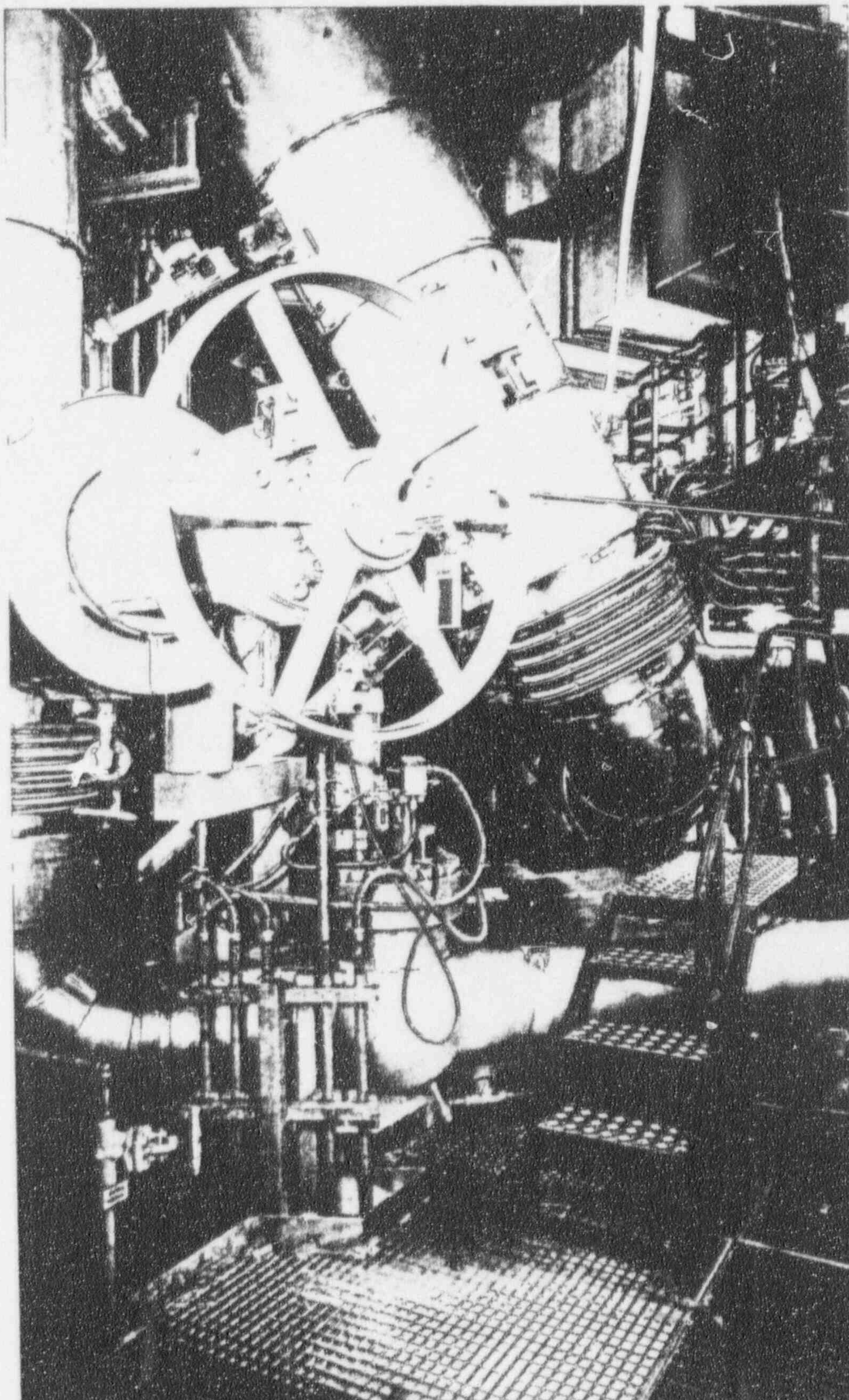

Figure 2: Photo Nr. 13 from [11], View of the Main Steam Pipe as well as the LPCS injection valve from azimuth 95° and a height of +10m. The dimensions of the insulation and snap-lock connections for the cassettes can be seen. A pipe whip restraint is visible at the bend of

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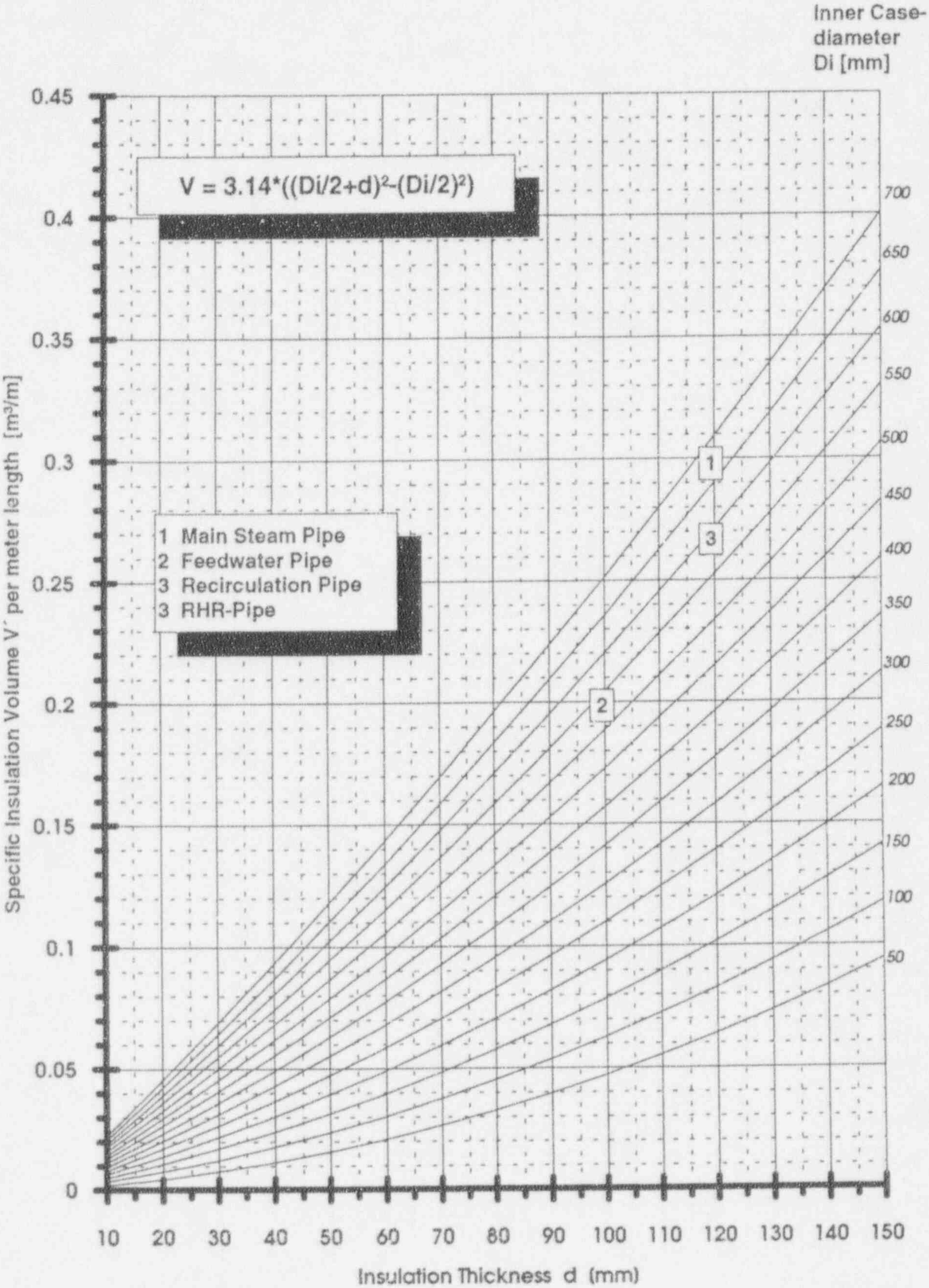

Figure 3: Insulation volume per meter of the pipe length excluding the steel sheet - innerdiameter

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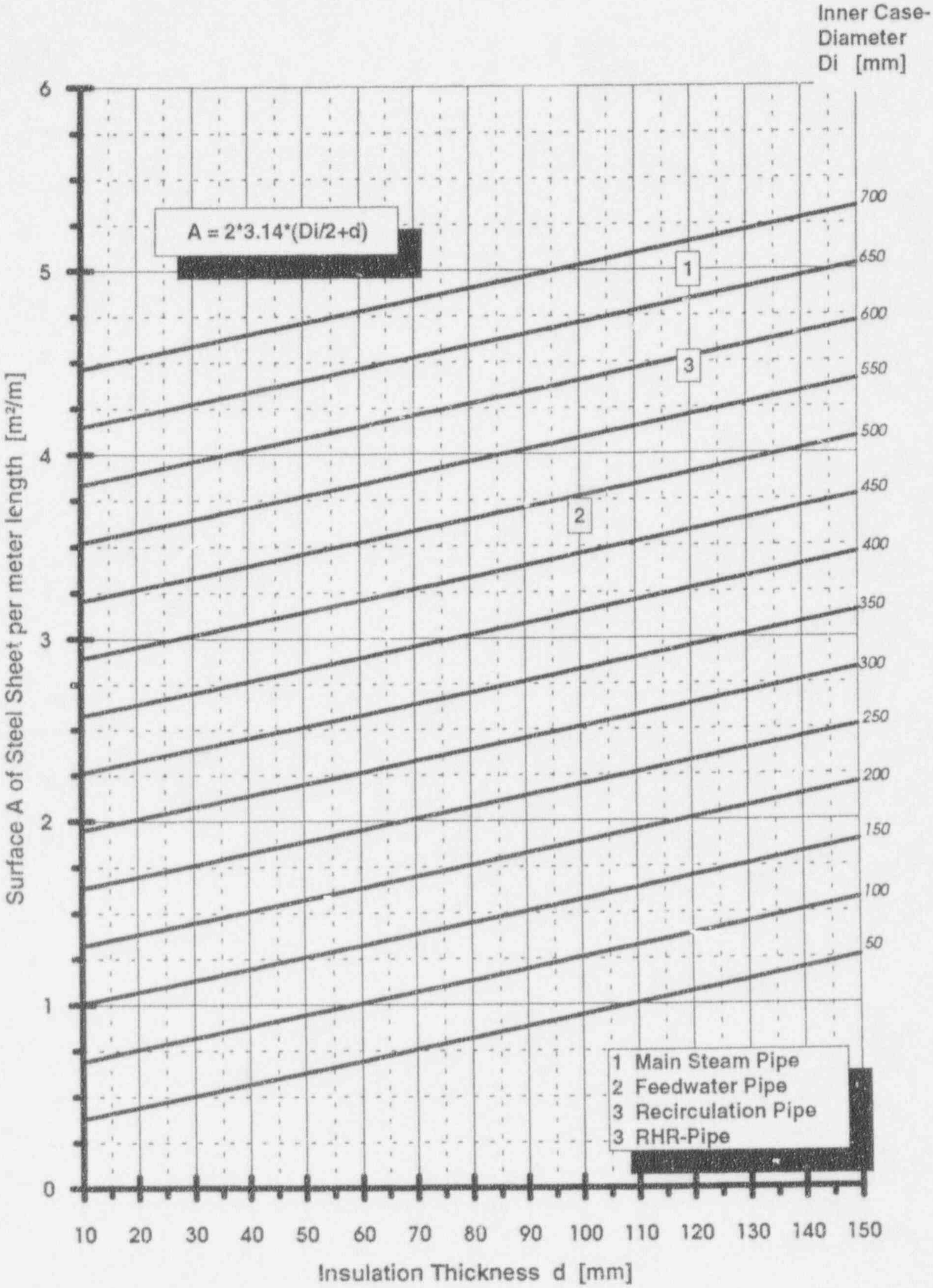

Figure 4 : For the insulation case, steel sheet quantity in m² per meter of the pipe length dependent on case inner radius D_i and insulation thickness d

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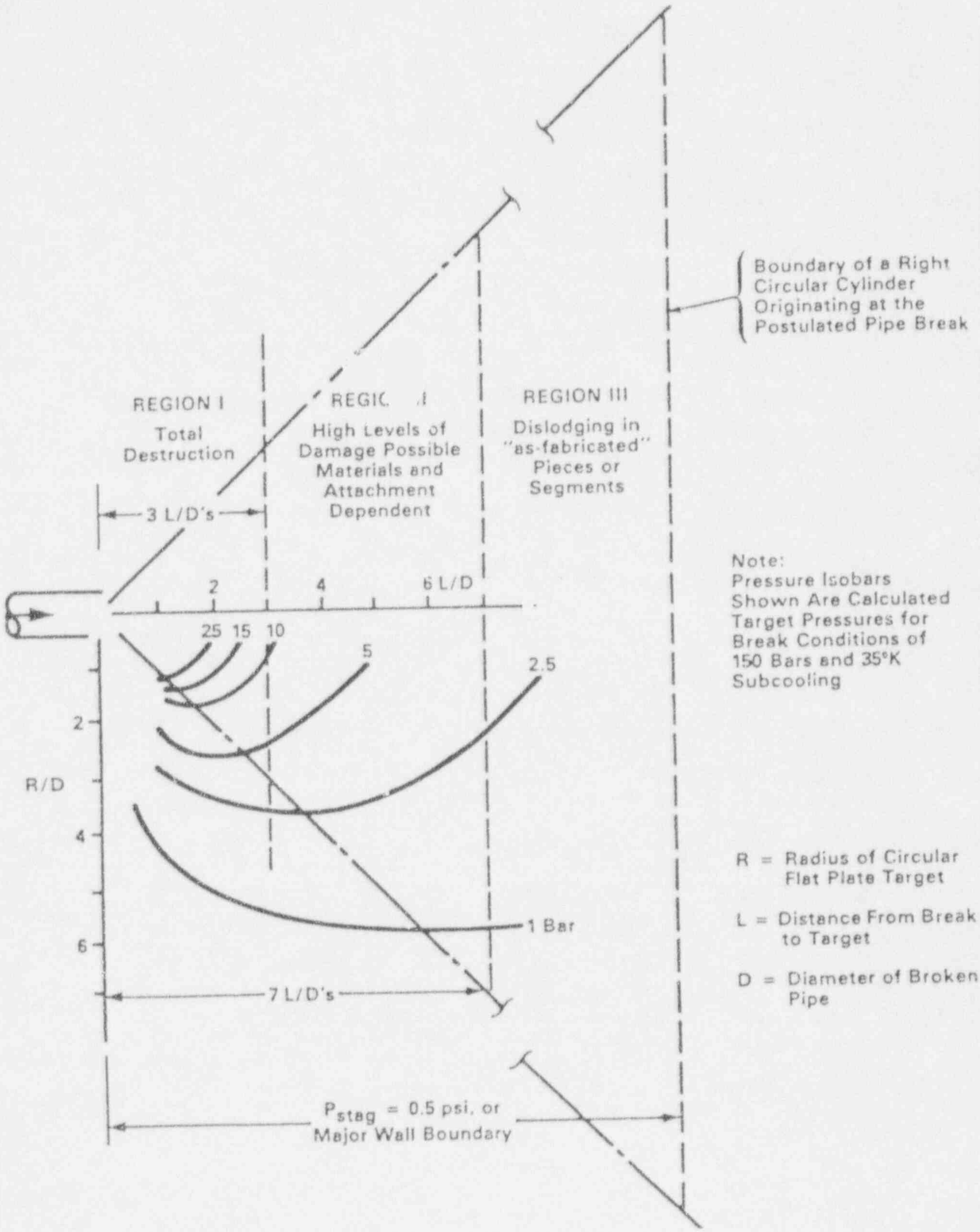
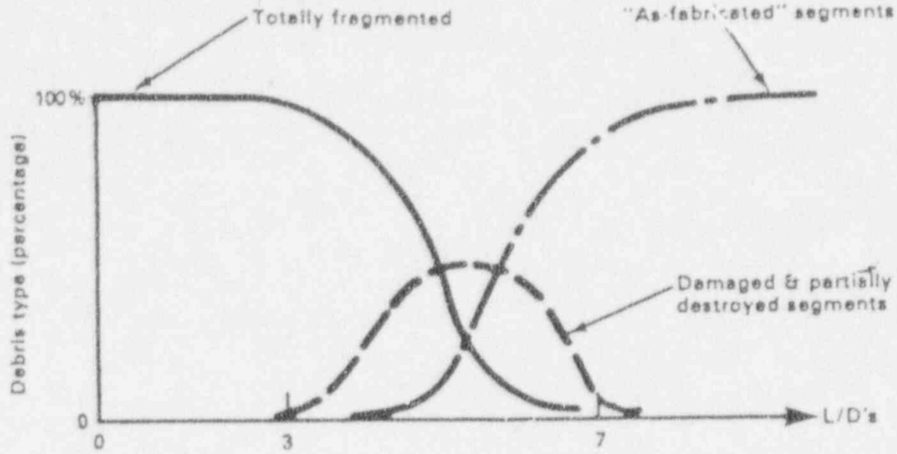
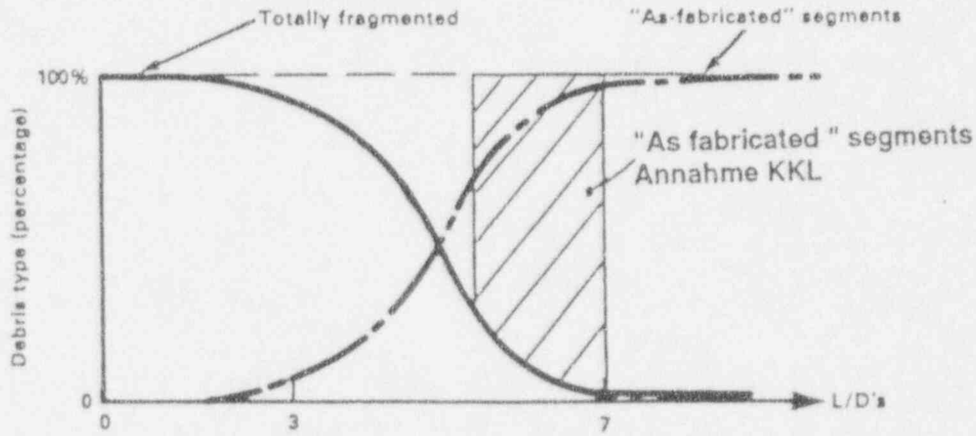


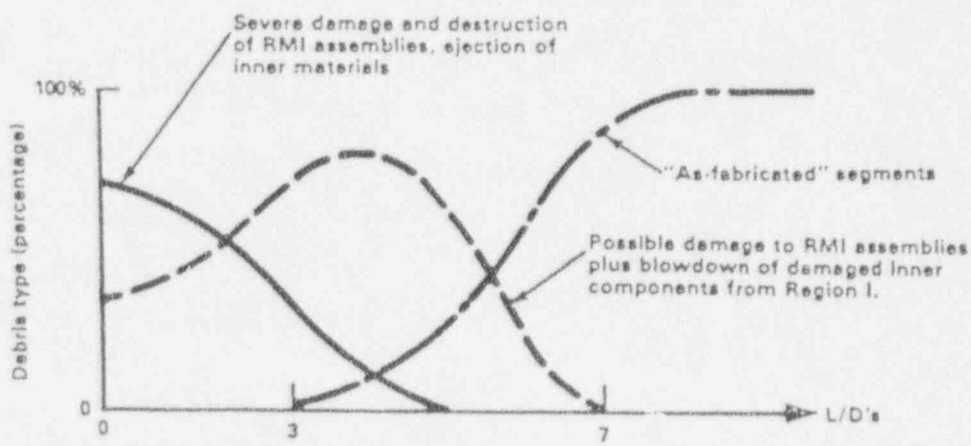
Figure 5 : Multiple zone model for the description of the destructive effect of a steam jet on the



Example for non-jacketed fibrous insulation materials.



Example for jacketed fibrous insulation materials.



Example for reflective metallic insulation materials.

Figure 6 : Influence of the applied insulation material on the amount released by the destructive

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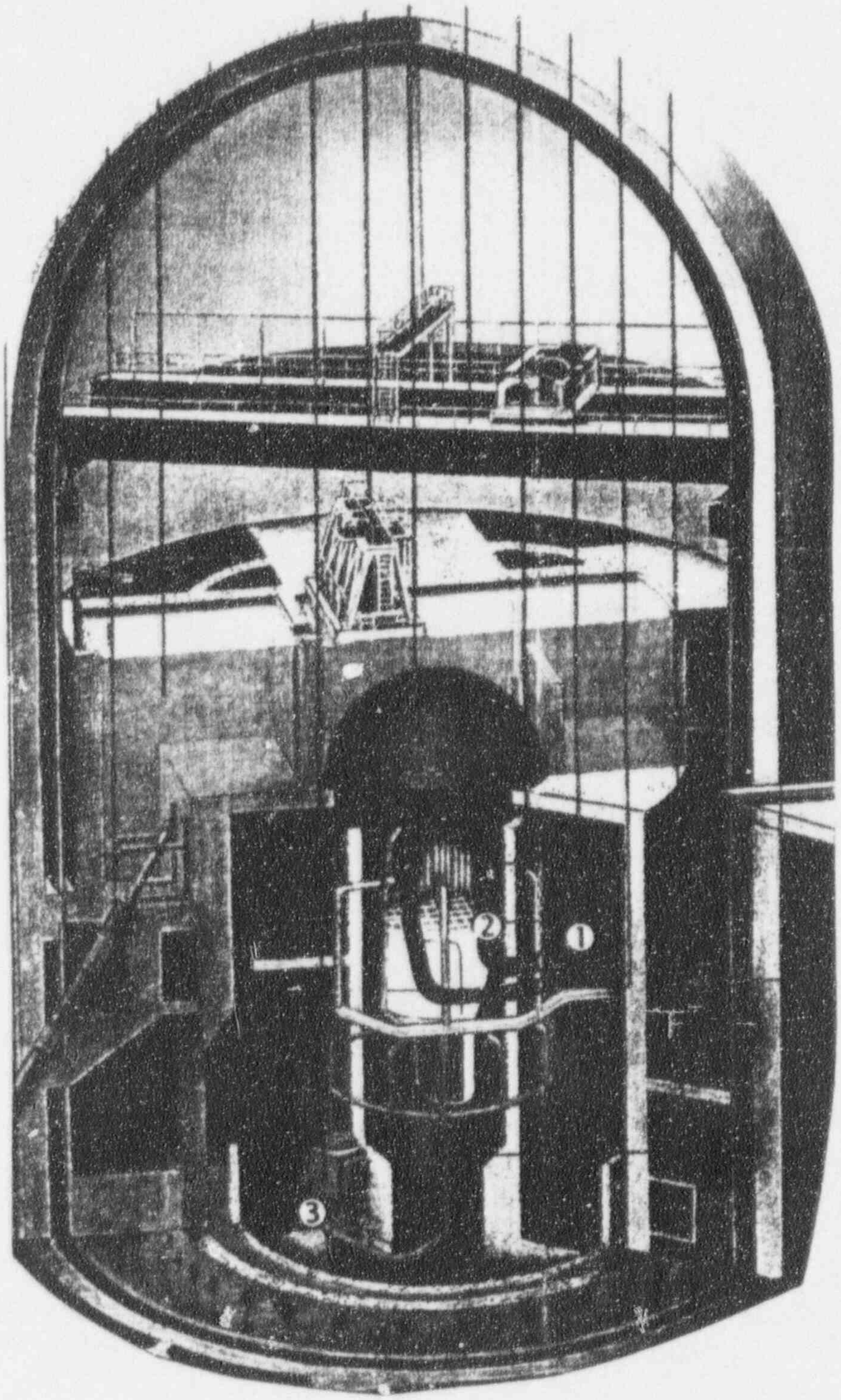

Figure 7 : Position of the three assumed pipe break locations for the evaluation of the quantity of the released insulation material. All three assumed locations lie in the eastern half of the Drywell and are not visible in this figure. For this reason the break locations are shown here in the symmetrical western half of the Drywell.

- ☐ Half sphere effective zone of the steam jet (Sphere radius 4.55 m)
- ■ Main Steam Pipe
- ■ Feedwater Pipe
- ■ Recirculation Pipe with RHR-Pipe
- ■ Concrete Structure

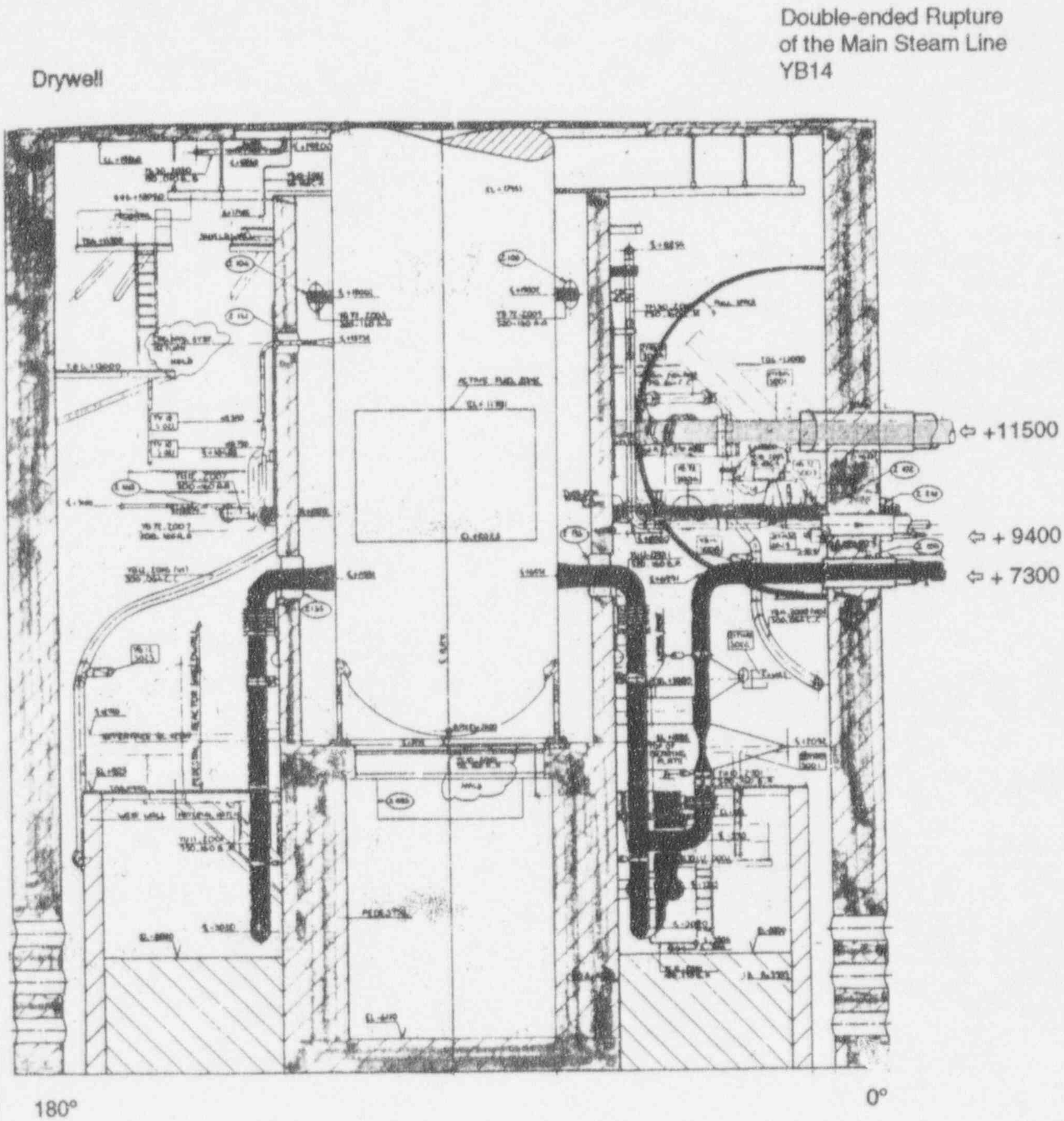

Figure. 8: Vertical cross-section 180° - 0° through the Drywell [12]. Yellow represents a section through the half-sphere effective zone of the steam jet emerging from rupture location ①. Portions of the Main Steam Pipes, Feedwater Pipes, and as well as the RHR-pipes are affected by the steam jet.

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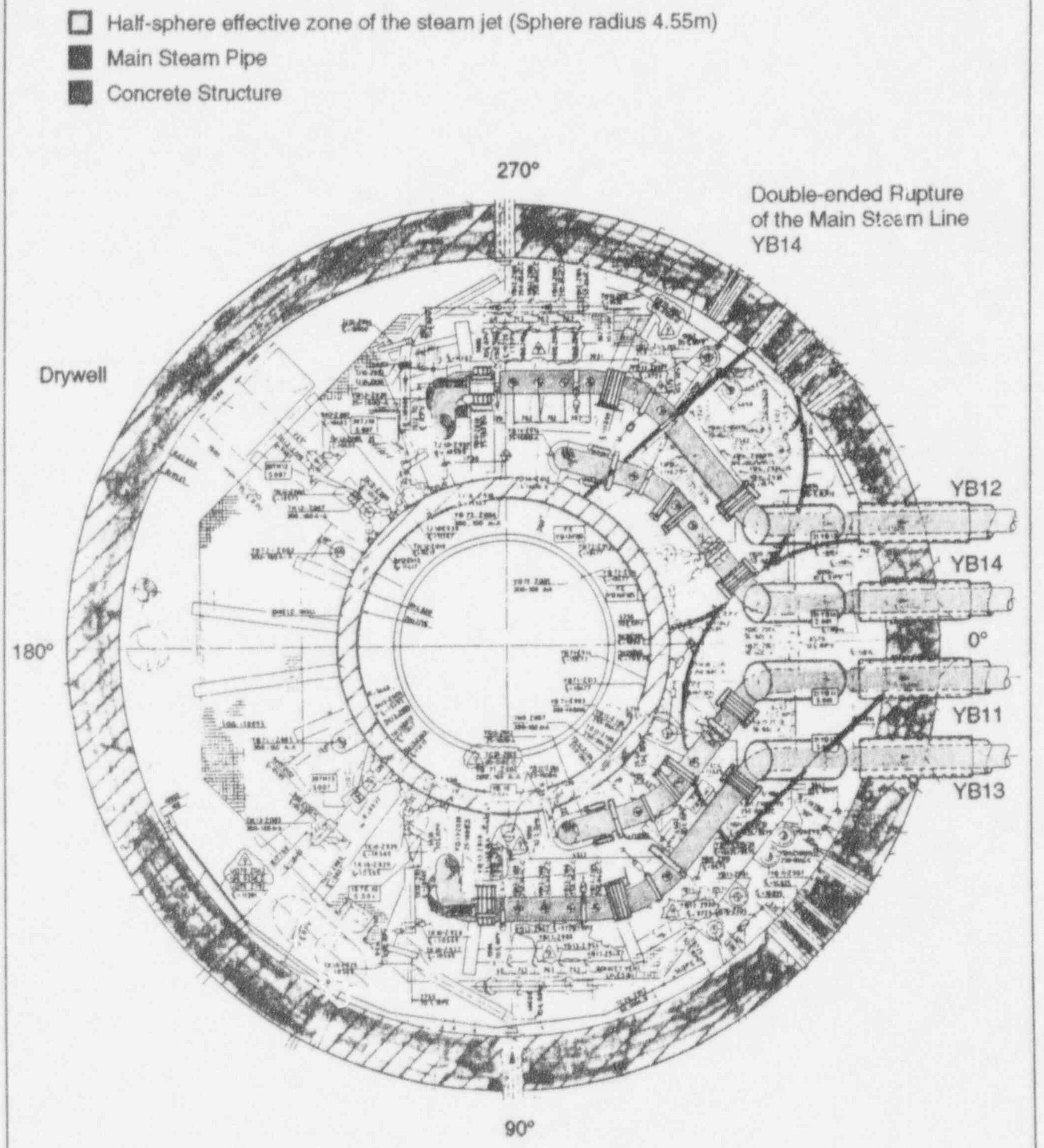

Figure. 9: Horizontal cross-section through the Drywell at the height of + 11500 [13]. Yellow represents a section through the half-sphere effective zone of the steam jet emerging from the rupture location ①. Part of all 4 Main Steam Pipes are affected by the steam jet.

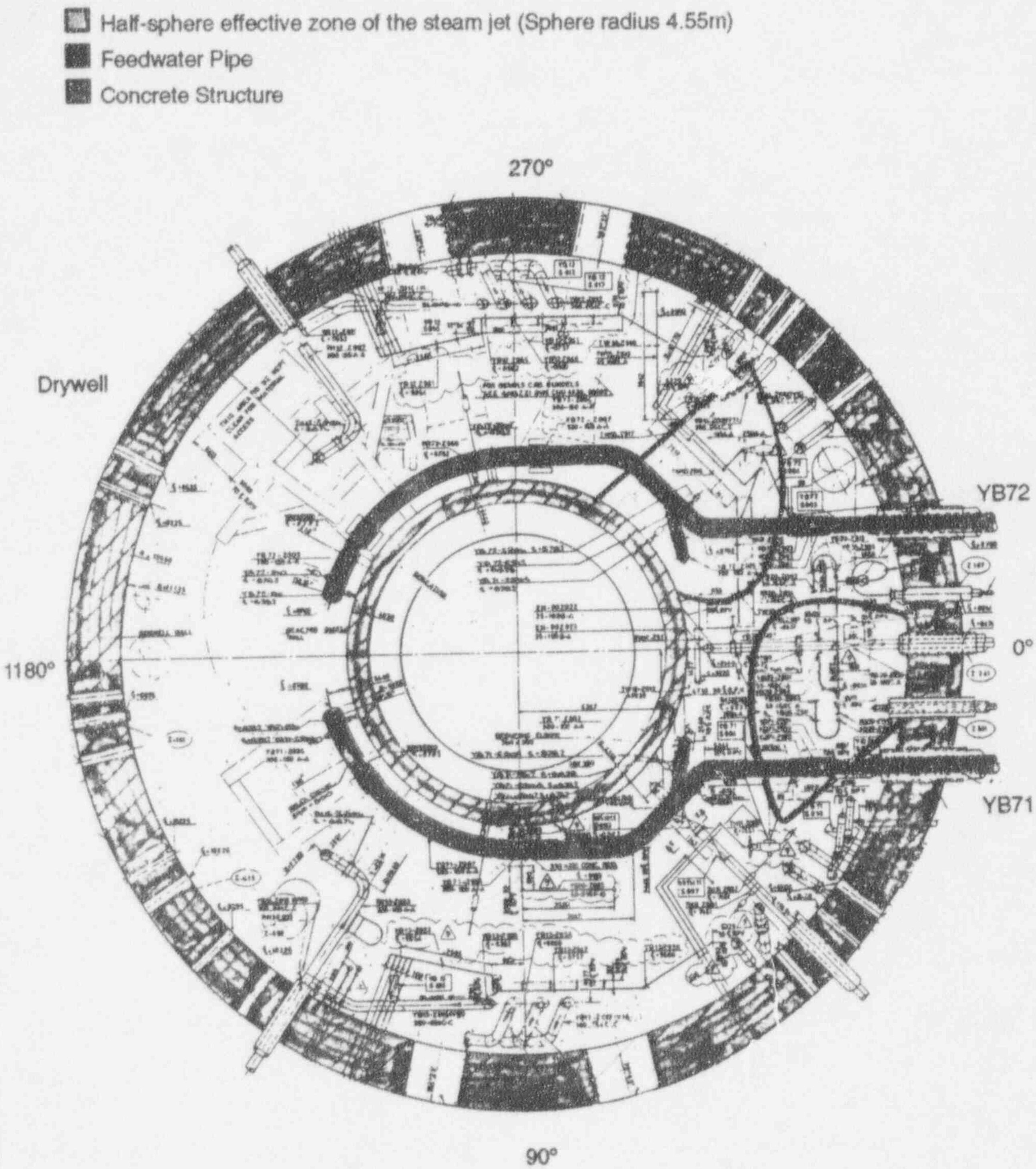

Figure. 10: Horizontal cross-section through the Drywell at the height of +9400 [14]. Yellow represents the surface section of the half-sphere effective zone of the steam jet through the emerging from the rupture position ①. Sections of both Feedwater Pipes are affected by the steam jet.

Half-sphere effective zone of the steam jet (sphere radius 4.55m)

Recirculation Pipe and RHR-Pipe (TH10)

Concrete Structure

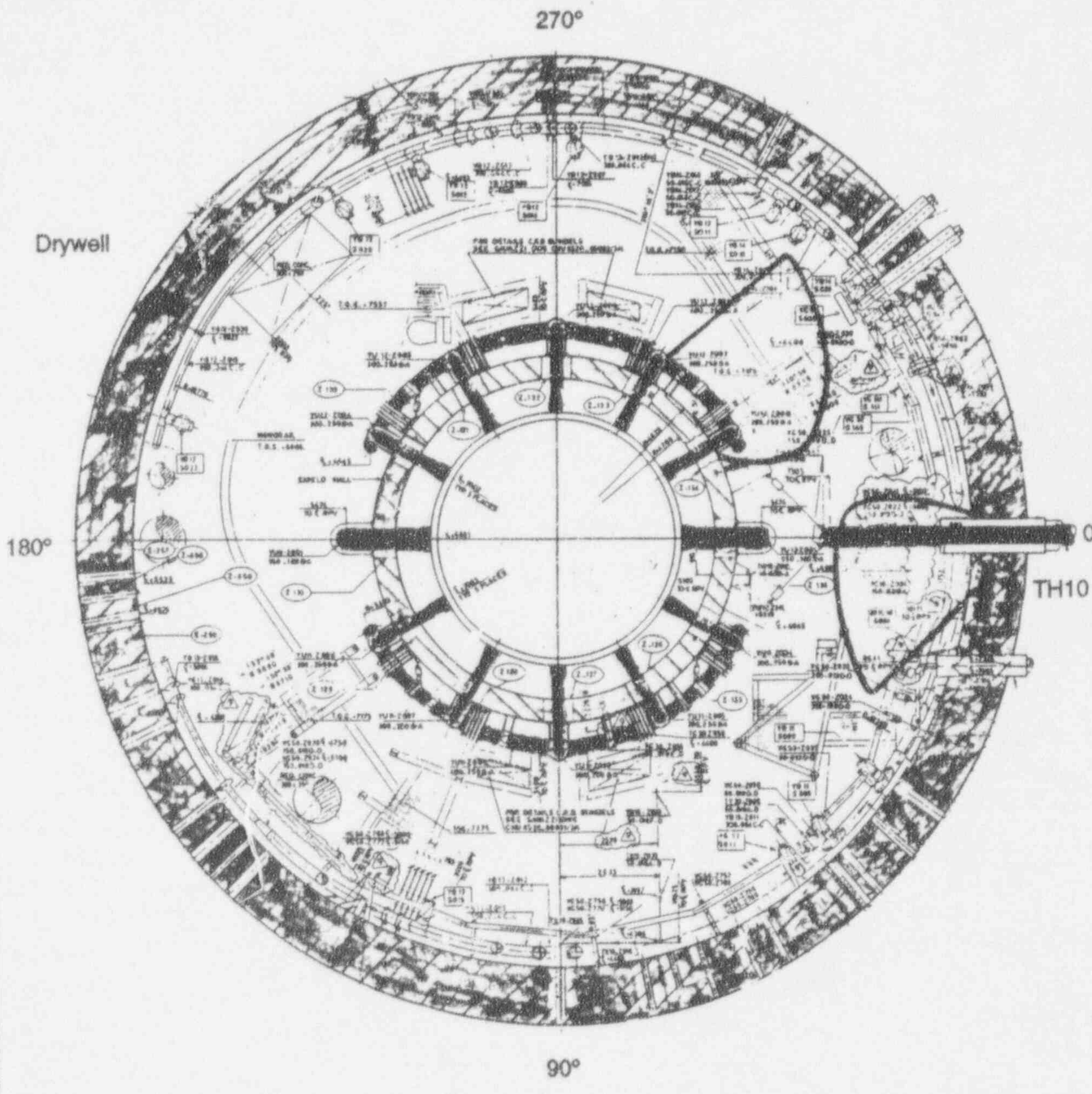

Figure. 11: Horizontal cross-section through the Drywell at the height of +7300 [15]. Yellow represents the section through the half-sphere effective zone of the steam jet emerging from rupture location ①. Part of RHR-Pipe and as well as two risers of the Recirculation Lines are affected by the steam jet.

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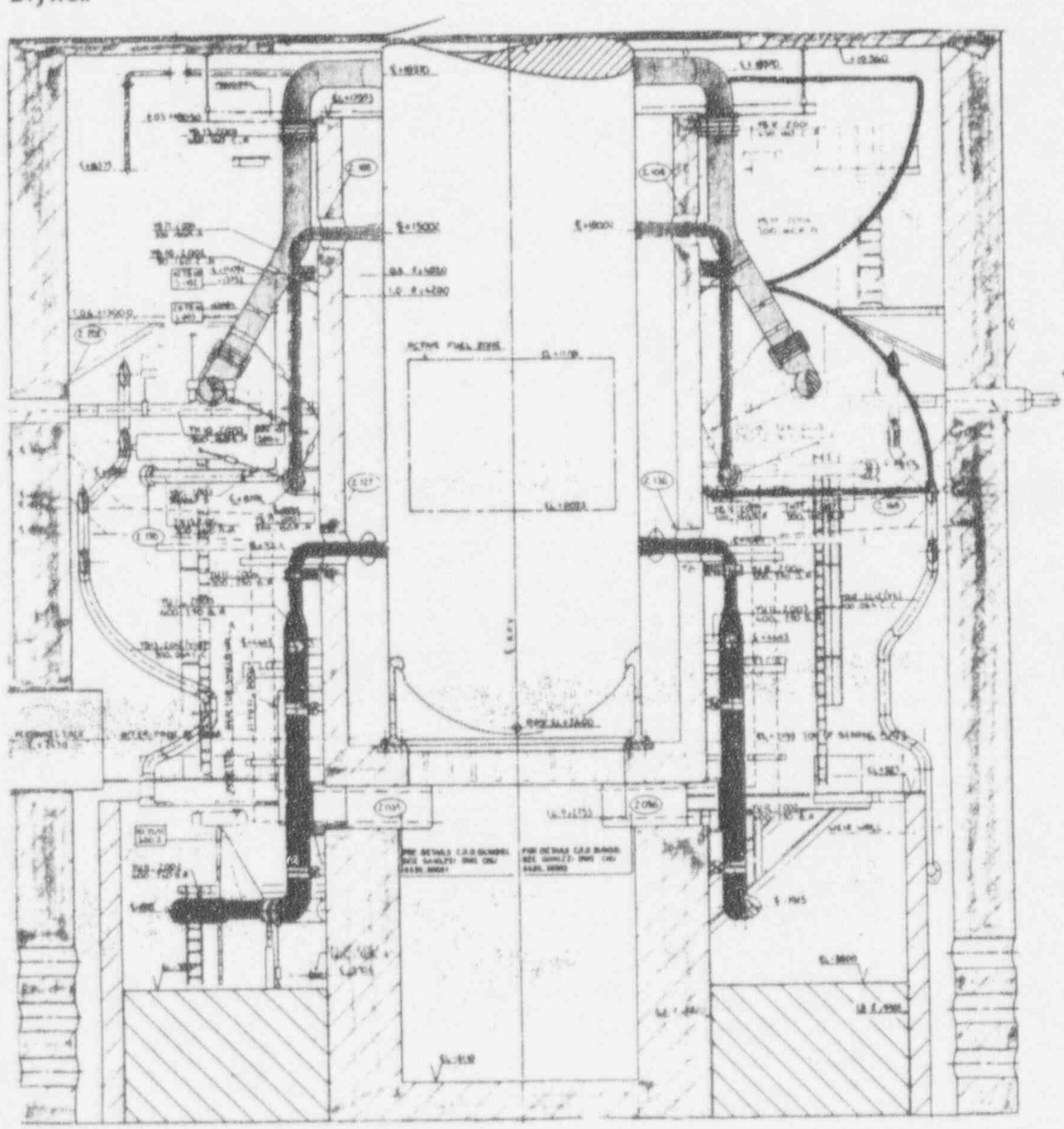
- ☐ Half-sphere effective zone of the steam jet (sphere radius 4.55m)
- ■ Main Steam Pipe
- ■ Feedwater Pipe
- ■ Recirculation Pipe
- ■ Concrete structure

Drywell

Double ended Rupture of the Main Steam Line YB14



⇦ +11500

⇦ + 9400

90° 270°

Figure. 12: Vertical cross-section 90° - 270° through the Drywell [16]. Yellow represents the surface through the half-sphere effective zone of the steam jet emerging from rupture location ②. Sections of the Main Steam Pipe and as well as the Feedwater Pipes are affected by the steam jet.

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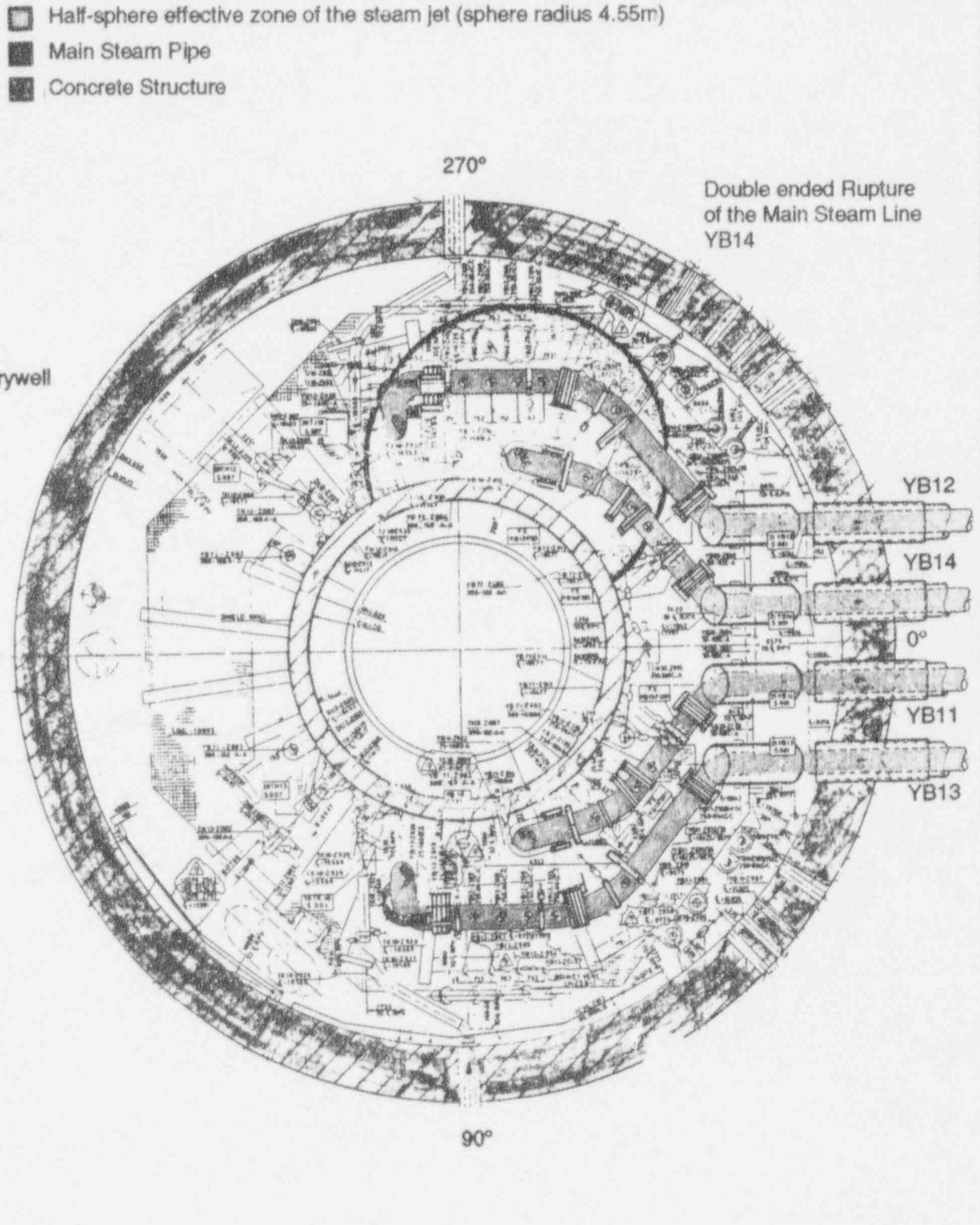

Figure. 13: Horizontal cross-section through the Drywell at the height + 11500 [13]. Yellow represents the section through the half-sphere effective zone of the steam jet emerging from rupture location ②. Sections of the Main Steam Pipe YB12 und YB14 are affected by the steam jet.

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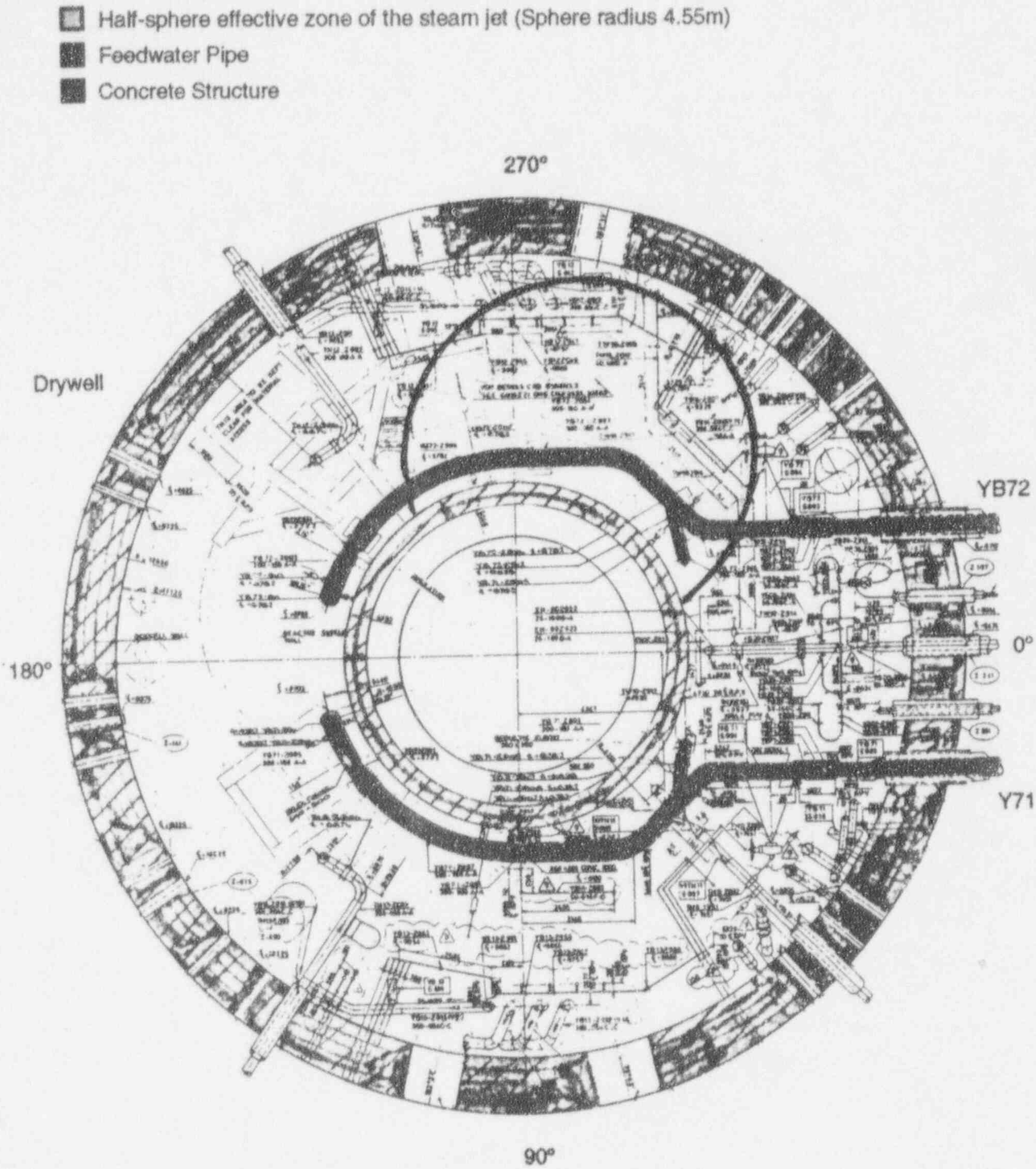

Figure. 14: Horizontal cross-section through the Drywell at the height + 9400 [14]. Yellow represents the section through the half-sphere effective zone of the steam jet emerging from the rupture location ②. The Feedwater Pipe YB72 is affected by the steam jet.

☐ Half-sphere effective zone of the steam jet (Sphere radius 4.2 m)

■ Main Steam Pipe

■ Feedwater Pipe

■ Recirculation Pipe with RHR-Pipe

■ Concrete Structure

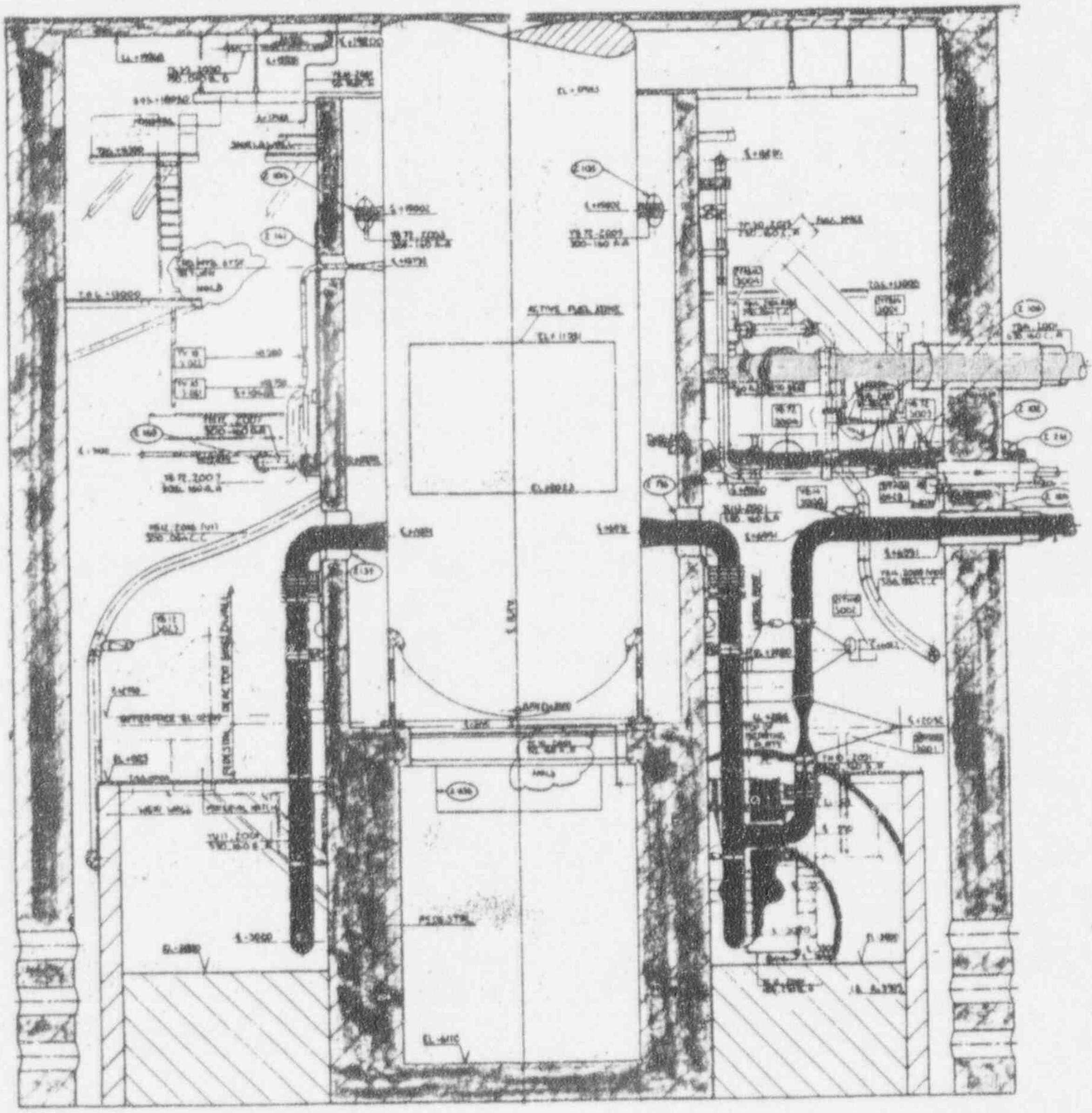

Figure. 15: Vertical cross-section 180° - 0° through the Drywell [12]. Yellow represents the section through of the half-sphere effective zone of the steam jet emerging from rupture location ③. The inner red circle shows the steam jet extension in the plane containing the Recirculation Pump Assembly. Part of the recirculation pipe and the whole Recirculation Pump Assembly as well as the RHR Pipe are affected by the steam jet.

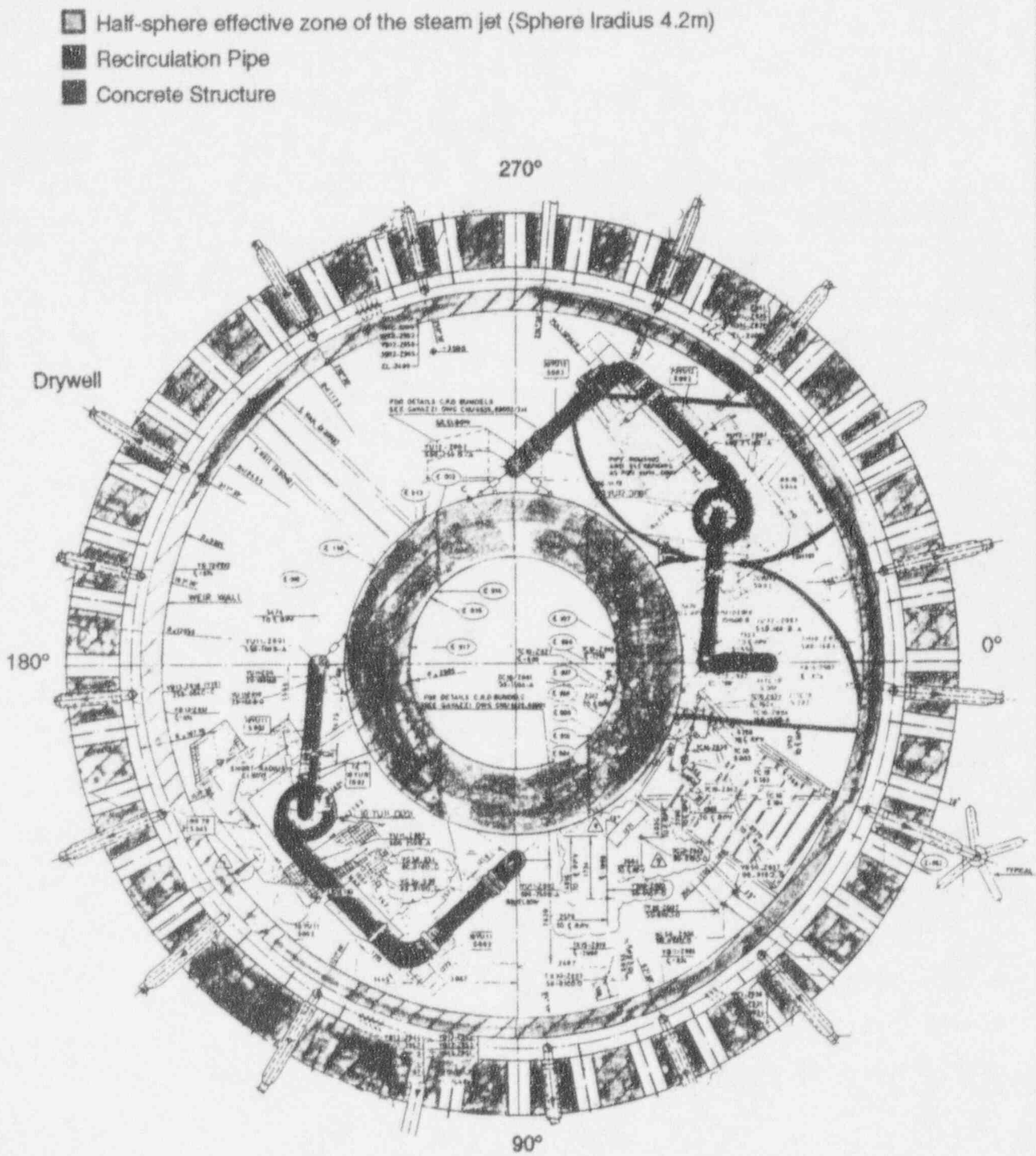

Figure. 16: Horizontal cross-section through the Drywell at the height -3400 [17]. Yellow represents the section through the half-sphere effective zone of the steam jet emerging from rupture location ③. Section of the Recirculation Pipe YU13 including the Pump Assembly and the RHR-Pipe are affected by the steam jet.

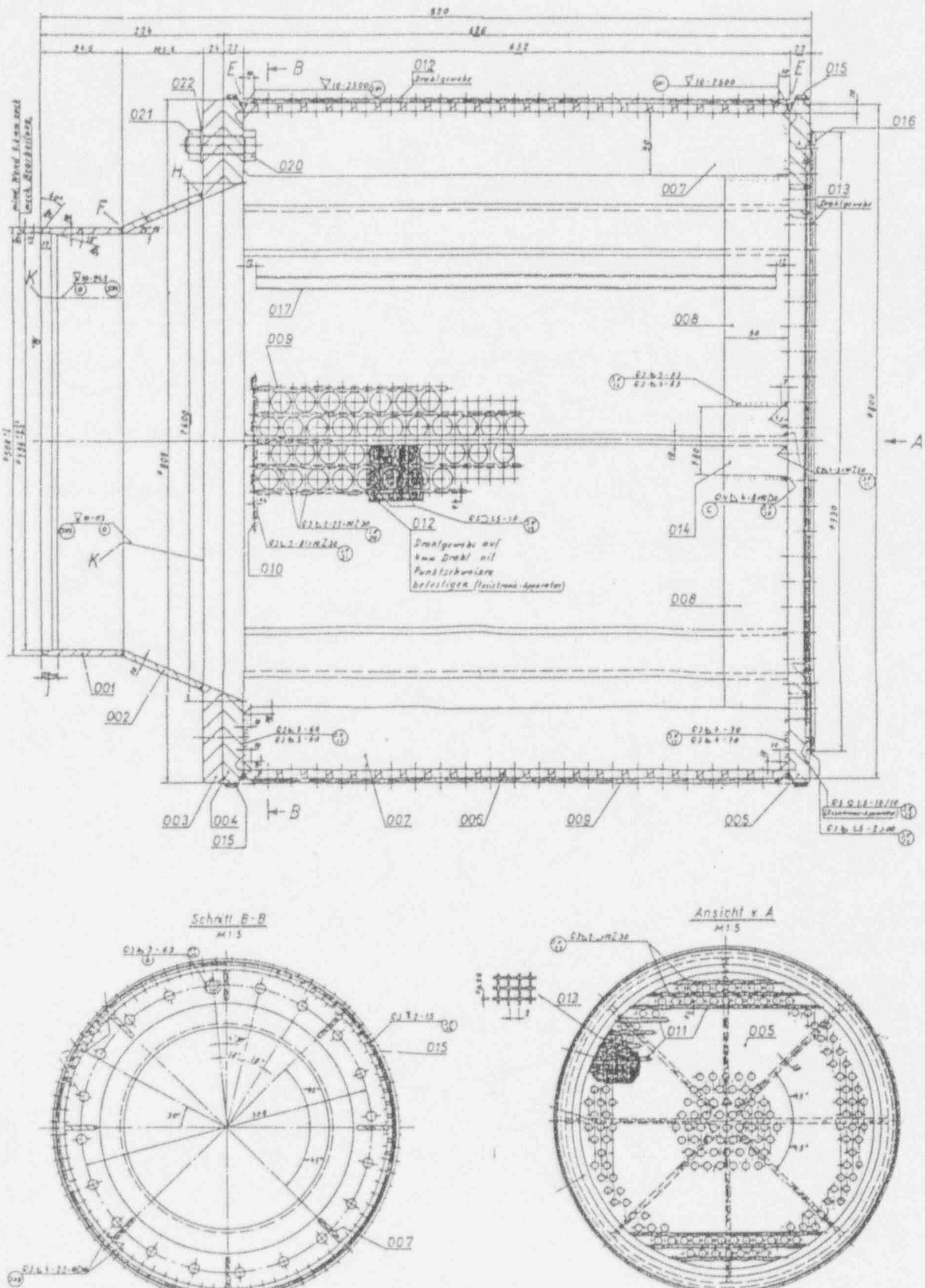

Figure. 17 : Detail drawings of the 500 mm strainer; extracts from Sulzer drawing 0.192.160.470

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NPSH CALCULATIONS FOR MINIMUN SUPPRESSION POOL LEVEL, RPV INJECTION AT RUNOUT FLOW FOR ECCS SYSTEMS.

MINIMUN SUPPRESSION POOL LEVEL PER SAR IS 0.61 m ABOVE THE TOP OF THE TOP ROW OF VENTS. THIS CORRESPONDS TO PLANT ELEVATION OF −2110 mm.

$$NPSH = P_{ATM} + P_{SUCT} + h - P_{VAP}$$

WHERE:
- P_{ATM} = ATMOSPHERIC PRESSURE (10.34 m)
- P_{SUCT} = MEASURED SUCTION PRESSURE
- h = HEIGHT OF SUCTION GAGE OVER REFERENCE POINT
- P_{VAP} = VAPOR PRESSURE AT 100 °C

NOTE: 1 bar = 10.2 m
P_{SUCT} AND h MUST BE MULTIPLIED BY THE RATIO OF THE DENSITY OF WATER AT 100 °C AND THE DENSITY OF WATER AT THE TEST TEMPERATURE.

Figure. 18 : Calculation of NPSH [6]

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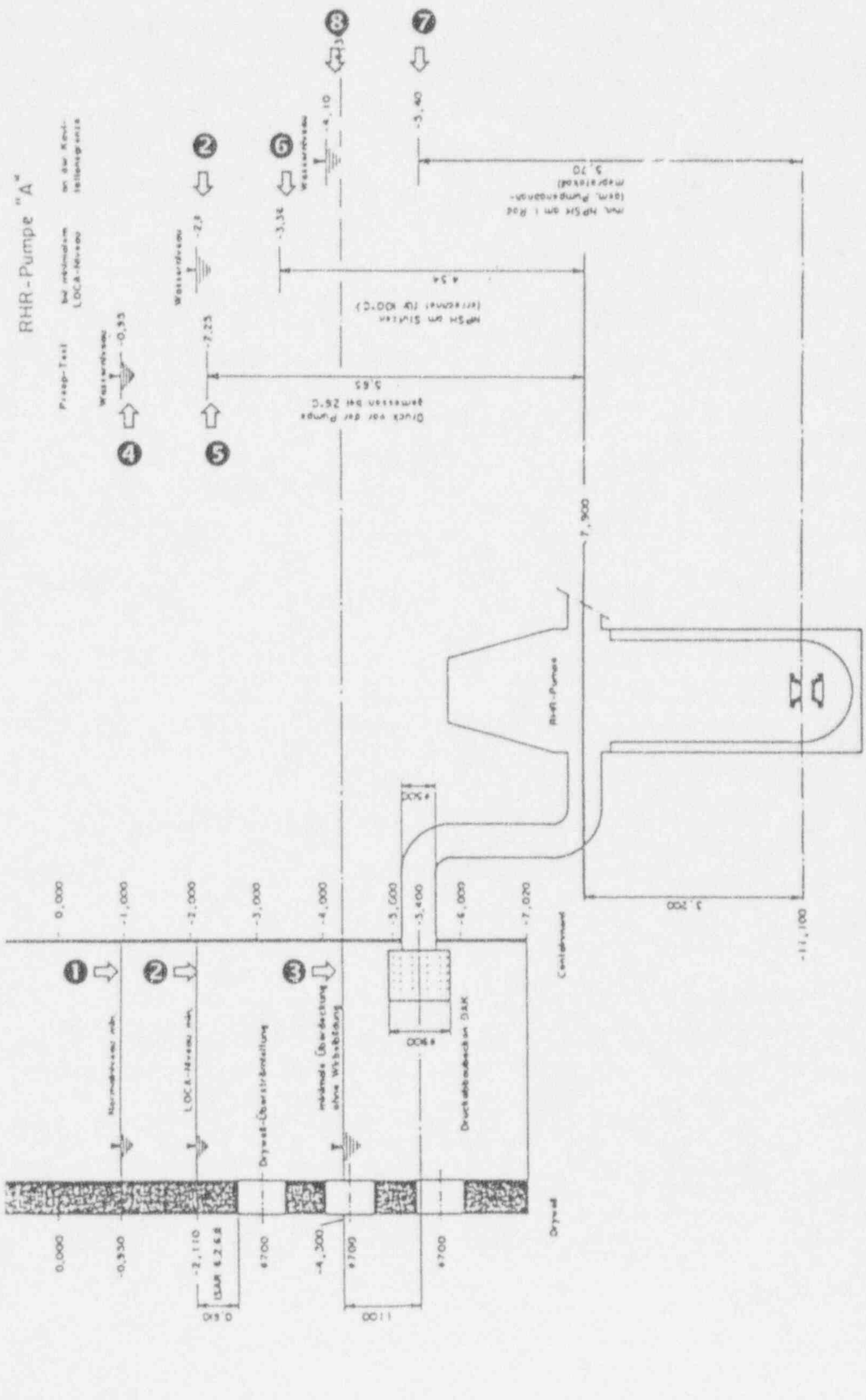

Figure. 19: Effective Suction portion of the RHR-Pump "A" [6]

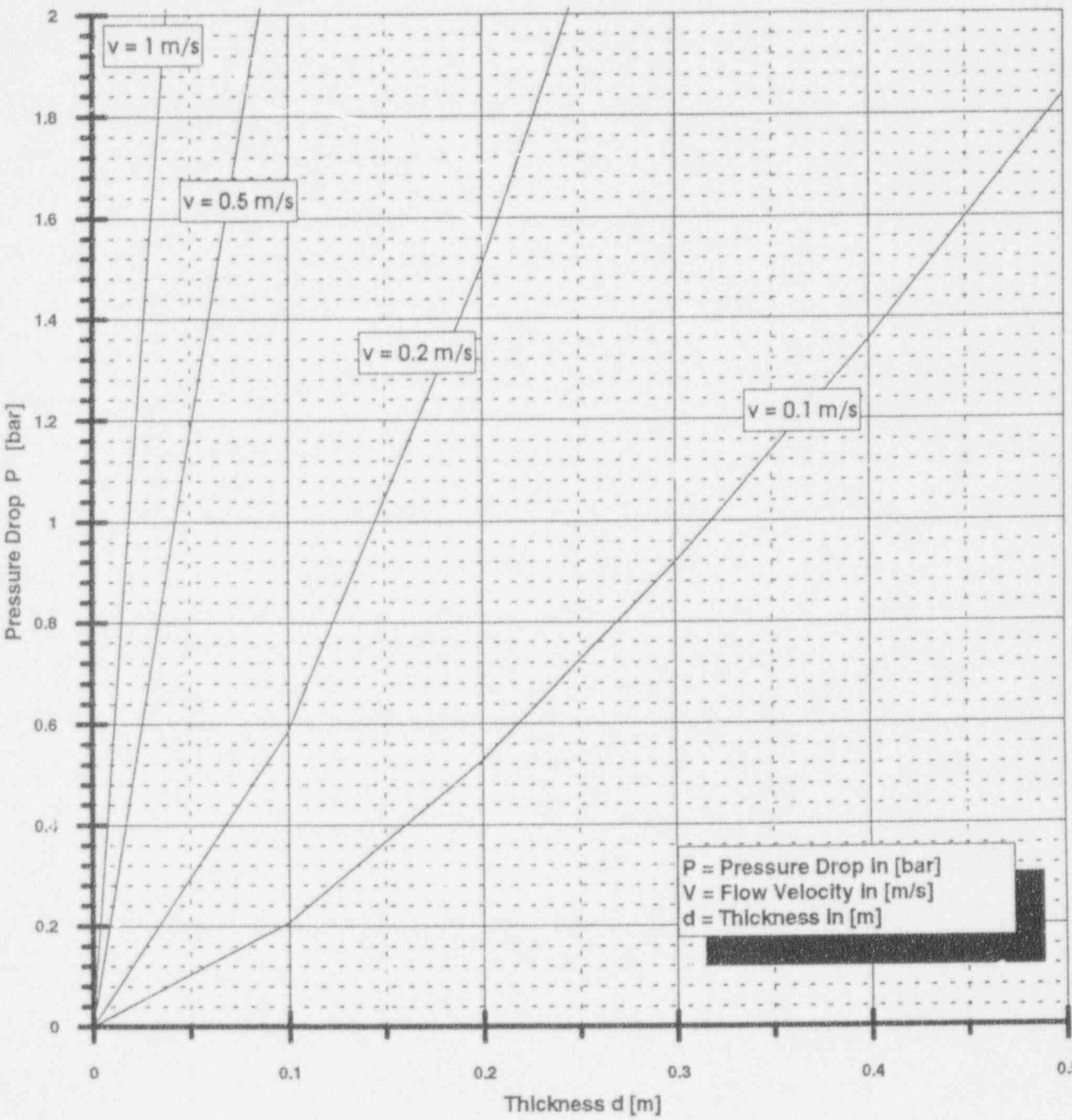

Figure. 20 : Pressure drop Δp through the mineral wool insulation deposit depending on the flow

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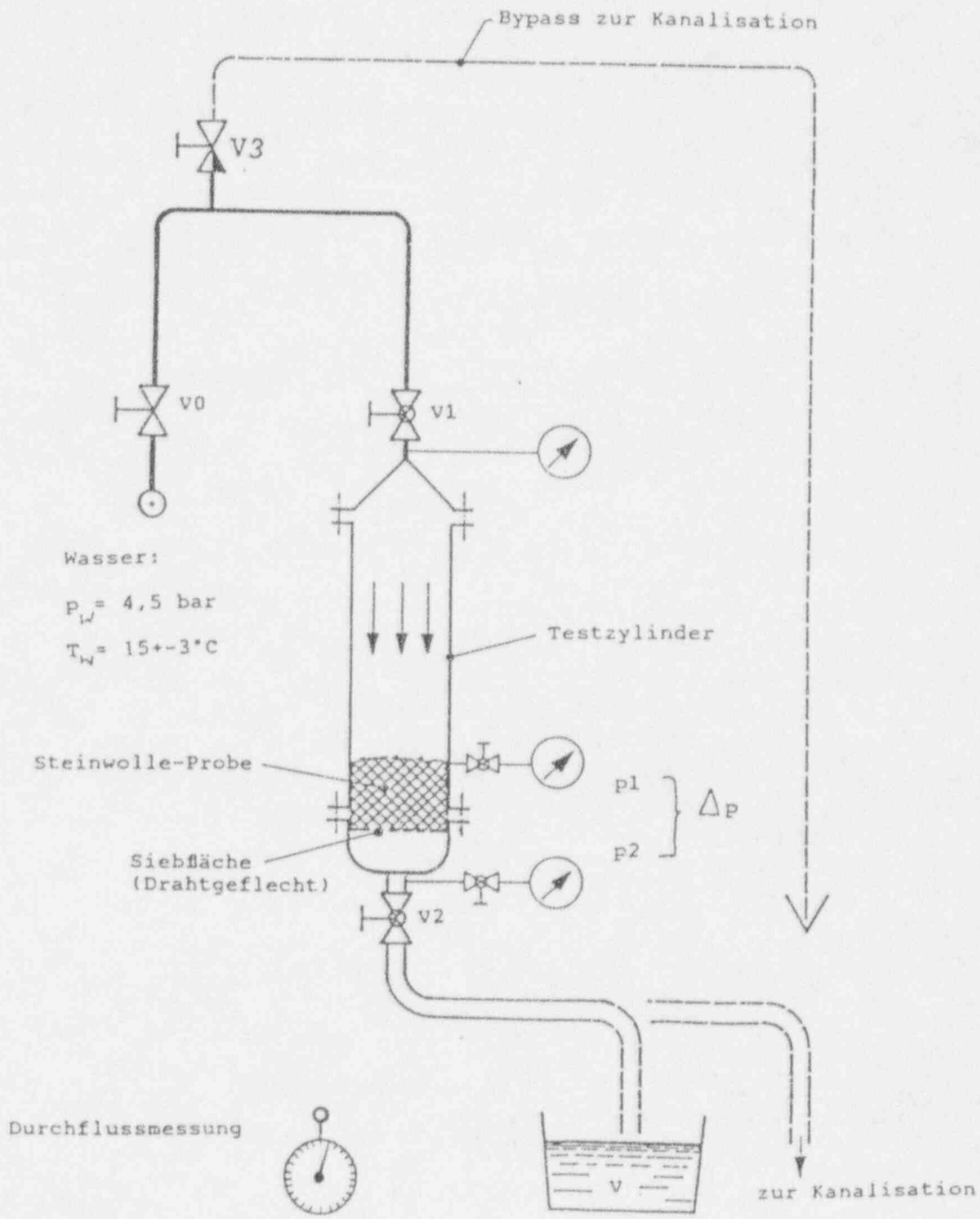

Figure. 21 : Illustration of the Sulzer experiment to determine the pressure drop Δp from the mineral

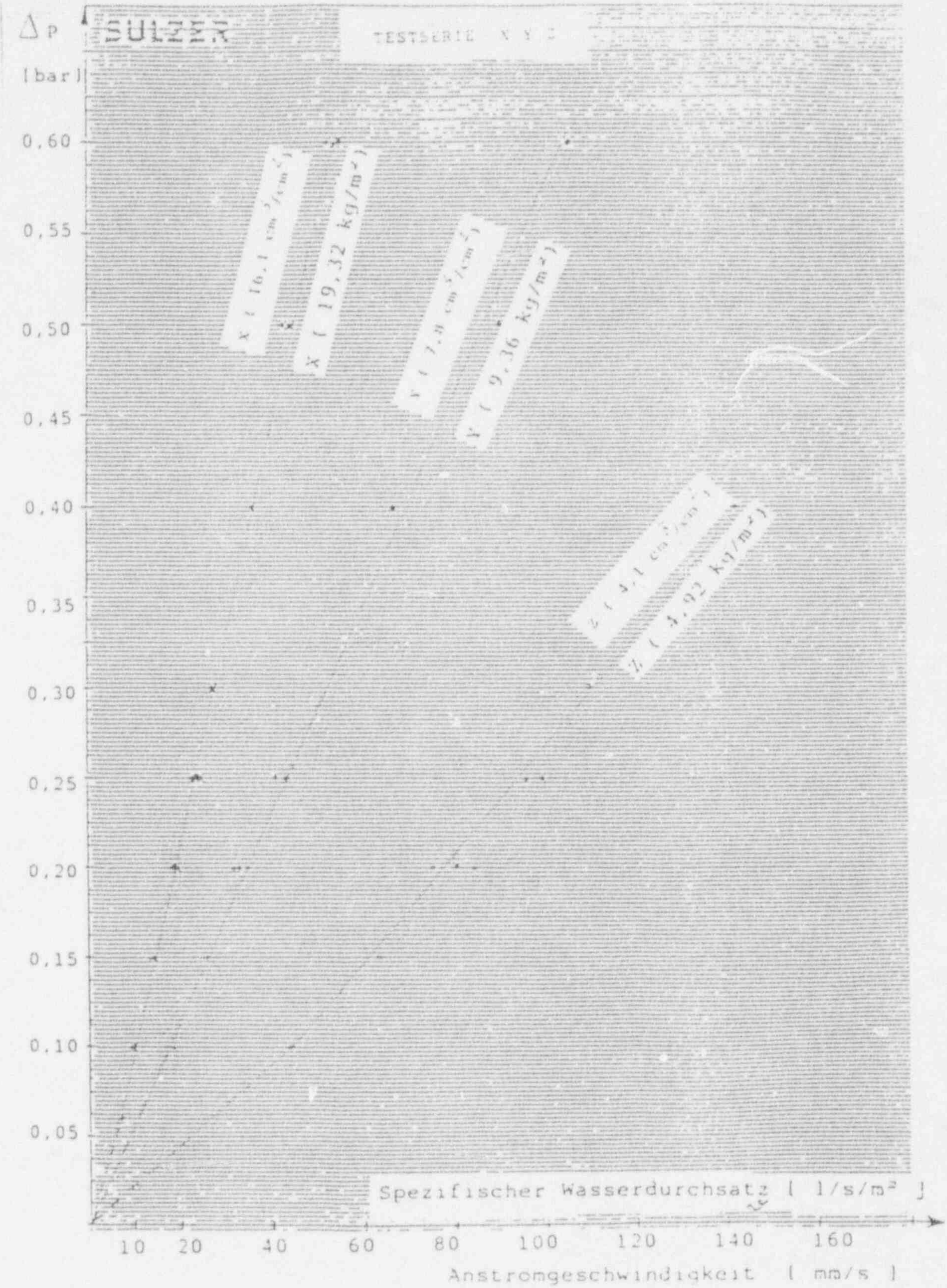

Figure. 22 : Pressure drop over the strainers as a function of the velocity and the specific strainer surface loadings. Test series with the shredded mineral wool with stir-mixing. T = 15 +- 3°C [8].

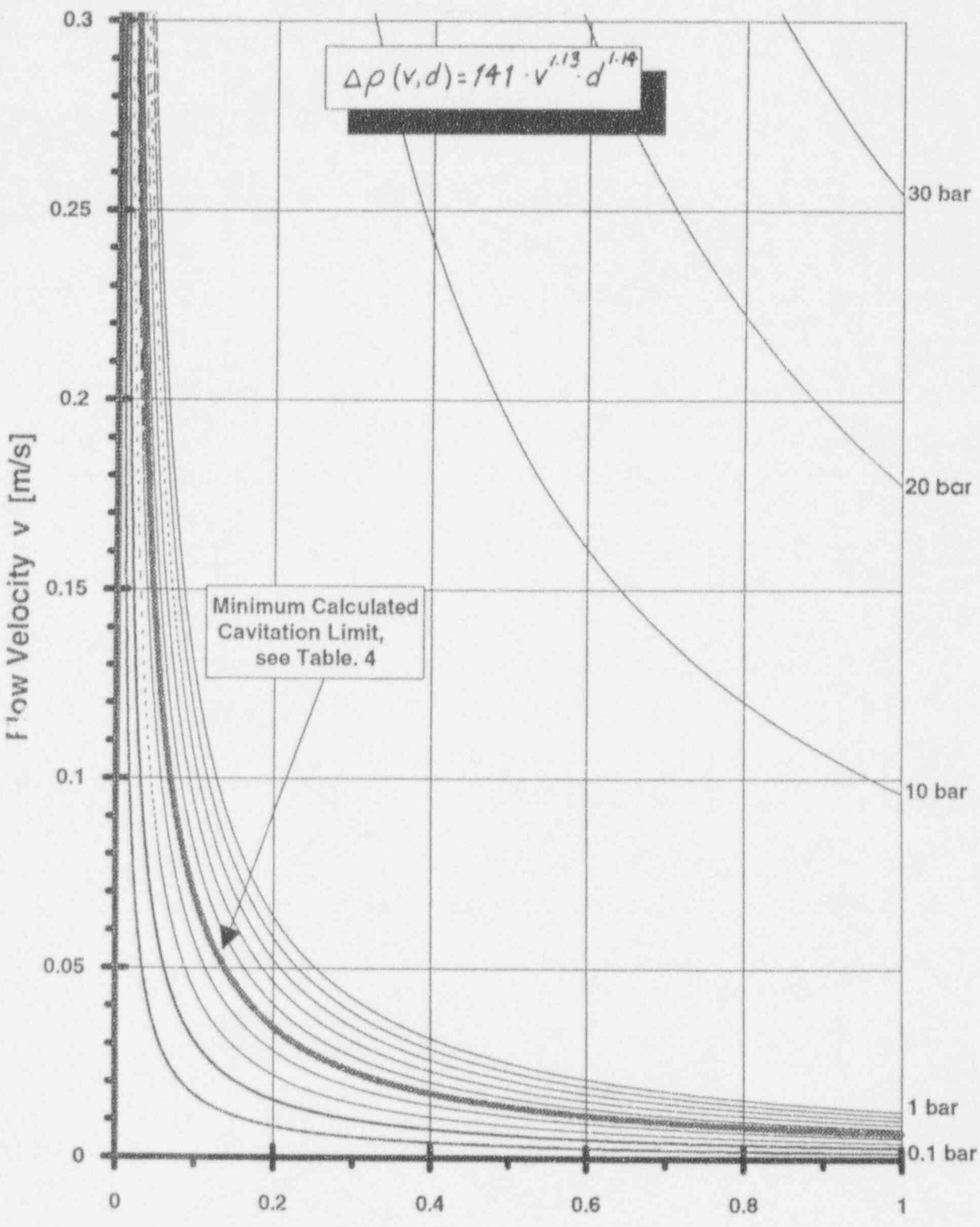

Figure. 23 : Pressure drop as a function of the flow velocity and the deposit thickness on the strainer. The curves are given for pressure drop of 0.1 bar to 1.0 bar in steps of 0.1 bar and curves for 10, 20, and 30 are given as well. The curve for the maximum allowable pressure drop is also shown as the cavitation limit.

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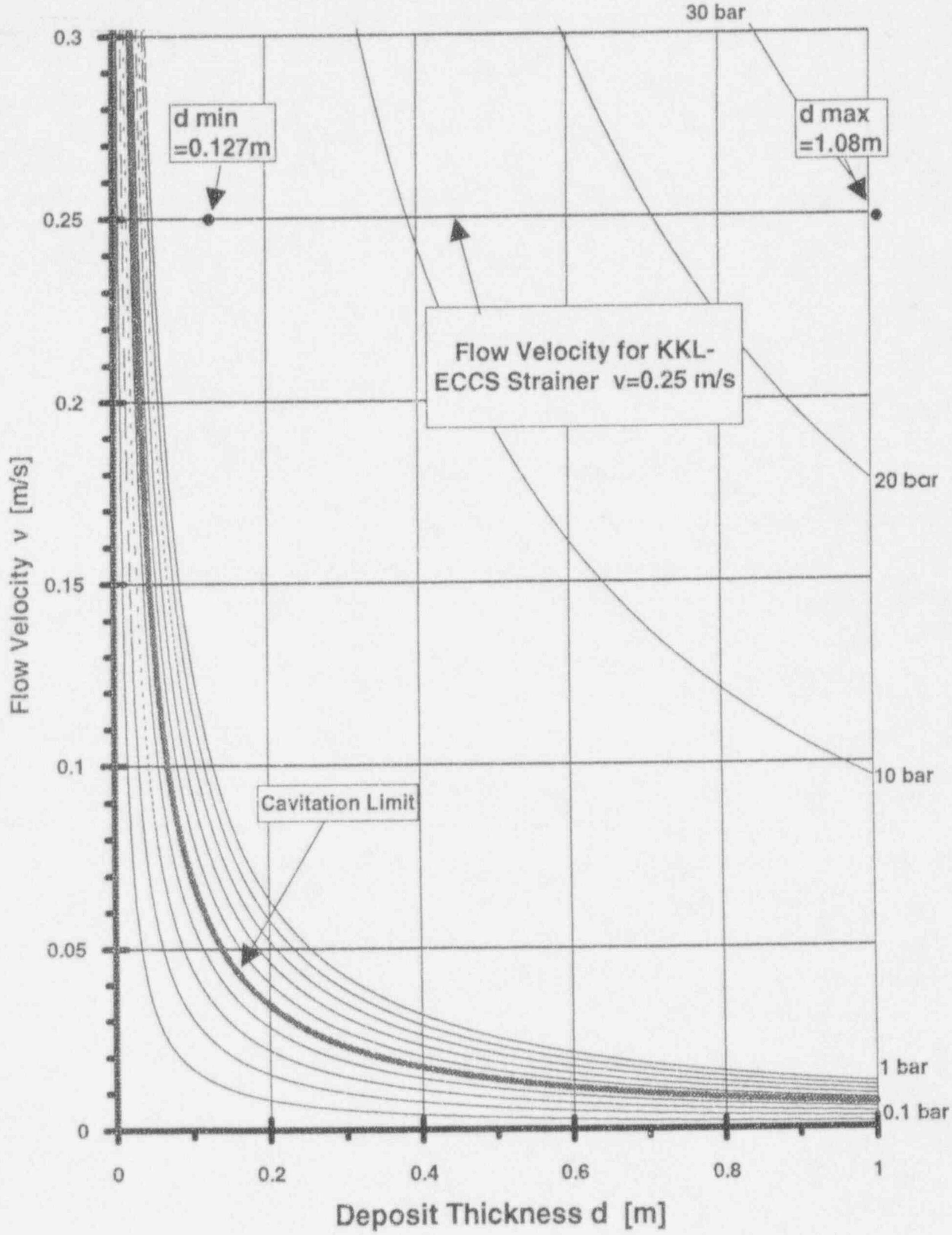

Figure. 24 : Pressure drop as a function of the flow velocity and the deposit thickness on the strainer. The curves are given for pressure drop of 0.1 bar to 1.0 bar in steps of 0.1 bar and curves for 10, 20, and 30 are given as well. Both points for the minimum and maximum amounts of released insulation material lie clearly about the allowable pressure drop Δp_{allow}.