ENCLOSURE 2

MFN 13-085

TRACG Quench Front Model Description and Qualification

Non-Proprietary Information– Class I (Public)

IMPORTANT NOTICE

This is a non-proprietary version of Enclosure 1, from which the proprietary information has been removed. Portions of the enclosure that have been removed are indicated by an open and closed bracket as shown here [[ ]].

TRACG Quench Front Model

Introduction

This paper describes the updated quench front model, its implementation into TRACG [1], and the validation of the quench model. The quench front model is based on a solution to the one and two-dimensional heat conduction equations and is implemented as a correlation for the net heat transfer associated with the quench front propagation. The quench front model has been updated to correct an error in the quench front heat transfer coefficient for bottom reflooding, and to better capture the heat transfer ahead of and behind the quench front. The updated quench front model has been validated by comparison to Halden tests, which were conducted with Zircaloy clad boiling water reactor (BWR) fuel rods at conditions representative of a BWR anticipated transient without scram instability (ATWSi) event, and loss-of-coolant accident (LOCA) tests using electrically heated simulated fuel rods. The agreement with the data validates the TRACG quench front model.

TRACG Quench Front Model Description

The TRACG model for the axial conduction controlled quench front propagation is documented in the TRACG Model Description [1] Section 6.6.13. It simulates the one- and two-dimensional solutions of References 2 and 3 and was retained from TRAC-P1A [4] which was the starting point for the development of the BWR versions of TRAC [5] and TRACG. The model is based on a solution to the two-dimensional heat conduction in the cladding around the quench front location [6]. Figure 1 is an illustration of the temperature profile and heat conduction at a quench front.

Ahead of the quench front the wall is in film boiling at a high temperature T_w^+, the wall surface temperature is equal to the quench front temperature T_o at the quench front, and behind the quench front, the wall temperature quickly approaches the saturation temperature. Heat is conducted axially in the wall due to the temperature drop from the region ahead of quench front to the region behind the quench front and outwards to the liquid in the region behind the quench front. The quench front model correlates the total heat transfer to the liquid behind the quench front due to this heat transfer at the quench front. The total heat transfer per unit perimeter to the fluid behind the quench front due to the two dimensional heat conduction in the cladding, axially from the dry to the quenched regions, and radially to the fluid in the in the quenched region, is given by Equation 1.

$$q'_q = k_w (T_w^+ - T_{sat}) \left(\overline{Bi} (1 + 0.4 \overline{Bi}) \right)^{0.5} \quad , \tag{1}$$

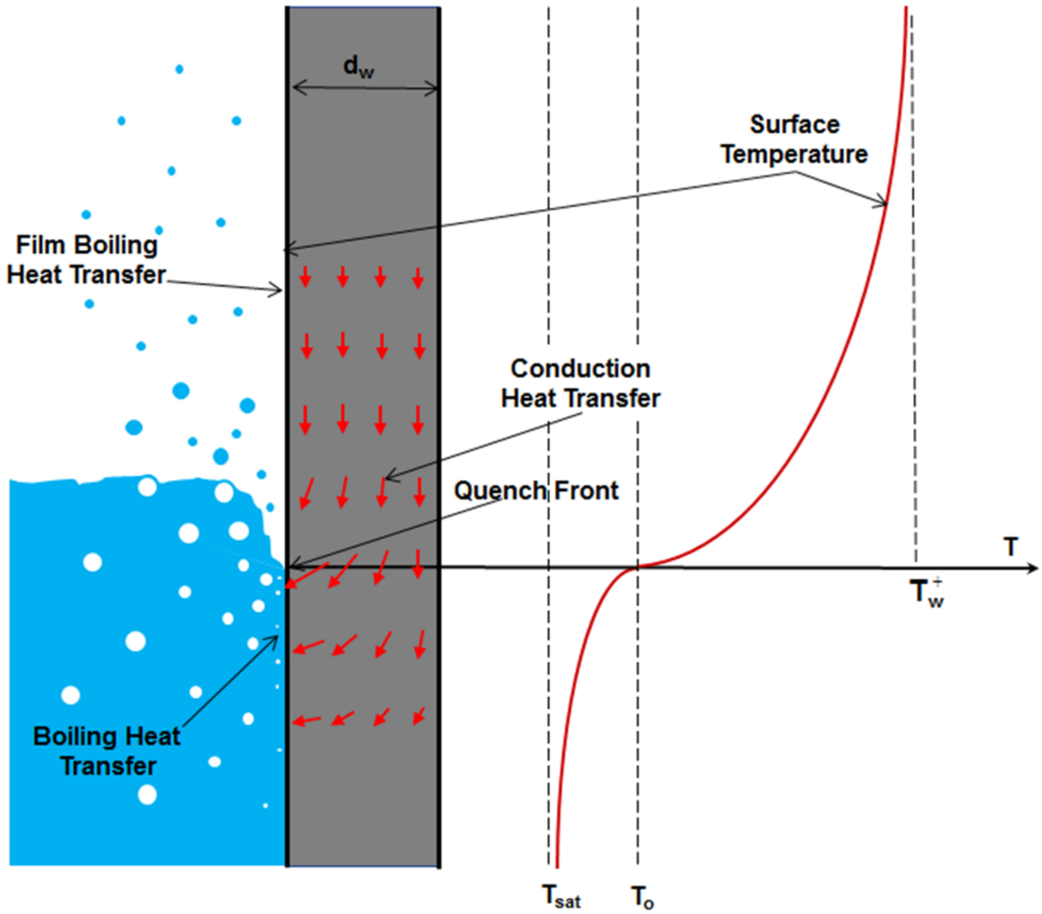

Figure 1. Axial Conduction Controlled Quenching

In this equation, the modified Biot number $\overline{Bi}$ is given by Equations 6.6-153 – 6.6-156 in the TRACG Model Description [1]. These equations are repeated here,

where:

$$\overline{Bi} = \frac{Bi}{\overline{T}^2} \quad \text{(Reference 1 Eq. 6.6-153)}$$

$$Bi = \frac{h_q d_w}{k_w} \quad \text{(Reference 1 Eq. 6.6-154)}$$

$$\overline{T} = \frac{\sqrt{\Theta}}{1-\Theta} \quad \text{(Reference 1 Eq. 6.6-155)}$$

$$\Theta = \frac{T_w^+ - T_o}{T_w^+ - T_{sat}} \quad \text{(Reference 1 Eq. 6.6-156)}$$

and:

h_q = Heat transfer coefficient in the short region with high heat transfer just behind the quench front

T_o = Quench front temperature

T_w^+ = Wall temperature just ahead of the quench front

d_w = Wall thickness

k_w = Thermal conductivity of the wall material

The heat transfer coefficient h_q, which is used in the Biot Number (Equation 6.6-154 of Reference 1) for bottom flooding, was calculated by Equation 6.6-158 of Reference 1 and had been retained from TRAC-P1A [4] and TRAC-BD1 [5], which also employed Equation 1 for the calculation of the quench front propagation. It is based on the work by Yu, Farmer and Coney [8]. This model is described below:

$$h_q = \left(\frac{F_q}{\Delta T_q} \right)^2 \tag{2}$$

$\Delta T_q = T_o - T_\ell$ is the difference between the Leidenfrost temperature and the liquid temperature. In the above expression:

$$F_q = \alpha F_s \tag{3}$$

$$F_s = 4.24 \cdot 10^4 v_\ell^{0.15} \tag{4}$$

$$\alpha = \begin{cases} \left(1 + v_\ell \Delta T_\ell^2\right)^{0.13} & \text{for } (1 + v_\ell \Delta T_\ell^2) \le 40 \\ 0.4839\left(1 + v_\ell \Delta T_\ell^2\right)^{0.346} & \text{for } (1 + v_\ell \Delta T_\ell^2) > 40 \end{cases} \tag{5}$$

where v_ℓ is the liquid velocity and $\Delta T_\ell = T_s - T_\ell$ is the liquid subcooling.

The expression for α as described in Reference 5 incorrectly used $\Delta T_q = T_o - T_\ell$ instead of $\Delta T_\ell = T_s - T_\ell$ as described in the original paper by Yu, Farmer and Coney [8]. This has been corrected in TRACG04 and α is calculated correctly as described by Equation 5 above consistent with Yu, Farmer and Coney's paper. The high value of the quench front heat transfer coefficient is consistent with the observations in Reference 9. These models for the quench front heat transfer coefficient and the total quench front heat transfer have been used in the qualification against the Halden Tests. For quenching from the top by a falling film on the surfaces a value of [[ ]] is used as described in Reference 1.

TRACG Quench Front Model Implementation

The implementation of the quench front model is described in the context of reflooding from the bottom. The implementation for quenching from the top due to a falling film is similar. [[

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TRACG Quench Front Model Validation

The TRACG quench front model has been validated by comparison to the Halden tests and to LOCA tests. The Halden test were dryout and rewet tests with BWR fuel rods conducted in the Halden test reactor at rated pressure and linear heat generation rates typical of BWR anticipated transient without scram (ATWS) conditions. TRACG has been compared to four Halden tests. The LOCA tests using electrically heated simulated fuel rods include the Thermal-Hydraulic Test Facility (THTF), Two-Loop Test Apparatus (TLTA) and Rig of Safety Assessment (ROSA)-III test facilities.

TRACG Quench Front Model Validation – Halden Tests

TRACG input models were created to augment the validation basis of the TRACG quench front heat transfer model by simulating four Halden Third-Series [7] experiments. They are performed with actual fuel rods with Zircaloy cladding, at high power, and at high pressure (around 7 MPa). In addition, quenching is observed at temperatures above TRACG-calculated T_{min}.

The four Halden experiments that resulted in quenching from elevated temperature (>650°C) are simulated with TRACG. They are Experiments 3, 4, 11c, and 12. Unless noted otherwise, all TRACG cases are performed with the quench model on and with the modified (no void term) Shumway correlation for T_{min}. Validation of the Shumway correlation [10] as implemented in TRACG is documented in Reference 18.

<u>Experiment 3</u>

The TRACG clad temperature result is shown in Figure 2. The calculated results show good agreement with the measured temperatures around the time of the quench.

<u>Experiment 4</u>

The TRACG clad temperature result is shown in Figure 3. The calculated results show good agreement with the measured temperatures around the time of the quench.

Several cases were performed to assess the effect of turning off the TRACG quench model and lowering the T_{min} compared to the modified Shumway T_{min}. T_{min} is lowered by assuming Stainless Steel 304 (SS304) material properties in the modified Shumway correlation. Figure 4 shows the calculated clad temperature results compared to the measured data. The results show that the quench model is effective in reducing the clad temperature. [[

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Experiment 11c

Experiment 11 involved a series of 6 dryout tests. Rather than attempt to model the series, only the dryout that resulted in the highest temperature is assessed. This portion of the test occurred between 900 and 1,000 seconds and is called Test 11c.

For Experiment 11, [[

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The clad temperature result is shown in Figure 5. The results show that the TRACG quenching model produces calculated temperatures that compare reasonably well to the test measurements.

Experiment 12

For Experiment 12, [[

]] The calculated clad temperature result is compared to the measured values in Figure 6. The results show that the calculated TRACG quenching occurs similar to the test.

Several cases were performed to assess the effect of turning off the quench model and lowering T_{min}. T_{min} is lowered by assuming SS304 material properties in the modified Shumway correlation. [[

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Figure 7 shows the various calculated clad temperature results compared to the test data. The results show that the quench model is effective in reducing the clad temperature and that quenching is crucial to adequately model the test.

In summary, the above TRACG comparison to the Halden experiments validates the TRACG quench model at ATWS with instability conditions.

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Figure 2. TRACG Clad Temperature Results Compared to Test 3

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Figure 3. TRACG Clad Temperature Results Compared to Test 4

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Figure 4. TRACG Clad Temperature Results Compared to Test 4 – Effects of Quench Model and T_{min} Model

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Figure 5. TRACG Clad Temperature Results Compared to Test 11

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Figure 6 TRACG Clad Temperature Results Compared to Test 12

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Figure 7. TRACG Clad Temperature Results Compared to Test 12 – Effects of Quench Model and T_{min} Model.

TRACG Quench Front Model Validation – LOCA Tests

To further assess the TRACG quench model, selected LOCA Integral System Tests (ISTs) were evaluated with and without the quench model activated. Cases were selected for tests performed at facilities that had previously been evaluated in the TRACG Qualification LTR [11]. Selected cases are those where the test data temperature traces indicate a quench. The tests evaluated in this response are: THTF transient blow down Tests 3.03.6AR, 3.06.6B, and 3.08.6C [12, 13]; TLTA Test 6423 [14]; and ROSA-III Tests 912 [15] and 926 [16]. All tests except for THTF Test 3.03.6AR were previously evaluated in Reference 11. Relevant details for the re-evaluations presented here are summarized in Table 1. All the TRACG calculations were executed using the Shumway T_{min} correlation with the void term disabled and the cladding material appropriate for the test as indicated in Table 1.

The temperatures presented in Table 1 show that generally the maximum temperature calculated by TRACG [[

]] for these LOCA-like cases the maximum temperature is reached and begins to decrease based on precursory steam cooling that exists prior to when the quench occurs. The LOCA scenarios are unlike the ATWSi scenario because for LOCA the cladding has a longer heatup time at a much lower heat flux in a fluid environment where there is very little liquid water. The ATWSi scenario with power and flow oscillations near the operating reactor pressure is much better represented by the Halden test cases where the reactor remains at power, flow is reduced to produce the boiling transition and is later increased after the dryout to simulate the flow surge, which causes the return to nucleate boiling.

Table 1: Test Data and TRACG Comparison Summary for LOCA-Like Scenarios

Test	Clad Material	Maximum Temperature[1] (K)				Quench Velocity[3] (m/s)		Estimated Pressure (MPa) at Time of Quench
		Test Data	TRACG		Elev-ation[2] (m)	Avg. Along Rod	Last Second Before Quench	
			Quench Model OFF	Quench Model ON				
THTF 3.03.6AR	Stainless Steel	949	[[		3.6	0.08	0.43	5.6
THTF 3.06.6B	Stainless Steel	1135			3.6	0.11	0.32	5.8
THTF 3.08.6C	Stainless Steel	1204			2.4	0.10	0.07	6.6
TLTA 6423	Inconel	802			2.0	0.01	0.05	0.60
ROSA-III 912	Inconel	839			0.94, 1.11	0.02	0.15	1.4
ROSA-III 926	Inconel	784		]]	0.94	0.01	0.07	0.40

Notes:

1 The *Maximum Temperature* corresponds to the peak value for the specific rod and location that is being compared.

2 The elevation indicates where the maximum temperature was taken for the test data and TRACG. The maximum temperature from the node plotted for the respective test and elevation is used. For ROSA-III 912, the TRACG calculated temperature peak occurs for the node at 1.11 m so it is the temperature trace at that elevation that is tabulated and plotted.

3 The *Quench Velocity* was calculated by dividing the distance the quench front traveled by the elapsed time to travel that distance based on the TRACG indicated position of the quench front with time.

Table 1 shows that for THTF Tests 3.03.6AR and 3.06.6B the calculated quench velocity over the last second before the quench at the thermocouple (T/C) elevations are 0.43 m/s and 0.32 m/s, respectively (16.9 inch/s and 12.6 inch/s). The ATWSi power/flow oscillations occur near the normal operating pressure of a BWR whereas for the LOCA-like test cases the quench occurs for a range of lower pressures as indicated in Table 1.

Calculated TRACG temperature traces with time are compared to the test data in Figures 8 through 13. The red curves labeled "TRACG Nominal" in these figures are from calculations where the quench model was turned OFF. The blue curves labeled "TRACG Quench" are with the quench model turned ON. The green and turquoise curves show the measured data. For these LOCA scenarios the quench front movement is limited by the rate of liquid water addition rather than the inability to return to nucleate boiling. Steam produced lower in the bundle serves to reduce measured temperatures at the higher elevations before the quench front propagates to the maximum measured temperature elevation. It is this precursory cooling process that is the reason both the measured and calculated temperature traces are trending downward even before quenching occurs. Quench is suggested at the *shoulder* in the measured temperature trace where the temperature suddenly drops.

It is not always possible from the measured temperature traces to distinguish a temperature drop due to quenching and a drop due to an improvement in the heat transfer mode that results when the surface temperature is reduced below the T_{min}. The need to make this distinction is not essential because the TRACG quench and T_{min} models work together. The T_{min} model defines the maximum surface temperature for which return to nucleate boiling can occur if there is sufficient liquid. When the surface temperature ahead of the quench front is above T_{min}, the quench model has a higher relative importance because it provides for heat removal via axial conduction to liquid near the saturation temperature that exists below the quench front. On the other hand, if the surface temperature decreases below T_{min} above the quench front then a higher heat transfer coefficient is calculated above the quench front and the axial temperature profile and thus the quench heat removal mechanism are decreased. The TRACG Quench calculations presented in Figures 8 through 13 demonstrate that the TRACG quench and T_{min} models are working well together in matching the quench temperature data. For example, consider the results in Figure 9 for THTF Test 3.06.6B. For pressures between 5 and 6 MPa the Shumway correlation [10] predicts a T_{min} value of about 770 K for stainless steel for low flows and no void enhancement. Graphically it can be seen [[

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For comparison with the TRACG calculations and the test data, the TRACE calculated results are depicted by the purple curves in Figures 8, 9, and 10. The Groeneveld-Stewart T_{min} correlation (derived from Inconel data) is used in TRACE [17] to predict a T_{min} value around 685 K at 5 MPa. This value is about 90 K lower than the Shumway prediction for stainless steel at 5 MPa. The effect of the lower value for T_{min} is most apparent in the purple curves on the left side of Figure 9 and the right side of Figure 10. Primarily because of the lower value for T_{min}, TRACE predicts a quench temperature that is lower than the data by at least 50 K.

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Figure 8. Temperature Comparison for THTF Test 3.03.6AR

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Figure 9. Temperature Comparison for THTF Test 3.06.6B

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Figure 10. Temperature Comparison for THTF Test 3.08.6C

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Figure 11. Temperature Comparison for TLTA Test 6423

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Figure 12. Temperature Comparison for ROSA-III Test 912

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Figure 13. Temperature Comparison for ROSA-III Test 926

Conclusion

The updated quench front model and its implementation into TRACG have been described. The updated quench front model has been validated by comparison to tests from the Halden test reactor at conditions representative of a BWR ATWS event and by comparison to LOCA tests using electrically heated simulated fuel rods. The excellent to slightly conservative agreement of the calculated temperature results with the data justifies the application of the TRACG quench front model.

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