Parametric Study of Runaway Reactions

Yuri Nekhamkin, Dov Hasan, Eitan Wacholder, and Ezra Elias

Faculty of Mechanical Eng., Technion IIT, Haifa, 32000, mereagh@tx.technion.ac.il

Keywords: Safety, Runaway, Oxidation.

Introduction.

Criteria for runaway conditions in water-cooled reactor cores during hypothetical accident conditions were previously derived for various scenarios [1, 2] to determine whether for a given set of conditions the situation could lead to a runaway reaction or measures could still be taken to alleviate the situation and to mitigate the results. The present work extends this analysis by quantitatively accounting for the effect of additional parameters.

Description of the Work.

It is realized that in a hypothetical severe accident nuclear fuel rods can under certain extreme conditions undergo runaway oxidation reactions in which the heat of oxidation exceeds the rate of cooling. Figure 1 describes the configuration considered in this paper and defines the geometrical parameters in terms of the relative height $\mu = z/L$. In a partially uncovered core, three major regions may be identified: Single-phase liquid at the bottom, then a two-phase (gas-liquid) layer and a single-phase water vapor region having an initial length of $L(1-\mu_0)$. The initial fuel pellet radius is r_0 and the outer cladding radius is R_0.

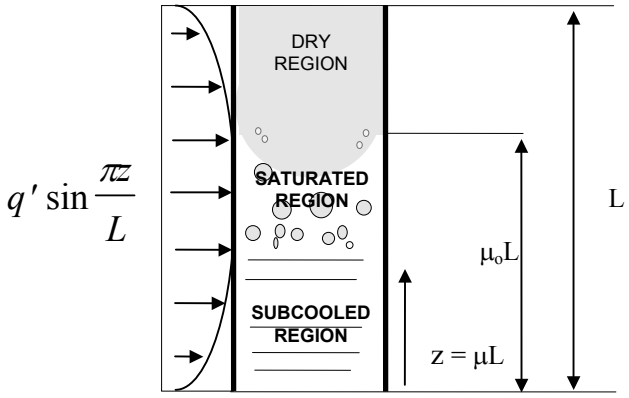

Figure 1: Schematic of heated channel

In a previous paper by the authors [3], an exact transient solution of the fluid velocity and temperature fields for the first, single-phase liquid, zone was derived, which resulted in an analytical expression for the location of the boiling boundary (lower boundary of the second, two-phase, region) as a function of time for a given saturation temperature. The upper boundary of the boiling zone, which is practically the quench front, can be obtained from a heat balance over the two-phase region. The following analysis considers the combustion kinetics and heat balances in the third, dry, region for the case of constant core level, taking into account the possibility

of runaway reactions.
The governing differential equations for the rod dimensionless temperature θ and oxide layer thickness η, were derived in [1] as:

$$\frac{d\theta}{d\tau} = \frac{e^{\left(\frac{\theta}{1+\beta\theta}\right)}}{\eta} - \frac{\theta}{\omega} \tag{1}$$

$$\frac{d\eta}{d\tau} = \frac{e^{\left(\frac{\theta}{1+\beta\theta}\right)}}{\eta} \tag{2}$$

The dimensionless parameters here extend those presented in [4, 5] by including a spatially distributed nuclear heat-source term, as follows:

$$\beta = \frac{T^*}{B}, \qquad \theta = \frac{T_c - T^*}{\beta T^*}, \qquad \eta = \frac{\delta}{\delta^*}, \qquad \tau = \frac{t}{t^*} \tag{3}$$

The parameter *B* is derived from the activation energy, and for the Zircaloy-Steam reaction *B*=22900 K. The characteristic temperature T^* is defined as:

$$T^* = T_s + \frac{[C_f(T_s - T_o) + r][1 + \cos(\pi\mu_o)]}{C_s(1 - e^{-\phi})[1 - \cos(\pi\mu_o)]} \tag{4}$$

Here T_s and T_o are the saturation and inlet temperatures, respectively, r is the latent heat of vaporization and C_f, C_s are the water and steam specific heats, respectively. The characteristic oxide thickness δ^* and time t^* are defined as:

$$\delta^* = \frac{\beta T^* C_{Zr}(R_o^2 - r_o^2)}{2Q_o R_o}, \qquad t^* = \left\{\frac{T^* \beta C_{Zr}(R_o^2 - r_o^2)}{2Q_o R_o}\right\}^2 \frac{e^{(1/\beta)}}{k_r} \tag{5}$$

C_{Zr} is the cladding specific heat, Q_o is the steam/metal reaction heat per unit mass of *Zr* and k_r is a chemical reaction constant ($k_r = 3.968 \times 10^{-5}\ m^2/s$). ω is defined as:

$$\omega = \frac{\pi^2[C_f(T_s - T_o) + r]C_{Zr}(1 - \mu_o)[R_o^2 - r_o^2]\rho_{Zr}}{q_o'[1 - \cos(\pi\mu_o)]C_s(1 - e^{-\phi})t^*} \tag{6}$$

where ϕ combines the water inlet mass flow rate, $\dot{m}$ (rate of steam production), the convective heat transfer coefficient, α_{cv} and the total rods' surface area, A_c:

$$\phi = \frac{\alpha_{cv} A_c (1 - \mu_o)}{\dot{m} C_s} \tag{7}$$

Results.
The set of equations (1) and (2) exhibits both exponential and direct or inverse linear dependence on θ and η, and on the parameters β, ω. The relative magnitude and effect of these parameters are demonstrated in Fig. 2, which exhibits two branches in

the dimensionless time-to-ignition, τ_{ign}, curves as a function of ω. For small values of ω the 2nd term on the RHS of eq. (1) dominates while its effect diminishes at large values of ω. Clearly, when ω is in the range of 2.5 to 3 the time-to-ignition is at its minimum.

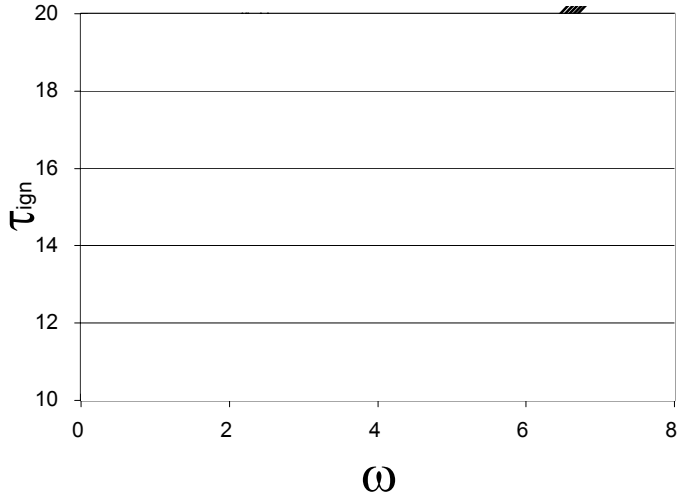

Figure 2: Non-dimensional time-to-ignition as a function of parameter ω.

The set of representative initial conditions used in Fig. 2 is $\tau = 0$, $\eta = 10^{-5}$ and $\theta = -15$. Due to the nature of the equations, the influence of these initial conditions on the results is considerable only in the right-hand branch of the curves, i.e., when $\omega > \omega_{\min}$. Here $\omega_{\min}$ is the value of ω that corresponds to a minimum in ignition time τ_{ign}. As indicated before in [5] and [6] the effect of β on τ_{ign} is clearly of secondary importance. For a given *B*, uncertainty in β reflects mainly the degree of knowledge of the physical properties, and to a lesser extent, the state.

In the present case, β includes, through T^*, the effect of the quench-front location along to the axially unevenly distributed nuclear power. Therefore, in Fig. 2 one may observe dependence of the critical ω on β. This extends somewhat the results presented in [1] in which a "universal ω" value of about 2.4 was defined. Figure 2 also demonstrates the relative effect of the various non-dimensional parameters. For instance, the effect on τ_{ign} of ω is clearly higher than that of β. This is further demonstrated in Fig. 3, which depicts $\omega_{\min}$ and ω_{crit}, that is the value of ω that is critical for ignition.

It is noted that the range of β, taken here between 0.01 and 0.05 covers more than the applicable range of the physical problems encountered in severe accident. Figure 3 also shows that the sensitivity to small variations in β of the likelihood of having the reaction running away as expressed by ω_{crit}, is given by:

$$\frac{\partial \omega_{crit}}{\partial \beta} = 8.75 \qquad (8)$$

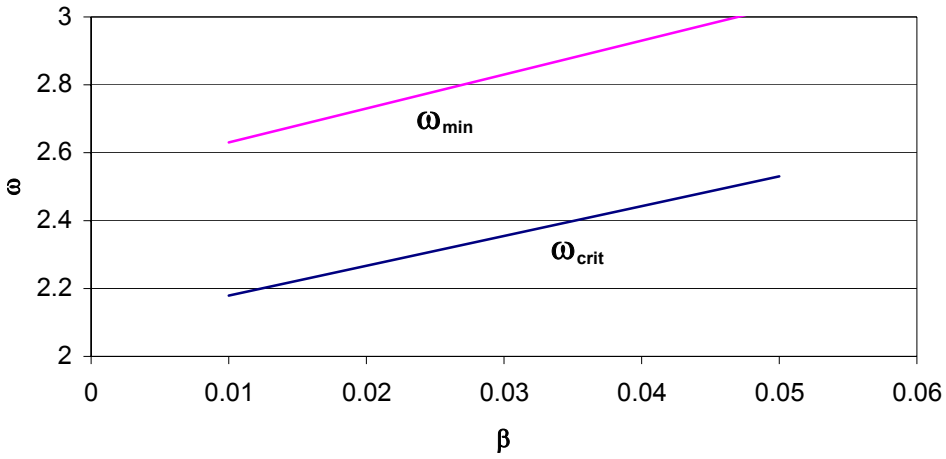

Figure 3: Parametric influence on $\omega_{\min}$ and ω_{crit}

Conclusions.

It is emphasized that the parameter ω signifies clad heating from the initial rod uncovery value to temperatures where exothermal reactions prevail. Therefore, if there is no possibility to keep $\omega < \omega_{crit}$, then ω should be maximized in order to gain time for corrective actions to prevent ignition and runaway reaction.

Acknowledgments: This research was partially supported by the Israel Atomic Energy Commission (IAEC)

References.

[1] Y. Nekhamkin, V. Rosenband, D Hasan, E. Elias, E. Wacholder and A. Gany, "*Oxidation and Heat Transfer Considerations in Degraded Core Accident"*, TOPSAFE98, Valencia, April 1998.

[2] Dov Hasan, Yuri Nekhamkin, Valeri Rosenband, Ezra Elias, Eitan Wacholder and Alon Gany, *"Nuclear Fuel Cores Thermal Hazards Criteria"*, The 20th Conference of the Nuclear Societies in Israel, 1999.

[3] D. Hasan, Y. Nekhamkin, V. Rosenband, E. Elias, A. Gany and E. Wacholder, *"An exact solution of the moving boiling boundary problem"*, Nucl. Engn. Des. 203 (2001) pp. 243 - 248.

[4] N. N. Semenov, ZhRFKhO, Ch. Fiz., 60, 241 (1928).

[5] B. I. Khaikin,V. N. Bloshenko, and A. G. Merzhanov, *"On the Ignition of Metal Particles, Combustion, Explosion, and Shock Waves"*, Vol. 6, No. 4, 1970.

[6] *D. A. Frank-Kamenetskii, "Diffusion and Heat Transfer in Chemical Kinetics", Nauka, 1967, 2nd ed., Plenum Press (New York), 1969.*