KfK 3359
Juni 1982

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ISSN 0303-4003

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(Paper presented to the IAEA Specialists' Meeting on Water Reactor Fuel Element Performance Computer Modelling, Preston, March 15-19, 1982)

Summary.

SSYST is a code-system for analysing transient fuel rod behaviour under off-normal conditions, developed conjointly by the Institut für Kernenergetik und Energiesysteme (IKE), Stuttgart, and Kernforschungszentrum Karlsruhe (KfK) under contract of Projekt Nukleare Sicherheit (PNS) at KfK. Main differences versus codes with similar applications are
(1) an open-ended modular code organisation, and
(2) a preference for simple models, wherever possible.

While the first feature makes SSYST a very flexible tool, easily adapted to changing requirements, the second feature leads to short execution times. The analysis of transient rod behaviour under LOCA boundary conditions takes 2 mins cpu-time (IBM-3033), so that extensive parametric studies become possible.

The paper gives an outline of the overall code organisation and a general overview of the physical models implemented. Besides explaining the routine application of SSYST in the analysis of loss-of-coolant accidents, examples are given of special applications, which have led to a satisfactory understanding of the decisive influence of deviations from rotational symmetry on the fuel rod perimeter.

SSYST, ein Code-System zur Analyse des transienten LWR-Brennstab-Verhaltens unter Störfall-Bedingungen.

Zusammenfassung.

SSYST ist ein Code-System zur Analyse des transienten Brennstab-Verhaltens unter Störfall-Bedingungen. Es wurde gemeinsam vom Institut für Kernenergetik und Energiesysteme (IKE), Stuttgart, und dem Kernforschungszentrum Karlsruhe (KfK) entwickelt, Auftraggeber ist das Projekt Nukleare Sicherheit (PNS) im KfK. Hauptunterschiede gegenüber Codes mit ähnlichem Aufgabenspektrum sind
(1) ein ausbaufähiger, modularer Aufbau des Codes, und
(2) die Bevorzugung einfacher Modelle, soweit möglich.

Die erste Eigenschaft gewährleistet eine hohe Flexibilität, so daß SSYST leicht wechselnden Anforderungen angepaßt werden kann. Die zweite Eigenschaft führt zu kurzen Ausführungszeiten. Die Analyse des transienten Stab-Verhaltens unter den Randbedingungen eines Kühlmittelverlust-Störfalls benötigt 2 min CPU-Zeit (IBM-3033). Damit werden umfangreiche Parameter-Untersuchungen möglich.

Der Bericht beschreibt die Gesamt-Organisation des Codes und gibt eine allgemeine Übersicht über die implementierten physikalischen Modelle. Neben der Beschreibung von Standard-Anwendungen von SSYST für die Analyse von Kühlmittelverlust-Störfällen werden einige Beispiele von Sonder-Anwendungen angeführt, welche zu einem befriedigenden Verständnis des entscheidenden Einflusses geführt haben, den Abweichungen von der Rotationssymmetrie auf dem Stabumfang haben.

SSYST, a Code-System for Analysing Transient LWR Fuel Rod Behaviour under Off-Normal Conditions.

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1. Introduction.

SSYST /1,2/ is a modular code-system for analysing transient fuel rod behaviour, comparable in its field of applications to the codes FRAP-T /3/ and MABEL /4/. SSYST has been developed conjointly by the Institut für Kernenergetik und Energiesysteme (IKE), Stuttgart, and Kernforschungszentrum Karlsruhe (KfK) under contract of Projekt Nukleare Sicherheit (PNS) at KfK. The differences between SSYST and the two other codes, FRAP-T and MABEL, mainly concern overall code organisation and the degree of detailedness in physical modelling. Starting in 1974, the development of SSYST led in 1977 to a first version SSYST-1, operational both on CDC and IBM computers. In 1979, at KfK an improved IBM-version of SSYST-2 became operational, which has been made available to external users in 1981. Additional improvements and extensions are part of the working version of SSYST-3, which will be released in 1982. Application runs have been performed mainly with SSYST-2 and SSYST-3.

SSYST has been designed for analysing the transient behaviour both of single fuel rods under conditions of hypothetical loss-of-coolant accidents (LOCA) and of fuel rod simulators used in a number of safety research experiments at KfK /5,6,7/. Fig.1 shows, as an example, the cross section of the REBEKA fuel rod simulator at one axial elevation. At another elevation a similar cross section, with other materials and dimensions, may appear. To model such simulator, SSYST describes it as a straight stack of axial segments, each of which consists of a set of coaxial straight cylinder shells. The same model yields a satisfactory description of a deformed fuel rod, consisting at each elevation of only 3 material zones. This description may be used, as long as no bending or similar asymmetrical deformation occurs. Under some restrictions, SSYST-2 can also model asymmetrical deformations approximately, yielding some very important results (cf. 4.8, 5.3).

The desire to respond flexibly to changing requirements induced PNS to support the development of an open-ended modular code-system, rather than a large stand-alone code, for which specifications made initially may become very difficult to change at a later stage. Flexibility in the specification of geometry is only one aspect. The long-standing experience IKE Stuttgart had with a modular code-system RSYST-1 /8/ for reactor physics calculations led to a design of the systems architecture of SSYST along the lines of RSYST-1. This holds, even though in the meantime numerous changes have increased considerably performance and convenience to the user.

2. SSYST architecture.

The basic philosophy of the systems architecture of SSYST is easily explained, referring to fig.2. Transient behaviour of a fuel rod in a LOCA or a simulator in an experiment is resolved into a sequence of time-steps, a typical number being 1000 steps. In each time step the changes occurring are treated as a superposition of independent actions. Such actions, which in one time step are treated separately, are heat transport, change of the thermal conductance in the gap between fuel pellet and cladding, change of internal pressure, deformation of the fuel rod, oxidation of Zircaloy cladding, changing boundary conditions etc. Provisions have been made to distinguish between a coarser grid of macro time-steps used for coupling different physical phenomena and finer grids of micro steps used internally in the separate physical models. Within each physical model arbitrary integration schemes may be operative for one macro time-step, the complex transient involving all relevant physical phenomena being treated by explicit integration on the macro time-step scale.

2.1. Code organisation.

To implement this scheme, the code-system SSYST is organised as follows. A clear distinction is made between program (code) and data. All data are kept as standardized data blocks in permanent or temporary data bases. The program consists of a nucleus and an arbitrary number of so-called modules, which can be linked to the nucleus. The nucleus is written in FORTRAN IV with a few subroutines in ASSEMBLER (about 100 lines of code). All modules consist of FORTRAN subroutines. The modules are semi-autonomous programs, each performing a specific task, e.g. modelling one of the physical phenomena listed above. No module, excepting some weakly integrated programs, reads input of its own. Instead, it has to access the data bases via a small number of coupling subroutines, which are part of the nucleus. In the same way results are returned to the data bases and thus become accessible to other modules. The nucleus performs the task of the data base manager and, in addition, it contains the driver program, which controls program execution using a low-level user-oriented command language.

2.2. Command language.

The basic element of the command language is a fixed format record consisting of a keyword, which specifies an action to be performed, and a group of 5 integer parameters, which may be accessed by the module involved. If the module needs additional data, they are usually obtained via standard coupling routines in the nucleus, using linked-list techniques. Some keywords or modules use follow-up records in specific formats as augmentations to the basic command format.

The keywords of SSYST can be grouped into two categories, the first group calling modules which model separate physical phenomena. The second group, identified as auxiliaries in fig.2, activates general purpose modules, which perform a large number of administrative and/or numerical tasks. Such tasks are the creation, deletion, copying or listing of data blocks, performing algebraic transformations on data blocks or transformations by integration or call of standard functions. Other important tasks implemented by this group of general purpose keywords are logical operations, counting and program loop execution. The number of keywords in this general-purpose category is about 90, whereas about 30 keywords are application-oriented, i.e. model physical phenomena.

2.3. SSYST data blocks.

Data blocks are standardized and typed, they consist of a fixed format descriptor vector and a variable data section. Main types are:

(1) Real (integer) matrices (vectors). This block type holds specifications of geometry and material compositions, temperature fields and similar data. The convention is to keep data of different physical types in separate data blocks.
(2) General control blocks containing both integer and real data. They are used for general control of program execution and inter-module communication.
(3) Tables of material properties or similar data. All usual interpolation schemes may be selected.
(4) Sequences of command language records. These SPEICHER-blocks may be activated as macro commands and constitute the basic element of loop execution in SSYST, used in simulating physical transients.

2.4. Resulting advantages.

This code-organisation, for which a more detailed description is given in /1,2/, has some important advantages:

- Each physical model is represented by a separate module.
- Interfaces between modules and the system are standardized, typed data blocks.
- As a consequence, any physical phenomenon may be modelled on different levels of sophistication, simply by exchanging modules.
- Each module may be simulated by general-purpose modules, which will generate the required constant or time-varying data as output to the data bases.
- The user selects, by normal program input, only those modules which he thinks relevant for his problem, avoiding thus costly modelling of irrelevant physical phenomena.

- The open-ended design makes it easy for the user to include, temporarily or permanently, module modifications or complete modules of his own, without perturbing the system.
- It is easy to link stand-alone codes, either by weak integration into SSYST or using simple interface routines, which read a suitable intermediate file from the stand-alone code and convert its contents to standard data block formats.
- Restart capability is an inherent systems feature, directly related to the splitting between code and data.

2.5. Supporting utilities.

On the other hand, this flexibility introduces also some inconveniences for the user. Every new user needs a few days of instruction to become familiar with SSYST conventions. The input for a typical application run is voluminous, consisting of between a few hundred and one thousand records (cards). Without some additional support, even an experienced user has difficulties in writing or checking new input decks. Modifying input for parametric surveys usually necessitates identical or related changes at several positions of the input.

To assist the user in parametric surveys, a support module VARIO /2/ is available under SSYST-2, which processes free-formated and symbolic input to modify ready-made master input decks. Such masters are available for a number of standard applications. Each master may be considered a virtual SSYST implementation of a stand-alone code, the user's action being reduced to that for typical stand-alone codes.

Under SSYST-3 a preprocessor program PREPRO /9/ is supplied with the additional capabilities of checking globally complete input decks and aiding in specifying loader instructions.

3. LOCA analysis with SSYST.

Figs. 2-4 demonstrate the application of SSYST-2 to the analysis of a single fuel rod under the conditions of a hypothetical LOCA. The flow diagram of fig.2 shows that the initial steady-state conditions for the fuel rod may be supplied by the code COMETHE III-J /10/, which at KfK has been loosely linked to SSYST (COMETHE is a proprietary code, not part of the SSYST package). The rest of initialization is done by general purpose modules and a first step in the SSYST run to bring temperature distribution, pressure etc. to steady-state equilibrium.

During the blow-down phase of the LOCA, transient boundary conditions are provided from RELAP4/MOD6 /11/. By some minor modifications the RELAP4 edit package has been enabled to process its plot-restart file into an interface file, which is read by the interface module REL-BIB of SSYST-2. An identically structured interface file can also be easily obtained from other primary systems codes.

Similar boundary conditions for the refill-flood phases are provided by the weakly integrated SSYST-modules WAK /12/ or REFLOS /13/.

With boundary conditions supplied during the whole transient, fully integrated SSYST-modules model the transient behaviour of the fuel rod in all 3 phases (blow-down, refill, flooding) of a LOCA. General purpose (auxiliary) modules are extensively used throughout the transient, e.g. for writing a plot file, and for the final evaluation.

3.1. Coupling a primary systems code to SSYST.

In fig.3 coupling between RELAP4 and SSYST is demonstrated in some more detail. In a first step a primary systems analysis is performed for the blow-down phase, using a global thermohydraulics model of the core. In step 2 plenum transient pressure p(t) and enthalpy h(t) from step 1 are used as boundary conditions for a single channel analysis with RELAP4, which models a selected coolant channel in more detail. Typically for LOCA analysis, this is a channel in the peak power or other sensitive area.

The RELAP4 plot-restart file from step 2 is processed in a RELAP4 edit run to yield the interface file for SSYST, containing transient boundary conditions for a number of axial nodes of the rod. The number 22 used in fig.3 is arbitrary, but representative. The boundary conditions normally needed are the temperature of the coolant $T_c(t)$, the clad-to-coolant heat transfer coefficient HTC(t), both required by the heat transport modules, and the pressure p(t) in the coolant that contributes to cladding deformation. In addition, the normalized transient decay power is passed from RELAP4 to SSYST.

3.2. Sample case, performance.

Fig.4 is a plot obtained from such a LOCA simulation. The upper curve (left scale) shows the cladding temperature at a mid-plane position of a highly rated fuel rod. For a short time, during blow-down, it exceeds 1200 K, reaching a second maximum of 1050 K during the refill-flooding phase. Almost all rod deformation (lower curve, right scale) occurs in the second heat-up phase, the small kink at the cross-over of the curves is due to shrinking at quench time.

The complete simulation of a LOCA by SSYST-2 takes about 2 mins cpu-time on an IBM-3033 computer. Of course, this does not include the RELAP4 runs. But these are usually done only once, the RELAP4 output serving for many subsequent SSYST runs, e.g. in a parametric survey.

The very favourable execution speed is achieved partly by code features listed previously, partly by details of the systems implementation, which were introduced with version SSYST-2 and decreased systems overhead drastically. Finally, in modelling physical phenomena, preference was given to efficient algorithms and to simple models, under the impression that inevitable uncertainties in the initial and boundary conditions would invalidate any more sophisticated approach. The open-ended design of SSYST would permit necessary refinements in modelling at any later stage.

4. Physical models in SSYST.

In this section the main physical models (modules) will be described very briefly. Going into details would be quite possible for some models, but in other cases description and justification of one model would take the space of a separate paper. The authors therefore have restricted themselves to give a more general overview.

4.1. Heat transport.

Methods for solving the heat transport equation are well-known. Of some importance for LOCA analysis is the pronounced temperature-dependence of the material properties involved. The SSYST library includes tables for some standard materials, for which the user can easily substitute tabulations of his own.

Module ZET-1D.

ZET-1D solves the transient heat transport equation for a radial grid. Neglecting axial heat transport (1D stands for 1-dimensional) is justified in most rod geometries. Under SSYST-2 time-integration uses a semi-implicit Crank-Nicholson scheme /14/. Under SSYST-3 the more stable fully implicit scheme is available as a user option.

Module STT-1D.

STT-1D, available under SSYST-3, is the stationary supplement to the transient 1-dimensional heat transport module ZET-1D. This module is recommended for calculating pre-LOCA equilibrium conditions.

Module ZET-2D.

ZET-2D solves the transient heat transport equation for a 2-dimensional (r,z) grid. This module must be used, when heat transport in the zones of contact between the fuel pellet stack and gas plena of fuel rods is relevant. Also for modelling experimental set-ups. In this module, time integration uses the Alternating Direction Implicit (ADI) scheme.

Module STT-2D.

STT-2D is the stationary supplement to the transient 2-dimensional heat transport module ZET-2D. The technique of solution is Successive Line Over-Relaxation (SLOR).

4.2. Gap conductance.

In an open gas-filled gap, e.g. between fuel pellet and Zircaloy cladding, radiative heat transport may be important. In all versions of SSYST, including SSYST-3, radiative heat transport is considered only in one, viz. the outermost, gap. This restriction may be removed in case of necessity, although it would involve some effort in code reorganisation. Two modules are available.

Module WUEZ.

In the case of an open gap, heat conduction in the gases He, Kr and Xe

and radiation are considered as contributing to overall heat conductance in the gap. The third possible contributor, convective heat transport in the gas, is neglected.
For the closed gap, i.e. contact under pressure between fuel pellet and cladding, the familiar Ross-Stoute model /15/ is applied.

Module URGAP.
This module is the SSYST implementation of the gap conductance model developed for the URANUS code /16/. While for the open gap physical modelling follows essentially the same lines as in WUEZ, the contact case is treated differently. Great care has been taken in the mathematical/numerical formulation to avoid any unphysical discontinuity between the conductance computed for a very narrow and the fully closed gap. Thus, artificial oscillatory transients, which would be due only to numerical effects, are completely avoided.

4.3. Internal gas pressure.

The gas pressure in the gap between fuel pellet and cladding from one side and the counter pressure in the coolant channel from the other side are the forces which lead to deformation of the cladding during a LOCA. While pressure in the coolant channel is one of the transient boundary conditions provided by a primary systems code like RELAP4, the internal gas pressure is computed by SSYST. Two modules are available.

Module SPAGAD.
This model assumes, that at any moment gas pressure in the upper and lower gas plenum of the rod, in the gap, in dishing volumes and open pores are at equilibrium. Global fission gas release is treated by a simple correlation /17/, which considers 3 temperature regions of the fuel. Contributors to total gas pressure are primarily the filling gas He and the inertial fission products Kr and Xe. Other volatile fission products may be included in the calculation, but in most practical cases their contribution is neglegible.

Module PIPRE.

This model considers mainly the inertial gases He, Kr and Xe as contributing to rod internal pressure. The model considers 3 effective rod volumina, viz. the upper and the lower gas plenum connected by the gap between pellet and cladding, as well as dishing volumes and open pores. The pellet-cladding-gap changes form and size during a LOCA transient. Gas pressure is treated as a local variable, and streaming between upper and lower plenum and the gap is modelled.

4.4. Rod deformation.

For the deformation of an axially extended rod with rotational symmetry the module STADEF is available. Effects of azimuthal asymmetry may, for one axial zone, be semi-quantitatively investigated with the module AZI (cf. 4.8). A fully 3-dimensional model of cladding deformation is under development at KfK.

Module STADEF.

STADEF models the symmetrical deformation of a rod, especially the Zircaloy cladding. As for the fuel pellets, only thermal expansion and elastic compression are considered. Cladding deformation during contact with the pellet is by contact pressure. With an open gap, the normal situation in LOCA analysis, radial deformation of the cladding is treated by 1-dimensional shell theory. This treatment may, as a user option, be extended by including a first order correction for axial coupling of the radial deformation at adjacent elevations.

Very satisfactory numerical performance for this deformation model was achieved by explicitly integrating for each time step a creep rate expression. The creep rate for each (temperature,stress)-state is obtained from internal tables based on a Norton model. Details of this NORA model, including recent improvements incorporated in SSYST-3 are reported in an accompanying paper /18/.

Under SSYST-2 the user has to specify a limiting value of strain as a 'burst criterion' sufficient for practical applications. Under SSYST-3 a proper burst criterion using a strain fraction rule is included, the same applies to the module AZI (cf 4.8). For details refer to the accompanying paper /18/.

4.5. Zircaloy oxidation.

For LOCA analysis and as an evaluation model the very elementary and conservative module ZIRKOX is appropriate. For more realistic modelling, valid also at elevated temperatures, a multi-layer oxygen diffusion model MULTRAN, based on the SIMTRAN code /19/, has been developed and will be integrated into SSYST-3 in the very near future.

Module ZIRKOX.

The module calculates Zircaloy oxidation, its contribution to the heat balance and a correction to the clad-to-coolant heat transfer coefficient. The model assumes oxidation only on the outer cladding surface. Cladding is assumed to consist of 2 layers, the outer binding all oxygen as ZrO_2, the inner layer consisting of the original Zircaloy-4. Oxidation rate follows a simple parabolic law, the parameters of which the user may insert from the Baker-Just correlation /20/ or any other source.

4.6. Refill and flooding.

At KfK, an early version of the code WAK /12/, developed at KWU, has been weakly integrated into SSYST, to obtain boundary conditions for the rod models during the refill and flooding phases. These are the same boundary conditions as obtained from RELAP4 for the blow-down phase, including transient decay power. For a more realistic investigation at KfK the flooding code REFLOS /13/, obtained from GRS, is used. Both codes are not normally distributed with the SSYST-2 source. The full integration of the 2-phase flooding code REFLUX /21/, also obtained in a version adapted by GRS, is under way.

4.7. Hydraulics in the subchannel.

As was explained, in the analysis of the transient behaviour of fuel rods during blow-down we normally rely on transient coolant temperature and clad-to-coolant heat transfer coefficients as supplied by a primary systems code, e.g. RELAP4. But during the blow-down the heat transfer coefficients may be affected by changes in the heat flux, when the cladding lifts off from the pellet, an effect not modelled in the primary systems code. This led to the development of the following

Module ZETHYD /22/.

This module combines the capabilities of the module ZET-1D for transient heat transport in and out of the rod with a simplified computation for the enthalpy distribution inside the coolant channel. From the axial distribution of enthalpy temperature and heat transfer coefficients are derived. Enthalpy, pressure and mass flow at the channel inlet and outlet are taken from RELAP4 as transient boundary conditions. The simplifying assumptions for calculating the transient enthalpy distribution are: No acceleration of the fluid by pressure gradients or friction, constant mass flow at all elevations. Several integration options are at the user's disposal. Integration of heat transport in the rod and in the channel, instead of coupling independent modules, was necessary to overcome numerical instabilities, indicating some limitation of the basic modular concept of SSYST.

4.8. Azimuthal effects.

Experimental evidence obtained since 1977 /6/ indicated that initial azimuthal asymmetries on the cladding surface, caused by eccentric position of the pellet, by initial asymmetric cooling, or by variations of initial cladding thickness, have a decisive influence on the whole deformation transient. By an autocatalytic mechanism an initially hotter section of the cladding is strained at a faster rate, stays nearer to the pellet, has to pass a higher heat flux than the favoured cooler section of the cladding and, thus, increases its temperature at a higher rate. The requirement to support such qualitative interpretations, at least semi-quantitatively, by adequate modelling led to the development of the following

Module AZI.

This module deviates, as an ad hoc development, to some degree from the strictly modular concept of SSYST. Heat transport, gap conductance, cladding deformation, and Zircaloy oxidation are treated by one module. It also has to model radiative heat exchange with surrounding rods, thus going beyond the single rod analysis usually performed with SSYST. So far, the module can treat only one selected axial zone, in which the most relevant deformation is expected. In order to perform fast computations in deformed spatial grids some efficient approximations had to be made, especially in coupling different physical phenomena. These simplifications seem justified, as for a concise treatment the most crucial parameter, viz. the pellet eccentricity, cannot be known but must be supplied as input by the user. Under SSYST-3 a new version of AZI is available, which can treat azimuthal variations of the cladding thickness. Also the burst criterion mentioned for STADEF has been implemented.

4.9. Other modules.

The application-oriented modules listed give an overview without a claim for completeness. Some modules listed in /1,2/ have been left out, having become obsolete. Worth mentioning as still active are the weakly integrated module RIBDTH /23/ for computing the initial fission fragment inventory and the modules RANDM and RAWAK, which have auxiliary functions in processing transient boundary conditions obtained from RELAP4 or WAK.

5. Applications.

SSYST has been applied to recalculate rod simulator experiments conducted on the experimental facilities COSIMA /5/ and REBEKA /6/ at KfK. In addition, in-pile experiments performed in the steam loop of the reactor FR2 at KfK /24/ have been analyzed. These experiments apply nuclear heating and steam cooling to simulate the refill-flooding phase of a LOCA, in which rod deformation is expected.
Finally, an extensive parametric survey /25/ has been conducted on the expected fuel rod behaviour under LOCA conditions. These calculations have shown that cladding deformation during a hypothetical LOCA is highly sensitive

(a) to details of the Zircaloy creep model, and
(b) to local temperature.

This high temperature sensitivity, for which a large amount of experimental evidence exists, leads to an extreme dependence on local power and on azimuthal temperature gradients caused either by pellet eccentricity and other imperfections of rod geometry or by minor variations of the thermal-hydraulics boundary conditions.

5.1. Recalculation of experiments.

Fig.5 shows a very favourable case of the recalculation of a FR2 inpile experiment. Size, form and location of the rod deformation are modelled quite satisfactorily, indicating the basic correctness of the SSYST models. In general, agreement between experiment and calculation is seldom as good as here. A more detailed analysis seems to indicate that in this special case the steep axial profile of boundary conditions in the experiment favoured a narrow localisation of maximum strain. Under these circumstances also the predictive capability of SSYST seems to be satisfactory.

If, on the other hand, the axial distribution of boundary conditions is rather flat, then minor local effects not included in the input data may determine the outcome of the experiment. The predictive capability of a code like SSYST will not be too good for such a case.

5.2. Parametric surveys and probabilistic analysis.

As in most practical cases some parameters, to which the transient behaviour of fuel rods is very sensitive, cannot be known with sufficient precision, one must have more confidence in results obtained from parametric surveys with a code like SSYST than in singular results. One obviously reliable result of a parametric survey is shown in fig.7, to which we will return (cf. 5.3).

The initial and boundary conditions for about 250 rods in a fuel element have stochastic components. Therefore, after a LOCA a wide distribution of their final deformations is expected. One may expect that incoherency in rod deformation will lead to lower degrees of flow restrictions in rod bundles than if all rods would deform coherently. To assess this feature, a probabilistic LOCA analysis for the most highly rated fuel element of a German PWR was performed, using a response surface method with Latin Hypercube sampling, multiple linear regression analysis over a set of free ansatz functions, statistical tests for the single rod response approximation and extension to the conditions in a bundle /25/. Figs.6a,b show probability density functions of peak cladding temperature (in the second heat-up phase) and final circumferential strain obtained for plausible distributions of the relevant input parameters. The study confirmed the optimistic expectations as to the influence of incoherency. Its main results were that

(a) cladding temperatures will always stay well below 1500 K, and

(b) significant deformations cannot be excluded.

But clustering of strongly deformed rods will not suffice to severely impede decay heat removal after the LOCA.

The new code-version SSYST-3 to be released in 1982 will contain the package of statistical routines used for performing this probabilistic LOCA analysis for a fuel element.

5.3. Investigation of azimuthal effects.

While the work reported in the foregoing paragraph showed that evaluation of simulated transient fuel rod behaviour, assuming rotational symmetry at all rods, leads to positive statements about the long-term coolability of rod bundles after a LOCA, it was of great interest to investigate the size and direction of the effects of azimuthal asymmetries.

Fig.7 demonstrates how total final circumferential strain at burst-time and final azimuthal temperature difference are correlated, when a constant pellet eccentricity in the (0.,1.)-interval is used as a parameter to classify the computed transients. Most important result of this model calculation, which still used a set maximum (local) strain to determine the burst point, was that increasing pellet eccentricity reduces total final azimuthal strain. Rupture is determined by the local strain at the hottest point, and this local strain is much higher. The experimental points, corresponding to a series of REBEKA bundle and single rod test, are sufficiently near the computed curve to support the validity of this model calculation.

Fig.8 is the result of a similar calculation performed for REBEKA 3 with the AZI-module containing the up-to-date NORA creep model and the burst criterion of SSYST-3. The fact, that in this case the dependence of the final azimuthal temperature difference on the assumed constant pellet eccentricity is truly linear, is coincidental. Other cases show some curvature. Very significant was the discovery that the measured average strain at the axial level of maximum blockage can be reconciled only with a very high value of assumed pellet eccentricity. Tentative calculations performed for several bundle tests, using the maximum value of 1.0 for pellet eccentricity, have been collected into fig.9. Although the phenomenon is not yet explained by a quantitative theory, the data shown seem to support this finding /26/.

5.4. Feed-back from users.

Generally, development of the code-system and the physical modules has progressed at satisfactory speed, when there was sufficient feed-back from users. In some cases, somewhat extreme choices of input parameters in user applications led to the discovery of errors, which would have stayed unnoticed in normal code testing.

More important was the intensive exchange with users, which took place in the development of the module AZI. In a similar fashion, the improvements introduced into the NORA creep model /18/ were considerably influenced by reports from independent users that the first model of NORA, used in SSYST-2, consistently showed Zircaloy to be weaker in simulations than in real experiments. In these two cases applications of SSYST definitely improved our understanding of the underlying physics and in return influenced modelling in SSYST.

6. Conclusions, future development.

SSYST has been shown to be a flexible tool for modelling transient fuel rod behaviour under off-normal conditions, which can also be applied to the analysis of safety-related experiments. The agreement between the understanding obtained from experimental evidence and model calculations is quite satisfactory. On the other hand, calculational accuracy of cladding deformations shows limitations due to considerable uncertainties in the initial state and the thermal-hydraulics boundary conditions.

Deviations from rotational symmetry of the fuel rods, which are likely to occur always, are difficult to model accurately, although calculations with simplified models show good qualitative agreement with experimental findings. Most important is that such deviations tend to reduce the amount of global rod deformation. Therefore the situation of rotationally symmetric geometry and boundary conditions for the rods, which is the standard case for codes like SSYST, is also a worst case, which can always be used as an evaluation model, for licensing etc.

We believe, that the models implemented now in SSYST are sufficient to assess the impact of a large break LOCA. For the analysis of small break LOCAs and experimental set-ups related to this type of accident, model improvements and new models of fuel-cladding interaction valid at higher temperatures will be needed. In addition, in many applications proper 2-phase thermal-hydraulics will be required. We hope that the modular structure of SSYST will enable us to convert gradually the contents of our code system in these directions without having to change its basic concept.

7. Acknowledgements.

The authors of this paper have for a long period been responsible mainly for the overall code organisation of SSYST and only for a minor part of the application-oriented modules. It would not be possible and also not fair, just to give a complete list of all persons, who at any time have contributed to this modular code-system.

Decisive contributions to the SSYST development have come from many members of the institute IKE, Stuttgart, and the institutes IRE, INR, IRB of KfK, Karlsruhe, who participated in the development of the nucleus and of modules. A special acknowledgement is due to all those, sometimes frustrated, users who were involved in validation.

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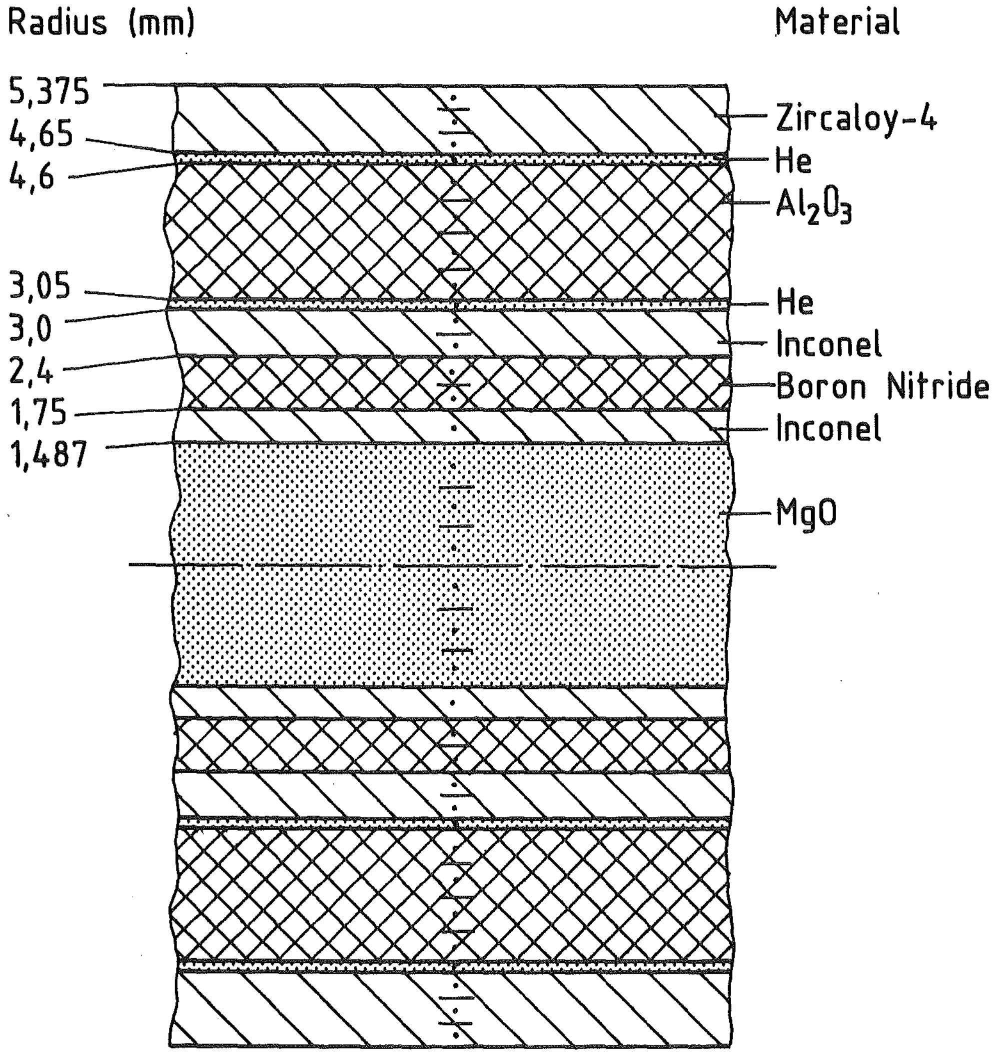
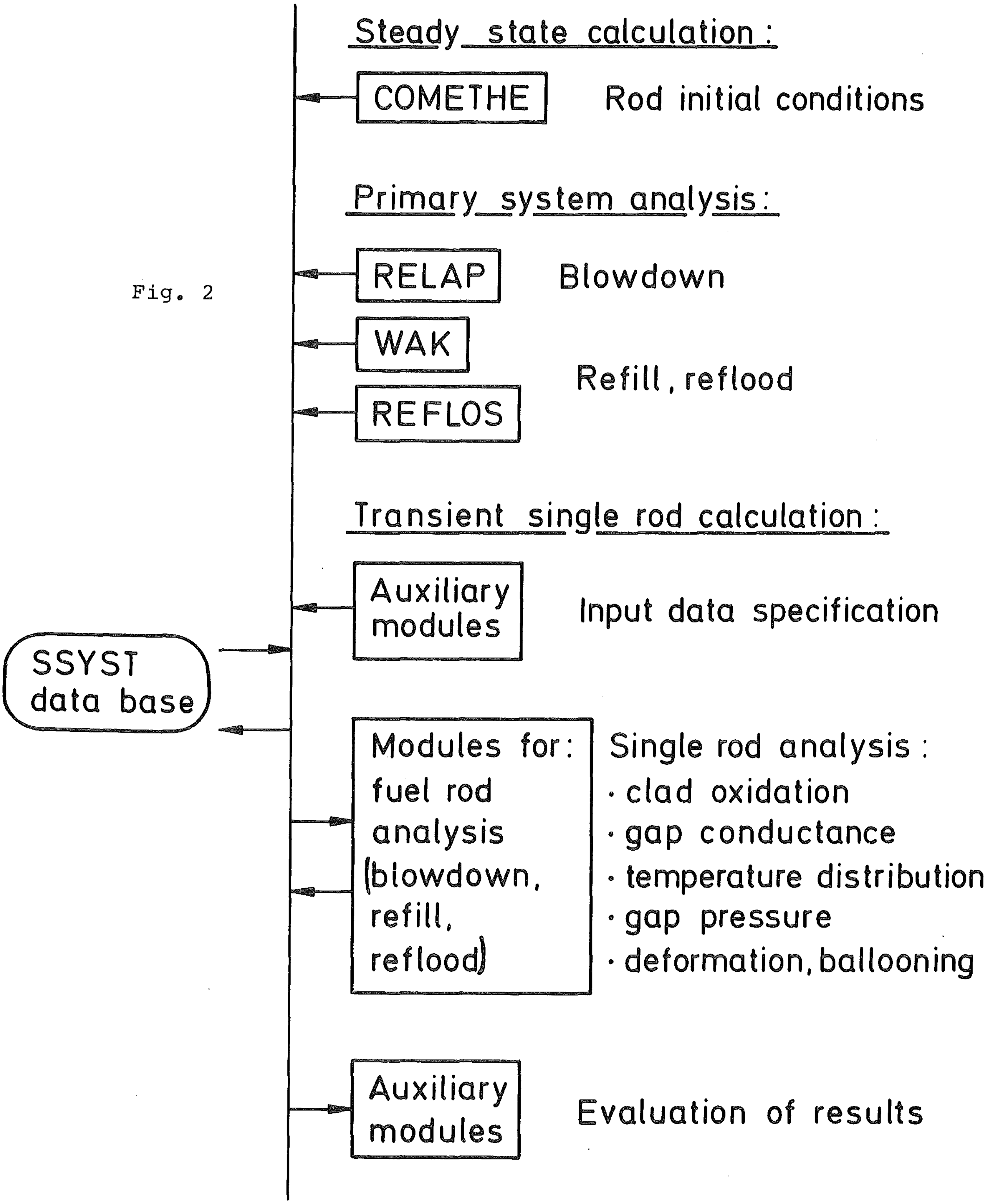


Fig. 1

KfK

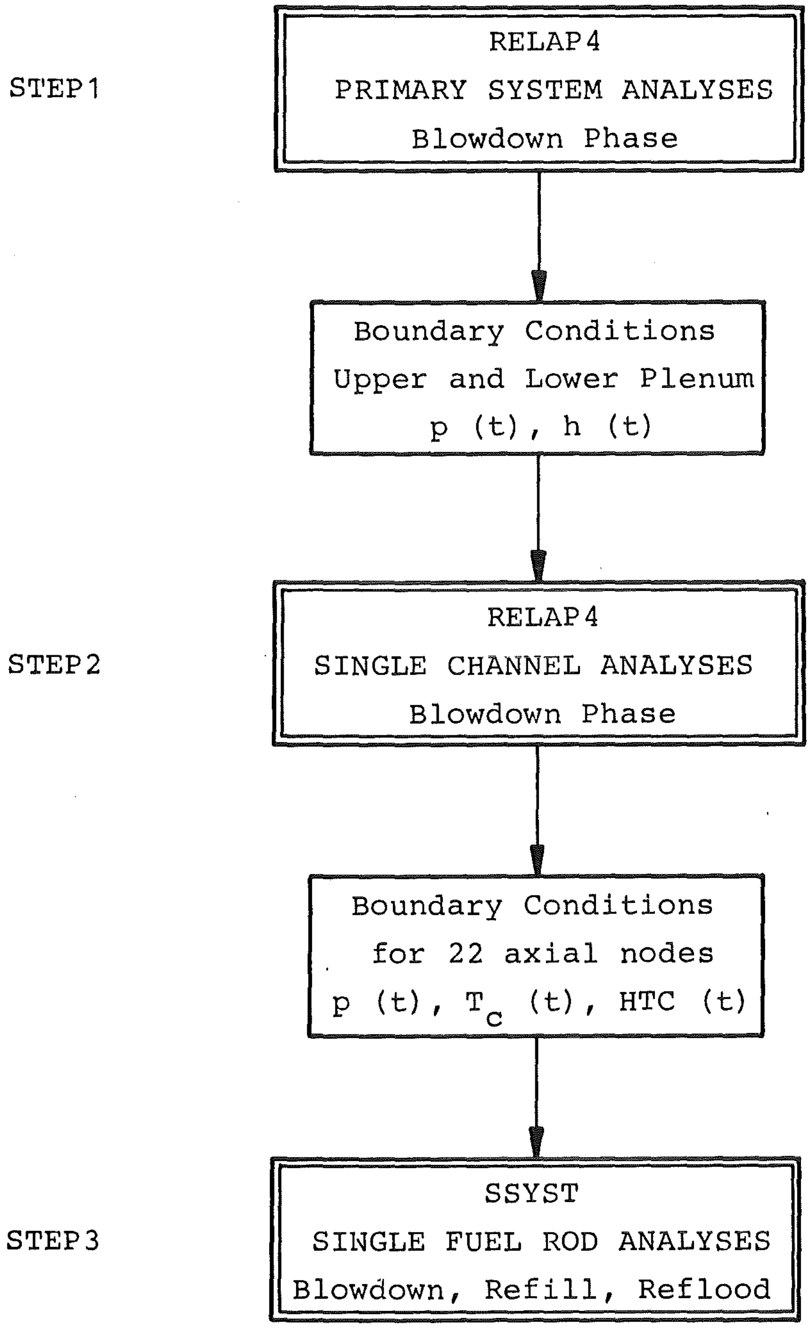
Cross Section of the REBEKA Fuel Rod Simulator

Fig. 2



SSYST-2: LWR Fuel Rod Safety Analysis

Fig. 3



KfK IRE

LOCA simulation with RELAP4 and SSYST

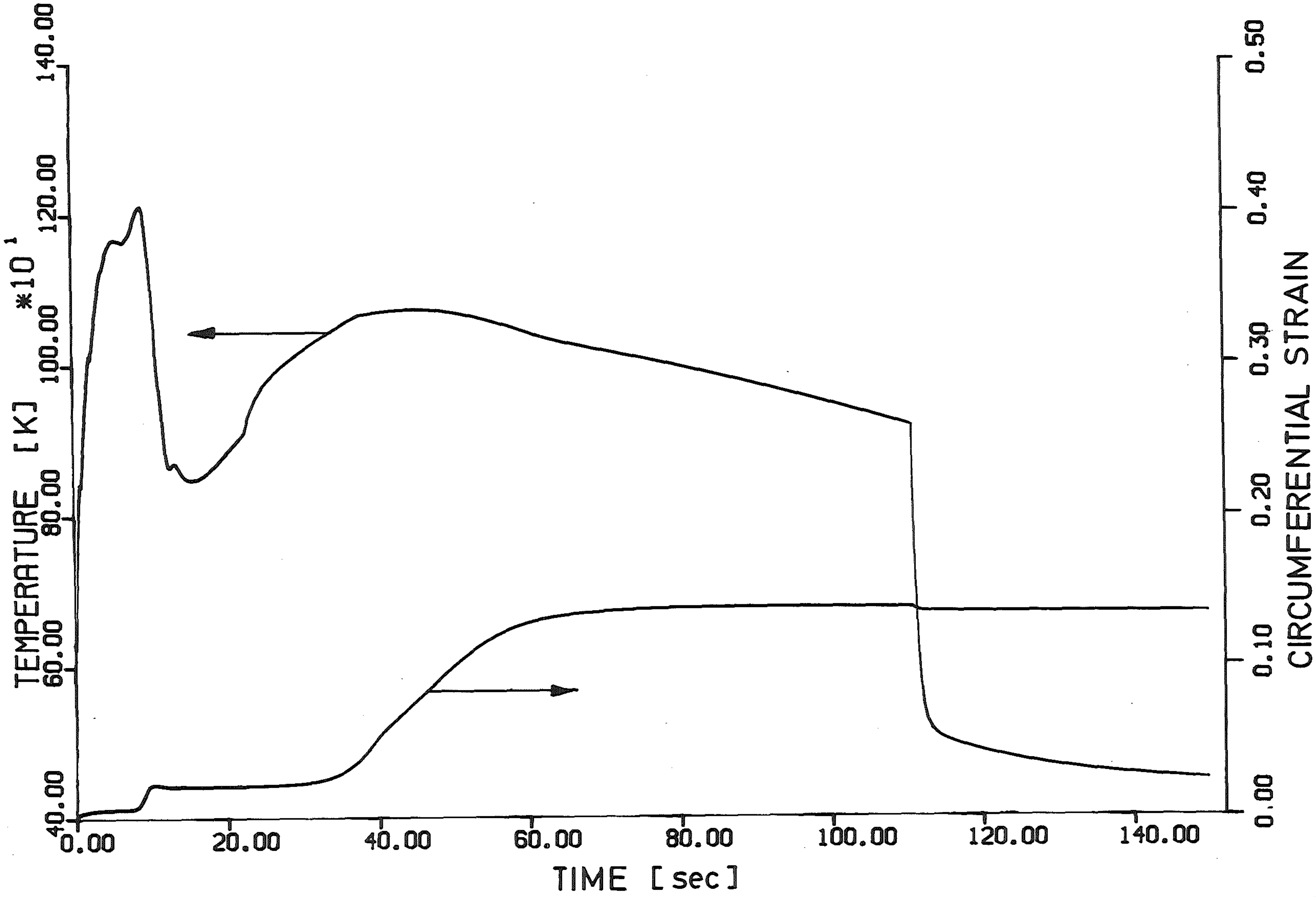


Fig. 4

Transient cladding temperature and circumferential cladding strain respectively for a PWR fuel rod following a postulated 2F-LOCA evaluated by SSYST

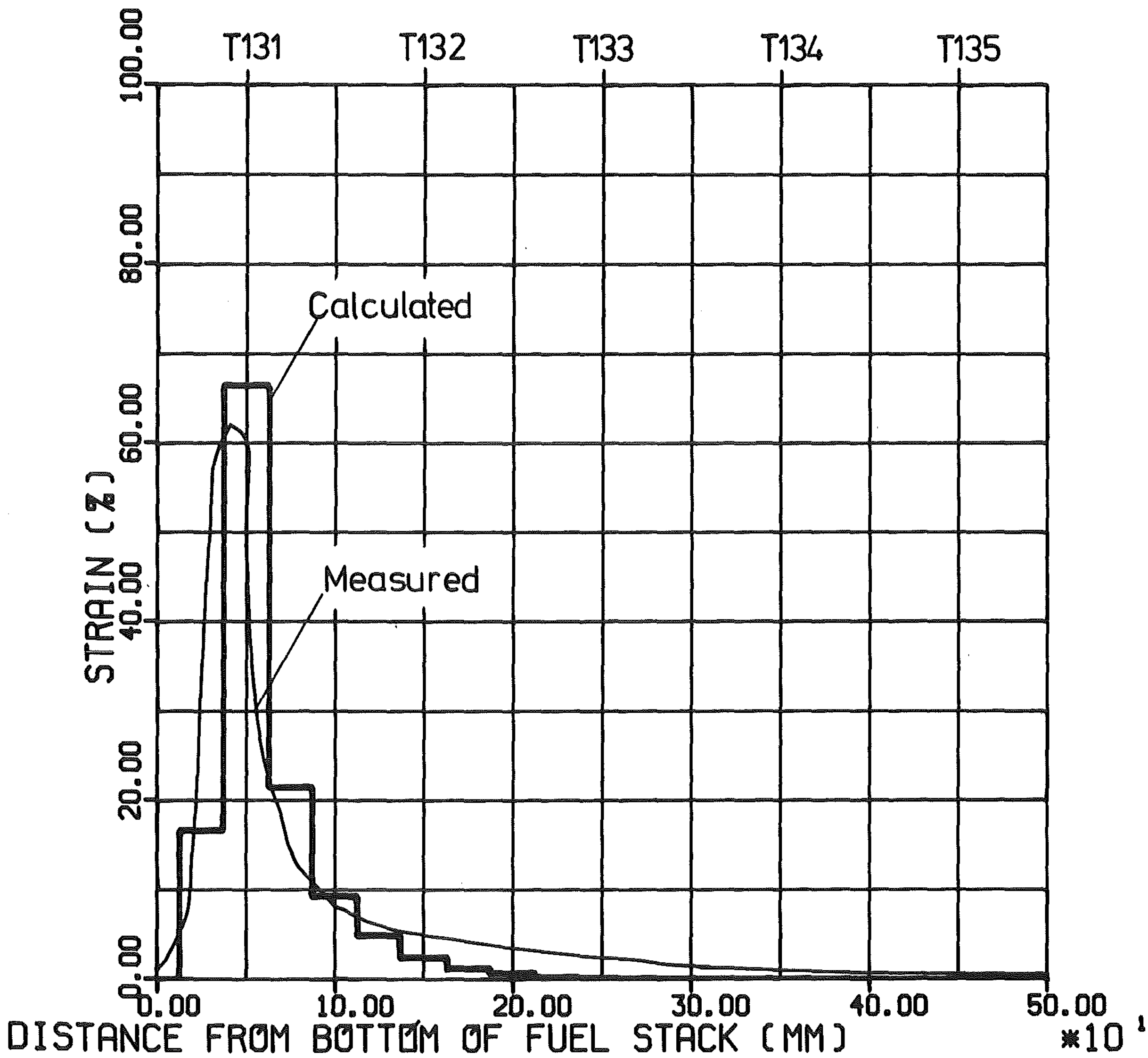


Fig. 5

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FR2 IN-PILE TESTS: TEST A 1.1

CALCULATED AXIAL STRAIN PROFILE USING MODEL 3

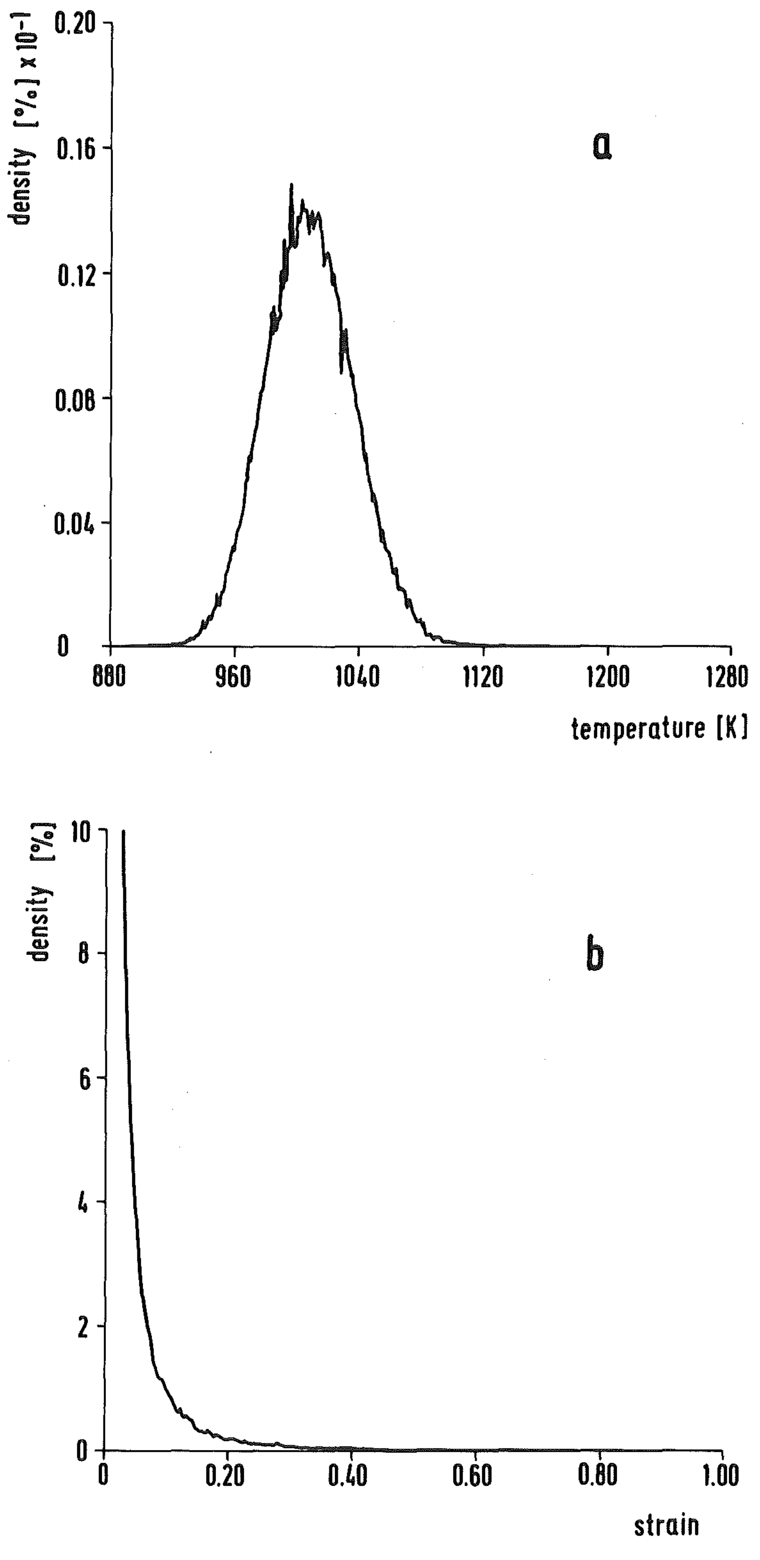


Fig. 6

KfK IRE

Probability density function of peak cladding temperature (a) and final strain (b)

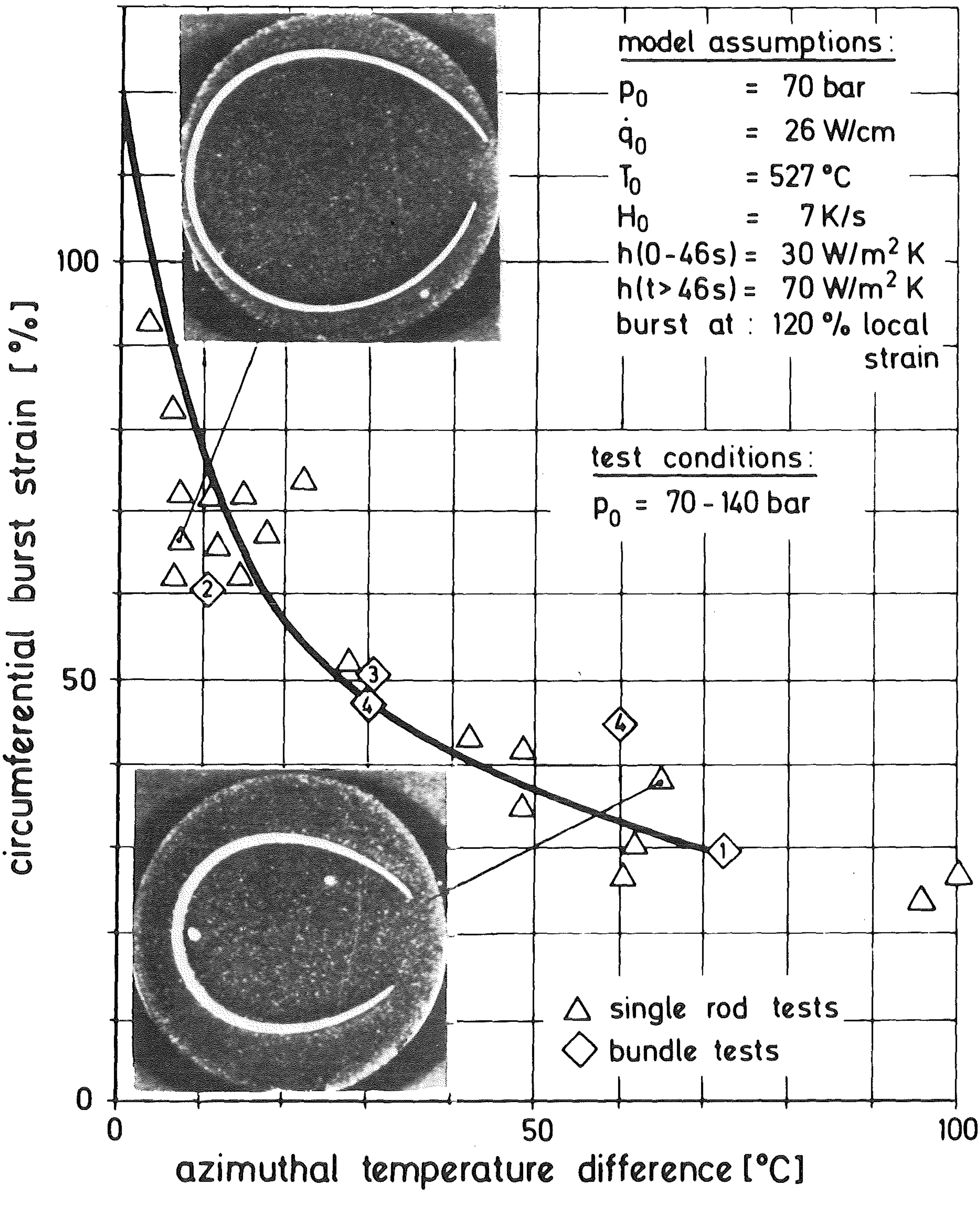


Fig. 7

Burst strain vs. temperature difference

(SSYST/AZI-prediction and test results)

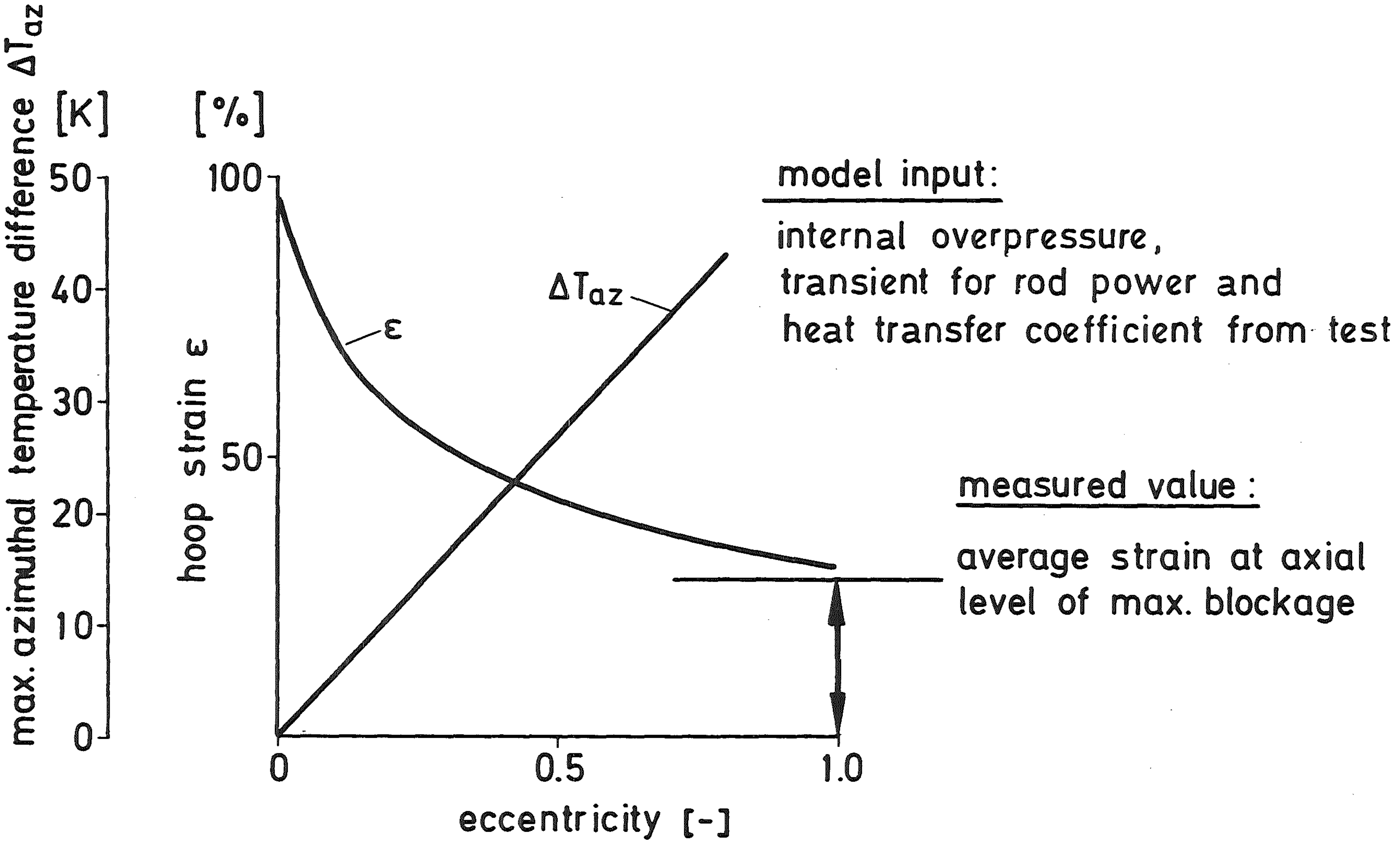
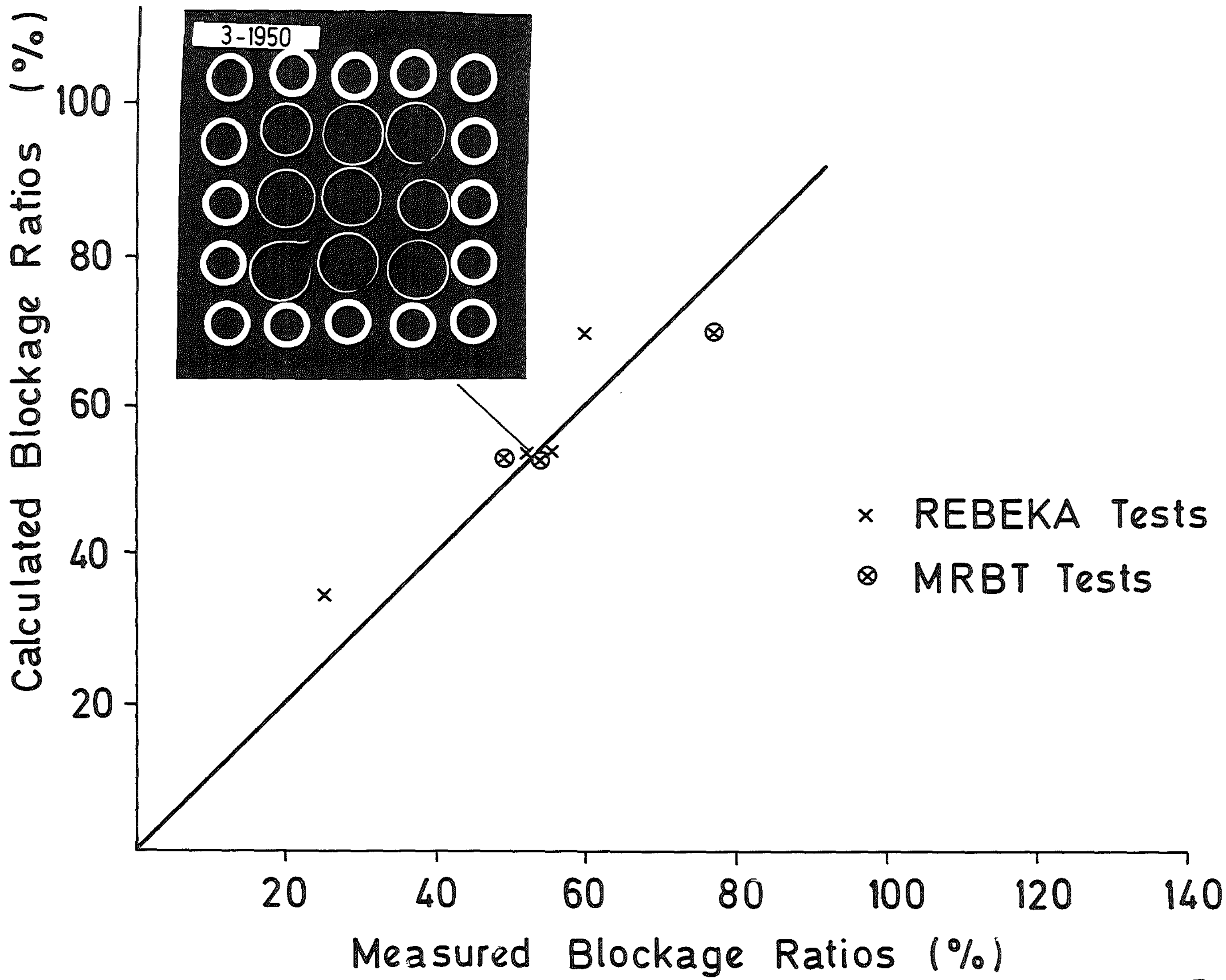


Fig. 8

Influence of eccentricity on azimuthal temperature difference and burst strain for REBEKA 3



KfK

Comparison of calculated and measured blockage ratios