CONF-841105--16

DE84 014535

Fuel and Control Rod Failure Behavior during Degraded Core Accidents

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As a part of the pretest and posttest analyses of Light Water Reactor Source Term Experiments (STEP) which are conducted in the Transient Reactor Test (TREAT) facility, this paper investigates the thermodynamic and material behaviors of nuclear fuel pins and control rods during severe core degradation accidents. A series of four STEP tests are being performed to simulate the characteristics of the power reactor accidents and investigate the behavior of fission product release during these accidents. To determine the release rate of the fission products from the fuel pins and the control rod materials, information concerning the timing of the clad failure and the thermodynamic conditions of the fuel pins and control rods are needed to be evaluated. Because the phase change involves a large latent heat and volume expansion, and the phase change is a direct cause of the clad failure, the understanding of the phase change phenomena, particularly information regarding how much of the fuel pin and control rod materials are melted are very important. In this paper, a simple energy balance model is developed to calculate the temperature profile and melt front in various heat transfer media considering the effects of natural convection phenomena on the melting and freezing front behavior. Without resorting to the complex numerical methods such as variable time step or coordinate transformation methods reported in the literature, the present calculational method only requires a simple fixed grid and fixed time step method to achieve the same degree of accuracy as that attainable by using sophisticated techniques. The developed scheme in conjunction with the Finite/Galertin Method is convenient to use for multi-dimensional and irregular boundary problems. The essence of this calculational method is solving the following governing equation for the heat transfer media undergoing phase change.

$$\left[(\alpha\rho C_p)_f + (\alpha\rho C_p)_s + \frac{(\alpha_f)_r}{L}\frac{\partial r}{\partial T} + \frac{(\alpha_f)_y}{R}\frac{\partial y}{\partial T}\right]\frac{\partial T}{\partial t}$$

$$= \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + Q \ ,$$

where Q is a volumetric heat generation rate, r and y represent coordinate variables, K is the heat conductivity, and ρ is the fuel smear density, and α_f and α_s are the volumetric fraction of fluid and solid phase, V is the velocity vector. In an effort to validate the developed calculational method, two conventional phase change problems are selected in the context of a comparison with a completely different phase characteristics independent of the current nuclear application. The calculated results of this study agree well with the existing study.

The study of the fuel and control rod behavior shows that there exist several modes of the clad failure depending on the temperature history of the clad material and the reactor accident conditions. If the volume of materials inside the fuel pin and control rod undergo a large thermal expansion by the temperature increase and phase change, the internal pressure can be much higher than the external pressure, especially for the lower reactor system pressure accident cases such as PWR/AD and BWR/TQUW accidents. In this case, the inside materials burst out into the reactor vessel. The second mode of the fuel pin and control rod failure is that the clad fails by the external pressure before the internal material vaporizes and pressurizes the fuel pin and control rod. This type of the failure mode can occur during a high pressure accident case such as TMLB' case. In this case, the clad will buckle in and the initial dispersion of its alloy material will be less severe than the first case. Besides this mechanical failure mode, there can be other types of failure mechanisms, namely, eutectic process and clad melting. However, the analytical and experimental study indicates that such failures occur after the mechanical failure condition is reached. In a typical PWR/TMLB' accident, the control rod fails by the large mechanical pressure generated by vaporization of Cadmium of the control rod alloy (Ag-Cd-In) before the control clad (stainless steel) starts to melt. The calculated results of this study show that the control rod fails approximately 20~25 minutes after the initiation of accident and it takes a few more minutes to reach the clad melting temperature of the clad.

A similar analysis for the PWR fuel rod behavior during an AD accident shows that the clad fails long before the fuel pin clad melting. As shown in Fig. 1, the fuel clads of the STEP-1 AD test rupture when the clad temperature is between 1040 K and 1200 K (10~13 min.), while the clad melts at 2100 K (~20 min.). The PBF/SFD-1 test indicates that the fuel rod failed at the clad temperature range of 1080~1230 K, which is close to the results of the STEP tests, even though the configuration of the test reactor is different. These two tests have a similar core heat-up rate. This paper discusses the results of the STEP series tests, which are designed to simulate various core heat-up rates and clad chemical oxidation behaviors, and this experimental study would disclose many important aspects of fuel and control rod failure behaviors.

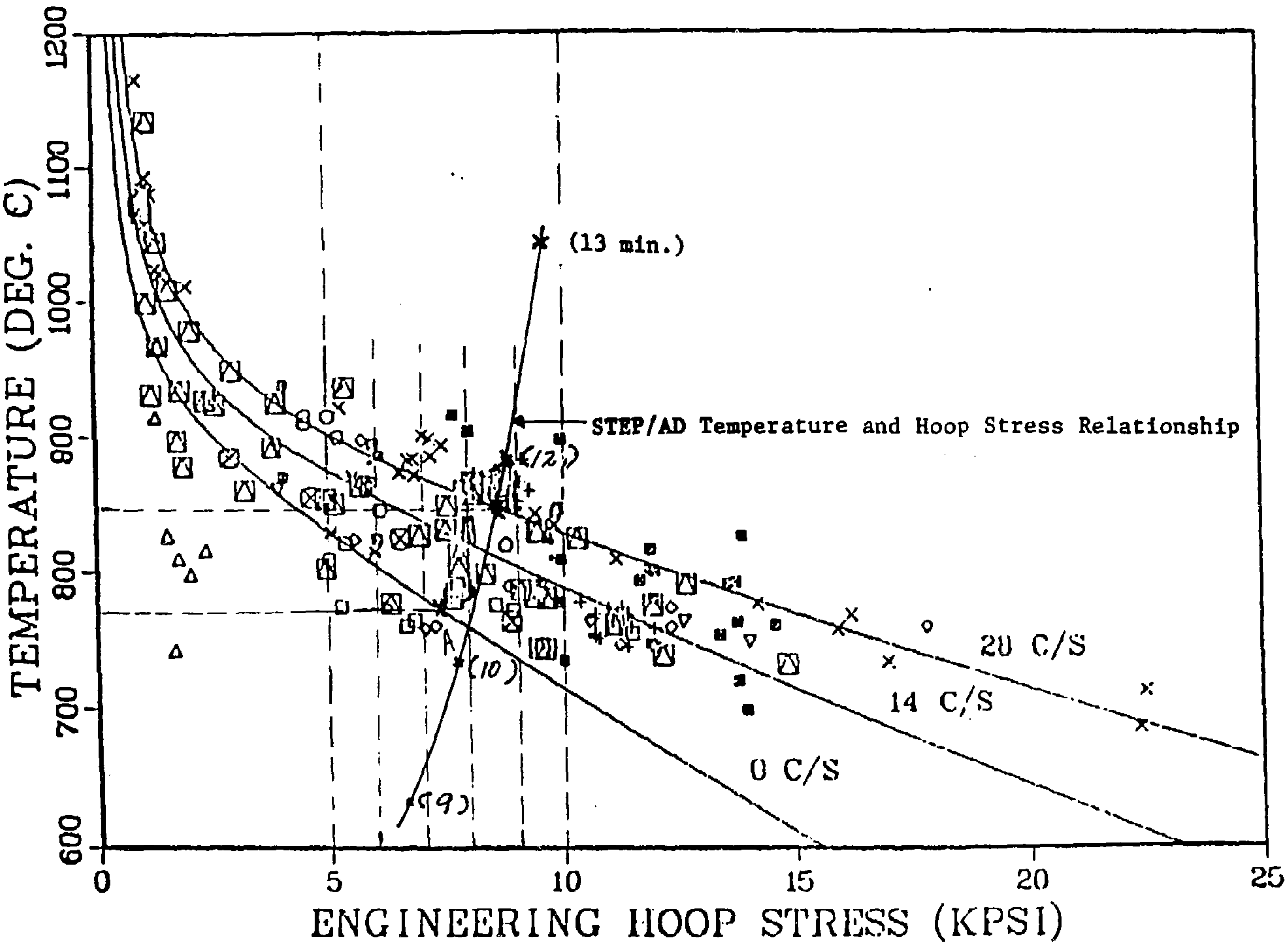

Fig. 1. STEP/AD Clad Temperature and Hoop Stress Behavior Versus Experimental Data