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Prediction of the lower head failure under severe accident

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ABSTRACT: The lower head deformation behavior model taking into account elastic, thermal, plastic and creep strain is considered. Two failure criteria based on consideration of the plastic and creep deformations are used for lower head failure prediction in this model. Lower head failure probability has been analyzed with the help of the model for two cases: without and with accident cooling of the vessel.

1 INTRODUCTION

Existing methodology of a severe fuel damage accident analysis considers the vessel rupture as a key point of accident scenario. Therefore the modeling of lower head deformation behavior is one of the most important tasks of safety analysis. The results of research program show that further efforts are necessary to develop lower head failure modeling approaches, Rempe et al. (1993). There exist some uncertainties in the prognostication of the mode and time of vessel lower head failure. The following sources of these uncertainties may be distinguished:

- modeling idealizations of real phenomenon and actual structures;
- thermal condition uncertainty under interaction between vessel and hot corium;
- incomplete understanding of material behavior and the limited data base of materials properties under accident conditions.

These features decrease advantages of usage of the detailed numerical techniques of deformation behavior as finite element method (FEM). Since the strain states in the lower head can change rapidly due to severe loads, the time steps in the order of seconds are necessary for validity of creep constitutive models. It leads to prolonged processing time because simulation to failure requires about thousands of time steps.

In this situation it is reasonable to develop simplified model of lower head deformation behavior and failure, retaining enough details to capture the important features of this problem. Furthermore the decrease of processing time can be very useful for a failure probabilistic analysis. Below one of the possible realizations of this approach is considered. Due to the fact that the first and the second of the above stated sources of prognostication uncertainties can not be described without the alternative models and additional experiments the objective of a proposed model is restricted by the analysis of material properties' uncertainties influence on the lower head global failure. However the uncertainty of thermal condition is a dominant factor of probabilistic aspects of failure time, but the uncertainty of deformation behavior caused by thermal condition uncertainties is not considered. It is assumed that the thermal accident conditions are known.

2 STRUCTURAL MODEL OF LOWER HEAD DEFORMATION BEHAVIOR

Main assumptions of developed structural model are:

- the lower head is considered as a set of symmetric about vessel axis hoop elements deformed independently;
- the hoop element is considered as a multylayer shell;
- the layer temperature along radial, hoop and meridian direction is constant;
- the vessel steel has elastic, plastic, creep and thermal expansion property
- the layer stress state is assumed biaxial; radial stress and strain are not considered.

Let's consider the basic equations which allow to describe the lower head stress-strain state kinetic with the account of these assumptions.

Let's divide the head hoop element into N layers through the wall thickness. Each layer is considered as a part of sphere. The center of sphere for all layers of one hoop element is the same. In the case of spherical symmetry the hoop and meridian layer strain are equal and they may be written as:

(1) $$\varepsilon_n(t) = \varepsilon_n^{el}(t) + \varepsilon_n^{pl}(t) + \varepsilon_n^{cr}(t) + \varepsilon_n^{th}(t),$$

where $\varepsilon_n(t), \varepsilon_n^{el}(t), \varepsilon_n^{pl}(t), \varepsilon_n^{cr}(t), \varepsilon_n^{th}(t)$ - total, elastic, creep and thermal strain in the *n*-th layer at time *t*.

Elastic and thermal strain are written as:

(2) $$\varepsilon_n^{el}(t) = \frac{(1-\nu)}{E_n(t)}\sigma_n(t); \qquad \varepsilon_n^{th}(t) = \alpha_n \Delta T_n(t);$$

where $E_n(t), \nu$ - the elastic modulus and Poisson ratio (it is assumed that Poisson ratio does not depend on temperature and it is equal to 0.3); $\alpha_n, \Delta T_n(t)$ - the average thermal expansion coefficient and the temperature increment in *n*-th layer.

Plastic strain is written as:

(3) $$\varepsilon_n^{pl}(t) = \int_0^{\sigma_n(t)} \frac{k_n}{E_n^{pl}} d\sigma_n,$$

where E_n^{pl} - the tangent plastic modulus according to $\varepsilon_{int}^{pl} - \sigma_{int}$ diagram; k_n - the loading condition coefficient: neutral loading and unloading conditions correspond to $k_n = 0$, loading conditions corresponds to $k_n = 1$; $\varepsilon_{int}^{pl}, \sigma_{int}$ - the intensities of plastic strain and stress. Under used assumptions $\sigma_{int} = |\sigma_n|$.

It is assumed that the correlation between the creep rate intensity and the stress may be written as:

(4) $$\dot{\varepsilon}_{int}^{cr} = A\sigma_{int}^{m} e^{-\frac{Q}{T}},$$

where A, m, Q - the creep constants. Then in accordance with associated flow rule the creep strain may be written as:

(5) $$\varepsilon_n^{cr}(t) = \frac{1}{2}\int_0^t A|\sigma_n(\tau)|^{m-1} e^{-\frac{Q}{T}} \sigma_n(\tau) d\tau.$$

Now we can write *N-1* equations based on the radial displacement continuity of considered hoop element under loading:

(6)
$$\frac{\varepsilon_{n+1}(t)}{\varepsilon_n(t)} = \frac{R_n}{R_{n+1}},$$

where $R_i\,(i = 1,2,\ldots,N)$ - the middle radius of i-th layer.

After substitution of (2), (3) and (5) in (6) we obtain the system of N-1 equations for unknown σ_n,N-th equation is based on the force balance:

(7)
$$\int_0^{h(t)} \sigma_n(t)dr = P(t)R(t),$$

where $P(t)$ - the internal vessel overpressure; $h(t)$ - the current wall thickness; $R(t)$ - the middle radius of hoop element.

Due to melting and failure the current number of layers (wall thickness) can change.

Two failure criteria are included in the considered model. According to the first criteria the layer fails if the plastic strain intensity exceeds the ultimate failure strain $\varepsilon_{ult}^{pl}(T)$. The second criterion is based on the analysis of material damage induced by creep strains. Using the correlation for time to rupture at the given stress and temperature the current damage of each layer is determined. A life fraction rule was used to calculate the damage under transient conditions. The life fraction rule assumed that material damage was cumulative.

Lower head global rupture occurs when all layers of the hoop element melt or fail.

3 PROBABILITY ANALYSIS OF THE LOWER HEAD FAILURE

The considered structural model was used for the analysis of lower head failure probability. It was assumed that uncertainties of lower head deformation behavior are caused by the uncertainties of vessel steel mechanical properties. It was assumed that the following parameters of structural approach are random variables:

- ultimate failure strain $\varepsilon_{ult}^{pl}(T)$;
- yield strength $\sigma_y(T)$ and ultimate strength $\sigma_b(T)$;
- tangent plastic modules E_n^{pl};
- creep rate $\dot{\varepsilon}^{cr}(T,\sigma)$;
- time to creep rupture $t^{ru}(T,\sigma)$.

Value X_i^{ζ} of the random variable X^{ζ} at i-th calculation is determined in the following way. The random number ξ_i^{ζ} from interval [0;1] generated by a random-number generator is transformed into a physical parameter quantity X_i^{ζ} according to the probability distribution $\rho^{\zeta}(X^{\zeta})$ of parameter X^{ζ}:

(8)
$$\xi_i^{\zeta} = \int_{-\infty}^{X_i^{\zeta}} \rho^{\zeta}(X)dX.$$

Before each calculation of an accident scenario a set of random parameters' values was defined according to the distributions of the parameter quantity. The mechanical properties of vessel steel were based on experimental results for SA533B1 stainless steel, Rempe et al. (1993).

It is assumed that the probability distribution of ultimate failure strain $\varepsilon_{ult}^{pl}(T)$ is a constant and ultimate failure strain varies between 2% and 10%.

The uncertainties of yield strength $\sigma_y(T)$ and ultimate strength $\sigma_b(T)$ are described by a normal distribution:

$$\rho(X) = \frac{1}{\sqrt{2\pi}a} e^{-\frac{1}{2}\left(\frac{X - X_m}{a}\right)^2}, \tag{9}$$

where X, X_m - random variable value and mean value of uncertain parameter; a - standard deviation.

At each calculation (event) the generated random quantities $\zeta_i^{\sigma_y}$ and $\zeta_i^{\sigma_b}$ define the position of the temperature dependencies of random values of yield strength $\sigma_y(T)$ and ultimate strength $\sigma_b(T)$ above or under the mean values.

It is assumed that the tangent plastic modulus does not depend on plastic strain. Using this assumption the current tangent plastic modulus is determined with the help of the yield and ultimate strengths as:

$$E^{pl}(T) = \frac{\sigma_b(T) - \sigma_y(T)}{\varepsilon_{ul}^{pl}}. \tag{10}$$

The uncertainty of a creep strains is described in the following way. Since the creep parameters in (5) are interdependent they can not be manipulated arbitrary as, for instance, yield and ultimate strengths. Therefore the random value of creep rate at the given stress and temperature is generated in this approach. The generation rule is based on the assumption of a normal distribution for the creep rate. It was suggested that standard deviation of the creep rate distribution at the given stress and temperature is a half of a mean value. Then after generation of a set of the random creep rates for each calculation (event) the creep parameters *A, m, Q* in (5) are determined by the least squares method.

To describe the time to creep rupture as a function of applied stress and temperature the following correlation was proposed:

$$t^{ru} = B\sigma_{int}^{-k} e^{\frac{G}{T}}, \tag{11}$$

where *B, k, G* - the constant of a creep rupture time.

Constants *B, k, G* for each calculation (event) were found in the same manner as creep constants *A, m, Q*, but in this case it was suggested that the standard deviation of the creep rupture time is equal to a quarter of a mean value.

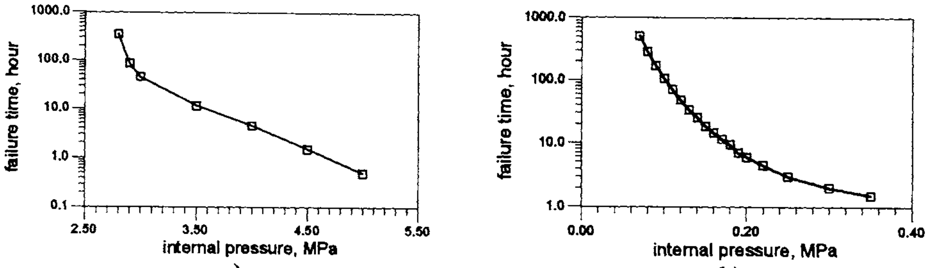
The experimental results for the creep rate and the time to creep rupture which were used as the mean values of these parameters are given in Rempe et al. (1993).

The quantity range between $X_m - 2a$ and $X_m + 2a$ limits all parameters described by the normal distribution. It is assumed that the uncertainty of elastic properties is negligible.

The probability of lower head failure is determined as the ratio of the number of the calculations (events) when the lower head has failed to the total number of calculation (events). The number of calculations (events) for each accident condition was equal to one thousand.

4 RESULTS

Two thermal accident scenarios were considered. The first one corresponds to the case when the forced water cooling was used for the external surface of the lower head. The



a) b)

Fig.1 Time to creep rupture of the lower head versus internal overpressure for the accident scenario with external cooling (a) and overheating (b).

second one corresponds to the case without forced cooling. Initial lower head thickness - 11.1 cm., initial internal radius - 2.19 m, initial temperature - 650K. For both thermal conditions it is assumed that the lower head is melting up to the thickness of 2.0cm. during the first hour. Then steady state thermal regime is formed. The temperature of internal surface of lower head at steady state regime is equal to melt point 1700K. The external temperature decreases to 400K during transient regime in the case of the first thermal regime. For the second thermal regime the external temperature increases up to 1000K.

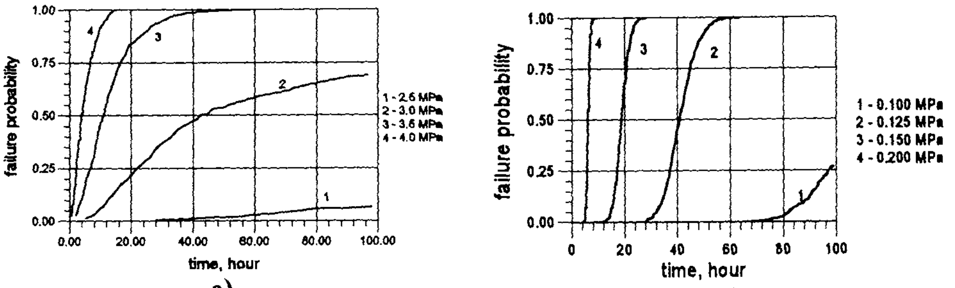
Let's consider the general character of the lower head deformation behavior before the consideration of lower head failure probability analysis.

The case with the first thermal condition: forced cooling of the vessel. The intensive plastic strains (about 2% under 3.0 MPa for the mean values of random parameters) are predicted during transient regime. Then the stress-strain state changes due to the creep. The intensive creep occurs in internal layers. The creep under considered condition leads to the stress redistribution trough the thickness and to the increase of tensile stress level in external layers. The additional plastic strains of the external layers are predicted at the steady state thermal and load regime. If the plastic strain in the external layers exceeds the limit value the external layers fail. The rupture of external layer leads to a sharp increase of load, which acts in the intact layers, and the global lower head failure. So, for the accident scenario characterized by the external cooling of the lower head the excess of plastic strain over the limit value is a dominant mechanism of lower head failure. However, the creep process activation is the necessary condition of the realization of this mechanism.

The time to creep rupture of the lower head versus internal overpressure for the accident scenario with external cooling is shown in Fig.1a. This dependence corresponds to the mean values of random parameters.

The case with the second thermal condition: overheating of the vessel. The failure mechanism for this thermal regime is another. High temperature trough wall thickness speed up the creep process in all layers of the vessel wall under the applied pressures which are less than pressures for the first thermal scenario. For example, the lower head failure will occur under internal overpressure 0.1 MPa within 70 hours. The time to creep rupture of the lower head versus internal overpressure for the accident scenario with vessel overheating is shown in Fig.1b. This dependence corresponds to the mean values of random parameters.

One can see from Fig.1a that the time of lower head failure increases infinitely under vessel overpressure 2.8 MPa. However the use of the deterministic approach can not estimate the reliability of failure prognostication. The use of the described probability approach allows to investigate the failure prognostication uncertainty caused by uncertainty of mechanical properties of the vessel steel. For example, for the above defined distributions of random parameters the lower head failure can be predicted even under internal overpressure 2.5 MPa. The failure probability under this condition is equal to 0.2. Therefore the safety conditions (thermal and mechanical loads) must be determined as the conditions under which the global rupture is negligible.



a)

b)

Fig.2. Time dependencies of lower head failure probability at different internal overpressure for the accident scenario with external cooling (a) and overheating (b).

The probabilities of the lower head failure for both considered cases versus time at different internal overpressures are shown in Fig.2.

Let's note one feature of the considered approach. The deterministic approach gives the average estimation of lower head capacity. But for the case of severe fuel damage accident it is necessary to know the low boundary estimation of safety accident conditions. For the simplest structural model such estimation can be made a priori by decreasing (for example) the strength properties. But more advanced models include many mechanical parameters describing various material properties. For these models the task of a priori determination of the properties' combination leading to the decreasing of the lower head carried capacity and quantity estimation of this decrease of the lower head carried capacity due to dangerous property combination is not a trivial problem. The above considered approach may allow to determine the quantity decrease of the lower head carried capacity due to dangerous property combination. Besides (if it is needed) this approach can give the answer to the question about the dangerous property combination. Therefore the described approach can be used as a tool of lower head deformation behavior analysis under severe fuel damage accident conditions.

REFERENCES

Rempe, J.L., S.A.Chavez, G.L.Thinnes & etc. 1993. Light Water Reactor Lower Head Failure Analysis. NUREG/CR-5642. EGG-2618.