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ABSTRACT

The FEBA forced feed reflood experiments included base line tests with unblocked geometry. The experiments consisted of separate effect tests on a full-length 5x5 rod bundle. Experimental cladding temperatures and heat transfer coefficients of FEBA test No. 216 are compared with the analytical data postcalculated utilizing the SSYST-3 computer code. The comparison indicates a satisfactory matching of the peak cladding temperatures, quench times and heat transfer coefficients for nearly all axial positions. This agreement was made possible by the use of an artificially adjusted value of the empirical code input parameter in the heat transfer for the dispersed flow regime. A limited comparison of test data and calculations using the RELAP4/MOD6 transient analysis code are also included. In this case the input data for the water entrainment fraction and the liquid weighting factor in the heat transfer for the dispersed flow regime were adjusted to match the experimental data. On the other hand, no fitting of the input parameters was made for the COBRA-TF calculations which are included in the data comparison.

Vergleich von Rechenprogramm-Ergebnissen mit FEBA-Versuchsdaten

Zusammenfassung

Die bei Zwangsfluten durchgeführten FEBA-Experimente schlossen auch Versuche mit unblockierter Bündelgeometrie ein, mit denen die Versuchsbasis gelegt wurde. Die Experimente bestanden aus Untersuchungen von Einzeleffekten unter Verwendung eines 5x5-Stabbündels von Original-Länge. Experimentell ermittelte Hüllrohrtemperaturen und Wärmeübergangszahlen des FEBA-Versuchs Nr. 216 werden verglichen mit analytisch ermittelten Daten, die sich aus der Nachrechnung mit dem SSYST-3 Rechenprogramm ergaben. Der Vergleich zeigt eine zufriedenstellende Übereinstimmung der maximalen Hüllrohrtemperaturen, Wiederbenetzungszeiten und Wärmeübergangszahlen für nahezu alle axialen Positionen. Diese Übereinstimmung ergab sich aber nur unter Verwendung eines künstlich angepaßten Eingabeparameters für den Wärmeübergang während der Nebelkühlung. In den Vergleich von Testdaten und Nachrechnungen sind einige Ergebnisse eingeschlossen, die sich aus Rechnungen mit dem Systemprogramm RELAP4/MOD6 ergaben. In diesem Fall wurden die Eingabedaten zum Wassermitrißmodell und zur Wichtung des Wasseranteils während der Nebelkühlphase angepaßt mit dem Ziel einer Übereinstimmung mit den Versuchsergebnissen. Dagegen wurde keine Anpassung der Eingabedaten für die Nachrechnungen mit COBRA-TF vorgenommen, dessen Ergebnisse in den Datenvergleich einbezogen wurden.

Content

1. Introduction

The thermal-hydraulics in a nuclear reactor core during a loss-of-coolant accident (LOCA) of a pressurized water reactor (PWR) depends mainly on the location and the size of the break in the primary coolant system. During blowdown emergency core cooling systems (ECCS) are initiated following the transient of the system pressure. It is assumed that the reactor pressure vessel is empty at the end of the blowdown phase. The low pressure emergency core cooling system needs some time to fill up the pressure vessel until the lower end of the core is beginning to be submerged in the rising water column (refill phase). At that moment, the main flow direction through the core is reversed from bottom to top, prevailing during the reflood phase.

At the beginning of the reflood phase, the cladding temperature are assumed to be above Leidenfrost temperature. As the liquid level reaches the bottom end of the core and starts to rise around the fuel rods, complex transient heat transfer and two-phase flow processes occur. Ahead of the quench front the cladding temperatures are affected by the rate of steam generated upstream and the thermal-hydraulic behavior of entrained liquid droplets. The reflood phase is terminated when all rods are quenched over the whole heated length.

For the safety research of nuclear reactors, a number of out-of-pile experiments were conducted. Such as FEBA [1], REBEKA [2], [3], SEFLEX [4], and FLECHT-SEASET [5] etc. The objective of these bundle tests was to provide experimental reflood heat transfer and two-phase flow data in simulated PWR geometries for postulated LOCA conditions. The measured data were used to develop and validate physical models for computer code providing qualified analytical tools for calculating realistic peak cladding temperatures and safety margins.

Computer code systems RELAP4/MOD6 [6], COBRA-TF [7] and SSYST-3 [8], [9] have been used to postcalculate a FEBA test.

The Investigation includes the following topics:

- Postcalculation of FEBA test No. 216 utilizing SSYST-3 computer code system.
- Comparison of FEBA test data with SSYST-3, RELAP4/MOD6 and COBRA-TF calculations.
- Capabilities and deficiencies of different codes in simulating the reflood phase of FEBA rod bundle test.

2. FEBA Program

Flooding Experiments with Blocked Arrays (FEBA) were conducted to study the effectiveness of emergency core cooling of pressurized water reactors with unblocked and blocked bundle geometries. The specific objectives of the separate effect tests under forced reflood conditions were[1]:

- To measure and evaluate thermal-hydraulic data for unblocked rod bundle geometries.
- To measure and evaluate the effects of grid spacers upon the thermal-hydraulic behavior.
- To measure and evaluate thermal-hydraulic data for blocked bundle geometries with and without bypass.

2.1 Test Facility

Figure 1 shows schematically the test loop. It is a forced flow reflood facility with a back pressure control system.

Indirect electrically heated rods are used to simulate the nuclear fuel rods. Figure 2 and Figure 3 show the axial layout and cross-section of the heater rod which has PWR dimensions. The cosine power profile of the fuel rod is approximated by 7 steps of different specific power. The left-hand side sketch of Figure 2 shows the axial power distribution of the heater rod with a heated length of 3900 mm for the 5x5 rod bundle tests. The right-hand side sketch of Figure 2 shows the axial position of seven grid spacers. In contrast to a nuclear fuel rod with a Zircaloy cladding and a gas filled gap, this heater rod is a "solid type" usually used for thermal-hydraulic tests without a gas filled gap between the NiCr cladding and the electrical insulation. The 5x5 rod bundle is placed in a square section housing with an inside width of 78.5 mm.

The heater rods are bolted to the top flange of the test section (zero level and therefore reference level for all axial bundle positions) and the lower ends penetrate through the test assembly pressure barrier. So the axial movement of the rods relative to the housing is allowed.

2.2 Instrumentation

Most part of the test instrumentation consisted of thermocouples (Chromel-Alumel). Cladding (TC), sleeve (TH), fluid (TF), housing (TK) and grid spacer (TA) temperatures were measured at various positions. Figures 4 and 5 show the axial levels and radial locations of the measuring devices.

2.3 Test Parameters

The test parameters varied are shown in Figure 6:

- Flooding rate given as flooding velocity, i.e., the velocity of the rising water level in the cold bundle.
- System pressure.
- Feedwater temperature.
- Bundle power

Flooding rate, system pressure and feedwater temperature were kept constant during the whole test run. At the begining of reflood, the feedwater was heated up by the hot environment of the lower plenum. Nevertheless, some few seconds later the feedwater temperature decreases and reached the desired value. The initial bundle power of about 200 kW was followed by a decay heat transient corresponding to 120 % ANS standard 40 s after shut down of the reactor.

2.4 Operational Procedure

For about two hours prior to reflood, the rod bundle was heated in an essentially stagnant steam environment to the desired cladding temperature using a low rod power. Figure 7 shows the initial temperature profile of FEBA test No. 216 just before reflood was initiated. When rising water level reached the bottom end of heated length, the input power was suddenly stepped up to the initial peak level of bundle power (see Fig. 6). More details are reported in Ref. [1].

3. Postcalculation of FEBA Test No. 216 Utilizing SSYST-3 Computer Code System

SSYST [8], [9], [10], [11] is a computer code-system for the analysis of transient behavior of single fuel rod under off-normal conditions as well as related experimental set-ups. It has been developed jointly by the Institut für Kernenergetik und Energiesysteme (IKE) of the University of Stuttgart and Kernforschungszentrum Karlsruhe (KfK) under contract of Projekt Nukleare Sicherheit (PNS) of KfK.

The main difference between SSYST and other codes of similar application concerns the overall code organisation, which is open-ended, highly modular and, thus, more flexible for SSYST than for comparable codes.

A second point, in which SSYST may differ from the comparable codes, is the degree of detail in physical modelling. It is tried to keep models as simple as permissible. In connection with efficient algorithms, this leads to acceptable computing times.

The purpose of SSYST code development was to analyse the fuel rod behavior during a LOCA. These questions have been raised during licencing procedures.

The code system consists of a nucleus, a data base and a set of modules. Each module solves a specific task. So the fuel rod behavior is broken down into its individual physical processes. For each process, e.g. heat transfer, rod internal pressure or deformation, a model and a module, respectively, are developed. Applying all these modules to each individual time step lead to the transient fuel rod behavior.

The present version, SSYST-3, has included all the modules related to fuel rod behavior under LOCA conditions.

For SSYST-3 calculations, initial conditions can be taken from FRAP-S [12] or COMETHE [13] analysis and the transient boundary conditions from RELAP [6] or REFLOS [14] run. These codes can either be called from SSYST-3 or special modules are available to transfer their results into SSYST-3. More details are described in Refs. [8] and[10].

REFLOS is a module to describe the refill and reflood phase of a LOCA. For the simulation of a reactor core a representative group of coolant channels and two fuel rods were modelled.

Thermal-hydraulic models for the reflood phase are based on the code FLOOD-4. It involves a simplified but complete primary circuit. For the liquid, the momentum equation is solved in core, lower plenum and downcomer. Special care has been taken to model the interactions between the heat transfer regimes in the core. Steam production and liquid oscillations between core and downcomer are taken into account. It uses simple models to calculate the velocity of the rising water level in the core. Driving force is the difference of the water level between the core and the downcomer. Both upper and lower quench fronts were created during reflood phase.

The model used in reflood phase is shown in Figure 8. Five components are taken into consideration (downcomer, lower plenum, test section, upper plenum, containment) which are simulated by seven control volumes and several junctions, which represent the flow resistance.

3.1 Simulation of FEBA Test

For the postcalculation of FEBA test No. 216, the bundle of 5x5 heated rods was simulated by one representative group of fluid channel and rod, which was subdivided into a stack of 195 slabs to model the heated length. Radially, 4 nodes were taken into account within the electrically heated rods.

The boundary conditions measured during the test were used as input data. Figure 7 shows the initial axial temperature profile of the cladding, which was an average value of the center subbundle of 3x3 heated rods. Figure 6 shows the transient bundle power, the rate of injected water which corresponds to a flooding velocity of about 3.8 cm/s in the cold bundle, the temperature of injected water which defines the fill enthalpy and the upper plenum pressure profile.

There are two possibilities to define the entrainment of coolant into the reactor core, through either downcomer or lower plenum. To simulate FEBA test, explicit coolant entrainment into lower plenum was taken into account. Also for the same reason, the deentrainment and fallback models were not used because no liquid appeared at the bundle outlet and no upper quench front was formed in FEBA test. The design of the top end of the test section excludes the possibility of liquid fall back into the heater rod bundle.

Figure 9 shows the calculating model for FEBA test No. 216, only three components of primary core system were provided for the forced feed water test: a full-length rod bundle and two plena.

The physical properties as a function of temperature were taken from code material tables.

3.2 Parameter Study

In REFLOS, a heat transfer calculation package selects and evaluates the appropriate heat transfer correlations. During reflood, there are nucleate boiling, transition boiling, film boiling, dispersed flow and superheated vapor cooling periods. The dispersed flow heat transfer calculation has a significant impact on the precursory cooling and consequently on the reflood turnaround time, maximum cladding temperature and the quench time.

A semi-empirical model formulated from FLECHT-SEMISCALE experiments is used to calculate heat transfer coefficients during dispersed flow [14]:

$$h = \frac{RE1 x P^{0.2} \left(\frac{L}{D_h} \right)^{0.7}}{(1 + D_z)^{RE2}}$$

Here:

h	= Heat transfer coefficient
RE1	= Constant, recommended value = 2 (user specified input)
P	= Pressure
D_h	= Hydraulic diameter
L	= Distance between collapsed level and lower quench front
D_z	= Distance between the point to be considered and lower quench front
RE2	= Constant, recommended value = 1 (user specified input)

The user specified constant, RE1 is a multiplier of the dispersed flow heat transfer coefficient. To evaluate the influence of this parameter, the constant RE1 has been varied in the range RE1 = 1.0 through 2.0. It was known from the initial axial temperature profile and decay power axial distribution that the maximum cladding temperature occurs not far away from the bundle midplane during the whole reflood phase.

A comparison of measured and calculated cladding temperature transients with different RE1 values is shown in Fig. 10 and Fig. 11. Cladding temperatures are plotted versus reflood time for an axial elevation of 2295 mm and 2840 mm from the bottom end of the heated length. It is evident that in early portion of dispersed flow, all calculated temperatures overpredict the measured data and increase with the decreasing RE1. Lateron, for RE1 = 1.0, the overprediction continues during the whole reflood phase. The quench time is also overpredicted. On the other hand, the temperature transient and the quench time are underpredicted for RE1 = 2.0. A reasonable agreement between calculated and measured temperature history and quench time is obtained for RE1 = 1.1. However, it should be mentioned that this fitting of the input parameter does point to the significance of an appropriate model for the dispersed flow heat transfer option.

4. Comparison of FEBA Test Data with Analytical Investigations

4.1 RELAP4/MOD6 Computer Program

For postcalculation of a selected FEBA reflood test, the computer code RELAP4/ MOD6 (Update 4) [6] was used. The code is based on assumptions of thermal equilibrium and equal velocity of the two phases. Several models are available in this code version to modify these assumptions. A local mass flow model is included for the heat transfer calculation when a mixture level exists within a control volume. An entrainment model provides the fluid conditions for the heat transfer calculations. A core superheat model accounts for thermal non-equilibrium between the two phases. A moving mesh is also provided. Neither a three-dimensional nodalisation is possible nor the influence of grid spacers or flow blockages can be taken into account. It should be noted that the use of artificially adjusted values of the empirical code input parameters for the water entrainment fraction and the liquid weighting factor in the heat transfer for the dispersed flow regime can significantly influence the cladding temperature history.

The simulation model used to describe the FEBA test is shown in Fig. 9. Three control volumes (lower plenum, test section, upper plenum) and three junctions (feedwater inlet, test section inlet and test section outlet) were taken into consideration. The bundle of 5x5 heater rods was simulated by one representative rod which was subdivided into a stack of 20 heated slabs to model the heated length. Radially, 8 nodes were taken into consideration within the electrically heated rod. More details are reported in Ref. [15]. Again, this RELAP study does point to the significance of appropriate models for entrainment and dispersed flow as they can strongly influence the cladding temperature prediction and consequently the degree of agreement between measured and calculated data.

4.2 COBRA-TF Computer Program

The COBRA-TF computer code [7] has been developed for best estimate safety analysis of LWR's. The computer code provides a three-field representation of the two fluids. The three fields are: Continuous vapor, continuous liquid and entrained liquid droplets. Each field is treated in three dimensions and is compressible. The conservation equations and equations for heat transfer from and within the solid structures in contact with the two fluids are solved using a semi-implicit, finite-difference numerical technique on an Eulerian mesh. The selection of either rectangular Cartesian or subchannel coordinates is provided. The constitutive relations include state-of-art physical model for the interfacial mass transfer, interfacial drag forces, the liquid and vapor wall drag, the wall and interfacial heat transfer, the rate of liquid entrainment and deentrainment, and the thermodynamic properties of the fluid. A mixing length turbulence model is included as an option.

A consistent set of heat transfer models has been implemented. It consists of five components: A conduction model, a heat transfer package, a quench front model, a dynamic gap conductance model for a nuclear fuel rod, and a subchannel - based radiation model.

Physical models allow to describe, as realistically as possible, the two-phase enhancement of convective heat transfer in the dispersed flow and the effects of grid spacers and flow blockages [16].

For the calculation with COBRA-TF, the FEBA test section was modelled using two representative fluid channels, one center channel and one peripheral channel. The 5x5 heater rods were simulated by two rods, one channel rod and one peripheral rod. Test section housing was described by a wall with an inside heat transfer surface and an insulated outer surface. Figure 12 shows the radial noding scheme of the bundle. To simulate the heated length of 3900 mm, 18 vertical mesh cells were chosen. More details are described in Ref. [17]. It should be mentioned that this study was carried out without any modification or enhancement of the code. A use of artificially adjusted values was impossible.

4.3 Comparison of FEBA Test Data with Calculations

Experimental results of FEBA TEST No. 216 and calculated results by computer codes SSYST-3, RELAP4/MOD6 and COBRA-TF are compared. The purpose is to evaluate the capabilities and deficiences of different computer codes in simulating FEBA test. The RELAP calculated data were taken from Ref. [15], the COBRA-TF results are described in Ref. [17]. For these computer code calculations, the measured boundary conditions which were used as input data were slightly different. In SSYST-3 and RELAP4/MOD6 calculations, the initial axial temperature profile, shown in Fig. 7, is an average value of the center subbundle of 3x3 heater rods. In COBRA-TF calculation, shown in Fig. 13, it includes the center rods (solid line), the peripheral rods (dashed line) and housing (dashed - dotted line), obtained by averaging the initial thermocouple readings of the individual instrumented axial levels. Other boundary conditions, such as system pressure, flooding velocity and inlet water temperature were exactly the same for the three computer code calculations. During the initial period of reflooding, the feedwater was heated up by the hot walls of the lower plenum. About 60 seconds after initiation of reflooding, the desired temperature of 40 °C was reached.

This behavior was taken into consideration providing the enthalpy boundary for the data input.

Figure 14 through 17 show a sequence of diagrams in which the measured and calculated cladding temperature are plotted versus reflood time. The measured data are marked by triangular symbols, the SSYST-3 calculated data by circular symbols, the RELAP results by x-symbols and the COBRA-TF simulations by diamonds. At the elevations 1750 mm and 1850 mm from the bottom end of bundle, the SSYST-3 code overpredicts the cladding temperatures during the whole reflood phase (Fig. 14 and 15). The quench times are reached later than in the experiment. At higher axial positions 2840 mm and 3385 mm, respectively (shown in Figs. 16 and 17), the temperatures are overpredicted for the early portion of the reflood phase. Lateron, the temperatures are slightly underpredicted. The quench times are reached insignificantly earlier than in the experiment.

The corresponding heat transfer coefficients are shown in Figures 18 through 21, which are related to the saturation temperature. At lower and middle axial positions, the SSYST-3 code calculated heat transfer coefficients are in good agreement with the measured data during early reflood phase. Lateron, the code underpredicts the measured data (Figs. 18 and 19), which leads to a delay of quench times. At higher axial positions (Figs. 20 and 21), the comparison between calculated and measured data show a good agreement for the entire reflood phase.

The divergence between measured and calculated heat transfer coefficient and consequently the divergence between measured and calculated cladding temperatures decrease with increasing distance from the bottom end of the bundle. This is mainly due to the heat transfer model used for the dispersed flow regime.

Even under this condition, the maximum cladding temperature overprediction is less than 70 K and the inaccuracy of the quench time prediction is less than 40 seconds.

The quench temperatures are slightly overpredicted for all axial positions.

RELAP4/MOD6 and COBRA-TF calculations show that in early portion of reflood phase both code overpredict slightly the measured data. Lateron, the temperatures are underpredicted. The quench temperature is well predicted in COBRA-TF calculations. The RELAP4/MOD6 calculations do not show the characteristic steep temperature drop during rewetting. This is mainly due to the plotting of coarse-slab calculated temperature which produces time-smoothed curves [15].

Another sequence of diagrams show a comparison of observed and computed cladding temperatures close to the grid spacer at the bundle midplane. Figure 15 illustrates the data comparison for an axial level which is located 100 mm upstream of the bundle midplane. Figure 23 shows a comparison for an axial level at 345 mm downstream of the same grid spacer.

As mentioned above, the divergence between measured and calculated temperatures decreases slightly with increasing elevation. However, immediately downstream of the grid spacer, i.e. for the axial level 1925 mm (plotted in Fig. 22), the SSYST-3 code overpredicts the measured data. This difference is presumed to be due to the apparent lack of a physical model to describe the effects of grid spacers.

This phenomenon can be confirmed by a comparison of the calculated and measured heat transfer coefficients (Figs. 19, 24 and 25). The same case can be seen in RELAP4/MOD6 calculations as well [15]. A plausible mechanism of heat transfer during reflood phase is the cooling effect of smaller droplets generated from the relatively inactive large droplets which are intercepted by the grid spacers. Due to their large surface to mass ratios, these small droplets may penetrate the boundary layer and serve as effective agents for evaporation heat transfer in the regions just downstream of the grid spacers [15].

Figure 26 shows a comparison of measured and calculated quench front progressions. The SSYST-3 code underpredicts slightly the quenchfront progression for the lower and middle portion of the bundle and overpredicts this behavior for the upper most portion. The RELAP as well as the COBRA-TF calculated quench times become slightly shorter than the experimental as the axial elevation increases.

5. Conclusions

FEBA test run #216 has been compared against postcalculations using SSYST-3 computer code. In this comparison are included selected data which result from RELAP4/MOD6 [15] and COBRA-TF [17] postcalculations. From these investigations it can be concluded:

- The postcalculated data, such as peak cladding temperatures, quench times and quench temperatures are in reasonably good agreement with the measured data for nearly all axial positions of heated rod. This comparison may lead to the conclusion that SSYST-3 and RELAP code do a satisfactory job in prediction the reflooding behavior. However, it should be noted that this degree of agreement was made possible only by the use of artificially adjusted parameters after the corresponding experimental results had already been known. On the other hand, no fitting of the input data was made for COBRA-TF.

- Only under these conditions, the results of SSYST-3 calculations compare well with RELAP4/MOD6 and COBRA-TF calculated data.

- These apparent deficiencies of the SSYST-3 and RELAP4/MOD6 computer codes point to the pressing needs of improved physical models for the dispersed flow regime and the implementation of improved models which describe the effects of grid spacers in the dispersed flow.

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7. Illustrations

Fig. 14: Comparison of measured and calculated cladding temperatures at axial level 2225 mm of FEBA test No. 216.

Fig. 15: Comparison of measured and calculated cladding temperatures at axial level 2125 mm of FEBA test No. 216.

Fig. 16: Comparison of measured and calculated cladding temperatures at axial level 1135 mm of FEBA test No. 216.

Fig. 17: Comparison of measured and calculated cladding temperatures at axial level 590 mm of FEBA test No. 216.

Fig. 18: Comparison of measured and calculated heat transfer coefficients at axial level 2225 mm of FEBA test No. 216.

Fig. 19: Comparison of measured and calculated heat transfer coefficients at axial level 2125 mm of FEBA test No. 216.

Fig. 20: Comparison of measured and calculated heat transfer coefficients at axial level 1135 mm of FEBA test No. 216.

Fig. 21: Comparison of measured and calculated heat transfer coefficients at axial level 590 mm of FEBA test No. 216.

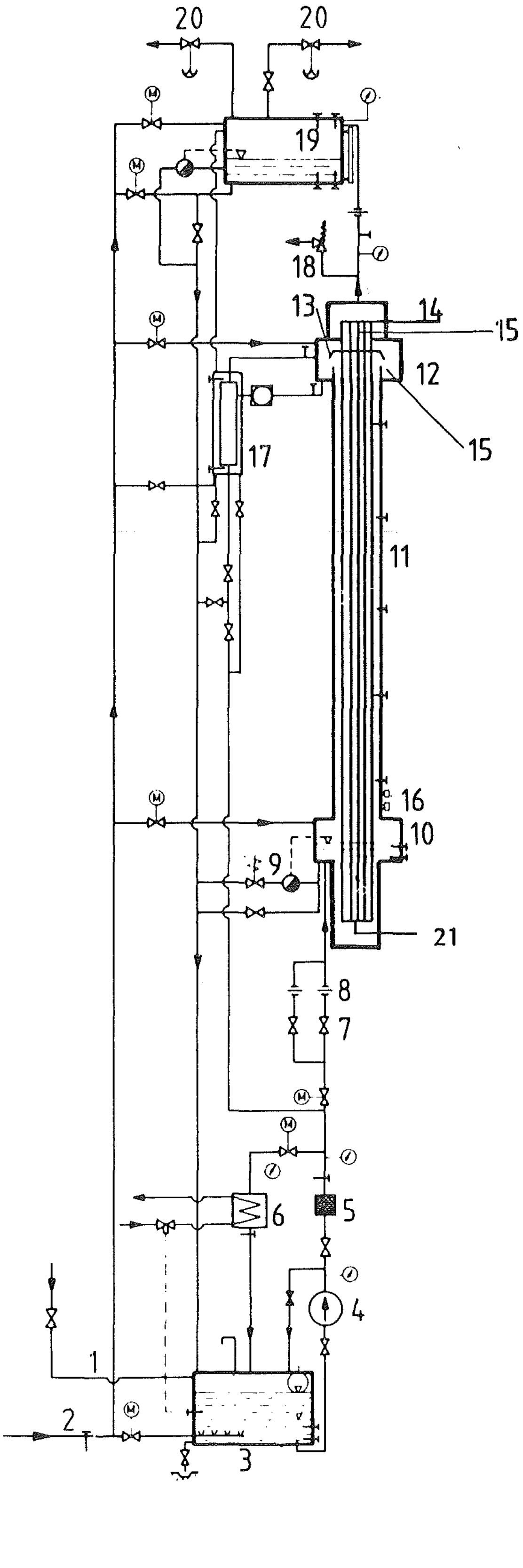
Fig. 22: Comparison of measured and calculated cladding temperatures at axial level 1925 mm of FEBA test No. 216.

Fig. 23: Comparison of measured and calculated cladding temperatures at axial level 1680 mm of FEBA test No. 216.

Fig. 24: Comparison of measured and calculated heat transfer coefficients at axial level 1925 mm of FEBA test No. 216.

Fig. 25: Comparison of measured and calculated heat transfer coefficients at axial level 1680 mm of FEBA test No. 216.

Fig. 26: Comparison of measured and calculated quench front progression of FEBA test No. 216.



LEGEND

1 Water Supply
2 Steam Supply
3 Storage Tank
4 Water Pump
5 Filter
6 Heat Exchanger
7 Throttle Valve
8 Turbine Meter
9 Water Level Regulation Valve

10 Lower Plenum
11 Test Section
12 Upper Plenum
13 Water Separator

14 Power Supply
15 Rod Instrumentation Exits
16 Water Level Detector
17 Water Collecting Tank
18 Outlet Valve
19 Buffer
20 Pressure Regulator
21 Filling Gas Supply

Figure 1. FEBA test loop.

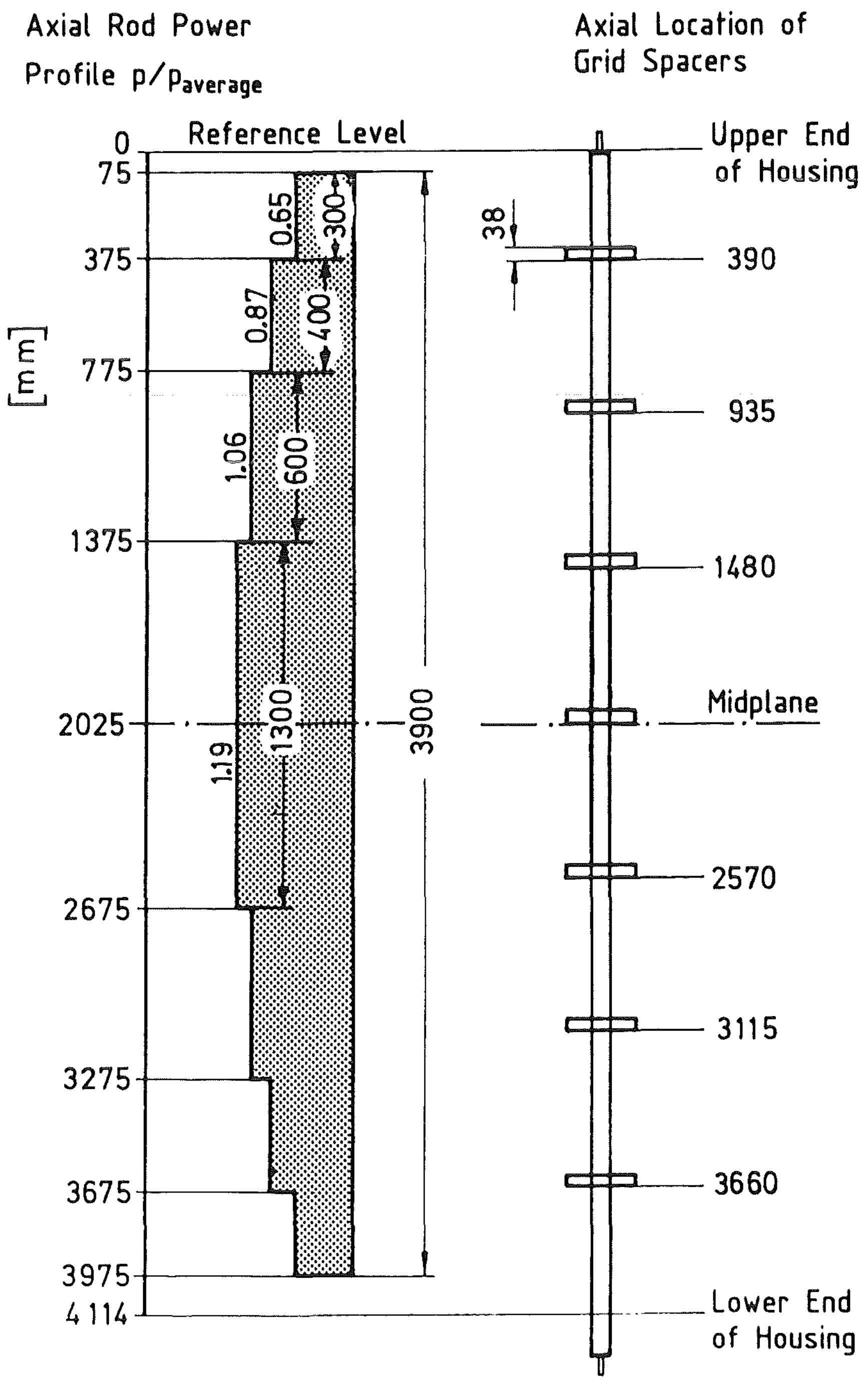


Figure 2. Axial heater rod layout.

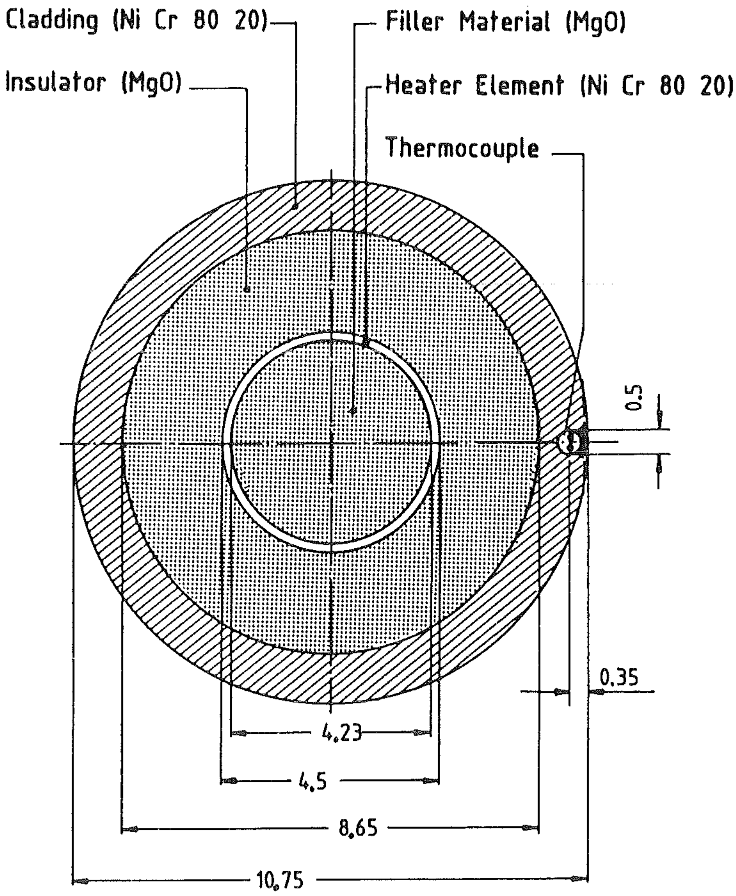
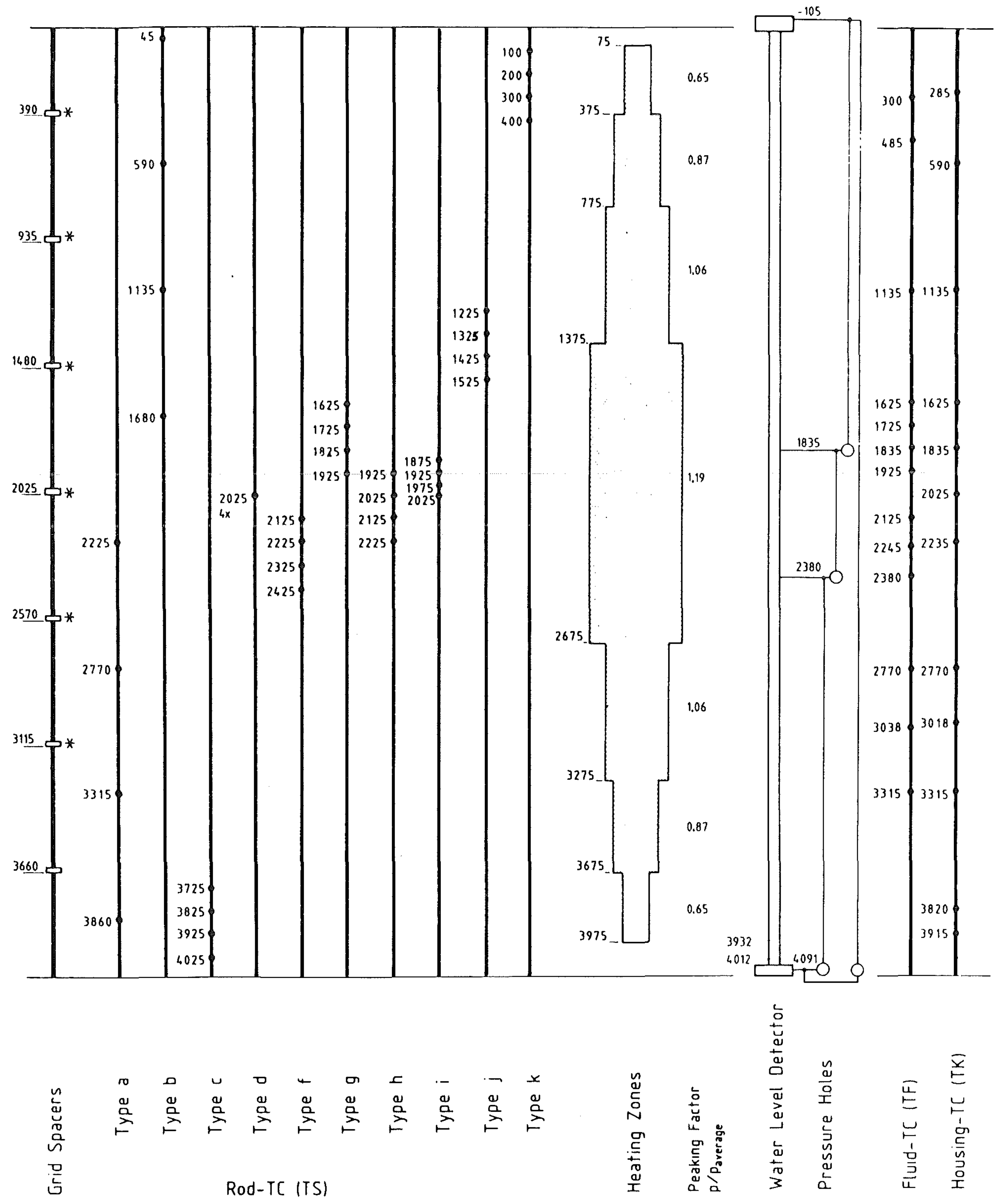
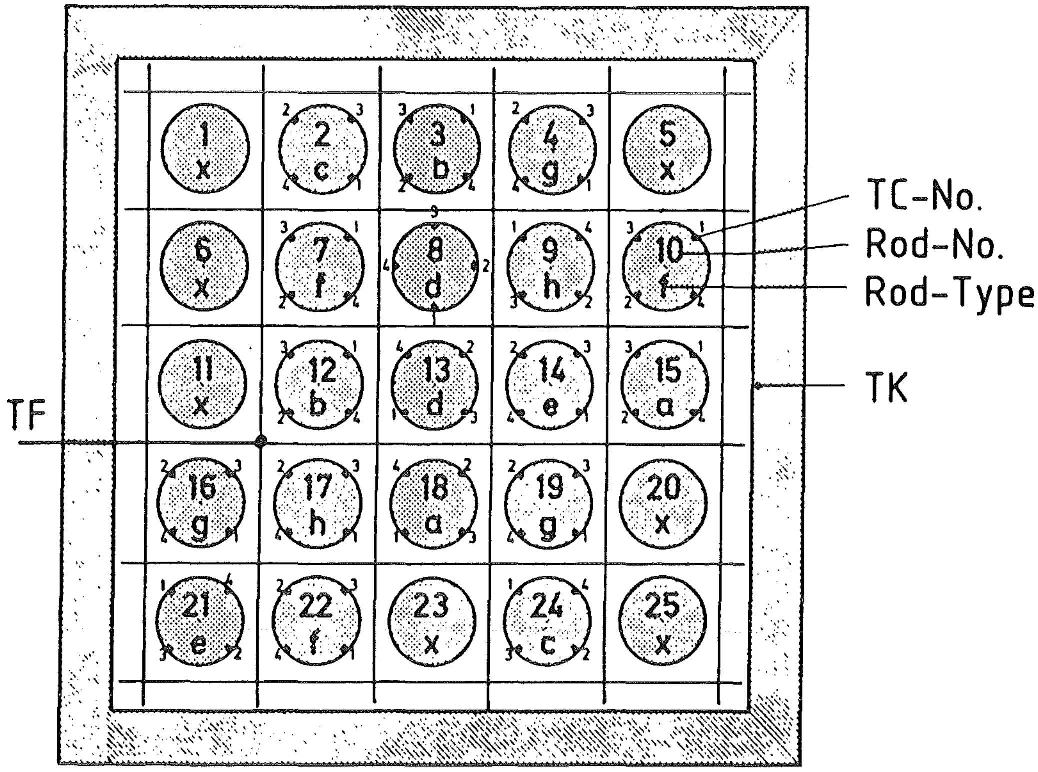


Figure 3. Cross-section of FEBA heater rod.



* Grid spacer instrumented

Figure 4. Axial levels of measuring positions.

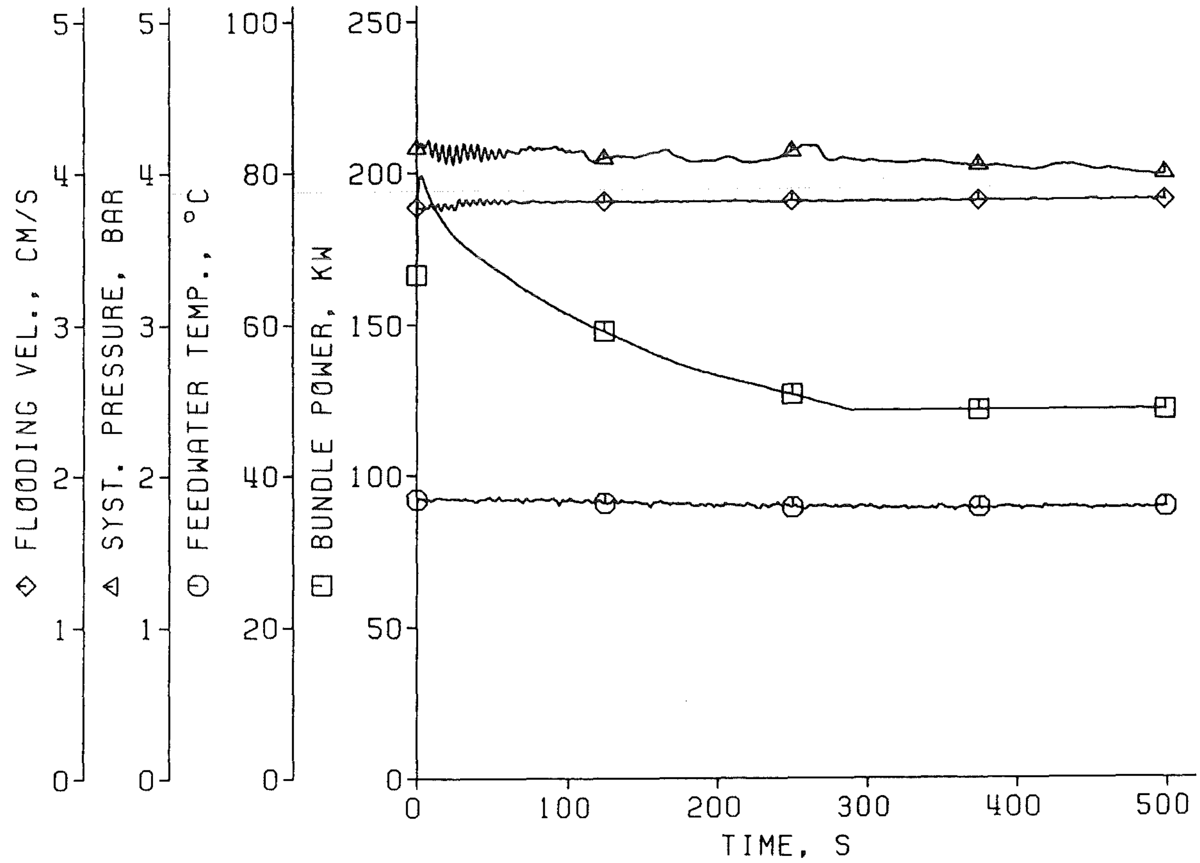


Rod Type	TC No.	Axial Level mm
a	1	2225
	2	2770
	3	3315
	4	3860
b	1	45
	2	590
	3	1135
	4	1680
c	1	3725
	2	3825
	3	3925
	4	4025
d	1	2025
	2	2025
	3	2025
	4	2025

Rod Type	TC No.	Axial Level mm
e	1	2075
	2	2125
	3	2175
	4	2225
f	1	2125
	2	2225
	3	2325
	4	2425
g	1	1625
	2	1725
	3	1825
	4	1925
h	1	1925
	2	2025
	3	2125
	4	2225

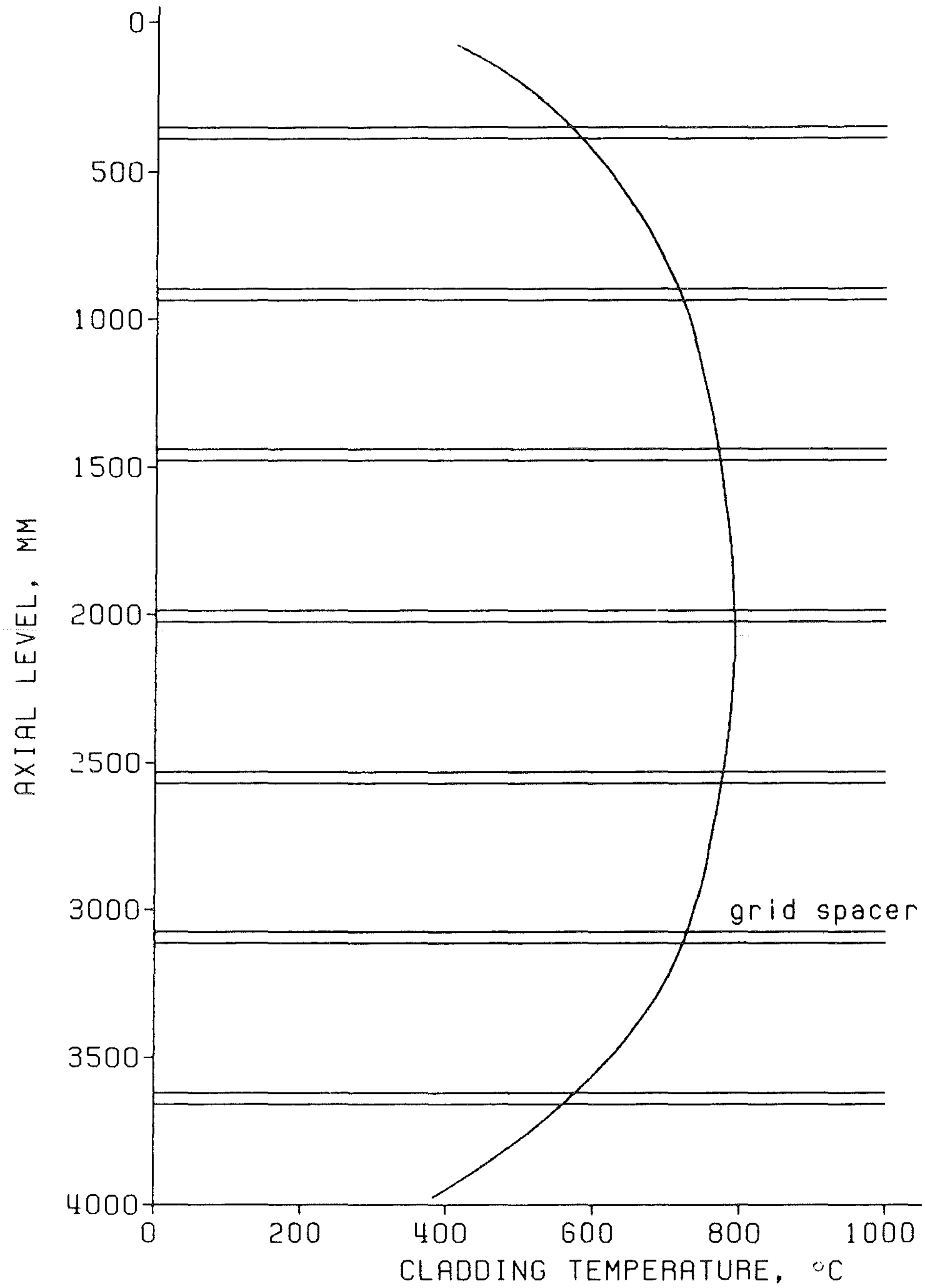
Rod Type	TC No.	Axial Level mm
x	without TC's	

Figure 5. Radial and axial location of cladding, fluid, and housing TC's of FEBA test series I.



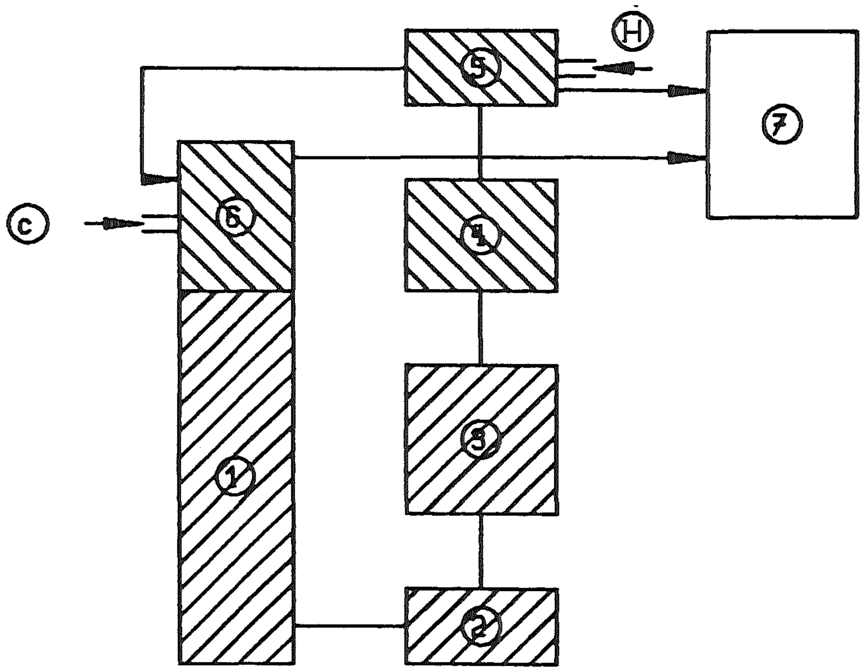
decay heat	120%	ANS standard
flooding rate	3.8	cm/s (cold)
system pressure	4.1	bar
feedwater temperature	40	°C

Figure 6. Flooding parameters of FEBA test No. 216.



decay heat	120%	ANS standard
flooding rate	3.8	cm/s (cold)
system pressure	4.1	bar
feedwater temperature	40	°C

Figure 7. Initial axial temperature profile of claddings in FEBA test No. 216.



1 Part of the downcomer filled with water

2 Lower plenum

3 Part of the core filled with water

4 Part of the core filled with steam and two-phase mixture, respectively

5 Volume of upper plenum, pipes, steam generator and pressurizer

6 Part of the downcomer filled with steam and two-phase mixture, respectively

7 Containment

C Cold leg injection

H Hot leg injection

Figure 8. Scheme of reflood phase for SSYST3-calculations.

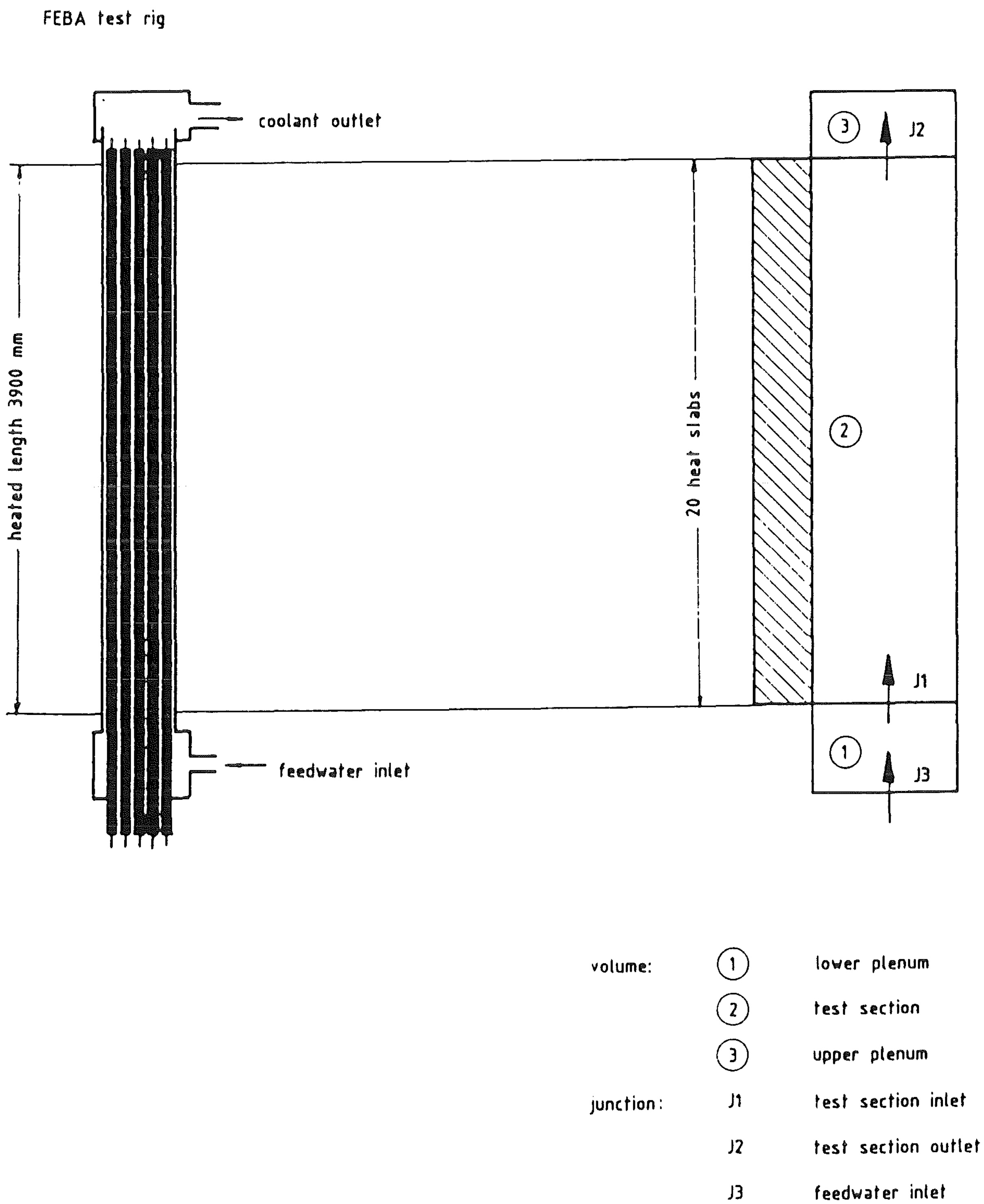
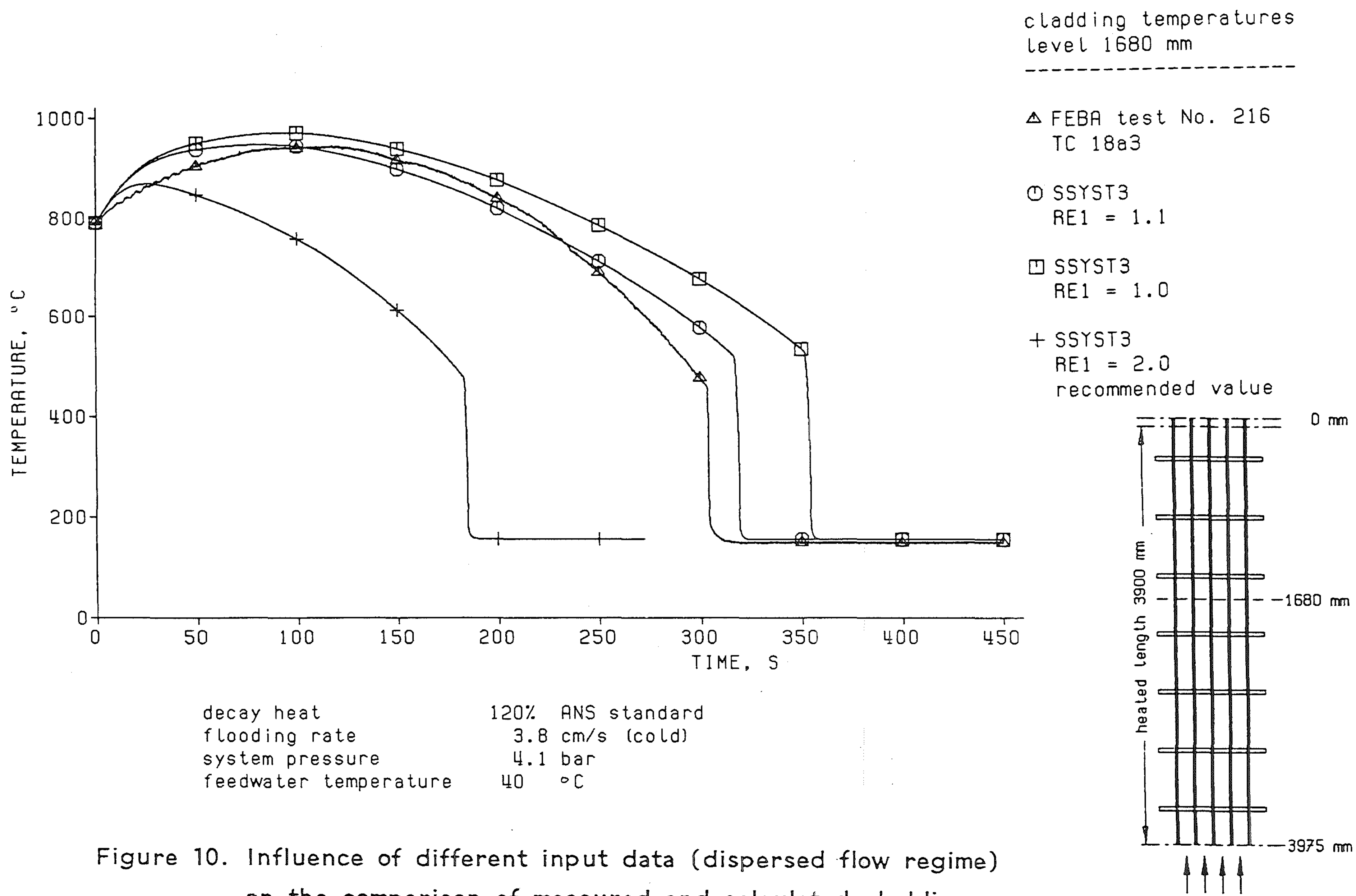


Figure 9. FEBA test rig, SSYST-3 and RELAP6/MOD4-model.



decay heat 120% ANS standard
flooding rate 3.8 cm/s (cold)
system pressure 4.1 bar
feedwater temperature 40 °C

Figure 10. Influence of different input data (dispersed flow regime) on the comparison of measured and calculated cladding temperatures at axial level 1680 mm of FEBA test No. 216.

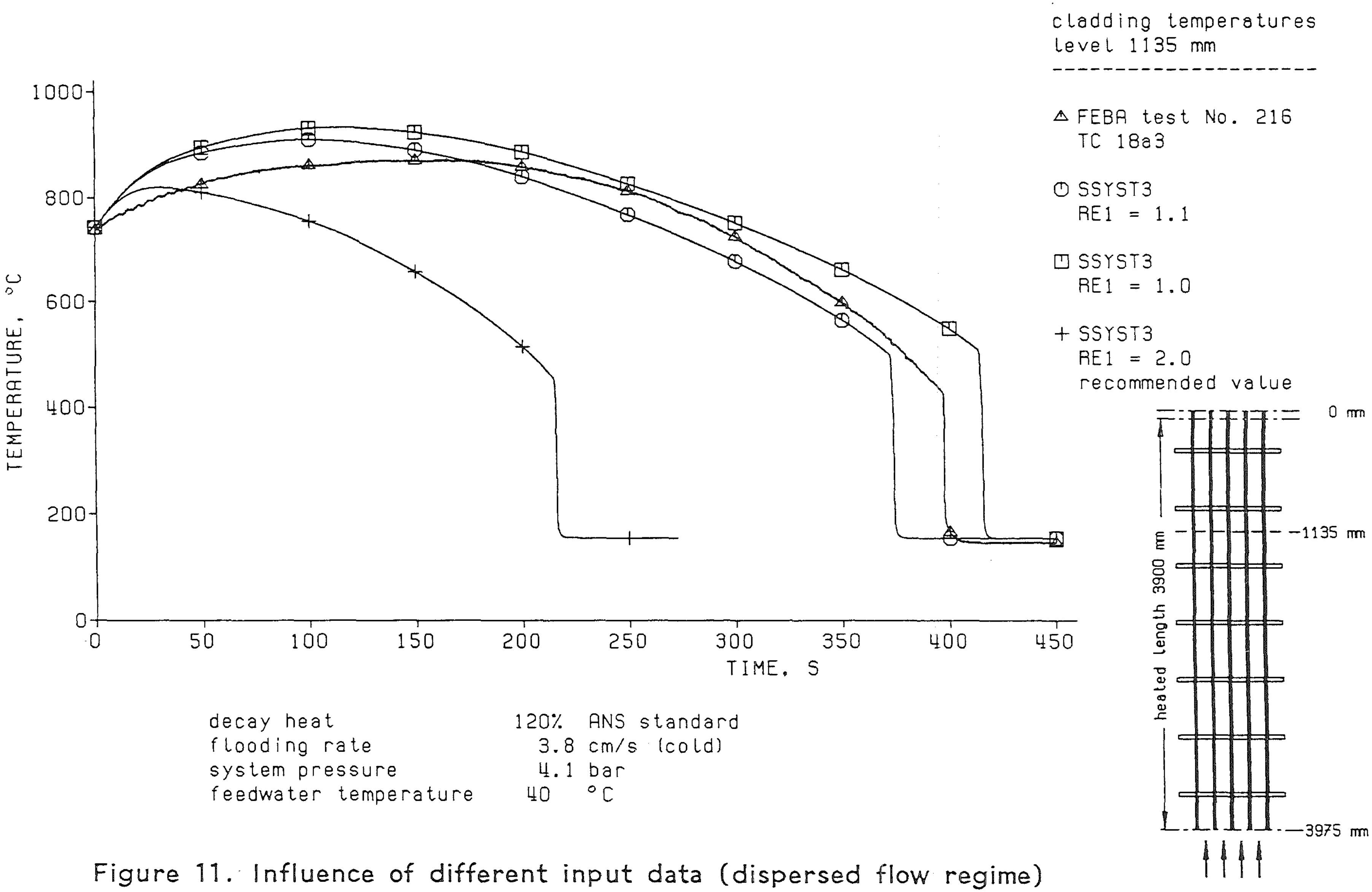


Figure 11. Influence of different input data (dispersed flow regime) on the comparison of measured and calculated cladding temperatures at axial level 1135 mm of FEBA test No. 216.

Rod diameter	10.75 mm
Rod pitch	14.3 mm
Housing width	78.5 mm
Housing thickness	6.5 mm

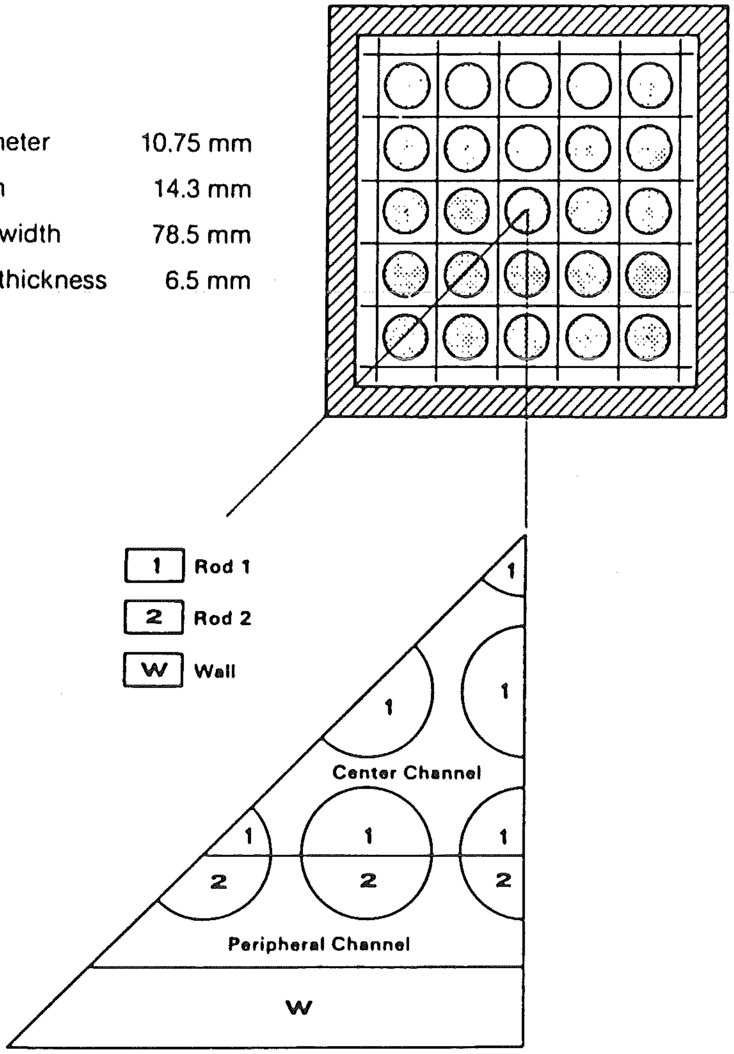
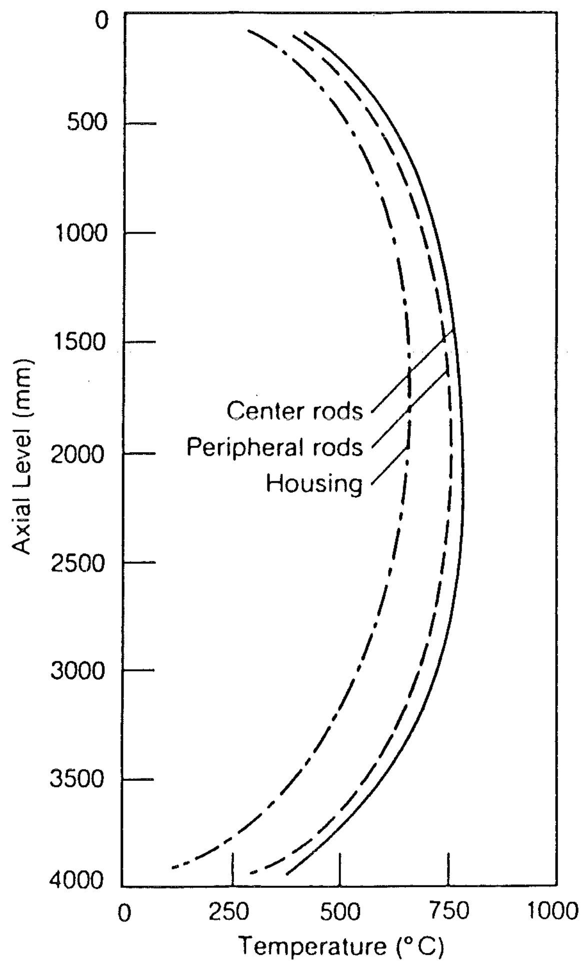


Figure 12. Radial noding scheme of FEBA test section for COBRA-TF calculations.



FEBA test No. 216
FEBA rod bundle
Gapless rods
Flooding velocity 3.8 cm/s
System pressure 4.1 bar

Figure 13. Initial axial temperature profiles of claddings and housing in FEBA test No. 216.

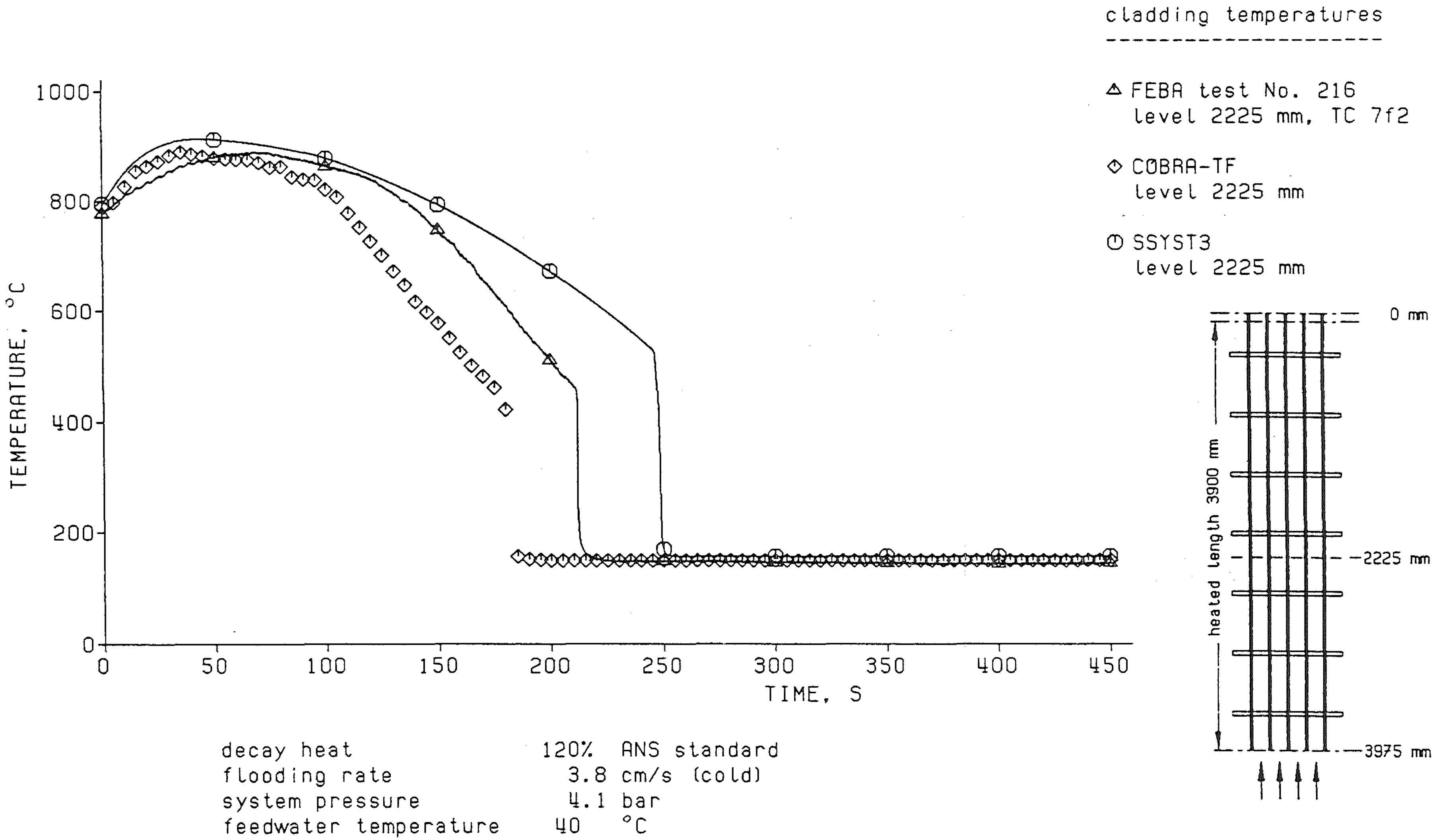


Figure 14. Comparison of measured and calculated cladding temperatures at axial level 2225 mm of FEBA test No. 216.

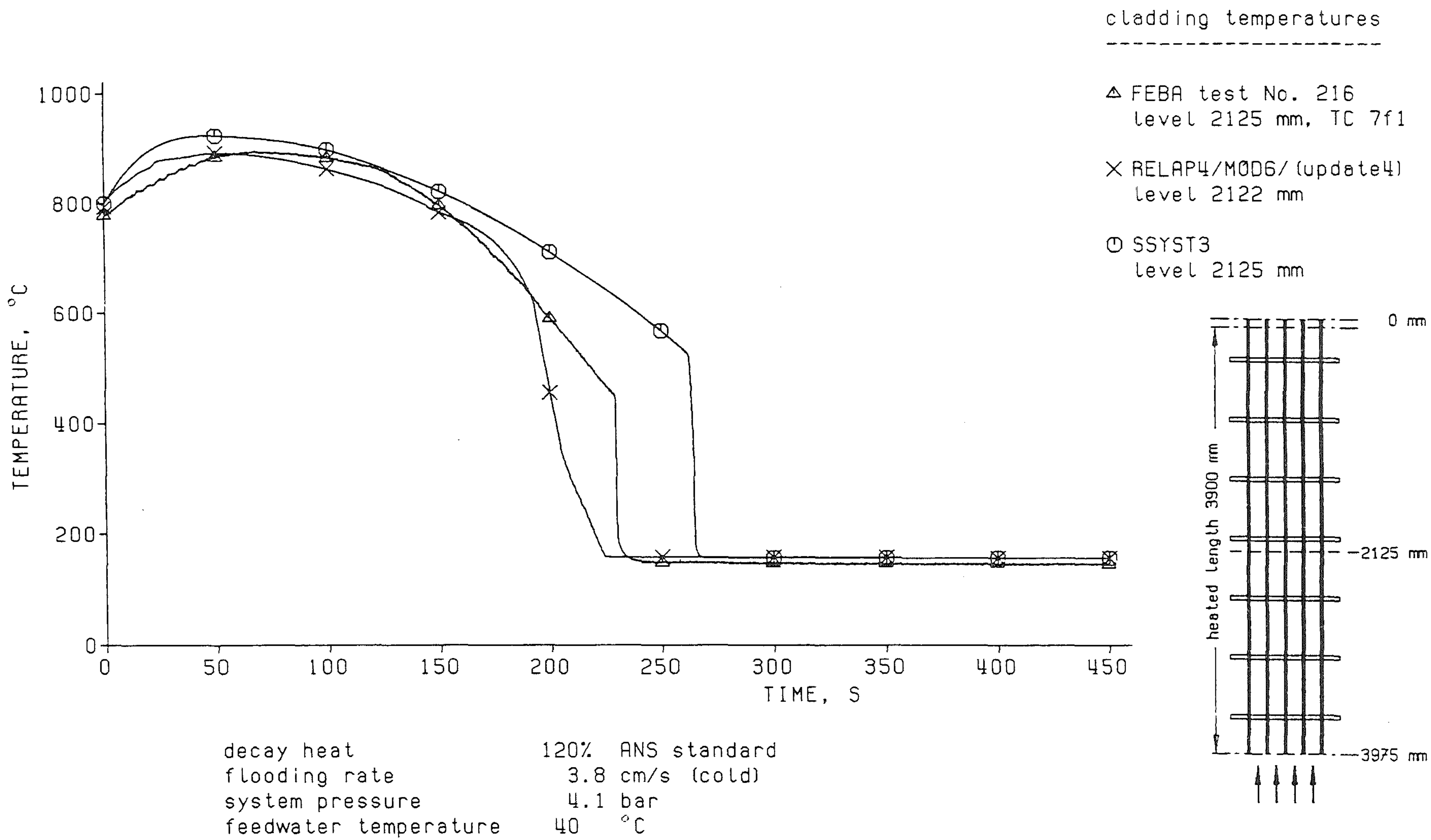


Figure 15. Comparison of measured and calculated cladding temperatures at axial level 2125 mm of FEBA test No. 216.

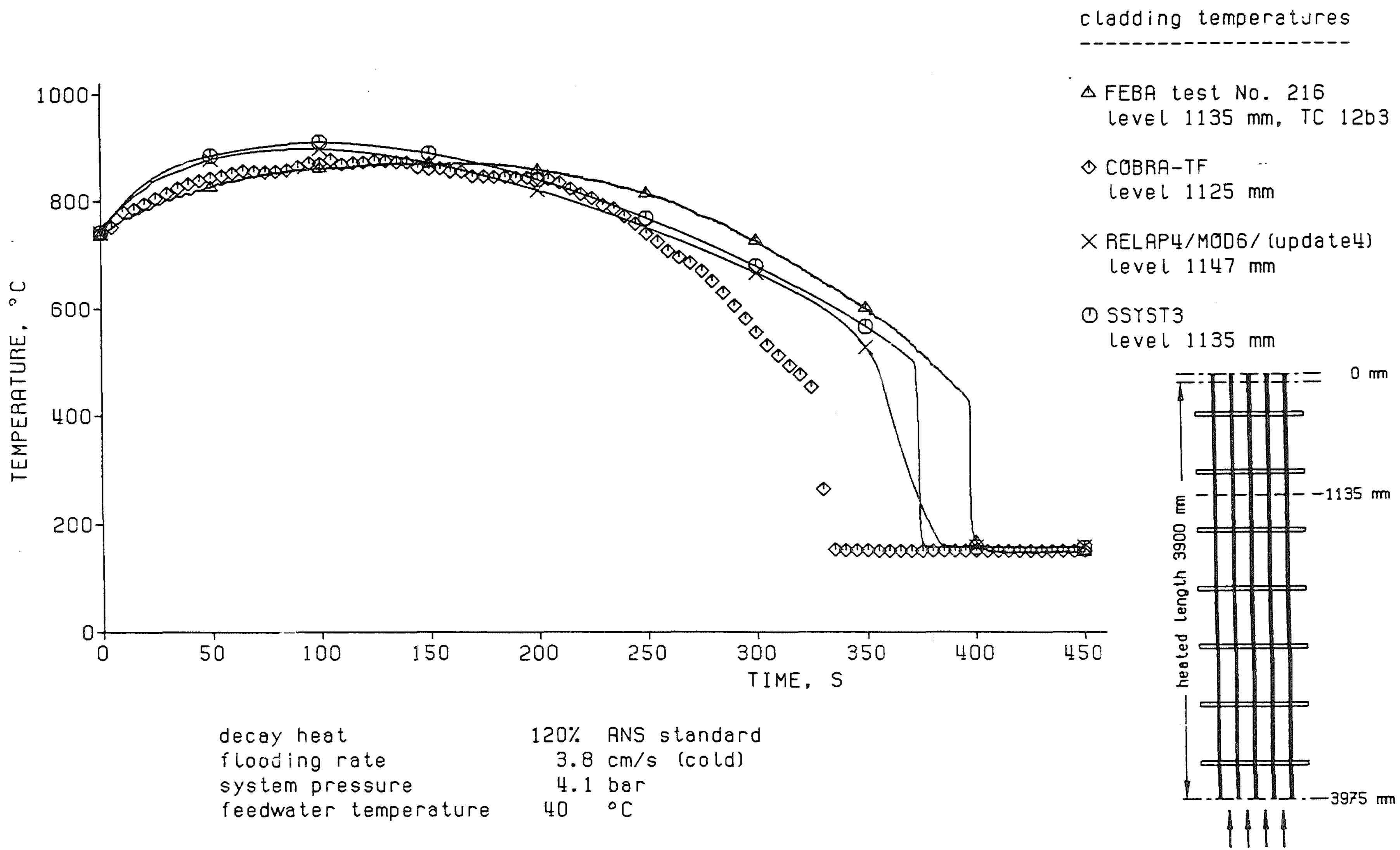


Figure 16. Comparison of measured and calculated cladding temperatures at axial level 1135 mm of FEBA test No. 216.

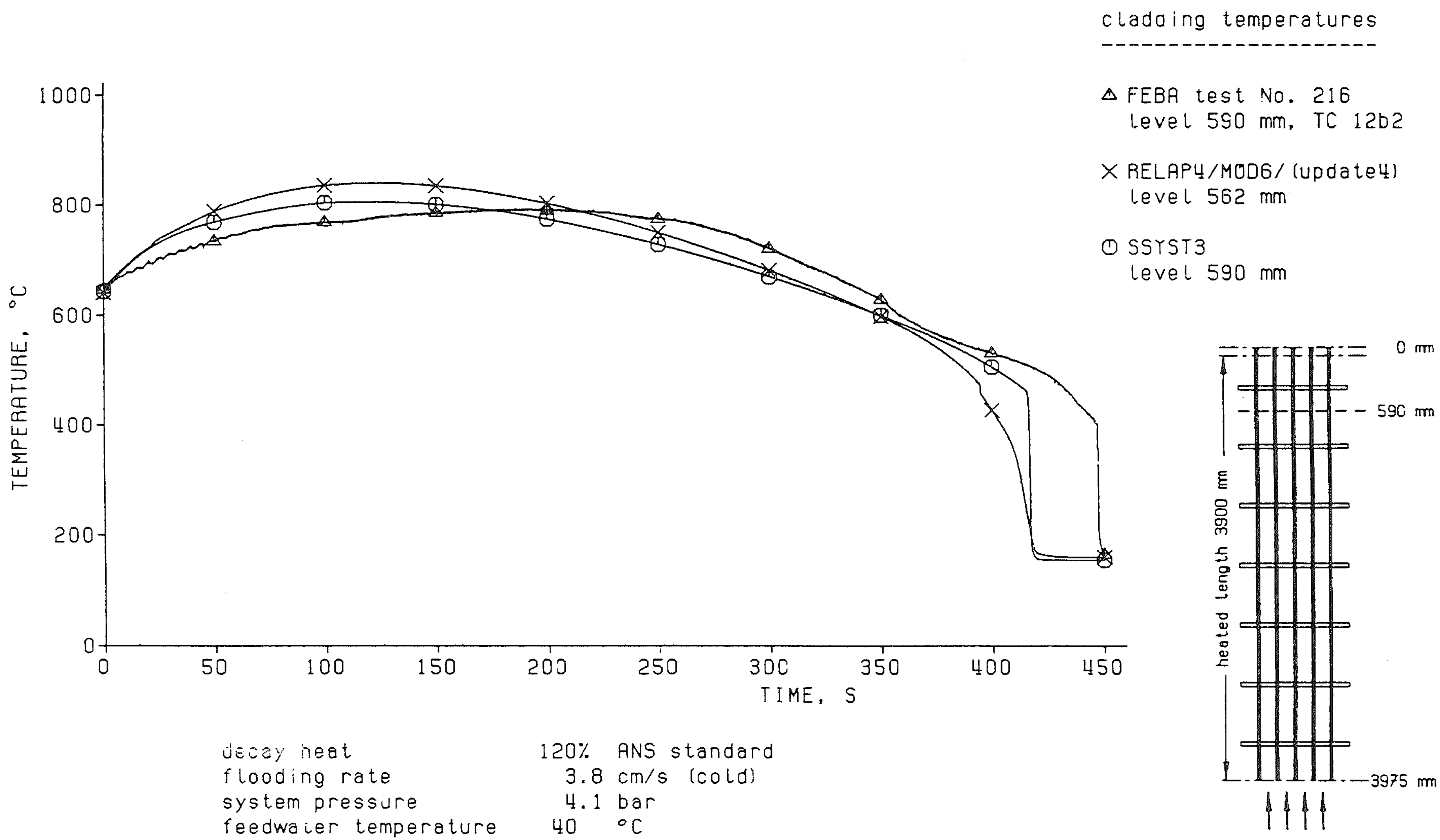
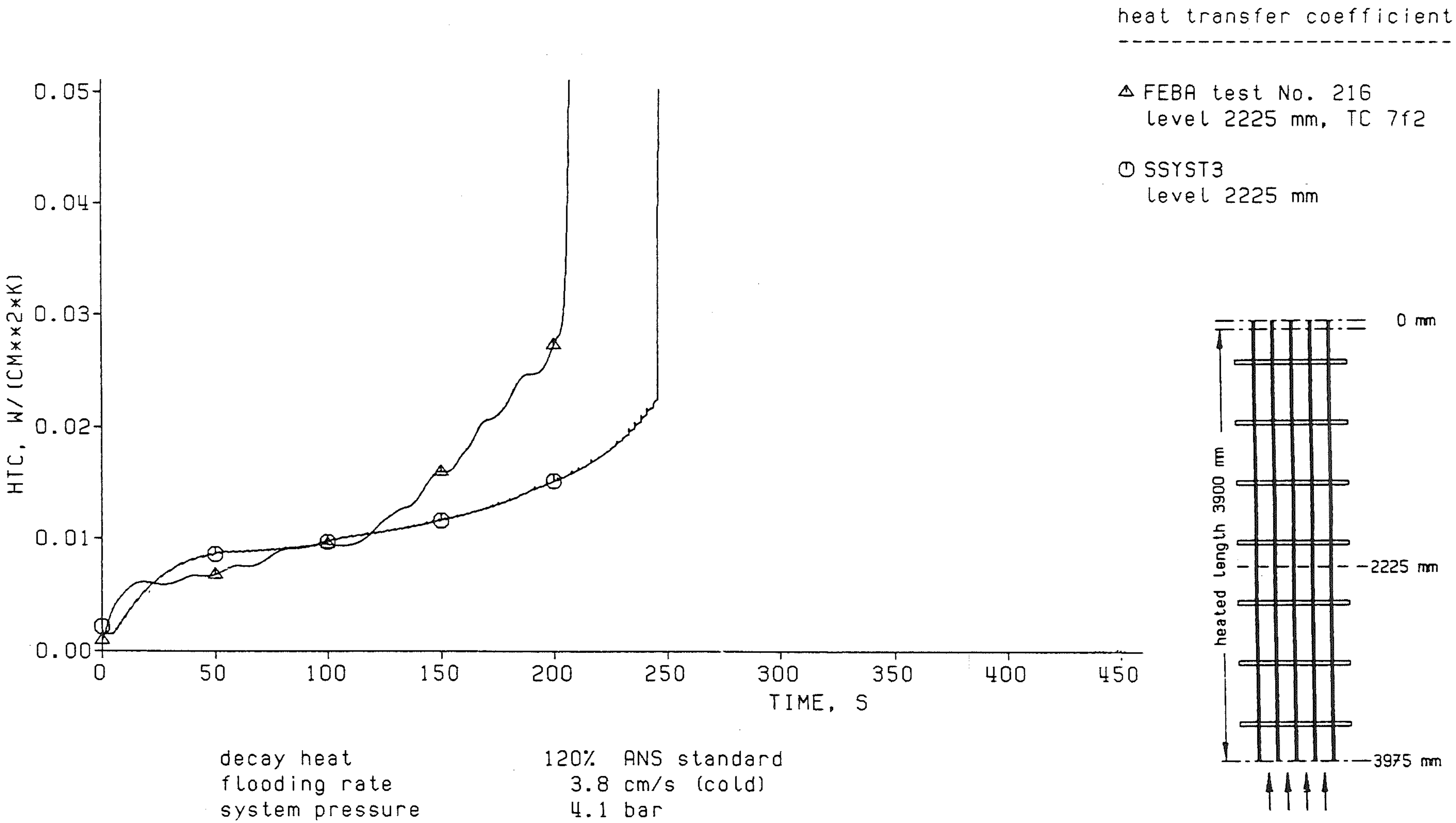
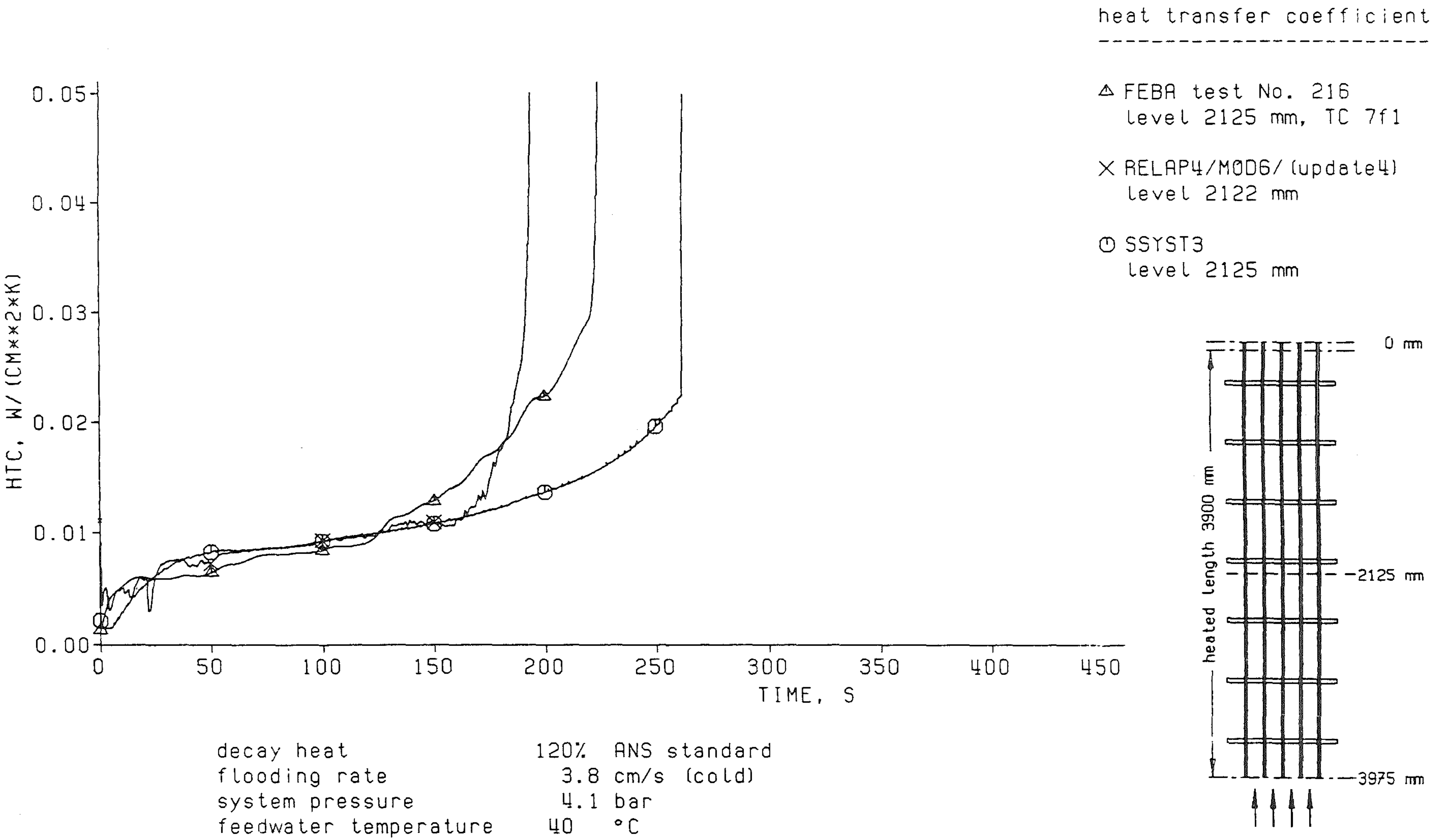


Figure 17. Comparison of measured and calculated cladding temperatures at axial level 590 mm of FEBA test No. 216.



decay heat	120%	ANS standard
flooding rate	3.8	cm/s (cold)
system pressure	4.1	bar
feedwater temperature	40	°C

Figure 18. Comparison of measured and calculated heat transfer coefficients at axial level 2225 mm of FEBA test No. 216.



decay heat	120% ANS standard
flooding rate	3.8 cm/s (cold)
system pressure	4.1 bar
feedwater temperature	40 °C

Figure 19. Comparison of measured and calculated heat transfer coefficients at axial level 2125 mm of FEBA test No. 216.

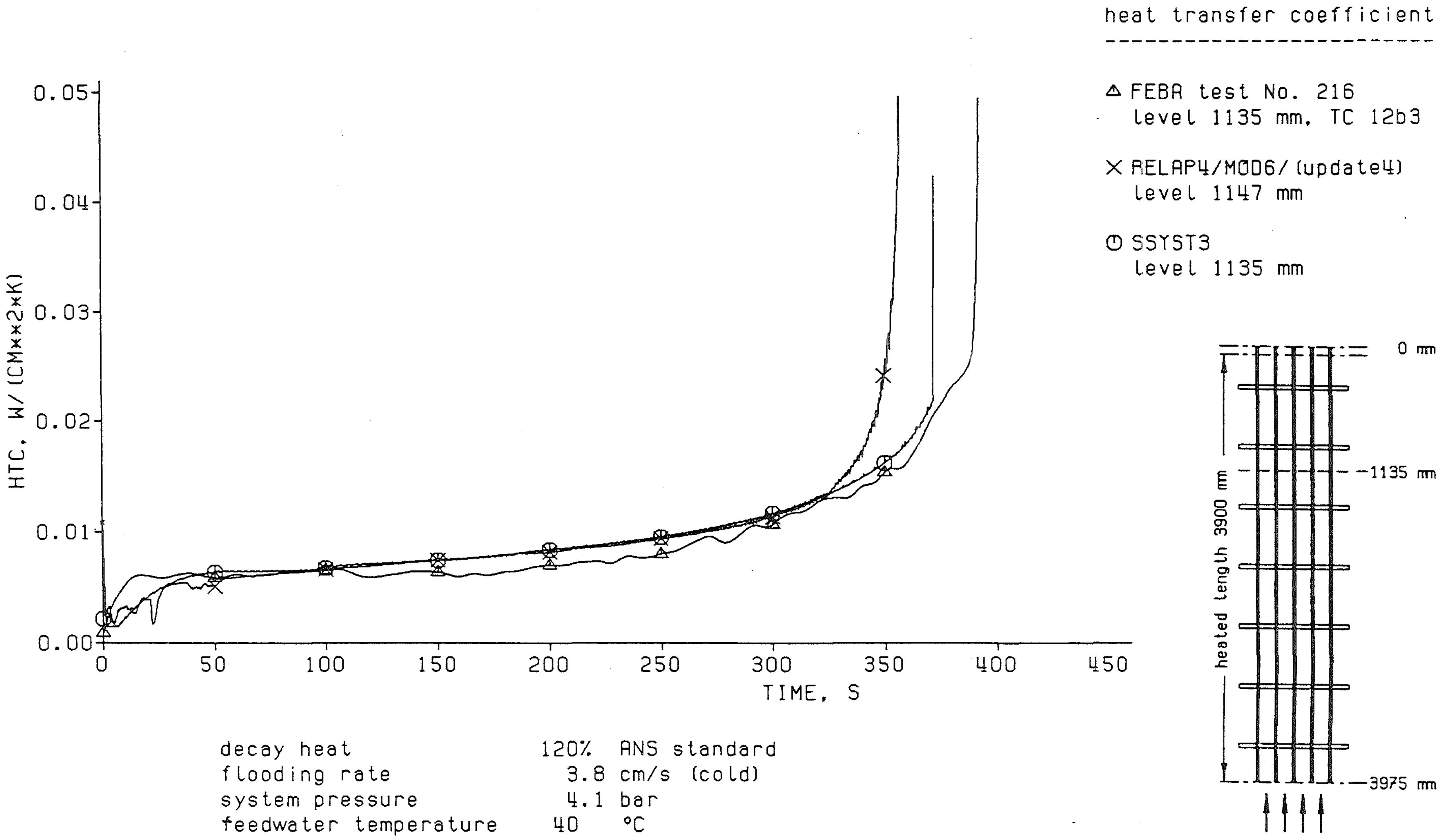


Figure 20. Comparison of measured and calculated heat transfer coefficients at axial level 1135 mm of FEBA test No. 216.

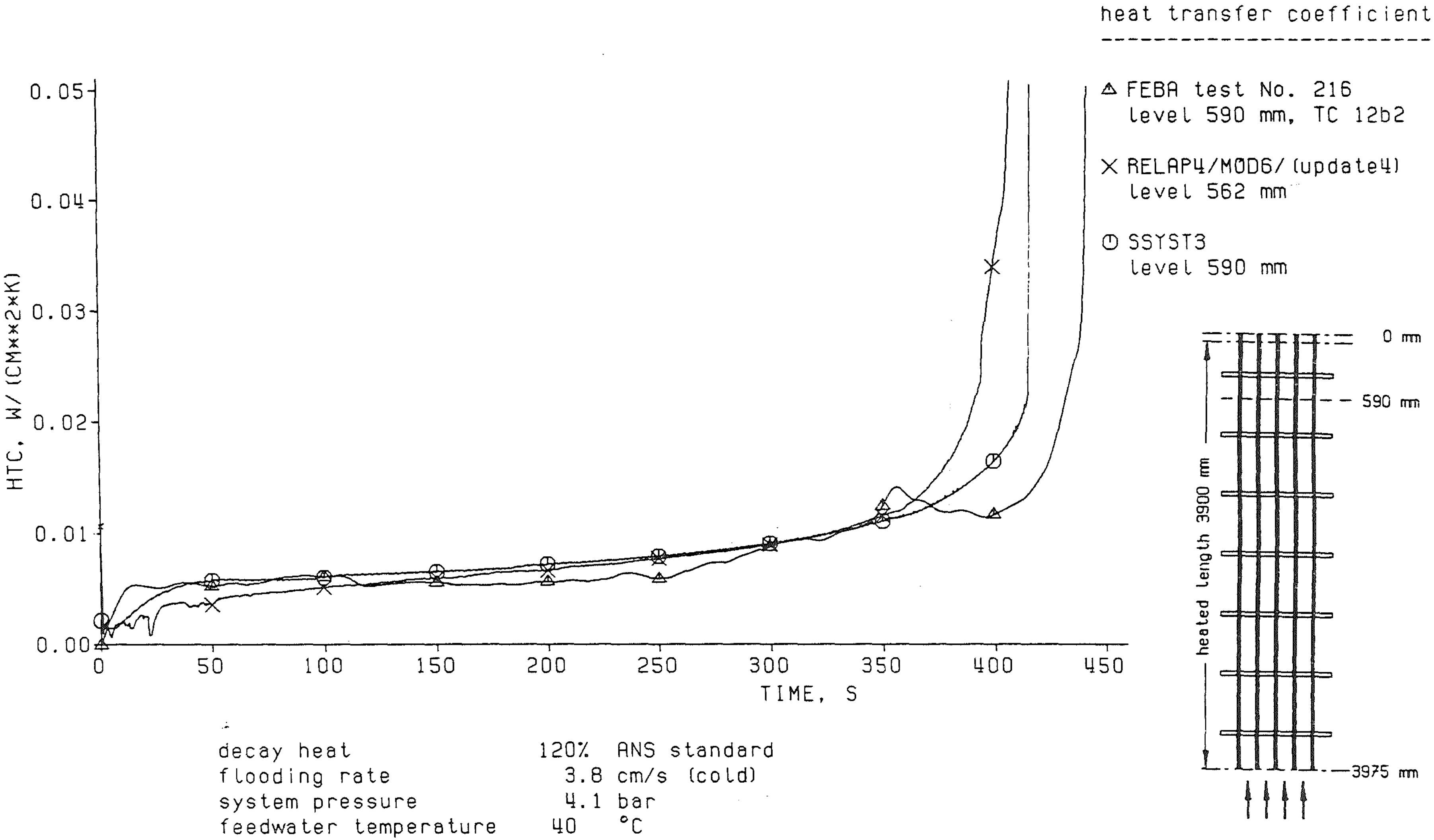


Figure 21. Comparison of measured and calculated heat transfer coefficients at axial level 590 mm of FEBA test No. 216.

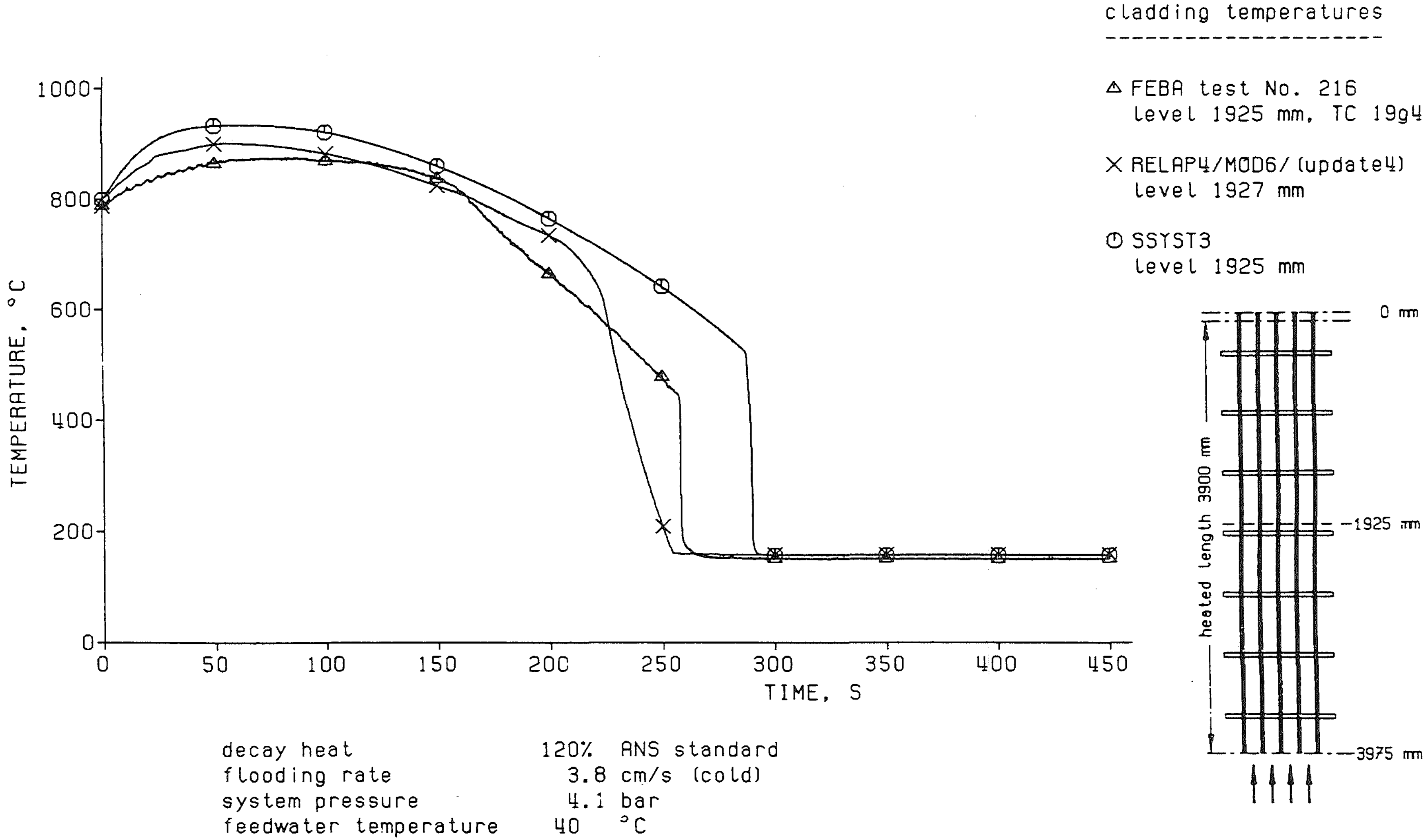


Figure 22. Comparison of measured and calculated cladding temperatures at axial level 1925 mm of FEBA test No. 216.

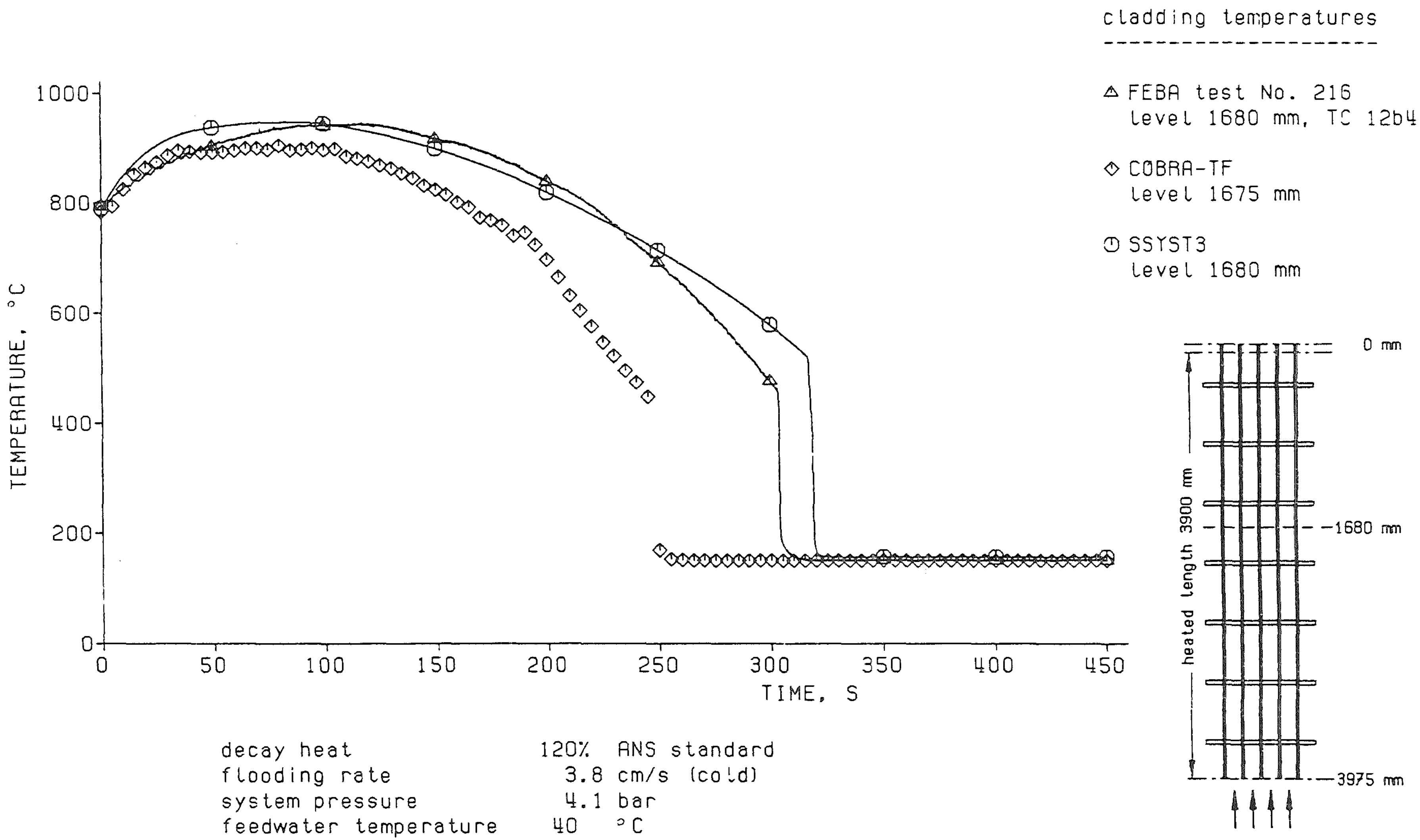


Figure 23. Comparison of measured and calculated cladding temperatures at axial level 1680 mm of FEBA test No. 216.

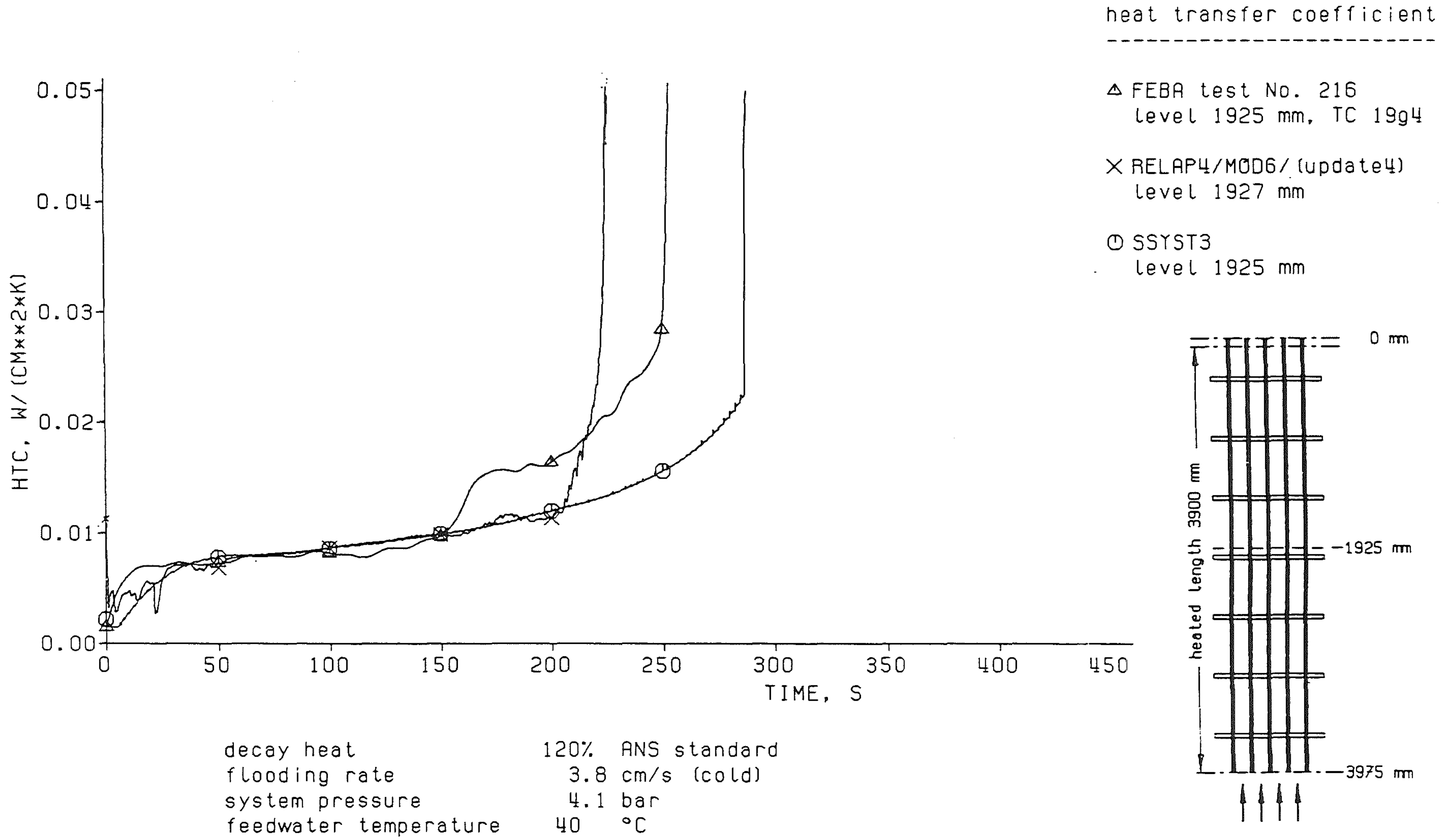
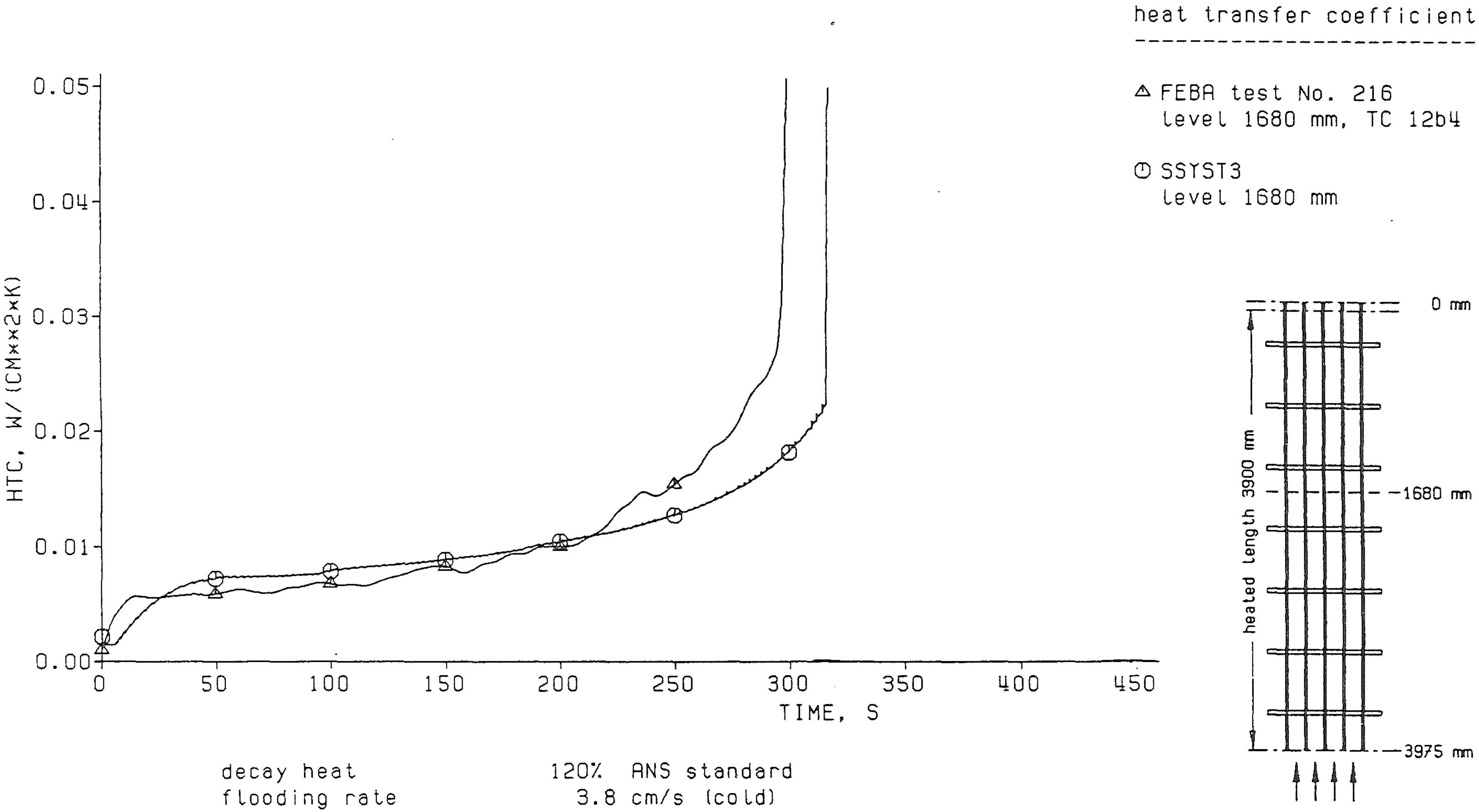
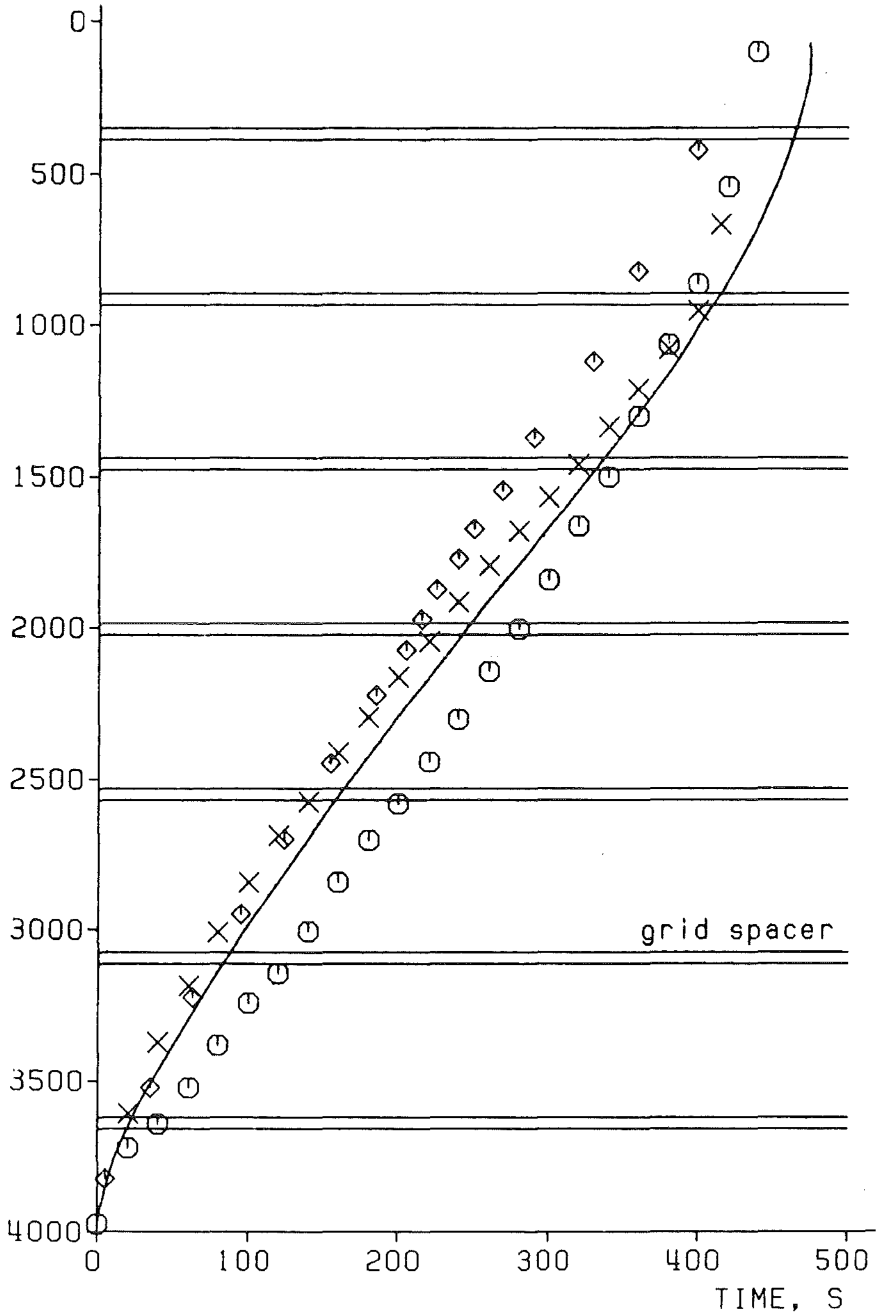


Figure 24. Comparison of measured and calculated heat transfer coefficients at axial level 1925 mm of FEBA test No. 216.



decay heat	120%	ANS standard
flooding rate	3.8	cm/s (cold)
system pressure	4.1	bar
feedwater temperature	40	°C

Figure 25. Comparison of measured and calculated heat transfer coefficients at axial level 1680 mm of FEBA test No. 216.



decay heat	120%	ANS standard
flooding rate	3.8	cm/s (cold)
system pressure	4.1	bar
feedwater temperature	40	°C

----- experiment, FEBA test No. 216
◇ ◇ ◇ calculation, COBRA-TF
× × × calculation, RELAP4/MOD6 (update4)
⦶ ⦶ ⦶ calculation, SSYST3

Figure 26. Comparison of measured and calculated quench front progression of FEBA test No. 216.