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Failure Probabilities of LMFBR-Components Under Extreme-Load Conditions

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S u m m a r y

In the course of the risk analysis of the LMFBR (SNR-300) in the Federal Republic of Germany /1/ a quantitative assessment of the failure probabilities of the mechanical structures has been performed. The paper presents the engineering approach applied and the calculated failure probabilites of the main structures of the primary circuit in the case of core disruptive accidents with different energy levels and temperature conditions. Core disruptive accidents are generally classified as hypothetical accidents.

In the licensing procedure of the SNR-300 the integrity of the mechanical structures of the primary circuit was assessed using a deterministic approach. For exteme-load conditions, like core disruptive accidents, a limit strain criteria method has been developed and presented in /2/. In the case of core disruptive accidents parts of the primary system and reactor internals will experience large plastic deformations, depending on the energy released during the accident. The calculation of failure probabilities under such extreme loading conditions are performed using a simplified method. The method allows the determination of failure probabilities between the range of operational loading and ultimate loading conditions. It is based on the limit strain criteria /2/, failure rates given by statistical evaluations and engineering experience. A check of this approach by a simple Monte-Carlo calculation showed good agreement for the case of a vessel weld containing defects.

In the risk analysis of the LMFBR two loading conditions have been investigated for the internal structures and primary piping of the SNR-300. The variation of the component temperature and material characteristics have been taken into account. The determined conditional failure probabilities are presented.

1. Introduction

In the assessment of the safety of the German Liquid-Metal-Fast-Breeder-Reactor (LMFBR) - SNR-300 - a risk analysis has been performed on behalf of the Parliament of the Federal Republic of Germany /1/. This analysis was regarded as a supplemental evaluation to the regular licensing procedure.
In the licensing procedure it was required to evaluate also the consequences of accidents beyond "Design Basis accidents" like hypothetical power excursions (Bethe-Tait-accident). The assessment of the integrity of the reactor-vessel, internal structures and primary piping was based on the limit strain criteria /2/ and in some cases on stress citeria similar to level D conditions of ASME code Section III. It could be shown that for a mechanical energy of 370 MJ the integrity of the relevant structures is retained.
In the course of the risk analysis it was necessary to determine the conditional failure probabilities under such extreme loading conditions. The approach applied and the results of the analysis are described.

2. Approach and Analysis

The structures to be analysed are shown in Fig.1. Tab. I shows the results of the dynamic elasto-plastic calculation for selected important areas. The limit strains and stresses are tabulated.
For the analysis of failure probabilities different methods are possible in principle.

Regarding the

- various design of component parts
- loading conditions
- time- and temperature dependent material characteristics
- defect distribution

it was concluded that a sophisticated analytical model would require a tremendous effort and even so the results would be questionable due to the uncertainties of some variables. Statistical data for such problems are also not available.

In order to determine probabilities of failure an engineering approach was developed which shows the conditional probability of failure as a function of the usage fraction of the limit strain, Fig.2. For a limit strain usage fraction $\leq 0{,}2$ the function is compared to a statistical

evaluation of failure rates of pressure retaining components /3/.
In the range of the usual design code limits reasonable agreement is achieved. Failure probabilities at the limit strain (usage factor = 1) are based on experimental investigations and the concept of limit strain /2/.
Above a strain usage fraction of 0.2 the function was checked against a Monte-Carlo calculation for the case of a vessel weld including weld defects as described below.
Whether failure is occurring at a given loading is determined by the distributions of the independent variables of the limit state equation. Any design variable becomes defined as a result of the evaluation of a series of measurements. It can be defined at different distances from the median value of the distribution, depending on the kind of problem. Specifications usually define a value that is a 2,5 or 5 % fractile of the distribution. However usually the distance between specified value and median-value and the type of distribution in not known.
There is a large variety of relationships to be considered between failure probability and relative loading, depending on the complexity of the structure investigated.
In our study to support our general relationship between the conditional probability of failure and the relative loading we have calculated a typical mode of failure that has a simple limit state equation and beyond that a somewhat known distribution of its independent variables. The question is about the probability of failure of a circumferential weld of the reactor vessel caused by a high internal pressure impulse as a consequence of a power excursion. The resistance of this weld at high loadings depends on the size of the largest flaw occuring in this weld.
There are some data known that can be used for determination of a statistics of occurrence of flaws in welds. The problem to be solved and its Monte-Carlo simulation are outlined in Fig.3. The solutions have been obtained by a repeated application of this scheme. The number of flaws is supposed to be Poisson distributed. The average number of flaws more than 0.7 mm in depth have been calculated to be $\lambda = 0,23/m$ in accordance with ideas about the number of weld beads in the weld /4/. The depth of the flaws has been determined from a truncated γ-distribution /5/.
It has been assumed that there was no dispersion of the flaw size dependent strain-at-failure, within one simulation. As a consequence it appeared to be allowable to determine the strain-at-failure of the deepest flaw alone.
The distribution of the flaw size dependent strain-at-failure has been determined by an evaluation of different experiments /6/ with wide-plate-

specimens of the stainless steel of the reactor vessel. For the approximate results this simplification seemed permissible.
The experiments /6/ have been evaluated for a flaw-depth dependent mean value and dispersion of the strain-at-failure. Further, Normal-and Weibull- distributions have been fitted to the results. The zero value of the Weibull-distribution has been determined to be 0,3 times the mean value for all flaw-depths.
The Monte-Carlo Simulation has been performed with both a Normal- and a Weibull - distribution. Taking into account two different but in this domain customary distributions shows the range of possible results, in particular in the range of very small probabilities.

Table II shows the results. Two specified values of the ultimate strain have been indicated there. 12,5 % as a specified strain of failure means the 5 % fractile of the distribution of the ultimate strain if a flaw of 10 % of wall thickness is postulated. In the licensing procedure a value of 14,5 % is spezified as the basis for the concept of limit strain /2/.This value can be calculated to be the 12,6 % fractile of the distribution if the same assumption is made about an existing flaw. Both statements assume a normal distribution.
The results of this calculation show a good agreement with the general relationship between the conditional probability of failure and the relative loading.

3. Results

In the course of the risk study of the SNR-300 a large variety of accident sequences have been investigated.
The results of the calculation of conditional probabilities of failure for two power excursion accidents of different intensities are given in Table III.
It can be seen that at an energy of 150 MJ the integrity of the whole structure is given by a suitable margin of safety. At an energy of 400 MJ the ultimate deformation capacity of the structure is reached. Considering the uncertainties in the model the results are consistent with the deterministic evaluation of the structure done in the licencing procedure. The areas selected for the analysis of the vessel and the internal structures show comparable probabilities of failure. This means that the ultimate deformation capacity is used at several parts of the whole structure.

4. Conclusions

In the course of the risk analysis of the LMFBR (SNR-300) a quantitative assessment of the conditional probabilities of failure of important mechanical structures has been performed. The engineering approach applied was compared to an analytical model and is supported partly by failure statistics of pressure-retaining components and experimental investigations. The results of the analysis have shown that the integrity of the components is retained up to an energy level of about 400 MJ.

5. References

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Unpublished data

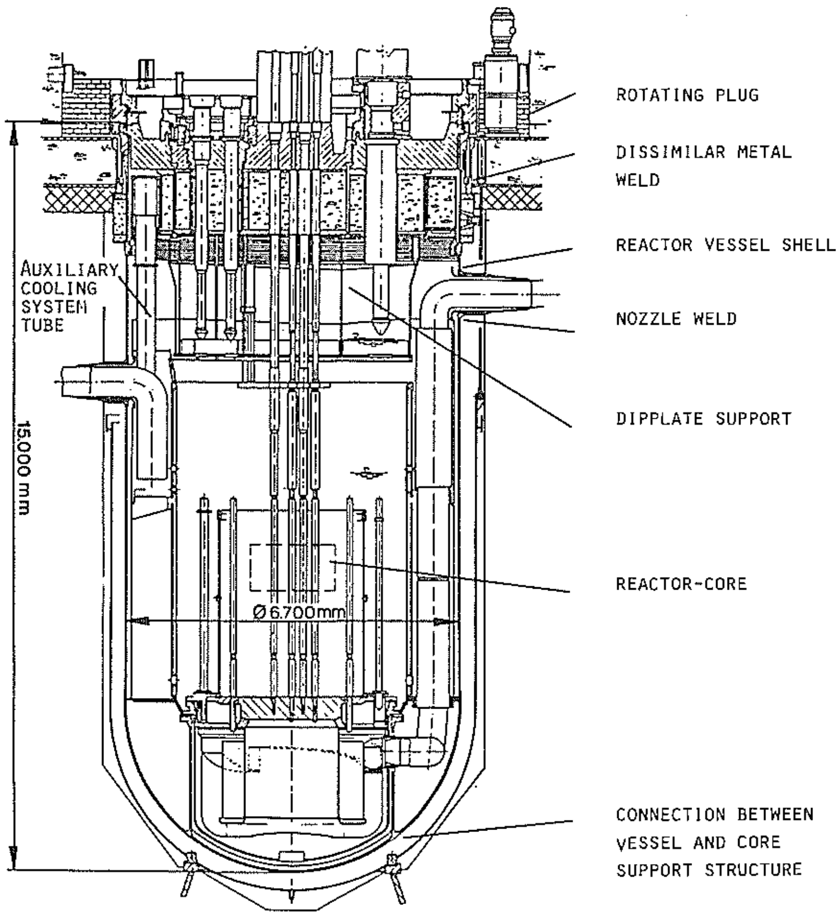

Fig. 1: Investigated regions of the Reactor vessel and Internals

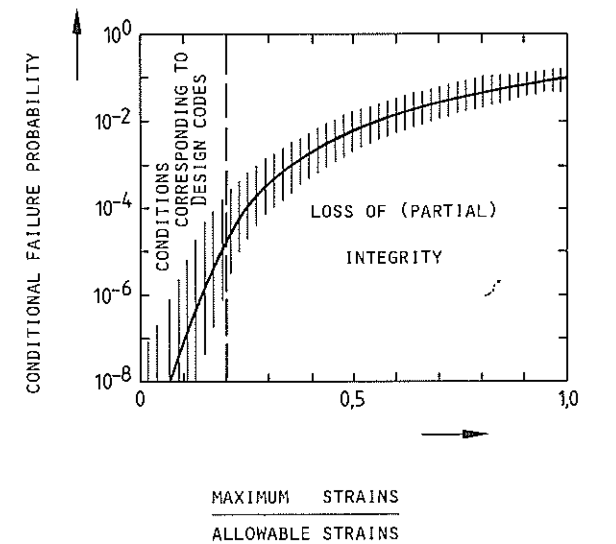

Fig. 2: Failure probability for Components in respect to the strain usage Factor

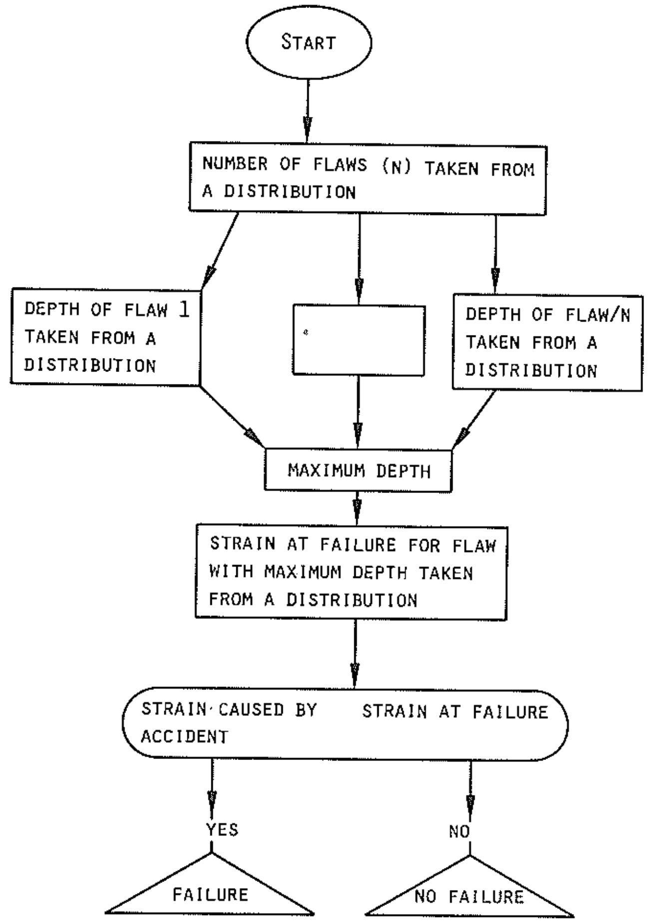

Fig. 3: Calculation scheme for conditional probability of failure

COMPONENTS	MAXIMUM STRESSES OR STRAINS	ALLOWABLE STRESSES OR STRAINS	COMMENTS
REACTOR VESSEL SHELL	5,5 % EQUIVALENT STRAINS	7,5 % - 9 % 1) ALLOWABLE STRAINS	FOR THE ALLOWABLE STRAINS ALL REDUCING STRAIN FACTORS UP TO END OF LIFE (EOL) HAVE BEEN TAKEN INTO ACCOUNT.
NOZZLE WELD	9 % EQUIVALENT STRAINS	10 % ALLOWABLE STRAINS	
CONNECTION BETWEEN VESSEL AND CORE SUPPORT	10,5 % EQUIVALENT STRAINS	14,5 % - 18 % 1) ALLOWABLE STRAINS	EXPERIMENTAL VALUES ARE FROM WIDE-PLATE-AND VESSEL-TESTS
DISSIMILAR METAL WELD	270 N/MM² EQUIVALENT STRESSES	290-350 N/MM² ALLOWALBE STRESSES	ALLOWALBE STRESSES CORRES PONDING TO THE VALUES FOR FAULTED CONDITIONS
AUXILIARY COOLING SYSTEM	115 N/MM² STRESSES (BOLT)	250 N/MM² ALLOWABLE STRESSES	
DIP-PLATE SUPPORT	50 N/MM² STRESSES (PRESSURE)	115 N/MM² ALOWABLE STRESSES	ALLOWABLE STRESSES EXCLUDING INSTABILITY
PRIMARY COOLANT PIPING SYSTEM	5 % EQUIVALENT STRAINS	7,5 % - 9 % 1) ALLOWABLE STRAINS	IN RESPECT TO THE SMALL WALLTHICK - NESS HIGHER ALLOWABLE STRAINS WOULD BE POSSIBLE

1) DEPENDING ON THE MULTIAXIAL STRESS DISTRIBUTION

TAB. I: REACTOR VESSEL AND PRIMARY COOLANT PIPING SYSTEM: MAXIMUM STRESSES AND STRAINS RESULTING FROM A 370 MJ MECHANICAL ENERGY EXCURSION AND COMPARISON WITH THE ALLOWABLE VALUES

CALCULATED STRAINS (%)	UTILIZATION RATE IF ALLOWABLE STRAINS ARE 12,5 %	UTILIZATION RATE IF ALLOWABLE STRAINS ARE 14,5 %	FAILURE PROBABILITY NORMAL-DISTRIBUTION	FAILURE PROBABILITY WEIBULL-DISTRUBUTION
2,9	23,2	20	$3{,}5 \cdot 10^{-4}$	10^{-4}
4,4	34,9	30	$1{,}5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$
5,8	46,5	40	$2{,}7 \cdot 10^{-3}$	$2{,}2 \cdot 10^{-3}$
8,7	69,8	60	$1{,}2 \cdot 10^{-2}$	$1{,}6 \cdot 10^{-2}$
11,6	93	80	$4{,}2 \cdot 10^{-2}$	$5{,}6 \cdot 10^{-2}$
14,5	116	100	$1{,}1 \cdot 10^{-1}$	$1{,}2 \cdot 10^{-1}$

TAB. II: RESULTS OF THE MONTE-CARLO PROCEDURE

COMPONENTS	FAILURE PROBABILITY FOR 150 MJ 1)	FAILURE PROBABILITY FOR 400 MJ 1)	COMMENTS
REACTOR VESSEL SHELL	$2 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	LOSS OF INTEGRITY (HIGH LEVEL OF STRAINS RESULTING FROM BENDING)
NOZZLE WELD	10^{-2} 2)	10^{-1} 2)	PARTIAL LOSS OF INTEGRITY (STRAINS RESULTING FROM BENDING)
CONNECTION BETWEEN VESSEL AND CORE SUPPORT	10^{-3}	10^{-2}	PARTIAL LOSS OF INTEGRITY (STRAINS RESULTING FROM BENDING)
DISSIMILAR METAL WELD	$2 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	LOSS OF INTEGRITY (SAFETY FACTOR AGAINST FRACTURE: 1,4)
AUXILIARY COOLING SYSTEM	10^{-3} 2)	10^{-2} 2)	PARTIAL LOSS OF INTEGRITY (STRAINS RESULTING FROM BENDING
DIP-PLATE SUPPORT	10^{-3} 2)	10^{-2} 2)	LOSS OF INTEGRITY (INSTABILITY FAILURE)
PRIMARY COOLANT PIPING SYSTEM	$2 \cdot 10^{-3}$ 2)	$2 \cdot 10^{-2}$ 2)	PARTIAL LOSS OF INTEGRITY

1) MECHANICAL ENERGY EXCURSION

2) THE NUMBER OF COMPONENTS TAKEN INTO ACCOUNT

TAB. III: REACTOR VESSEL AND PRIMARY COOLANT PIPING SYSTEM: FAILURE PROBABILITY.