Fatigue Monitoring by Computer Aided Visualization of Transients and Calculation of Fatigue Usage by Algorithm

K. Benitz, A. Kalk, W. Pache – Westinghouse Reaktor GmbH, Mannheim

ABSTRACT

In the German BWR Gundremmingen measurement and evaluation systems are installed for operation accompanied fatigue monitoring. In this paper it is shown how the fatigue monitoring is supported by computer aided visualization of transients and calculation of fatigue usage by algorithm.

In a first step the measurement data are checked, presorted and reduced. Then automatically created graphs are presented to the user for significant time periods. Temperature curves measured at the outer wall could be converted into inner wall temperature curves. The stresses caused by transient and quasi-static loads are calculated by using the transformation laws of the Green's functions or by linear interpolation. Using the Rainflow-Hysteresis-Counting-Method together with design fatigue curves the partial fatigue usages are calculated and at last the total fatigue usage is presented.

All these functions are included in VBA-Moduls for MS EXCEL®97. When the VBA-Moduls are implemented for the special monitored position, the further use of FE-Models is no more necessary.

INTRODUCTION

According to the German Rule KTA 3201.4 [4] and recommendations of the Reaktorsicherheitskommission for German Nuclear Power Plants operational data has to be surveyed concerning the integrity of components and the containment. The influence of the detected loads on the fatigue usage has to be evaluated and thus the quality of the components has to be assured.

For this task in the German BWR Gundremmingen (2-unit plant near Ulm, each unit 1340 MWe) measurement and evaluation systems are installed since 1994 for the so called „operation accompanied fatigue monitoring" (Westinghouse Reaktor-Systems CUSTOS/VISO).

These systems fulfil two tasks:

- The first primary objective is to detect and visualize fatigue relevant transients and to improve system operation modes. By use of the graphic visualization some unknown non specified transients such as thermal stratification have been detected, which could be significantly reduced by specific actions. Thus damage to plant components could be prevented.
- The second objective is the support of the documentation of the transients and the calculation of fatigue usage factors of certain components which have been determined as higher loaded.

This paper presents the computer aided actions and the data flow (Fig. 1) starting with the measurement processing and ending with the presentation of the actual fatigue usage of a surveyed part.

MEASUREMENTS

For each unit about 350 measurements are scanned in time periods of 2÷5s and are temporary stored in binary format. The measurements are mainly out of plant instrumentation (fluid temperatures, pressures, valve positions, fluid levels, mass flows, electrical power) but also additional installed measurements of the outer wall temperature.

MEASUREMENT PREPROCESSING

In a first step a plausibility check of the measurement data is done by the program CUSTOS by comparing of the values with the measurement ranges. It is further checked whether the single measurement has changed significantly during the last time period. In this case the measurement data are saved permanently in so called group files in ASCII-format separate for every surveyed part. Every group file contains only those measurement data which are relevant for the specific part. Thus a significant data reduction and pre-sorting for the subsequent steps is done.

For the measurement parameter (measurement time period, difference-value for permanent storing, result of plausibility check) additional files are created to document the measurement quality.

MEASUREMENT VISUALIZATION

In the following visualization step graphs of the data are created automatically by the program VISO-TRANSIENT for the whole operation period as well as for detailed time periods which have been determined as periods where significant transients have occurred. These are events such as normal start up or shut down but also unnormal cases such as thermal stratification or cold water injections (Fig. 5).

The created graphs are formatted MS EXCEL®97-diagrams which could be easily included in a report but could also be modified by the user by menudriven procedures within the VISO-TRANSIENT session or directly by EXCEL

commands. VISO-TRANSIENT is used for „older" data (operation periods since installation in 1994 until the actual period with a delay of less than 12 hours). The equivalent program VISO-ONLINE is used to create graphs for the actual data (delay 1 min.) for the surveillance during tests.

After the visualization those transients are selected for the further processing, which could be fatigue relevant. This decision is done mainly by regarding temperature amplitude, temperatur gradient, pressure amplitude and frequency.

CALCULATION OF INNER WALL TEMPERATURE

For a stress analysis for thermal loading the temperature distribution at the fluid faced surface is necessary, which is normally the inner surface of a part. For some cases only the outer wall temperature is available. For these measurement data, the program VISO-TINTRA is used to solve the so called inverse heat conduction problem. The measurement data are smoothed in a first step and transformed by an interpolation polynom in a data curve with equidistant time steps. Afterwards the differential equation of heat conduction is solved numerically. The result is the temperature distribution across the wall, the inner wall temperature and additionally the fluid temperature if a heat transfer coefficient is specified (Fig. 6).

CALCULATION OF FATIGUE USAGE

In the last step the fatigue usage is evaluated by the program VISO-FATIGUE.

The first substep is the calculation of the stresses at the positions being known to have the highest fatigue usage. A „normal" fatigue calculation with a FEM-model for the design loads and design frequencies must exist as a precondition showing these positions. With this FEM-model stress curves for the surveyed positions are calculated for additional unit loads. These unit loads include quasi-static loads like pressure or external loads as well as transient temperature loads. In the last case the stress curve for a step temperature change of $\Delta T = 1$ K on characteristic regions of the surface of the part is calculated (Fig. 3). This stress curve $\sigma_{Green}(t)$ is called „Green's function", and has to be evaluated for different kinds of temperature changes such as homogeneous change at the total inner surface by plug flow but also for thermal stratifications. For the nozzle in Fig. 3 nine Green's functions are necessary (Fig. 4).

All these unit loads are calculated only once for each surveyed position and are stored in a VISO-FATIGUE-Modul specific for this position (Green's Function program in Fig. 2).

In the next substep the stress curves caused by the real measured transients are calculated.

The stresses caused by the quasi-static loads are calculated by linear interpolation of the results of the corresponding unit loads:

$$s_p(t) = s_{p,\,Ref}\,\frac{p(t)}{p_{Ref}} \tag{1}$$

$$s_{External\ Loads}(t) = s_{External\ Loads,Ref}\,\frac{T_{External}(t) - T_{Ref}}{\Delta T_{Ref}} \tag{2}$$

where $\sigma_{p,\,Ref}$ and $\sigma_{External\ Loads,\,Ref}$ are the stresses caused by the reference loads p_{Ref}, T_{Ref} and ΔT_{Ref}. $T_{External}(t)$ and $p(t)$ are the measured values for the pressure and the temperature at the time t. For the nozzle in Fig. 3 for example $T_{External}$ could be the wall temperature of the pipe connected to the nozzle, which causes external loads.

The stresses σ_T caused by the transient local temperature loads are calculated by the use of the transformation laws of the Green's functions [1]:

$$s_T(t) = \int_0^t s_{Green}(t-t)\,\frac{\partial}{\partial t}\,T(t)\,dt \tag{3}$$

where σ_{Green} is the stress caused by the step temperature load (Green's function) defined above and T(t) is the inner wall temperature at the time t, which has been calculated by VISO-TINTRA. The kind of Green's function to be used to solve the integral is chosen by the user for each transient. For cases with simultaneous transients in different regions of the part the integral must be solved also for different Green's functions. The total result is got by superposition afterwards.

Example cold water injection in Fig. 5: Simultaneously decreasing temperature in the upper and lower part but with a linear thermal stratification; than the influence of the upper temperature curve 1 at the top is calculated with Green's function No. 2, the influence of the temperature curve 7 at the bottom with Green's functions No. 3.

For parts with an inhomogeneous material distribution or cases with local inhomogeneous temperature distribution there is an additional stress at the begin of the transient, which is not covered by the equations above. The nozzle in Fig. 3 for example could be cladded with a different material and the temperature could be different from those of the wall of the vessel.

These „start-stresses" are also calculated by linear interpolation of the results of corresponding unit loads:

$$s_{\text{Inhomogen Mat}} = s_{\text{Inhomogen Mat, Ref}} \frac{T(t=0) - T_{\text{Ref}}}{\Delta T_{\text{Ref}}} \tag{4}$$

$$s_{\text{Inhomogen Temp}} = s_{\text{Inhomogen Temp, Ref}} \frac{T(t=0) - T_{\text{Ref}}}{\Delta T_{\text{Ref}}} \tag{5}$$

where $\sigma_{\text{Inhomogen Mat, Ref}}$ and $\sigma_{\text{Inhomogen Temp, Ref}}$ are the stresses caused by the reference loads T_{Ref} and ΔT_{Ref} and $T(t=0)$ is the measured value for the temperature at the time at the begin of the transient.

At last the total stress curve σ_{Total} is got by superposition of all single stresses:

$$s_{\text{Total}}(t) = s_T(t) + s_p(t) + s_{\text{External Loads}}(t) + s_{\text{Inhomogen Mat}} + s_{\text{Inhomogen Temp}} \tag{6}$$

In the following substep the stress curve is simplified by reducing to the points of the relative peak values and these values are assigned to classes spanning a certain value region. Thus from all stress curves a chronological sorted load sequence curve is created (Load Sequence program in Fig. 2).

In the last substep a fatigue analysis is done. The Rainflow-Hysteresis-Counting-Method (HCM, [2]) is a counting method for fatigue strength evaluation based on material behaviour (Masing- and Memory-Behaviour). This algorithm is used to determine and to count the closed and unresolved load cycles in the stress-strain curve. The stress range S_i is given by the difference between the value range of the load cycle. According to the fatigue curves in the KTA 3201.2 [3] the partial fatigue usage d_i is calculated for every load cycle. With the frequencies n_i counted after summation the total fatigue usage d_{total} of the surveyed part is calculated (HCM program in Fig. 2).

The main results are presented on a formatted MS EXCEL®97-work sheet, which could be easily included in a report.

HARDWARE AND SOFTWARE

All programs are running on a standard PC under WINDOWS/NT.

The program CUSTOS is an executable file, which needs no further additional software after the installation. In the NPP Gundremmingen this program is running permanently. The results are stored in a Local Area Network with read-permission for the user.

The different moduls of the program VISO need the installation of MS EXCEL®97. All moduls are menudriven and therefore could be used without significant learning.

REFERENCES

1. S. S. Tang, A. Y. Kuo and P. C. Riccardella, „An Online fatigue system for power plants; Part I – Direct calculation of transient peak stress through transfer matrices and Green's functions", Design and Analysis Methods for Plant Life Assessment, American Society of Mechanical Engineers, PVP-Vol. 112 (1986)
2. U. H. Clormann, T. Seeger, „Rainflow-HCM, Ein Zählverfahren für Betriebsfestigkeitsnachweise auf werkstoff-mechanischer Grundlage", Stahlbau 3/1986
3. KTA 3201.2, „Komponenten des Primärkreises von Leichtwasserreaktoren, Teil. 2: Auslegung, Konstruktion und Berechnung", Fassung 06/1996
4. KTA 3201.4, „Komponenten des Primärkreises von Leichtwasserreaktoren, Teil. 4: Wiederkehrende Prüfungen und Betriebsüberwachung", Fassung 06/1999
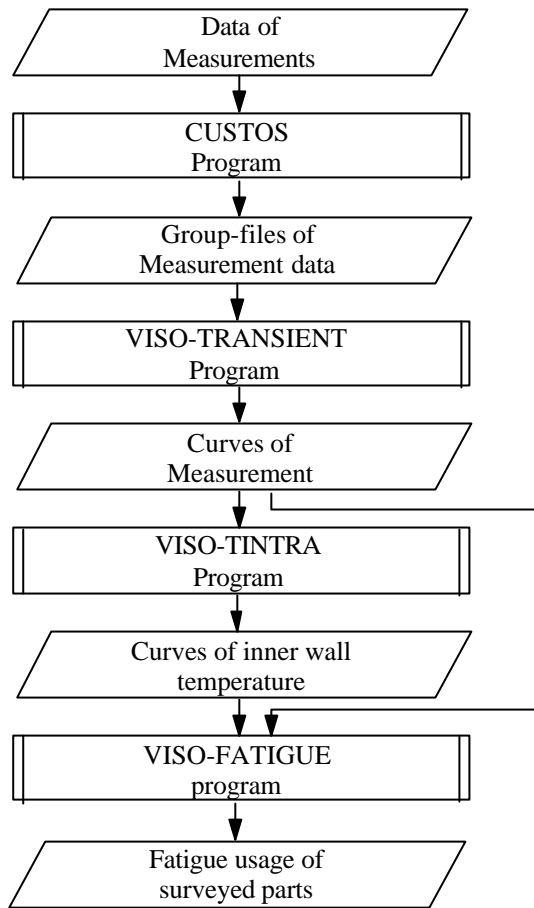
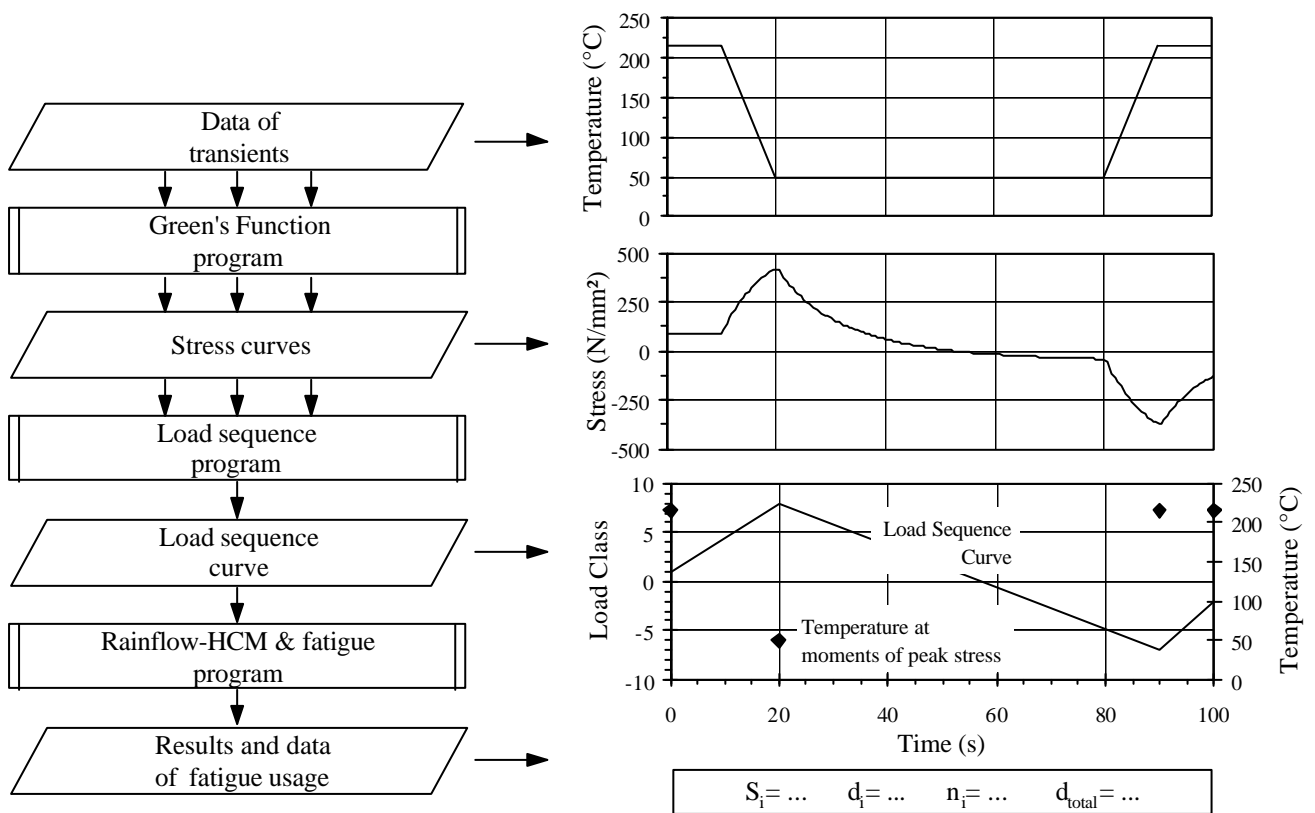**Fig.1   Computer aided fatigue monitoring with CUSTOS/VISO**
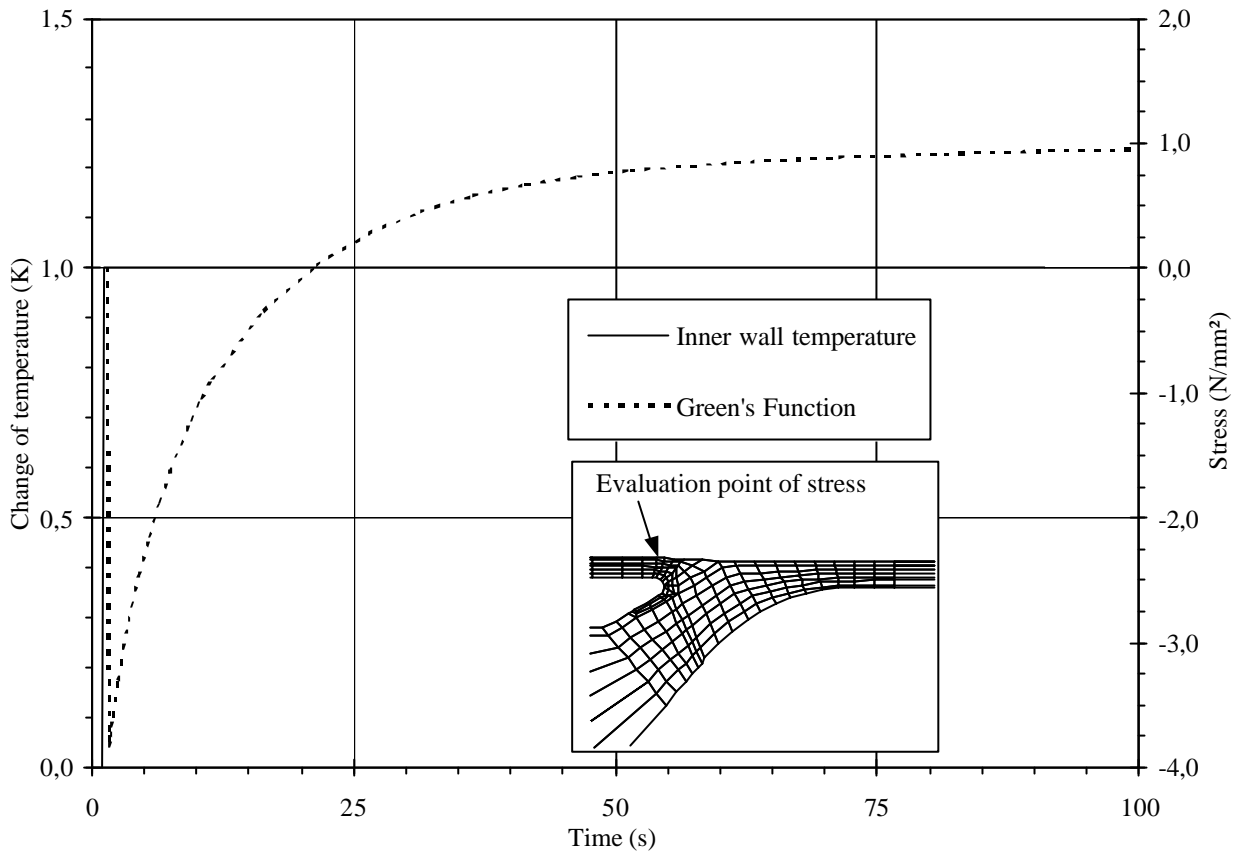

Fig. 2   Flow chart of VISO-FATIGUE program

Fig. 3   Stress curve (Green's Function) caused by unit temperature step

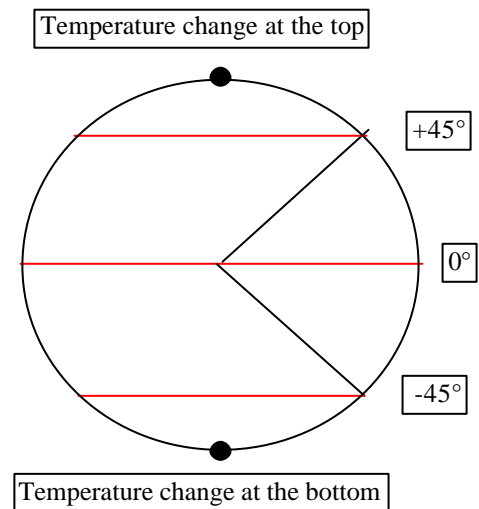| No.	Descrition of the transient
1	Transient with homogeneous temperature change (plug flow)
2	Transient with linear thermal stratification, temperature change at the top
3	Transient with linear thermal stratification, temperature change at the bottom
4	Transient with thermal stratification at 0° (abrupt), temperature change at the top
5	Transient with thermal stratification at 0° (abrupt), temperature change at the bottom
6	Transient with thermal stratification at 45° (abrupt), temperature change at the top
7	Transient with thermal stratification at 45° (abrupt), temperature change at the bottom
8	Transient with thermal stratification at -45° (abrupt), temperature change at the top
9	Transient with thermal stratification at -45° (abrupt), temperature change at the bottom

Fig. 4   Required Green's Functions for a horizontal nozzle
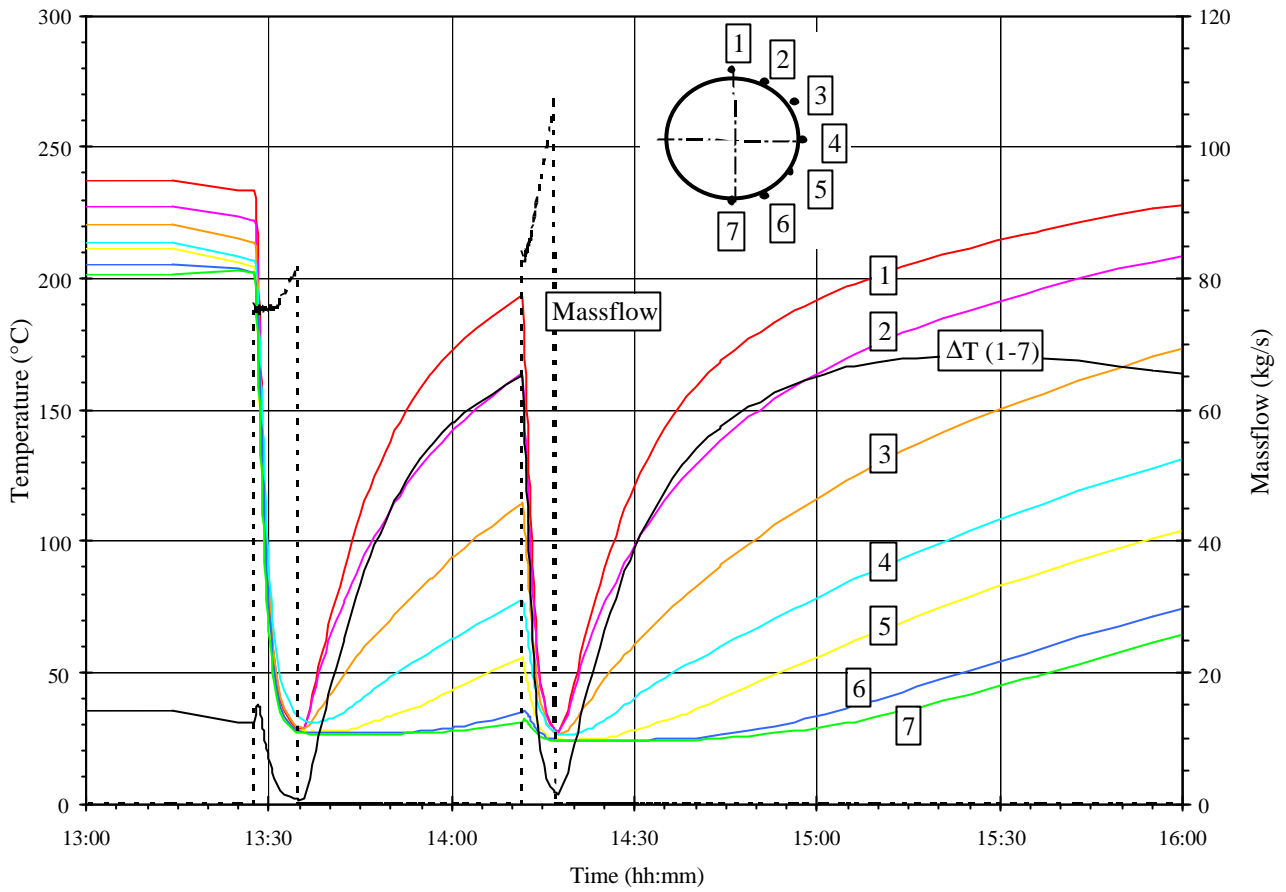
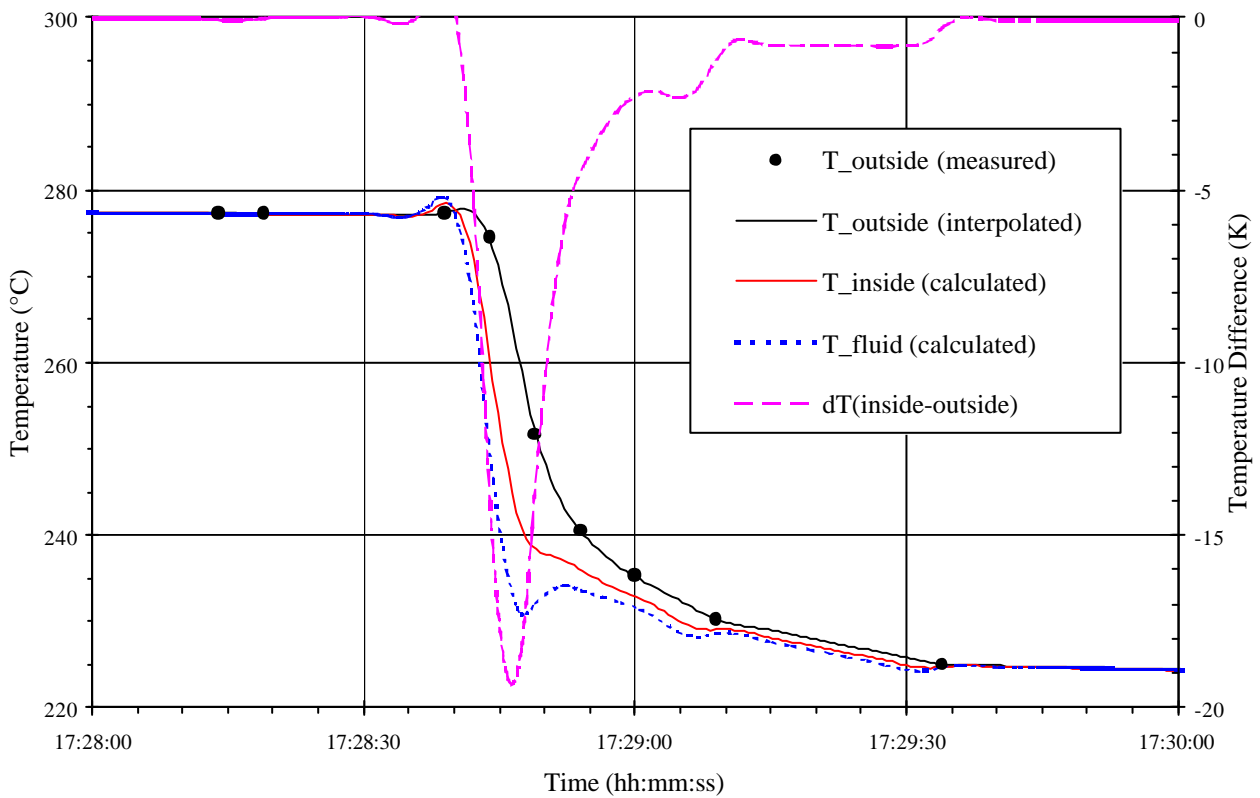**Fig. 5 Measurement of a cold water injection**

Fig. 6 Calculation of inner wall temperature and fluid temperature with VISO-TINTRA

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