Cladding failure probability modeling for risk evaluations of fast reactors

C.J.Mueller & J.M.Kramer
Argonne National Laboratory, Ill., USA

1 INTRODUCTION

This paper develops the methodology to incorporate cladding failure data and associated modeling into risk evaluations of liquid metal-cooled fast reactors (LMRs). Current U.S. innovative designs for metal-fueled pool-type LMRs take advantage of inherent reactivity feedback mechanisms to limit reactor temperature increases in response to classic anticipated-transient-without-scram (ATWS) initiators. Final shutdown without reliance on engineered safety features can then be accomplished if sufficient time is available for operator intervention to terminate fission power production and/or provide auxiliary cooling prior to significant core disruption. Coherent cladding failure under the sustained elevated temperatures of ATWS events serves as one indicator of core disruption. In this paper we combine uncertainties in cladding failure data with uncertainties in calculations of ATWS cladding temperature conditions to calculate probabilities of cladding failure as a function of the time for accident recovery.

2 METHODOLOGY

Although negative reactivity feedback may prevent early core disruption in an ATWS event, the fuel may be subjected to high temperatures for extended periods, depending upon the competition between reactor vessel heat rejection and core heat generation. The latter is caused by decay heat plus some, essentially equilibrium, level of fission power production depending on accident scenario. One measure of the probability of failure to achieve final shutdown in time to avoid core disruption in a metal-fueled core subjected to such long term heating can be obtained from the probability that the time t_r to coherently rupture fuel pins, via creep or eutectic penetration, is less than the time it takes for accident recovery, t_{ar}, either through intervention of the protection systems or operator action; i.e.

$$(1) \qquad P_f = \text{Prob}\,(t_r < t_{ar})$$

It may be assumed that t_{ar} and t_r are statistically independent. Then the expected value of this probability is given by

(2) $$\bar{P}_f = \int_o^1 P_f p(P_f) dP_f$$

(3) $$= \int_o^\infty \int_o^\infty \text{Prob}(t_r < t_{ar}) p(t_{ar}) p(t_r) dt_r dt_{ar}$$

(4) $$= \int_o^\infty p(t_{ar}) \left[\int_o^\infty \text{Prob}(t_r < t_{ar}) p(t_r) dt_r\right] dt_{ar}$$

(5) $$= \int_o^\infty p(t_{ar}) \left[\int_o^{t_{ar}} p(t_r) dt_r\right] dt_{ar}$$

where p(x) denotes the probability density (or frequency) function (pdf) of x and $p(t_{ar})$ is assumed to be known. The issue then becomes the determination of the pdf for fuel pin failure time.

3 CLADDING FAILURE CORRELATIONS

Fuel pin cladding options under consideration for U.S. metal-fueled reactors include both low swelling ferritic/martensitic alloys that appear to be creep-limited and austenitic alloys that appear to be fuel-clad-eutectic-penetration-limited under the sustained elevated temperature conditions of interest. The approach here draws upon and combines several sources of data and analytic modeling to determine maps of time to pin-failure. These sources include stress-rupture correlations to predict mean time-to-rupture via creep; uranium-iron eutectic formation and cladding melt-rate test data and modeling that are used to predict mean time-to-failure via cladding thinning and penetration; and deformation data measured in independent tensile tests and plastic flow modeling characterized as a function of irradiation history.

We illustrate the analysis here by considering simple cladding failure laws of the Arrhenius form

(6) $$\hat{t}_r = \exp(a_o + b_o/T), \text{ or}$$

(7) $$\ln \hat{t}_r = a_o + b_o/T;\ a_o<0,\ b_o>0;$$

where $\hat{t}_r$ is an estimate of the mean time to failure given that the fuel pin is held at the constant temperature T, and a_o and b_o are fitting parameters that depend on both the physical properties and the failure mechanism of the cladding. The temperature of interest in this work is the fuel-cladding interface temperature at the peak temperature region of the hottest subassembly(ies).

First we consider ferritic/martensitic alloy HT-9. Under end-of-life plenum pressures of 10 MPa, transient failure of HT-9 for long times (t>1 hr) at elevated temperature is governed by creep-rupture [1]. Eutectic penetration rates are much slower than creep rates so that the effects of wall thinning by cladding melting can be neglected. Dorn

parameter correlations of out-of-reactor transient tube burst data yield stress-rupture equations of the form of Eq. 6. For 10 MPa internal pressure the parameters a_o and b_o are -24.92 and 35315, respectively, where t_r is in seconds and T is given in Kelvins.

Austenitic stainless steel cladding alloys such as D9 have higher creep strengths than HT-9 cladding. Failure of metallic fuel pins clad with these alloys is governed by eutectic penetration rates under elevated temperature (T> 1000K) long time (t>1 hr) accident conditions [1]. The penetration rate $\dot{r}$ in this regime is given by

$$\dot{r} = \exp\ (22.847 - 27624/T),\ \mu m/s.$$

Failure occurs essentially when the cladding wall thickness h has been reduced to zero. The rupture time $\hat{t}_r$ is just

$$\hat{t}_r = h/\dot{r};$$

combining the above two equations again gives a simple cladding failure law of the form of Eq. 7. For a thickness of 560 μm, the constants a_o and b_o for D9 cladding are -16.52 and 27624, respectively.

4 ASYMPTOTIC CLADDING TEMPERATURE DISTRIBUTIONS

Distributions of asymptotic (essentially constant) cladding temperatures for ATWS initiators were obtained from SASSYS code [2] calculations. Specifically, SASSYS was used to characterize fuel pins in high power subassemblies in metal-fueled innovative designs under postulated ATWS initiators. The distributions incorporated uncertainties in the temperature histories due to limitations in ATWS modeling capability as well as uncertainties in the neutronic, thermal-hydraulic, and material property input data. From these distributions the pdf for t_r can be found from

$$p(\hat{t}_r)d\hat{t}_r = -\ p(T)\ dT \tag{8}$$

For example, if p(t) is normal with mean T_o and variance σ_T^2,

$$p(\hat{t}_r)d\hat{t}_r = -\frac{1}{\sigma_T\sqrt{2\pi}} \exp\ \{-.5[(T-T_o)/\sigma_T]^2\}dT \tag{9}$$

The last step in this development involves factoring in the uncertainty in the actual time to failure, given the estimated mean time to failure $\hat{t}_r$. If this last pdf is given by $q(t_r/\hat{t}_r)$

$$P_f = \int_o^{t_{ar}} p(t_r)dt_r = \int_o^{t_{ar}}\int_o^{\infty} q(t_r/\hat{t}_r)p(\hat{t}_r)d\hat{t}_r dt_r \tag{10}$$

$$= \int_o^{t_{ar}}\int_{\infty}^{-\infty} q[t_r/\ \hat{t}_r(T)]p(T)dT\ dt_r \tag{11}$$

To solve these equations to estimate P_f and its standard deviation, a Monte Carlo based strategy was used to

1. Sample temperatures from a distribution of maximum asymptotic temperatures calculated using the SASSYS code. (The results in this paper were developed from a normal distribution of such temperatures with a mean and standard deviations of 900K and 45K for the transient overpower scenario);
2. Sample rupture times from an assumed lognormal distribution of rupture times using Eq. 7 to calculate the mean and assuming 0.5 as the standard deviation; and
3. Develop statistical estimates of probability of failure as a function of assumed recovery time.

Of the generic ATWS initiators; i.e. the unprotected transient overpower (TOP), the unprotected loss-of-flow, and the unprotected loss-of-heat sink; the long term temperatures predicted for the TOP are most severe or most likely to lead to cladding failure under the mechanisms cited in this paper. Sample results for the TOP initiator are shown below. Although elaborate strategies assigning distributions to more of the parameters could have been used, the above simplified strategy adequately demonstrates the methodology and illustrates the sensitivity of inherent shutdown to the cladding failure parameters.

Calculated probabilities of pin failure before accident recovery.

Recovery Time (hrs)	D-9	HT-9
5	---	$\tilde{<}$ .01 ± .003
10	$\tilde{<}$ .01 ± .003	~ 0.015 ± .004
20	~ .02 ± .004	~ .04 ± .006
24 (1-day)	~ .03 ± .005	~ .05 ± .007

5 DISCUSSION AND CONCLUSIONS

Distributions for the probability of coherent pin failure as a function of time were generated from time-to-failure maps and predictions of time-at-temperature conditions from whole-core accident analyses. Specifically, SASSYS was used to characterize fuel pins in high power subassemblies in metal-fueled innovative designs under postulated ATWS initiators. These distributions incorporated uncertainties in the temperature histories due to limitations in ATWS modeling capability as well as uncertainties in the neutronic, thermal-hydraulic, and material property input data; they also incorporated uncertainties in the time-to-failure modeling and associated input. The probability of successful shutdown as a function of accident recovery time was then taken to be the probability of the inherent reactivity feedbacks and/or operation intervention successfully reducing core temperatures before coherent pin failure is predicted. Thus, these methods allow the probability of successful shutdown to be obtained as a function of best estimate safety margin predicted by conventional ATWS modeling, thereby allowing probabilistic risk and safety margin risk criteria to be factored directly into fuel pin design decisions.

Of the generic ATWS initiators, i.e. the unprotected transient overpower, the unprotected loss-of-flow, and the unprotected loss-of-heat sink, the long term temperatures predicted for the TOP are most severe or most likely to lead to cladding failure under the mechanisms cited in this paper. For this initiator, inherent shutdown mechanisms were predicted to avert cladding failure associated with core disruption with only a 1 to 1.5% chance of failure for an accident recovery time of 10 hours, depending on cladding selected. Sensitivities of this probability with accident recovery time are indicated in the table.

REFERENCES

[1] Bauer, T.H., G.R.Fenske and J.M.Kramer. Cladding failure margins for metallic fuel in the integral fast reactor. Paper C1/4 of these proceedings.

[2] Deitrich, L.W. and D.P.Weber. May 12-16, 1986. A review of U.S. models and codes for analysis of whole-core transients and accidents in fast reactors. International Conference on the Science and Technology of Fast Reactor Safety, Guernsey.

ACKNOWLEDGEMENTS

The authors would like to thank Ms. Lois Miller for preparing the manuscript.

Work supported by the U.S. Department of Energy, Office of Technology Support Program, under Contract W-31-109-Eng-38.