Transactions of the 17th International Conference on
*Structural Mechanics in Reactor Technology (***SMiRT 17***)*
Prague, Czech Republic, August 17 –22, 2003

Paper # D04-1

Ageing Management of the Steam Generators of the Nuclear Power Plant GKN

J. Bartonicek1), W. Zaiss1), F. Schöckle2)

1) GKN Gemeinschaftskernkraftwerk Neckar GmbH, Neckarwestheim
e-mail: Jaroslav.Bartonicek@GKN.de
2) AMTEC Services, Lauffen, Germany

ABSTRACT

The quality of components and systems in operation has to be assessed depending on the demands. Regarding mechanical components, three groups can be defined:

- group 1: Integrity Concept (guarantee of integrity)
- group 2: Preventive maintenance (maintain initial quality)
- group 3: Failure orientated maintenance (re-establish initial quality)

Components and systems that are relevant to the safety of a plant are classified into groups 1 and 2. These groups usually are target of ageing management programs.

Within the frame of ageing management, all ageing phenomena of the steam generators -amongst other components - are regarded and assessed in GKN.

The shells and the nozzles of the steam generators belong to group 1 (integrity has to be guaranteed). Physical ageing is assessed by intensive monitoring of the loads and the medium. Monitoring has first priority regarding the guarantee of integrity of the components in this group. In the paper, monitoring details (measurement points, measurement system) and significant results of the monitoring are discussed using the steam generators as an example. Non-destructive testing is a redundant measure. The effort of non-destructive testing and the testing intervals are determined by the results of monitoring. Technological ageing and the ageing of the concept is assessed by tracing and assessment of knowledge.

The steam generator (heat exchanger) tubes belong to group 2 (preventive maintenance), i.e. the quality in operation is maintained by use of repeated inspection and testing (non-destructive testing). There were some problems with wastage in the first years of operation of GKN I. Since a change in water chemistry these problems have been reduced, drastically. Loose parts fretting still occurs, from time to time. This effect is controlled by ndt and by a very sensitive leakage (activity) monitoring on the secondary side of the steam generators. In total, the number of closed pipes due to wastage and fretting is low.

KEY WORDS: nuclear, power plant, steam generators, ageing, ageing management, integrity, monitoring, preventive maintenance, failure orientated maintenance

INTRODUCTION

Safe operation as well as economical aspects of nuclear power plants depend highly on *integrity and function* of the components and systems in use. More general, integrity and function can be expressed in terms of *quality*.

The initial step to establish a required / demanded quality status of systems and components is performed during the *state of design*. Main goal of the design is to consider every possible damage mechanism of the future operation (by specification of loads, medium and environment and the selection of the materials). The knowledge during the state of design determines the reliability of the component. Goal of the design analysis (stress, fatigue and –if necessary - fracture mechanics analysis) is to demonstrate, that the results are within given limits. It is obvious that the design process does not provide conclusions regarding the state of component quality after a given period of operation.

The *manufacturing process* is important for the quality status of components, too. The demanded quality can only be achieved if there is a thorough control of material composition and behavior, of constructive details and of the desired fault-free state.

In *operation* integrity and function (safety, remaining life) of components and systems can be affected by ageing phenomena, **Fig. 1**. The ageing of the basic concept includes changes of the demands on a system and changes in the overall safety philosophy which result from experience (incidents, faulted conditions etc.). The existing status of systems and components has to be analysed periodically (e.g. in the frame of a periodic safety analysis). If there are deficits, components must be replaced or even new systems have to be built in. The ageing of technology is caused by changes in knowledge, e.g. regarding possible damage mechanisms, material or component characteristics, test procedures, calculation procedures. These changes in knowledge result from research or product development projects or from analysis of operation experience. For a careful analysis detailed evaluation of the existing design (as built – not from specification) and realistic load histories are necessary. As consequence of the analysis the operation procedure may be changed, it may be necessary to optimise the component and its bearing constructions or even replace it. Ageing of materials is a result of damage mechanisms in operation. Generally, changes of material characteristics, loads and medium cause material damage like material degradation, fatigue, corrosion, wear and combinations. Obvious results of these damage mechanisms can be changes in material behaviour, changes in surface structure, notches, crack initiation, crack growth, leakage, malfunction etc.. For systems and components where the damage mechanisms have to be under control, monitoring is the most appropriate measure. Monitoring of the *causes* for damage has significant advantages over monitoring of the *results* because there is the possibility to reduce the damage mechanism itself in time rather than to prevent follow-up failures (*pro-active procedure*).

The integrity of a component in operation (safety, remaining life) is determined by the real operation history, **Fig. 2**. As operation experience shows, failures, defects and not specified (new) loads are discovered during operation, e.g. stratification effects in feedwater pipes in surge lines or thermal effects in the region of valves. Additionally, demands (e.g. fixed in standards) and / or the knowledge base may be changed.

Therefore it is obvious that - after a certain period of operation – the state of quality is determined by the

- quality after design and manufacturing *and* by the
- measures that are applied to guarantee, maintain or re-establish this quality during the period of operation.

Part of the bundle of measures to assess quality during operation are monitoring of the loads, non-destructive testing, function tests, inspections etc. If necessary, maintenance action has to be performed to maintain or re-establish the initial quality.

The *demands on quality* can be individually defined for every component or system; the measures to guarantee, maintain or re-establish the initial quality depend on these demands on quality. On this basis it is possible to define groups of systems and components, resp. parts of components:

- group 1: Guarantee of integrity
- group 2: Preventive maintenance
- group 3: Failure orientated maintenance

Regarding the components of the first group the causes for damage in operation have to be controlled by monitoring. Monitoring of the consequences of possible damage is another redundant measure to prevent failure of these components. Part of this group are components that must not fail under safety aspects (and where in addition possible damage cannot be excluded) and those components that could induce major follow-up failures in case of their failure (even if the failure of the component itself could be managed). As this *proactive approach* reduces costs for repair, unexpected shutdown periods, follow-up failures etc. the utilities often increase the number of components in this group for economic reasons. As an example **Fig. 3** gives the components in this group for the utility GKN I.

In group 2 possible results of damage mechanisms have to be detected using preventive maintenance (incl. ndt). The measures have to be carried out periodically or depending on the condition of the component. Repair or replacement action should be scheduled in time (before failure); exceptionally, components of group 2 can fail. To prevent “common mode” failures the components must have an appropriate quality. This quality has to be proven during design and manufacture as well as by the assessment of the results of maintenance regaring the actual knowledge, too. All safety relevant components (except those that are in group 1) belong to this group 2.

All other components are classified in the third group. A failure of a system or a component in this group is not relevant to safety and to economical aspects of operation. Economical aspects, however, can be the reason to classify components in a “higher” group.

Regarding the steam generators of GKN I and GKN II, the shell of the components belongs to group 1 (guarantee integrity), the heat exchanger tubes are classified in group 2 (preventive maintenance).

GKN PROCEDURE

GKN uses the basis safety concept to quantify the safety and the integrity of components. The safety during operation depends on the one hand on the "quality status as result of production" (design and manufacturing) and on the other hand on the "independent redundancies" (in operation). These "independent redundancies" include monitoring of possible damage mechanisms in operation and the consideration of changes in knowledge and safety analysis procedures.

The integrity of components in operation cannot be demonstrated using only a comparison of the designed (specified) construction and material characteristics with the construction and material characteristics of the manufactured components (including material properties, geometrical details, fault-free state etc.). Operating experience is essential and must be considered. The number of possible damage mechanisms can be reduced, if the operation experience is evaluated steadily (results of maintenance, inspection, non-destructive testing, etc.). This is especially true with dynamic loads, corrosion, wastage and fretting problems. The potential causes of damage which cannot be excluded on the basis of the operating experience has to be monitored.

As shown in **Fig. 4**, the monitoring of the causes for a possible damage has first priority within the GKN - procedure to guarantee integrity of components (**GIMOP** – Guarantee of Integrity by Monitoring of Operation) . The loads in operation are the most important damage mechanism in German PWR´s; environmental effects are negligible in important systems. As a consequence, in GKN the loads are extensively monitored. The safety margin is quantified by use of stress analysis, fatigue analysis and fracture mechanics. In these calculations measured operational loads (results from monitoring) are used as the input for service levels A and B and for the pressure tests. For the calculation of emergency and fault levels C and D the most actual specified load histories are used. Using these loads, the safety determination is much more realistic than the safety determined from design analysis.

Monitoring of the results of a possible damage mechanism (inspection and non-destructive testing) is done to reduce remaining uncertainties. Experiences of other utilities and the results of research work are also considered.

ACTUAL STATUS OF THE STEAM GENERATOR SHELLS

Existing as-built / as-operated status

Construction details and the most important dimensions of the GKN I steam generators are shown in **Fig. 5**. For the analysis of the existing status every single material certificate of every single part of the steam generators was evaluated and fed into a database. Then the material characteristics were compared to current demands. The GKN II steam generators were manufactured according to the most actual standards and specifications. Therefore no deficits were recorded in this case.

The material compositions of the steam generator materials of GKN I only show a few minor differences compared with actual specifications. The characteristic values (mechanical-technological tests) lie within the specified limits (specification of 1973); they still lie within the limits of actual standards. Because the current stress limits are significantly lower than those used during design, the wall thickness of parts, which were not designed with additional safety margins, lie below the minimum wall thickness, that are necessary on the base of actual standards. This fact had to be analysed in stress and fatigue analysis. Other design deficits compared to actual designs are the use of longitudinal welds, and the welds in regions of geometric transitions.

Non-destructive testing after manufacture showed no damage. All (relevant) sections of the steam generators are inspected regularly. No damage has been found until today, which could be a result of operation. Eddy current wall thickness measurements of the steam generator tubes of GKN I showed wastage in early years. Further wastage was stopped by a change of water chemistry.

Loads

GKN has installed an extensive monitoring of the loads of important components. **Fig. 6** gives an overview of the local and global measurement points, that are instrumented at each steam generator of GKN I; additionally, **Fig. 7** shows the measurement point locations at the feedwater piping system near to the steam generators. The global and local measurement points of the steam generators of GKN II are located similarly.

In the regions of the feedwater nozzles of GKN I non-specified loads were discovered in the late 70´s. During startup and shutdown of the plant, when the steam production is low, there are temperature transients in the horizontal parts of the feedwater piping near the feedwater nozzle, which are a result of the non-steady feed water flow to the steam generators. An example of the measured data in the region of the feedwater nozzle can be seen in **Fig. 8**. This example shows, that the sludge system - specific in GKN I -determines the cycles near the feedwater nozzle; if the sludge system is in operation, additional hot water is fed into the feedwater piping. As a result, the temperature cycles in the region of the feedwater nozzle are smaller. At the feedwater nozzles of GKN II, similar loads due to stratification can be found. The characteristics of the stratification effects are different from those of GKN I as there is no sludge system connected to the feedwater piping in GKN II.

The non-steady feeding results in time dependent temperature transients and in local temperature distributions (stratification). If stress analysis and fatigue analysis have to be realistic, this must be taken into account, i.e. the events must be measured locally and analysed individually. The effect of the transients are concentrated in the region of the feedwater nozzle only, thanks to the specific construction of the feedwater distribution system. The temperatures in the steam generator do not show any changes, that could be related to the feeding processes.

Analysis of the loads

On the basis of real load data (i.e. data from monitoring), new stress analysis and fatigue analysis calculations were performed for important / representative parts of the component (the tube sheet and the connected sections, geometrical transitions (change in shell thickness, cone), feedwater nozzle, steam nozzle).

The stresses in the cylindrical sections (secondary side) exceed the current limits for design conditions due to the fact, that the wall thickness was determined on the base of conventional standards. However, for service loads in the levels A and B, the stresses are above the current limits. This reduction in safety margin (2.4 instead of 2.7) was agreed to be still acceptable, especially because there is a continuous monitoring of the existing loads. The other stress categories lie below actual limits, according to the new (more detailed) calculations. This was also the fact for the load levels C, D and P.

Non-specified transients are limited to the region of the feedwater nozzles only. The thermal loads show very different characteristics with time, so a sensitivity study was made to determine the relevant parameters. The study included

- temperature changes with time (uniform temperature over the cross section)
- temperature distribution in the cross section of the pipe (stratification)
- forces and moments acting on the nozzle, which result from the stratification in the piping system.

As the loads are rotation-symmetrical, the temperature changes with time have been studied with a 2-dimensional (2D)-FE-model. The maximum stress is calculated for the region between the thermal sleeve and the nozzle. This study showed, that the resulting stress values depend mainly on the temperature difference between the pipe and the steam generator. A temperature change (span 100 K) with a gradient of 5 K/s (uniform distribution across the cross section of the pipe) results in an increase of the maximum equivalent stress of about 24 MPa compared with the steady state stress of 269 MPa, **Fig. 9**. The effects of stratification and the stresses from global forces and moments acting on the nozzle were studied in a 3-D-FE-model. Results for GKN II are shown in **Fig. 10**.

The fatigue usage factor of the feedwater nozzle conservatively covers the other regions of the steam generator. The time histories of the temperature loads, the resulting stresses in the region of the feedwater nozzles, and the number of cycles have been evaluated. The fatigue analysis, that has been made according to the KTA 3201.2 standard, resulted in a usage factor of $D < 0.1$ (GKN I) for the past operating time of about 20 years and $D < 0.05$ (GKN II) for about 10 years of operation, now.

The increase of fatigue usage factors is expected to be significantly less than until today due to modification of operation (GKN I - startups and shutdowns are made with the sludge system in operation; GKN II – number of cycles minimized). Fracture mechanics analysis showed that postulated failures cannot grow under operational loads and there is a sufficient safety margin against failure.

MEASURES TO GUARANTEE INTEGRITY OF THE SHELLS IN FUTURE OPERATION

The existing high quality of the steam generators was proved with above analysis. This quality has to be maintained in future operation using appropriate measures. These measures can be separated in measures to control the causes of possible damage in operation and measures to control the results of possible damage.

In GKN the first priority is given to the monitoring of the *causes* of possible damage during operation, ref. to Fig. 5. Comprehensive monitoring of the loads is essential. The extensive global and local measurements, which are performed by GKN, turned out to be a correct choice; this procedure will be maintained in the future. Monitoring of water chemistry is part of the plant operation handbook. This monitoring is performed further; the results are included in future integrity analysis, too. NDT is used to control *results* of possible damage in operation. As there is an extensive monitoring of the causes for possible damage, NDT in general has less priority. On the other side there is a proved high quality status of the component. Therefore the NDT regions, methods and test intervals can be taken from KTA 3201.4 as recommended for „base safe components“.

In the case of GKN I, this procedure led to a drastic reduction of NDT-effort, as a lot of additional tests could be cancelled on the basis of above evaluations and the GIMOP procedure. Additionally, an extension of the inspection intervals from 4 to 5 years resp. 8 to 10 years was possible. The resulting cost reduction easily covers some more efforts on the side of monitoring of the causes.

STATUS OF THE STEAM GENERATOR TUBES

The steam generator tubes are categorized into group 2 within the ageing management procedure. Results of damage mechanisms in operation like reduction of wall thickness, cracks etc. are controlled by eddy current testing, regularly. The most recent review of the quality status was performed in 2001 (critical review of design aspects, actual structure, operation experience and actual knowledge).

In the years following the initial startup of GKN I, *all* of the tubes have been tested several times. In the early years of plant operation some tubes showed a reduction of wall thickness due to wastage and AVB-fretting. Those with a wall thickness less than 50 % nominal thickness have been shut with plugs. Using measures like chemical cleaning of the steam generators and a change of water chemistry (“high-AVT-conditions”) the reduction of wall thickness could nearly be stopped.

Until today, 10 tubes had to be closed due to damage caused by loose particals. **Fig. 11** gives a statistical overview regarding the tubes of the steam generators of GKN I. As a result of damage caused by operation, 4 tubes (YB30B001), 9 tubes (YB10B001) and 11 tubes (YB20B001) had to be shut.

Based on the existing quality, the number of steam generator tubes that are tested in future using ndt- methods has been reduced to the numbers given in the German nuclear standard (actually 10 % of the tubes in every 5 year interval).

CONCLUSIONS

For a long-term guarantee of integrity in operation it is necessary to prove / quantify the existing quality of the component in a first step; from this point on, this quality has to be conserved in the future operation using appropriate measures.

In most of the cases, the proofs of the design state and the state right after manufacturing are not useful, due to the analysis procedure (goals) and the specified data. The existing quality of a component is determined by damage mechanisms during operation; therefore only sufficient monitoring of the causes for operational damage results in a reliable quality status review.

Consequently, the monitoring of the *causes* for operational damage has first priority in the measures to guarantee integrity of a component. The analysis of the results of this monitoring enables an optimisation of operation parameters and a life time management of components. Non-destructive testing methods are redundant measures within this concept; they are used to find possible *results* of damage mechanisms. NDT can only be successful, if test method, test regions and test intervals are appropriate; this depends on the existing quality, knowledge about possible damage mechanisms and consequent monitoring of the causes for possible damage mechanisms.

An integral concept for a long-term life time management (guarantee of integrity) not only improves the safety of a utility, it improves economic aspects, too.

conceptual ageing	**physical ageing**
changes in demands	*damage mechanisms in operation like:*
• changes in safety philosophy	• material embrittlement
	• material fatigue
technological ageing	• corrosion
new knowledge about:	• wear
• possible damage mechanisms	• combination of above mechanisms
• materials and design characteristics	*causes are in general:*
• test procedures	• material (degradation)
• procedures for analysis	• load history
• calculation procedures	• medium / environment history

Fig. 1: Ageing Phenomena

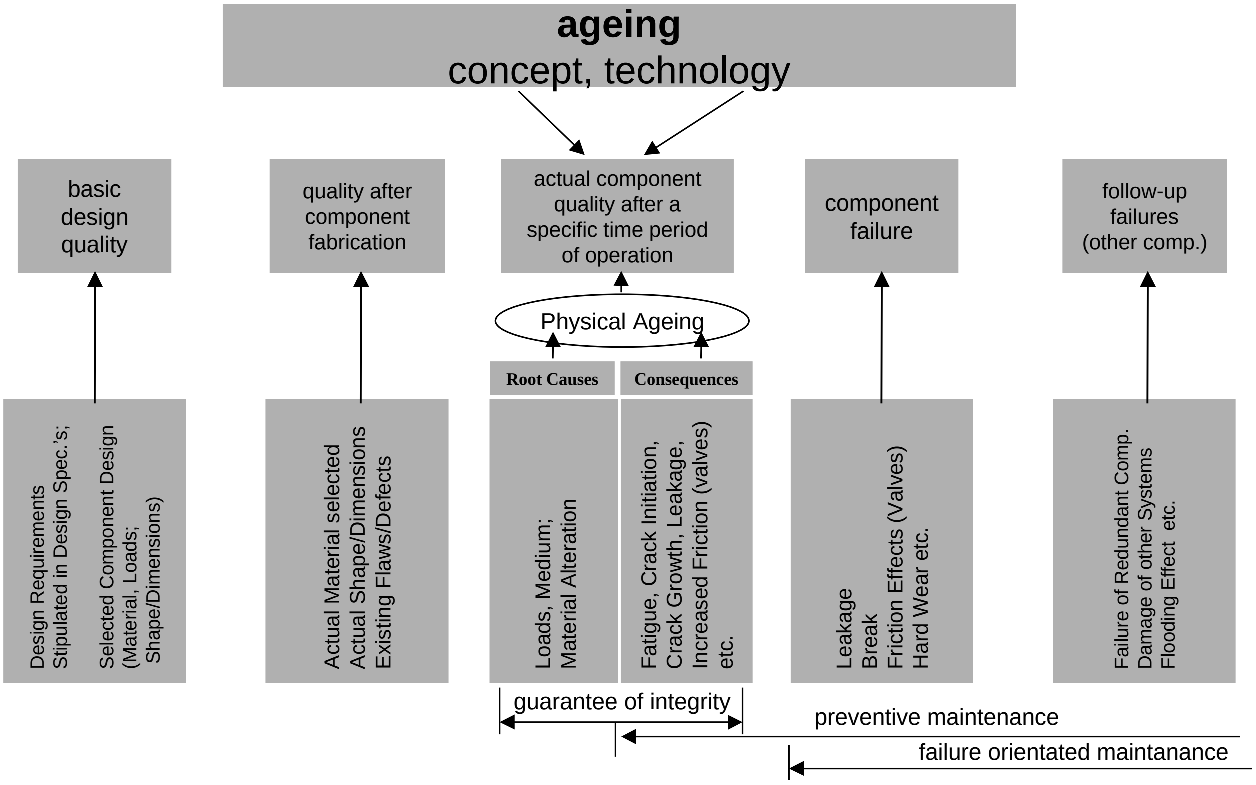


Fig. 2: Design Quality and Possible Degradation in Operation

- nuclear pressure vessel
- steam generators
- main coolant loops incl. shell of the pumps
- surge line
- pressurizer
- volume control system / charge line
- emergency an aftercooling system
- spray lines
- steam generator sludge system
- feedwater system (ZA- and ZB- building)
- main steam lines (ZA- and ZB- building)
- turbine shaft

Fig. 3: GKN I – Components in Group 1 (Integrity)

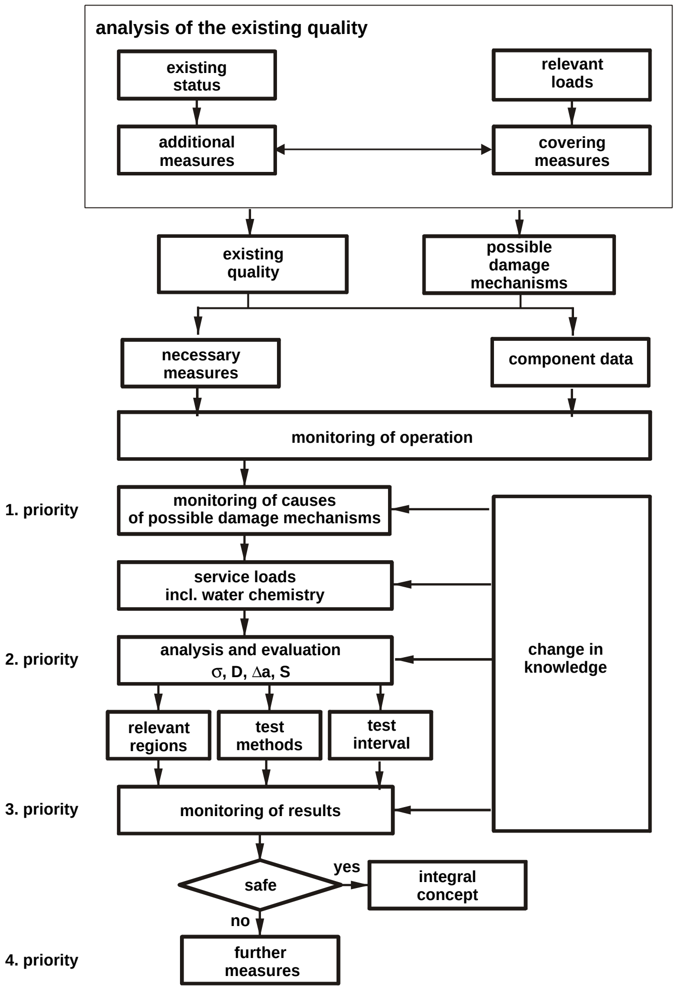


Fig. 4: GIMOP Procedure

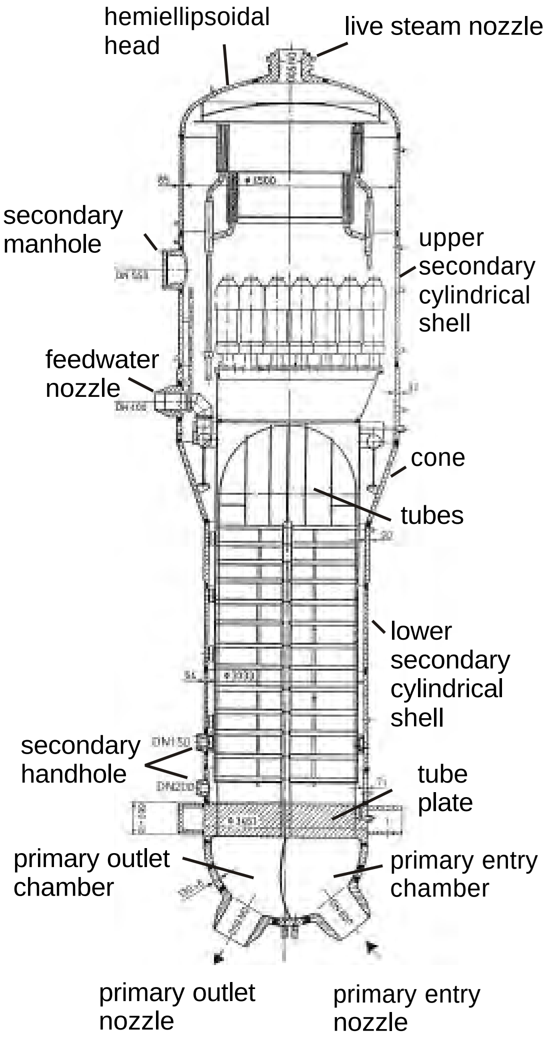
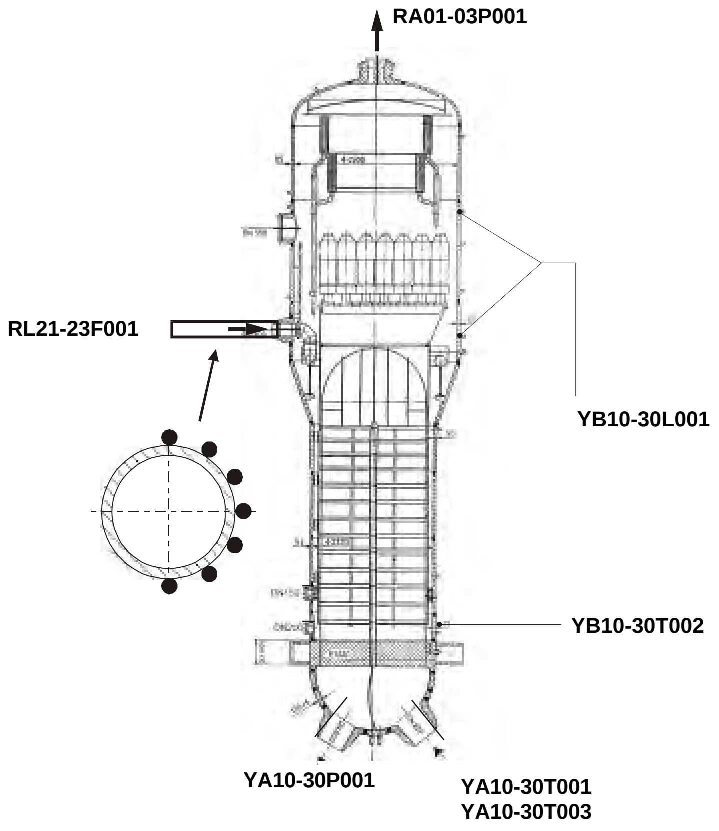


Fig. 5: Steam Generator GKN I



global :

- primary inlet temperature
- primary outlet temperature
- primary pressure
- feedwater mass flow
- feedwater temperature
- steam temperature
- steam pressure
- steam generator level

local :

- feedwater temperature distribution (3 sections)

Fig. 6: Monitoring at the Steam Generator GKN I

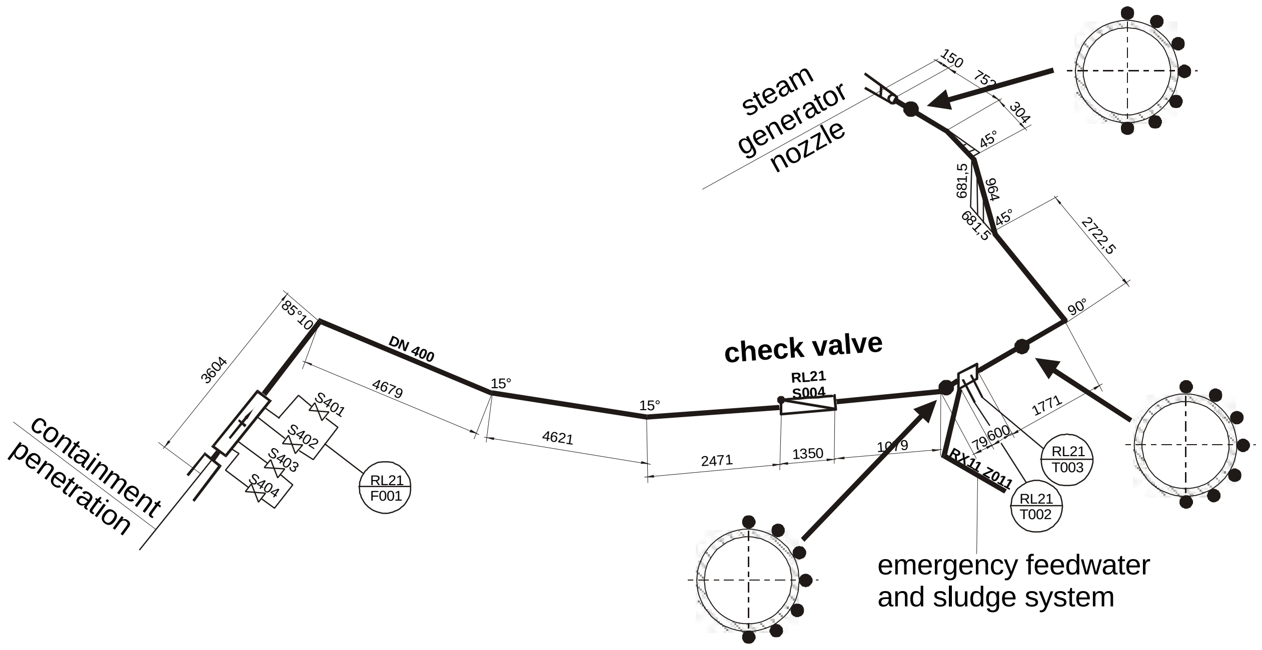


Fig. 7: Monitoring at the Feedwater Pipes of GKN I

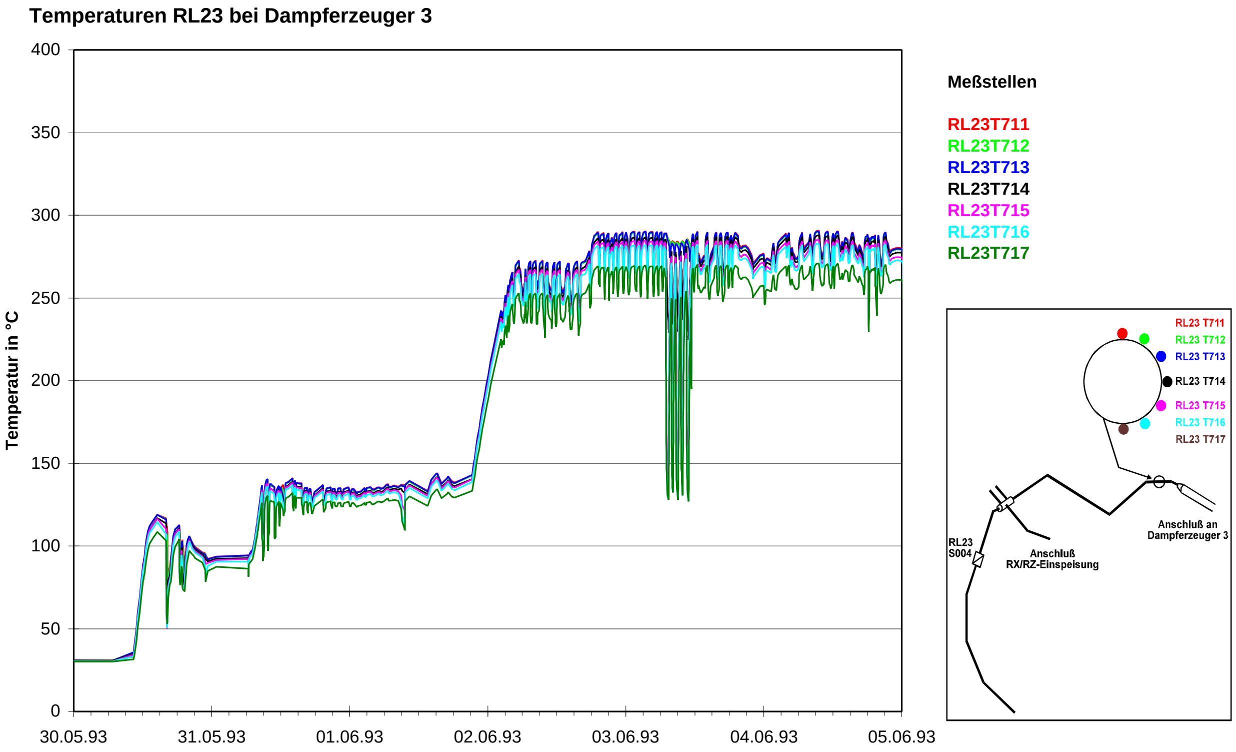


Fig. 8: Temperatures near Feedwater Nozzle of GKN I

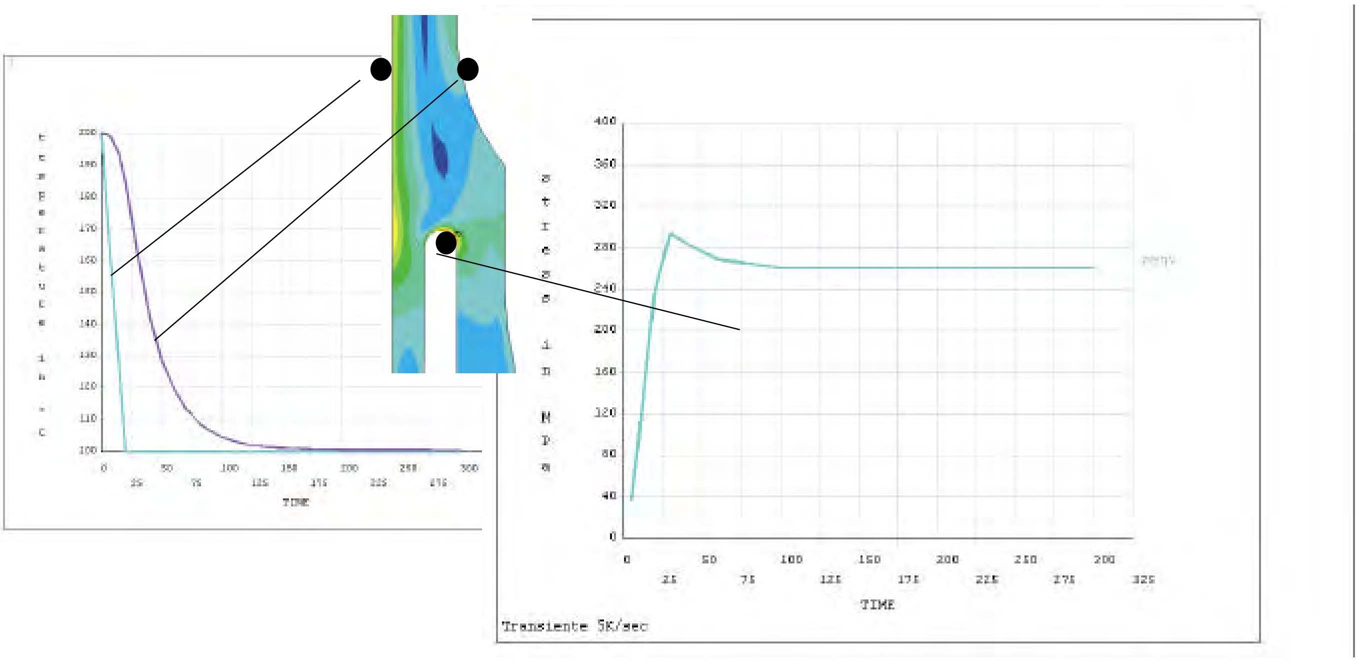


Fig. 9: Effect of a Temperature Transient on the Feedwater Nozzle

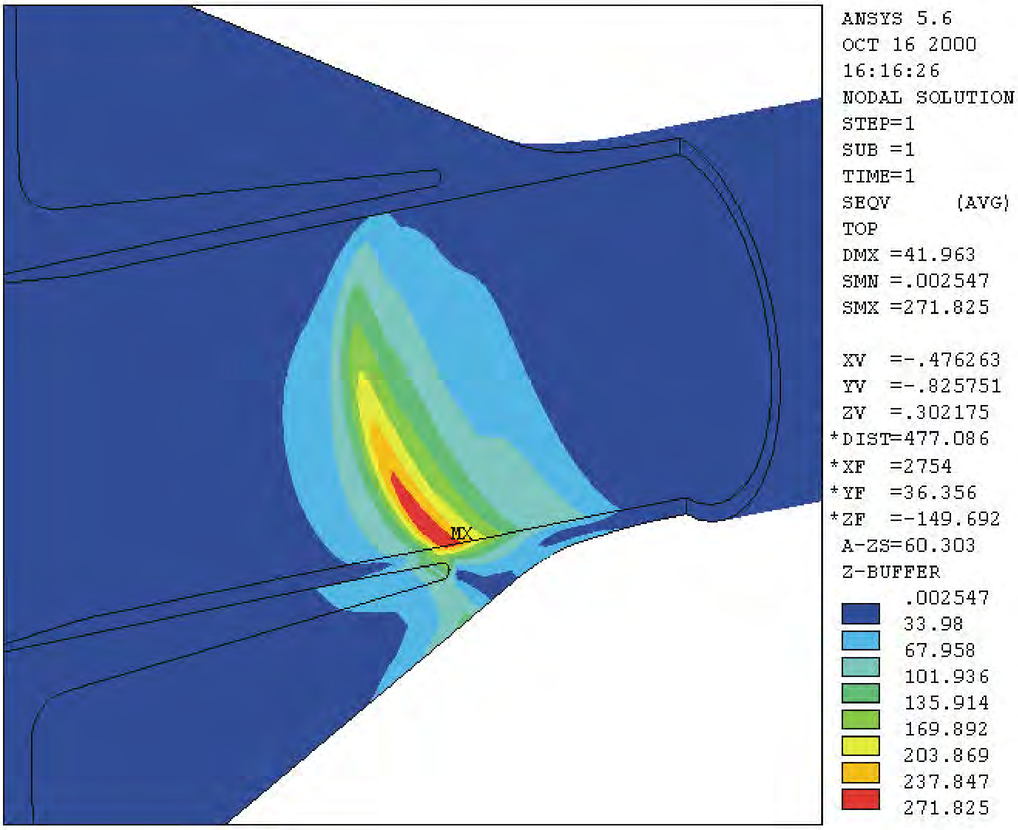


Fig. 10: Effect of Temperature Stratification on the Feedwater Nozzle

cause of damage	steam generator YB10B001 (DE 10)		steam generator YB20B001 (DE 20)		steam generator YB30B001 (DE 30)		sum of closed s.g. tubes
	inlet	outlet	inlet	outlet	inlet	outlet	
manufacturing/assembly	3	3	17	17	7	7	27
			1	1			1
wastage	--	--	2	2	2	2	4
AVB-fretting	3	3	1	1	2	2	6
LP-fretting	2	2	3	3	--	--	5
closed by error	1	1	--	--	--	--	1
removed tubes	3	3	--	--	--	--	3
sum of closed tubes during operation	9	9	6	6	4	4	19
total sum	12	12	24	24	11	11	47

Fig. 11: Closed Heat Exchanger Tubes of the Steam Generators GKN I