Reliability-Based Design of Structural Members for Nuclear Power Plants

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ABSTRACT

The reliability of load bearing structural members in NPP has been proved by
1st order reliability theory. Studies on the temperature development in safety
related compartments and the failure probability of adjacent concrete members
were performed. Special effects e.g. due to forced ventilation and fire extin-
guishing systems are accounted for in the calculations with a post-flashover
heat balance model. Simplified failure models describing the load bearing capa-
city of concrete members were applied to check the reliability of different
types of building members. The results indicate that the member temperatures
and the life loads are the most important parameters. Therefore the practical
design may be performed by using partial factors for the temperatures and re-
duction factors for the life loads. It turned out that as a rule 90 minutes
fire duration acc. to DIN 4102 is a sufficient value for NPP fire compartments.

1. INTRODUCTION

Within a comprehensive research program SR 144 /1/, sponsored by the Federal
Minister of the Interior, the requirements for structural fire safety in NPP in
Germany were checked with respect to the effect of natural and standardized
fires. The report presents one part of the whole investigation program whereby
the following topics will be discussed:
- modelling and estimating of fire effects in safety related compartments of a
  NPP with a pressure water reactor (PWR),
- simplified structural models for the assessment of concrete building elements
  for NPP,
- probabilistic assessment of structural members under natural and standard
  fires.

2. HEAT MODELS FOR STRUCTURAL FIRE SAFETY

2.1 Fundamentals

The prediction of time-temperature curves for compartments in NPP is very com-
plicated because there are many influencing parameters. Up to now, a complete
physical model for compartment fires is not at hand. The theoretical basis of
such calculation methods is given by the fundamental equations of heat and mass
transfer which are applied in the whole compartment or in certain parts of it.
The fire development is highly influenced by the following parameters:

- type and amount of combustible material,
- distribution, density and temperature of the fire load,
- oxygen supply to the burning surface of the material,
- ventilation of the compartment,
- thermal inertia of the building elements,
- influence of extinguishing systems.

For the sake of simplicity and with respect to the special question of fire design of structural members this report refers to a fire model for fully developed compartment fires /2/. The phase of ignition and fire spread in the model is accounted for by a simplified simulation procedure with variable spreading rates. The fire exposure of the structural members is related to the average compartment temperatures. The energy balance in the model is described by six energy terms comprising:

- combustion energy due to a ventilation controlled or fuelbed controlled fire,
- convective energy losses due to a natural or forced ventilation of the compartment,
- radiative energy losses through openings,
- energy losses due to the absorption of the building elements,
- intrinsic energy of the compartment gases and heat sinks,
- absorption energy losses due to the activation of extinguishing systems.

The developed   heat release model was calibrated by the data of fire tests derived from experiments with two types of fire loads. This limitation meets the current practice as the combustible materials in German NPP are more or less limited to oil in closed tanks and cable trays of different types and geometries.

2.2 Temperature-Time Curves

During the study 10 safety related areas in a NPP of a German PWR were investigated. The probable type of fire development was determined by a comprehensive sensitivity study. Main results of the heat balance calculations are published in /2/. In the following are discussed the results of calculations concerning a cable fire in a cable room of 340 m² floor area and an oil fire in an oil tank storage depot of 58 m², with an oil cup of 18 m².

For the cable room it was assumed that the initial fire area is 0.3 m². The average spreading rate on the cable trays was fixed at a rate of 1.0 cm/s which is an estimate on the safe side according to existing experiences. The whole cable tray area comprises 56 m². Fig. 1 shows the temperature-time curves for this room. Main parameter is the ventilation as the total fire load is fixed with 9000 kg PVC. The results indicate significant differences with respect to the different types of ventilation. The natural ventilation (2 doors open) leads to unfavourable conditions. On the other hand the time delay for the activation of the water spray system is comparatively large when the forced ventilation system works.

The simulations of oil tank fires led to similar results. A natural ventilation due to door openings leads to the worst cases (Fig. 2). In the calculations it was assumed that the leckage oil burns in an oil cup whereby the burning rates were controlled by the ventilation. The whole oil tank with 25.000 kg oil acted as a heat sink in the program and the temperature increase of the oil was calculated by assuming a mixed temperature for the fluid. The boiling point of the oil was not taken into account, but Fig. 2 indicates that boiling might occur after 40 to 50 minutes if no active fire protection measures are undertaken. The water spray system is early activated in this case and the suppression of

the fire is performed within 5 minutes if an automatic activation system is installed.

3.   DESIGN MODELS FOR REINFORCED CONCRETE MEMBERS

3.1   General Assumptions

In the following, the reliability of load bearing reinforced concrete members
e.g. a reinforced concrete ceiling, beam, wall and column (Fig. 3) under fire
attack is investigated. Such elements are common for the switch-gear building,
respectively. The following conservative assumptions are made:

- The simply supported members are designed for nominal loads (permanent and
  variable loads) according to the German standard DIN 1045 /3/.
- With respect to the fire safety a design according to the standard DIN 4102
  /1/ is assumed.
- The temperature exposure is choosen according to i) the standard time-tem-
  perature curve and ii) a natural fire which might occur in a typical cable
  room of a switch-gear building under sufficient natural ventilation (Fig. 1).

In detail the calculations comprise the following tasks:

- Estimating the temperatures within the building elements with respect to the
  compartment temperatures and determining the related material properties.
- Calculating the load-bearing capacity of the building elements under external
  loads and temperature stresses.
- Performing a probabilistic reliability analysis with regard to the statistical
  values of the essential parameters.

3.2 Temperature Increase of the Structural Members

The temperature profiles of the members are determined by heat-balance calcula-
tions for each time step. From these profiles the mean value of the temperatures
of the reinforcing steel bars in the tension zone and the mean value of the con-
crete element temperatures in the compression zone are computed. In the elements
according to Fig. 3 mainly the mean temperature of the reinforcement in the ten-
sion zone is of interest. This does not hold for the temperatures in the column.
Fig. 4 shows the average concrete $(T_b(t))$ and reinforcement $(T_s(t))$ temperatures
of the four investigated members under standard (dott.lines) and natural (full
lines) fire conditions. The temperature-dependent material properties were de-
termined by the help of the design curves given in literature /4/.

3.3 Design Equations

The safety margin of reinforced concrete members like ceilings and beams may be
determined as follows:

$$Z = M_R(t) - M_S \geq 0 \qquad\qquad (1)$$

$M_R(t)$ = bending moment capacity
M_S = actual bending moment in the critical cross section

The bending moment capacity M_R may be approximated by /5/:
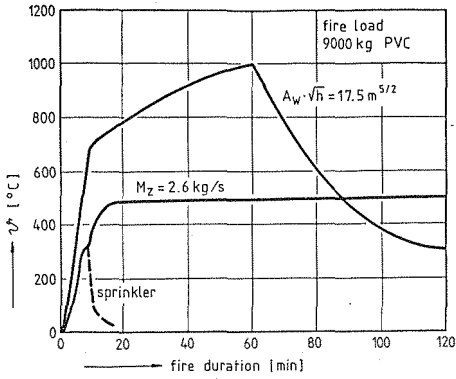
$$M_R(t) = A_S \cdot \beta_S(T_s) \cdot z \qquad\qquad (2)$$

Fig. 1: Temperature-time curves of a cable room

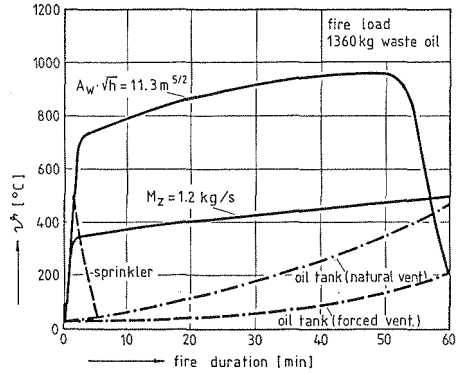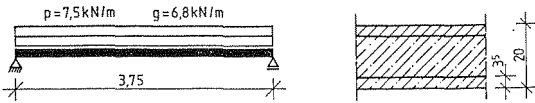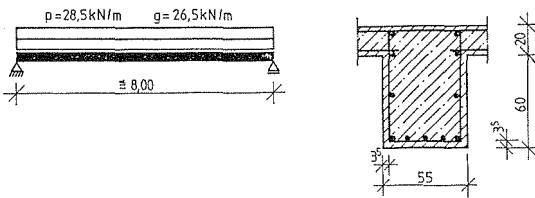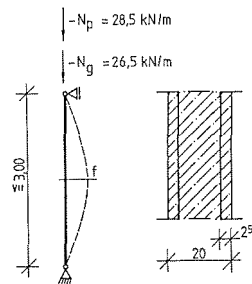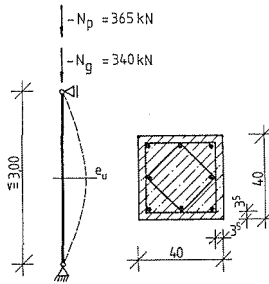Fig. 2: Temperature-time curves of an oil tank storage deposit

Fig. 3: Assumed building members and load actions for the probabilistic investigations

with area A_S of tension reinforcement, temperature-dependent yield strength $\beta_S (T_s)$ and internal leverarm z. The actual bending moment is:

$$M_S = (g + p) \cdot l^2/8 \tag{3}$$

with the distributed load g and p acc. to Fig. 3.

The bending moment capacity of summetrically reinforced walls and columns may be derived as follows:

$$M_R(t) = (1+1.5\cdot(0.1-\frac{h'}{d}))\cdot(0.42\cdot A_S\cdot\beta_S(T_s)\cdot d+0.35\cdot N\cdot d) \tag{4}$$

for $N \leq N_1 = 0.4 \cdot \beta_R (T_b) \cdot b \cdot d$
and

$$M_R(t) = (1+1.5\cdot(0.1-\frac{h'}{d}))\cdot(0.42\cdot A_S\cdot\beta_S(T_s)\cdot d+0.35\cdot N_1\cdot d)-0.26(N-N_1)\cdot d \tag{5}$$

for $N > N_1$ and $N = N_g + N_p$ according to Fig. 3.

Usually walls and columns are stressed by normal loads. In addition the columns are subjected to bending moments due to an unintended eccentricity e_u after /3/. Walls are subjected to bending moments due to the one-dimensional fire attack. The action of external loads is determined by

$$M_S (t) = N \cdot e (1 + \frac{1}{8} \cdot \frac{N \cdot l^2}{E I_w(t)}) \tag{6}$$

$e = e_u$ for columns and $e = f = \frac{l^2}{8} \cdot \alpha_T \cdot \frac{\Delta T}{d}$ for walls

$E I_w(t)$ = flexural stiffness (kN/cm²)

4.   RELIABILITY ANALYSIS

4.1   Introduction to the Method

The reliability analysis of concrete members is performed for the ultimate limit states defined by the design models in chapter 3. The basic variables X_i of the models are described by distribution functions. With the help of the error propagation law the mean value m_z and standard deviation σ_z of the safety margin Z according to equ.(1) is determined. The quotient

$$\beta = m_z / \sigma_z \tag{7}$$

is called safety index and is used as a measure of reliability. The scattering effects of the basic variables X_i with respect to the safety index ß can be evaluated by the so-called weighting factors α_{X_i} :

$$\alpha_{X_i} = \frac{\partial Z}{\partial X_i} \cdot \sigma_{X_i} / \sqrt{\sum_{j=1}^{n} (\frac{\partial Z}{\partial X_i} \sigma_{X_i})^2} \tag{8}$$

with the partial derivatives $\partial Z/\partial X_i$ and the standard deviations σ_{X_i}. The safety index ß and the weighting factors α_{X_i} depend on the time t after fire occurance.
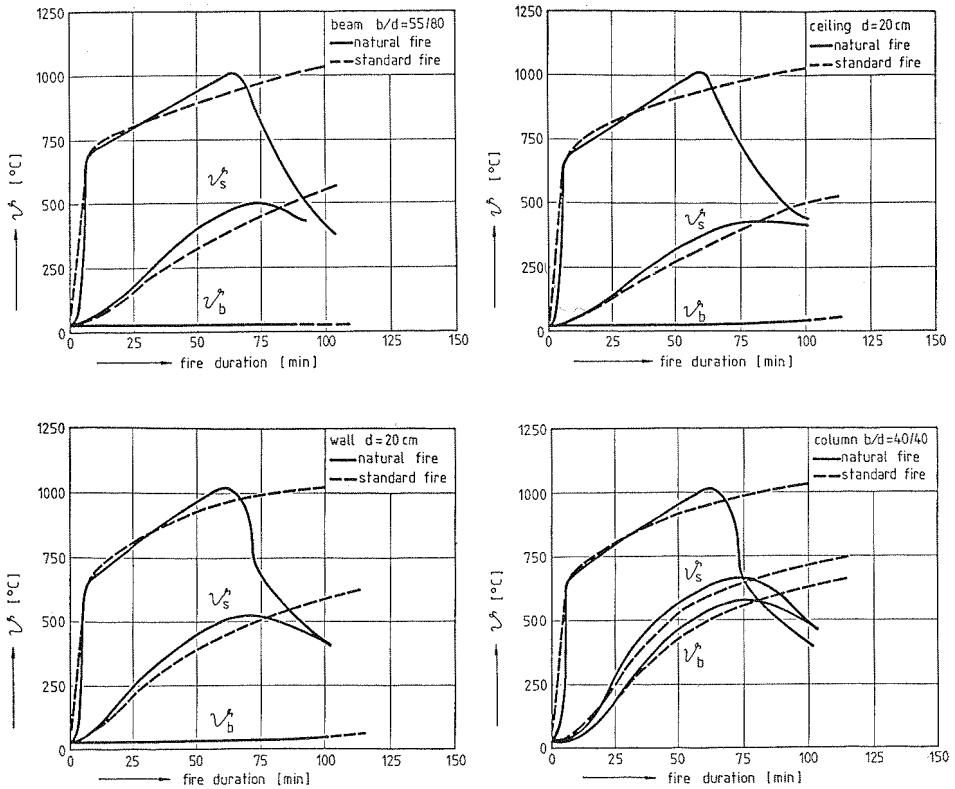
Fig. 4: Compartment and member temperatures of the investigated structural members

4.2 Random Variations and Uncertainties

Distribution functions for the most important parameters (basic variables) of the design models in chapt. 3 were chosen according to /5/. On Tab. 1 the nominal values of those parameters are defined as percentiles, in addition the types of distribution functions and the coefficients of variations are given. The numbers are in aggreement with those values which have been determined by performing several comparison calculations in the field of reinforced concrete design. The variation of the standard fire temperature-time curve are specified according to DIN 4102, part 2 /1/.

The variations of the temperature-time curve $T(t)$ in natural fires mainly depend on the

- specific rate of combustion $\dot{R}_{sp}$ in kg/m²h and the burning area,
- ventilation conditions, e.g. ventilation area A_w or ventilation rate M_z,
- amount of combustible material, e.g. fire load q,

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Tab. 1: Distribution assumptions for the basic variables of the design models

Parameter	nominal value	distribution function	coefficient of variation	comment
T, stand. fire	mean	log. normal	0.10	DIN 4102
T, nat. fire	mean	log. normal	0.20	Fig. 4
reinf. temp. T_s	mean	log. normal	0.20	Fig. 4
concrete temp. T_b	mean	log. normal	0.20	Fig. 4
yield strength β_s	5 %	log. normal	0.06	acc. to /5/
concrete strength β_R	5 %	log. normal	0.15	acc. to /5/
steel mod. E_s	mean	log. normal	0.05	acc. to /5/
concrete mod. E_b	mean	log. normal	0.10	acc. to /5/
reinf. cover u	mean	log. normal	0.25	acc. to /5/
perm. load g, Ng	mean	normal	0.05	acc. to /5/
live load	98 %	extremal I	0.40	natural fire
load p, Np	57 %	one year max.	0.05	DIN 4102

in the respective compartment. Sensitivity studies in /5/ led to the conclusion that during a fully-developed fire the standard deviation σ_T of the gas temperature T is nearly constant and may be evaluated as follows:

$$\sigma_{T(t)} = \sqrt{(\frac{\Delta T}{\Delta \dot{R}_{sp}} \cdot \sigma_{\dot{R}_{sp}})^2 + (\frac{\Delta T}{\Delta A_w} \cdot \sigma_{A_w})^2 + (\frac{\Delta T}{\Delta M_z} \cdot \sigma_{M_z})^2} \tag{9}$$

The standard deviations of the element temperatures $T_b(t)$ and $T_s(t)$ are lower than $\sigma_{T(t)}$. But the coefficients of variation approximately correspond to the coefficient of variation $V_{T(t)}$ of the gas temperature which depends on the fire duration. A maximum value $V_{T(t)} \approx 0.17$ has been estimated under different assumptions in /5/ and /2/.

In addition to the variations of the gas temperature one must consider the variations of the fire duration which is a - more or less linear - function of the fire load q. Under the assumption that in a NPP the determination of fire loads is individually performed a coefficient of variation $V_q = 0.1$ may be a sufficiently conservative estimate. As during the phase of a fully-developed fire the element temperatures increase nearly proportionally to the fire duration, the coefficient of variation V_q results in an additional variation of the element temperatures $T_{b,s}$. Assuming independence of the random variations of T and q the overall coefficient of variation may be derived,

$$V_{T_{b,s}} = \sqrt{V_{T(t)}^2 + V_q^2} \tag{10}$$

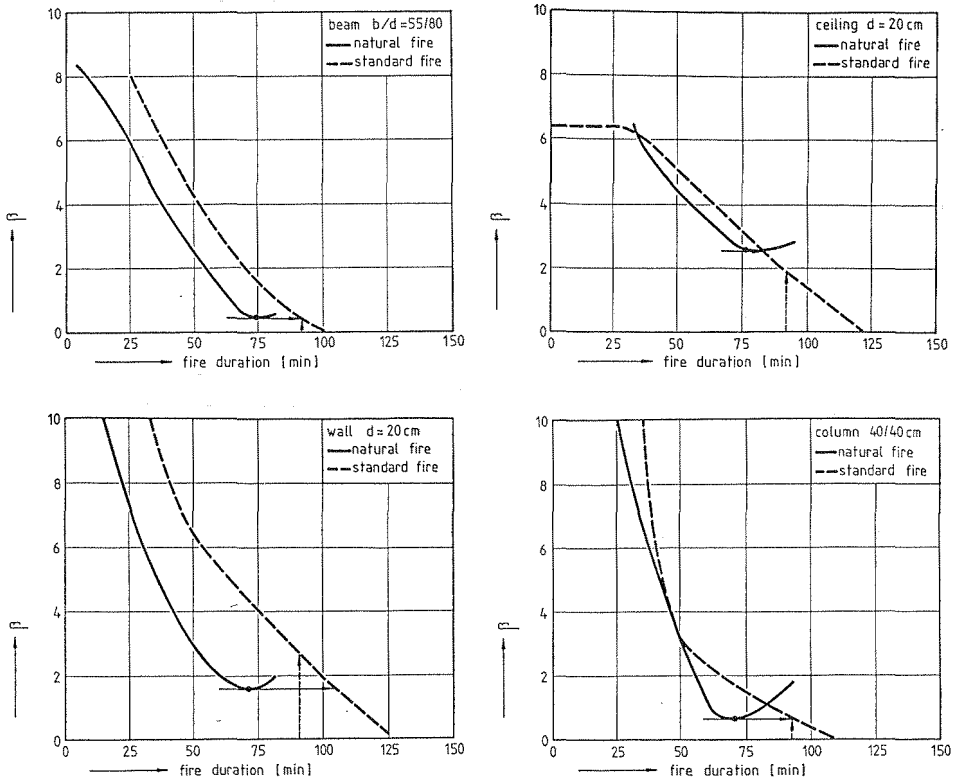yielding $V_{T_{b,s}} \approx 0.2$ (cf Tab. 1) as an average value.

Fig. 5: Safety index ß of the investigated structural members

4.3 Results of the Reliability Analysis

The safety index ß of the investigated members are shown in Fig. 5 for standard and natural fire exposures. During standard fires the F 90 class elements fail in the range of 100 to 125 minutes (ß = 0), whereby beams and columns approach the lower and ceilings and walls the upper limit. The probabilities of failure after attaining the nominal fire duration of 90 minutes are of the order of 25 to 30 percent (beams, columns) and 0.5 to 2 % (ceilings, walls). In this case the failure probabilities under natural fire conditions are of the same order as under a standard fire after 85 to 90 minutes.

The overall variations (σ_z) during the natural fire are partly more than 100% larger than under standard fire conditions, due to i) the larger scattering of $T_{b,s}$ and ii) the additional influence of scattering loads. In both types of fire the variations of the member temperatures are dominating. Beside this, the yield strength of the steel, the concrete strength in connection with the analysis of columns and the live loads contribute to the overall variations; the remaining parameters are negligible.

4.4   Safety Elements for Fire Safety Design

From section 4.3 safety elements for practical fire safety design of structural
elements may be derived. The required safety level is described by a target
safety index ß depending on the occurence rate of fires in a compartment, the
active fire protection measures taken to prevent a fire from spreading within
the whole compartment, and perhaps the total damage due to a severe fire.

Informations on the influences of parameter uncertainties are taken from the
weighting factors α_{X_i} of the basic variables X_i in Tab. 2 (cf. section 4.2).
The values α_{X_i} for the structural elements of Fig. 3 in the most critical phase
of the natural fire as well as the respective values after the equivalent fire
duration of the standard fire are summarized in Tab. 2.

Tab. 2:   Weighting factors α_{X_i} of the basic variables X_i for the structural
          elements in the natural and the standard fire

basic variable X_i	α_{X_i} for structural elements							
	ceiling		beam		wall		column	
	n	s	n	s	n	s	n	s
$\left.\begin{array}{c} T \\ T_s \\ T_b \end{array}\right\}$	−0.990	−0.837	−0.971	−0.881	−0.971	−0.911	−0.853	−0.617
$ß_R$	0.001	0.011	0.003	0.007	0.0	0.0	0.511	0.778
$ß_s$	0.126	0.244	0.076	0.151	0.040	0.098	0.004	0.01
E_b	0.0	0.0	0.0	0.0	0.0	0.0	0.001	0.001
E_s	0.0	0.0	0.0	0.0	0.0	0.0	0.001	0.001
h_s	0.023	−0.142	0.028	0.041	0.235	0.400	0.080	0.116
g,N_g	−0.012	−0.100	−0.053	−0.098	0.001	0.013	−0.017	−0.026
p,N_p	−0.054	−0.458	−0.218	−0.436	0.002	0.012	−0.066	−0.025

n = natural fire   s = standard fire

It is proposed to define design values of the basic variables with the target
safety index ß and the following conservative weighting factors:

α_{T_b,T_s} = − 0.95 for natural fires and − 0.85 for standard fires,

α_{p,N_p} = − 0.25 for natural fires and − 0.45 for standard fires,

$\alpha_{ß_R}$ =   0.5   for columns in natural fires and 0.75 in standard fires,

$\alpha_{ß_s}$ =   0.25 for natural and standard fires,

α_{h_s} =   0.25 for compression members in natural fires and 0.45 in standard
                  fires,

α =   0   for all other basic variables.

These design values may also be expressed with the help of the nominal values
given in Tab. 1 and partial safety factors γ as indicated in Tab. 3 for a range
of the safety index $2.0 \leq ß \leq 3.5$ (valid for nuclear power plant compartments).
In practical applications the partial safety factors for $ß_R$, $ß_s$ and h_s should
be taken as ~ 1.0.

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Tab. 3: Partial safety factors γ for the most important basic variables and design for natural and standard fires

basic variable	ß	γ for structural element							
		ceiling		beam		wall		column	
		n	s	n	s	n	s	n	s
T, T_b, T_s	2.0	1.43	1.18	1.43	1.18	1.43	1.18	1.43	1.18
	3.5	1.97	1.34	1.97	1.34	1.97	1.34	1.97	1.34
p, N_p	2.0	0.46	0.63	0.46	0.63	0.46	0.46	0.46	0.46
	3.5	0.68	0.83	0.68	0.83	0.46	0.46	0.46	0.46
$ß_R$	2.0	0.79	0.79	0.79	0.79	0.79	0.79	0.91	0.98
	3.5	0.79	0.79	0.79	0.79	0.79	0.79	1.02	1.16
$ß_s$	2.0	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
	3.5	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
h_s	2.0	1.0	1.0	1.0	1.0	0.88	0.78	0.88	0.78
	3.5	1.0	1.0	1.0	1.0	0.78	0.61	0.78	0.61

n = natural fire   s = standard fire

5. CONCLUSION

The report describes the theoretical determination of failure probabilities for structural members in NPP. Models for the determination of fire effects are presented. The temperature-time curves are evaluated by post-flashover heat models, whereby the effect of forced ventilation in the safety related buildings of the power plants is accounted for. Based on the reliability analyses also safety elements for practical fire safety design of structural elements are derived depending on a target reliability. It seems sufficient to define partial safety factors for the member temperatures and reduction factors for the nominal live loads whilst all other parameters may be used with their nominal values.

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