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Experimental and numerical investigation on thermo-mechanical behavior of fuel rod under simulated LOCA conditions

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ABSTRACT

The data from out-of-pile single rod experiments can provide vital information about transient temperature variation and deformation rate of the cladding which can be extensively used to assess the flow blockage under Loss of Coolant Accidents (LOCA). With this motivation, in the present investigation experiments were conducted at low heating rates (2–8 K/s) to simulate a LOCA scenario. The un-irradiated Zircaloy-4 clad tube was internally heated using a tungsten heater with alumina pellets as a fuel rod simulator in an inert atmosphere. The ballooning initiation led to a significant decrease in temperature rise rate owing to increase in gap width between pellet and cladding. A maximum hoop strain of 93% at 1080 K in the α-phase and minimum hoop strain of 28% at 1340 K in the β-phase was observed. The Azimuthal Temperature Difference (ATD) over the clad tube was below 18 K for all tests and therefore ballooning was essentially symmetrical. Based on the experimental results, a burst criterion has been developed to predict the burst by a code named 'TRAFR' (Transient Response Analysis of Fuel Rod). The predictions based on plasticity and creep deformation models were compared with experimental results. At high temperature, the PLASTIC model predicted too low burst strain due to hardening effect. The burst strain predictions by the CREEP model were in good agreement with the experimental results in all temperature zones. The time-dependent behavior of creep phenomena led to a gradual rise in hoop stress until burst. The predictions with CREEP model can be improved by optimizing stress exponent value at high temperature in β-phase where superplastic behavior of Zircaloy-4 is governed by dislocation climb induced creep. However creep behavior is more complex and as such no simple law is established.

1. Introduction

In the design of a nuclear power plant, hypothetical accidents like a LOCA are investigated so that suitable mitigating systems can be deployed to maintain the integrity of fuel cladding. At the initial stage of such an accident, the fuel rods get heated up and the external coolant pressure is lost. The rod internal pressure is large enough to cause plastic deformation of the cladding which leads to ballooning and burst. The high-temperature deformation and rupture behavior of clad tube is essential to evaluate the coolant flow blockage and design of Emergency Core Cooling System (ECCS). The fuel rod behavior under transient conditions has been investigated by several researchers for many decades and considerable experimental and analytical work has been performed to understand LOCA related phenomenon ("Nuclear Fuel Behavior in Loss-of-coolant Accident (LOCA) Conditions" OECD NEA-6846 (2009), ISBN 978-92-64-99091-3). Chung and Kassner (1979) investigated the effect of the internal pressure, heating rate and temperature on the ballooning deformation of Zircaloy-4 cladding. The cladding was directly heating in inert and oxidized atmosphere. They reported three super-plastic peaks - one in the low temperature α-phase and two in the high temperature β-phase region. At slow heating rates in β-phase, very small burst strain were observed because the Zircaloy has time for oxidation and embrittlement prior to rupture. Chapman et al. (1979) reported that clad deformation is extremely sensitive to small temperature variations at the surface. The irradiated low burn-up clad tubes were used to investigate thermo-mechanical behavior cladding under LOCA conditions. The clad tubes at the outer periphery were slightly bowed due to circumferential temperature variation and mutual contact during ballooning. Karb et al. (1982) investigated the influence of nuclear environment on the cladding failure behavior. Several tests were performed with both un-irradiated and pre-irradiated fuel rods (Zircaloy-4 cladding). The pre-irradiated cladding was internally heated using UO_2 pellets in the FR2 reactor (Karlsruhe, Germany), while un-irradiated tubes were internally heated using electrical heaters with alumina pellets. No significant effect was observed due to irradiation exposure over the cladding failure mechanism. Leistikow

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Nomenclature

a_c	Accommodation coefficient
A_θ	Structure-dependent constant (MPa)
Bi	Biot number
c_p	Specific heat (J/kg K)
E	Modulus of elasticity (N/m^2)
F_e	Emissivity Factor
F_a	Configuration factor
h	Heat transfer coefficient (W/m^2K)
h_{conv}	Convective heat transfer coefficient (W/m^2K)
h_g	Gap conductance (W/m^2K)
h_{gas}	Gas conductance (W/m^2K)
h_r	Radiative conductance (W/m^2K)
K	Thermal conductivity (W/mK)
L	Length of heated clad tube (m)
K_{gas}	Gas conductivity (W/mK)
K_p	Strength coefficient
m	Strain sensitivity factor
n_p	Strain Hardening Factor
n_1	Stress exponent
n_{mole}	Number of moles of gas
Nu	Nusselt number
P	Instantaneous pressure of rod (N/m^2)
P_o	Initial fill pressure of rod (N/m^2)
P_b	Burst pressure (N/m^2)
P_{gas}	Gas pressure (N/m^2)
Ra	Rayleigh Number
Ru	Universal gas constant (J/mol K)
q'''	Heat Generation per unit volume (W/m^3)
r	Local radius (m)
r_o	Initial radius of clad tube (m)
r_c	Outside radius of clad tube (m)
r_{ci}	Inside radius of clad tube (m)
r_m	Mean radius of clad tube (m)
Δr	Increment in radius (m)
r_p	Pellet radius (m)
s_b	Stefan Boltzmann Constant
T	Instantaneous temperature (K)
T_b	Bulk temperature (K)
T_{ci}	Clad inside surface temperature (K)
T_{clad}	Clad surface temperature (K)
T_{gas}	Gas temperature (K)
T_{int}	Initial temperature (K)
T_i^{n+1}	Temperature at current time step (K)
T_i^n	Temperature at previous time step (K)
T_{enc}	Enclosure temperature (K)
T_p	Pellet surface temperature (K)
T_{pl}	Plenum Temperature (K)
T_{ref}	Reference temperature (K)
t	time, (s)
t_c	Cladding Thickness (m)
t_g	Gap Thickness (m)
V_p	Plenum volume (m^3)
X_{jump}	Jump distance (m)
Greek letters	
ε_b	Burst strain
σ_b	Burst stress (N/m^2)
ε_{creep}	Creep strain
ρ	Density (kg/m^3)
ε_θ	Elastic strain
ϵ_{clad}	Emissivity of clad tube
ϵ_{pellet}	Emissivity of alumina pellet
ϵ_{enc}	Emissivity of enclosure
σ_θ	Hoop stress (N/m^2)
$\varepsilon_{plastic}$	Plastic strain
$\dot{\varepsilon}$	Strain rate (s^{-1})
ε_i	Strain at previous time step
ε_{i+1}	Strain at current time step
ε_{th}	Thermal strain
ε_{total}	Total strain
α	Thermal diffusivity (m^2/sec)
α_{th}	Thermal expansion coefficient

and Schanz (1985) reported that sever fuel damage type accidents could be initiated by slow temperature transients, followed by fast temperature escalation due to the exothermal heat evolved as consequence of the Zircaloy-4 reaction with steam, and finally lead to clad melting or disintegration of the core structure. Leistikow and Berg (1987) investigated that an exposure of fuel cladding in steam-air mixture environment may lead to much faster oxidation kinetics and consequently pronounced deterioration of fuel rods. Erbacher and Leistikow (1987) noted that ATD has a significant influence on the circumferential strain in α-phase and (α + β)-phase domain of Zircaloy-4 cladding. A large azimuthal temperature gradient around the periphery of the clad tube causes significant variations of the wall thickness in the ballooned region resulting in a small burst strain. Kim et al. (2004) reported that phase transformation from α to β phase plays an important role in the deformation of Zircaloy-4. The clad tube was directly heated using resistive heating and burst experiments were done under isothermal/transient heating conditions. Nagase et al. (2009) analyzed the cladding behavior of new materials under high burn-up ranging from 66 to 76 MWd/kg by an infra-red heating technique. They concluded that the effect of a high burn-up is not significant in terms of oxidation, ballooning and rupture behavior. Narukawa and Amaya (2016) investigated the effect of ATD on the ballooning and rupture behavior of Zircaloy-4 using IR heating. Recent experiments at Halden-IFA-650 series (Kekkonen, 2005) with high burn-up fuel regained attention of nuclear community towards issue of clad ballooning and fuel fragmentation. The experimental data has provided substantial information regarding fuel rod behavior under transient conditions for code validation and further improvement.

As the reliable prediction of fuel rod behavior is essential for a realistic safety analysis of nuclear reactors, several codes were developed in the past. One of the most popular codes is FRAPTRAN 2.0 developed by Pacific Northwest National Laboratory to predict the transient behavior of oxide fuel rods during reactor transients such as LOCA in a Light Water Reactor (Geelhood et al., 2014). The code calculates the temperature distribution within the fuel rod by the finite volume method using 'HEAT-1' code developed by Wagner (1963). The large plastic deformation during ballooning is calculated by the 'BALON2' model (Hagrman et al., 1981). The burst criterion for prediction of failure is based mainly on the experiments conducted by Chapman et al. (1979), Chung and Kassner (1979), Hobson and Rittenhouse (1972) where the heating rates were between 28 and 115 K/s. Manngard and Massih (2011), developed a cladding deformation model to predict the effect of oxygen on phase transformation by rule of mixture and concluded that oxidation significantly reduces the burst stress at high temperatures in β-phase.

It is apparent from the above literature review that the deformation is strongly governed by the temperature distribution over the surface of the clad tube and fuel rod condition prior to occurrence of an accident. The experiments conducted using direct heating techniques (Chung and Kassner, 1979) or IR heating techniques (Nagase et al., 2009; Narukawa and Amaya, 2016) where heat generation occurs within the cladding resulted in too large deformation during ballooning not typical of