# AN EMPIRICAL HEAT TRANSFER COEFFICIENT DURING QUENCHING[1]

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## ABSTRACT

*Heat transfer coefficients (HTC) during quenching of a fuel channel are assessed to provide the boundary condition in the calculations of thermal stresses in the pressure tube. Of particular interest is the quenching of the fuel sheath and pressure tube during an IBIF (Intermittent Buoyancy Induced Flow) cycle. This information is required to determine whether the pressure tube can be returned to service following a channel flow stagnation. An empirical heat transfer coefficient based on the critical heat flux was used for the calculation of the fuel and pressure tube temperature during the quench. The prediction has been compared with measurements in a few selected Cold Water Injection Tests (CWIT) to quantify the conservatism.*

## 1 BACKGROUND

Following a loss of shutdown cooling system forced flow circulation, the fuel and fuel channels will be cooled by natural circulation mechanisms. These natural circulation mechanisms are collectively referred to as CCAFF (Channel Cooling in the Absence of Forced Flow), which includes IBIF (Intermittent Buoyancy Induced Flow), single-phase liquid flow, and turbulent steam cooling. Initially during IBIF, the temperature of the coolant in the fuel channel increases due to the fuel decay heat. When the fluid becomes saturated, steam accumulates at the top of the pressure tube. During this period, the fuel sheath (FS) and pressure tube (PT) will heat up above the saturation temperature. When steam vents through one of the feeders, cooler water gradually fills up the channel, as the PT and the FS are quenched. During the quench, the PT inner surface will be cooler than its outer surface and the FS outer surface will be cooler than its inner surface. This through-wall thermal gradient results in thermal stresses in the pressure tube and fuel sheath, which may affect their serviceability.

The through-wall temperature gradient is sensitive to the heat transfer coefficient during the quench. The heat transfer coefficient depends on several parameters such as pressure, incoming flow rate and quality, PT and fuel bundle geometry. It also continuously

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[2] AECL Attachment

changes as the PT wall and fluid temperatures change. Therefore, modelling the HTC during quench is quite challenging, and historically a conservatively high constant value has been assumed.

In the present approach, an empirical heat transfer coefficient based on the critical heat flux is used for the calculation of the fuel and pressure tube temperature transient during the quench. The predictions have been compared with test measurements in the Cold Water Injection Tests (CWIT) to quantify the conservatism.

## 2 METHODOLOGY

The HTC is calculated based on the peak PT temperature and the maximum possible heat flux that can be removed from the inside wall. At any time during PT quench, the heat removed from the PT wall is less than the Critical Heat Flux (CHF). The CHF is calculated based on estimates of the coolant mass flux and quality during quenching for a horizontal tube geometry.

To confirm that a reasonable representation of the true HTC was obtained, CWIT experimental data was simulated using the MULTI-SMARTT computer code. MULTI-SMARTT provides a detailed two-dimensional simulation of the thermal response of both the fuel and PT at a given fuel channel cross section. The code includes models of circumferential and radial heat conduction in the fuel and PT, half-bundle geometry of 37-element or 28-element fuel bundles and radiation heat transfer between each fuel element and between the fuel elements and the PT.

CWIT is an out-of-reactor test program performed to examine channel behaviour following flow stagnation. Fuel sheath and PT temperatures were recorded during heat-up, steam vent and channel quench.

The HTC resulting in the best match of the experimentally observed maximum cooling rate is assessed. It is compared with the suggested HTC value to quantify the conservatism.

## 3 ADOPTED HEAT TRANSFER COEFFICIENT

At the start of the venting period in an IBIF cycle, the fuel bundles are cooled by film boiling. A relatively low HTC is expected during this period. The HTC increases during transition boiling, until it peaks at CHF. However, the HTC increases late in the quenching transient when the PT temperature is low and results in a relatively low $\Delta T$ through the PT wall.

The objective is to assess the maximum ΔT through the PT wall during the quench. The HTC to be used during the initial quench phase corresponds to the highest possible heat flux (the critical heat flux) divided by the wall superheat, i. e.,

$$HTC = \frac{CHF}{(T_w - T_{sat})} \qquad \text{[Eq. 1]}$$

where:

HTC = heat transfer coefficient [kW/m$^2$°C].
CHF = critical heat flux [kW/m$^2$].
$T_w$ = inside wall temperature at the start of the quench [°C].
$T_{sat}$ = coolant saturation temperature [°C].

## 4 CHF AT TYPICAL CONDITIONS DURING QUENCHING IN AN IBIF CYCLE

The CHF depends on the geometry, coolant mass flux, coolant quality and pressure. The thermalhydraulic conditions are evaluated based on CCAFF1.2.2 code simulations. CCAFF1.2.2 is a computer code used at Ontario Power Generation Inc. to simulate channel behaviour under initial no-flow conditions. The code predicts, among other parameters, the duration of flow stagnation, steam vent and refill. At the conditions of interest, a mass flux slightly below
500 kg/ s*m$^2$ is predicted during the quench.

Some quality exists at the beginning of the quench. However, as the CHF decreases with quality, a quality of 0.0 is conservatively used to evaluate CHF.

The Thermalhydraulic Evaluation Program (TEP) [1] was used to derive the CHF values. Table 1 lists the CHF values for the relevant range of channel pressures.

## 5 MULTI-SMARTT SIMULATION OF CWIT # 1431 AND # 1442

The CWIT tests results and the MULTI-SMARTT initial conditions required for simulation are summarised in Table 2. The temperature transient in the PT during quench is simulated using MULTI-SMARTT and the results are compared with the thermocouple measurements of the outside wall temperature recorded in CWIT # 1431 at 0.2 MPa(a) and # 1442 at 4.6 MPa(a). These tests were conducted with a 37-element fuel simulator, a cosine axial power profile and in-line end fittings. These particular tests were chosen to cover the entire range of pressures and highest PT peak temperatures at channel powers below100 kW. These conditions are representative of channel conditions in the shutdown state.

Only the outside wall temperature was measured. The inside wall temperature is related to the outside wall temperature by conduction through the wall. If the predicted cooling rate is higher than the cooling rate in the CWIT tests, then the adopted HTC is conservative for assessing the thermal stresses in the PT.

## 6 COMPARISON WITH EXPERIMENTAL DATA

Several values of the HTC were used to determine the best representation of the experimentally observed PT quench. Results are presented in Tables 3a, 3b and Figures 2, 3, 4 and 5. The best match of the maximum cooling rate of the outside PT wall was obtained with a HTC of 1.2 kW/m$^2$/°C for CWIT # 1431 and at a HTC = 2.0 kW/m$^2$/°C for CWIT # 1442.

The HTC derived with the suggested approach (HTC=3.5 kW/m$^2$/°C for test 1431 and HTC=25.2 kW/m$^2$/°C for test 1442) results in faster PT quench rate than observed and therefore is conservative with respect to the maximum through-wall temperature difference.

Since the maximum through-wall temperature difference is used in subsequent analysis of the thermal stresses, the following overprediction factor is calculated based on the through-wall temperature:

$$\text{Overprediction Factor} = \frac{\text{Through Wall } \Delta\text{T}(HTC_{proposed})}{\text{Through Wall } \Delta\text{T}(HTC_{bestestimate})} \qquad \text{[Eq. 2]}$$

The overprediction factor varies from 2.4 for CWIT # 1431 to 4 for CWIT # 1442. These overprediction factors are clearly conservative. However, derivation of more realistic values would require a more extensive evaluation of several CWIT experiments.

## 7 CONCLUSION

For assessing pressure tube thermal stress during quench a wall heat transfer coefficient needs to be derived. A constant HTC corresponding to CHF divided by the initial wall superheat provides a reasonable and conservative assessment of PT wall maximum cooling rate. This ad hoc HTC results in higher quench rates relative to those observed in CWIT # 1431 and CWIT # 1442.

## 8 REFERENCES

1. L.K.H. Leung, “Thermalhydraulics Evaluation Package (Computer Program Abstract for V3.0”, AECL Report COG-97-415, FFC-FCT-124 (Vol.8), September 1998.

**Table 1. Calculated Values for the CHF of the PT Inside Wall During PT Quench**

| Pressure [MPa(a)] | CHF [kW/m$^2$] |
|---|---|
| 10 | 1319 |
| 4.6 | 1772 |
| 1.4 | 1794 |
| 0.2 | 1128 |

**Table 2. Initial Conditions used in MULTI-SMARTT Simulation of CWIT # 1431 and # 1442**

| Test # | CWIT 1431 | CWIT 1442 |
|---|---|---|
| Pressure [kPa(a)] | 200 | 4600 |
| Initial coolant temperature [°C] | 35 | 100 |
| Axial Flux Factor | 1.485 | 1.485 |
| Radial Flux Factor | 1.13 | 1.13 |
| Channel Power [kW] | 50 | 100 |
| CHF [kW/m$^2$] | 1128 | 1772 |
| $\tau_2$ time to reach saturation in CWIT [s] | 268 | 274 |
| $\tau_3$ time to start vent in CWIT [s] | 1078 | 414 |

**Table 3a. CWIT # 1431 and # 1442 Measurements**

| CWIT # | PT Peak Temp [°C] | PT Outside Wall Maximum Cooling Rate [°C/s] | Through Wall ΔT [°C] |
|---|---|---|---|
| 1431 | 444 | 34 | Not measured |
| 1442 | 307 | 11 | Not measured |

**Table 3b. MULTI-SMARTT Simulation Results**

| CWIT # | PT Peak Temp [°C] | HTC [kW/m$^2$/°C] | PT Outside Wall Maximum Cooling Rate [°C/s] | Through Wall ΔT [°C] |
|---|---|---|---|---|
| 1431 | 444 | 1.2 | -34 | 37 |
| 1431 | 444 | 3.5 | -76 | 87 |
| 1442 | 329 | 2.0 | -11 | 12 |
| 1442 | 329 | 25.2 | -39 | 48 |

**Figure 1. Typical Heat Transfer Coefficient During the Quenching Process**

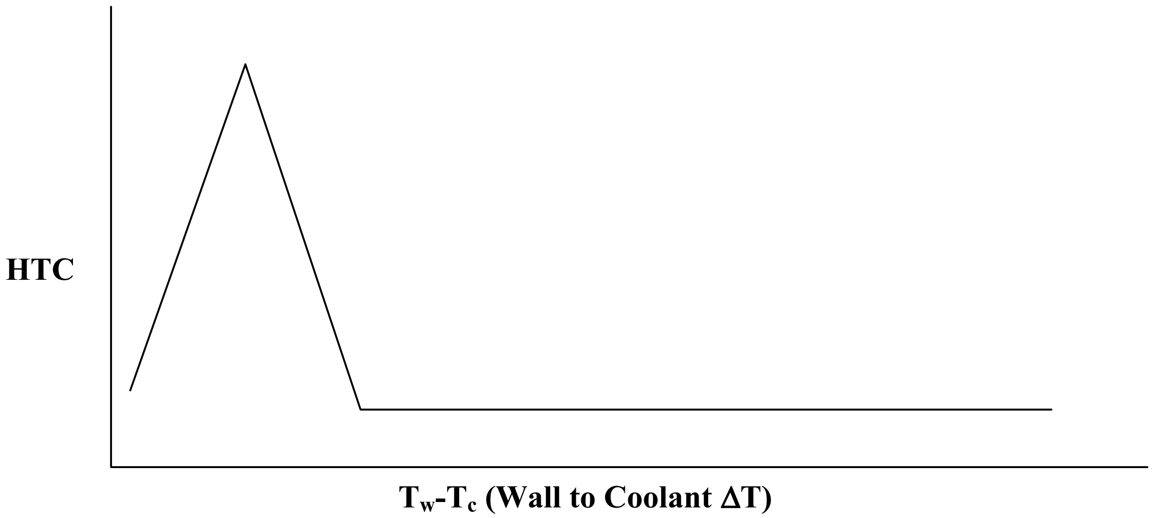

**Figure 2: MULTI-SMARTT PT Temperature Simulation of CWIT-1431 Test**

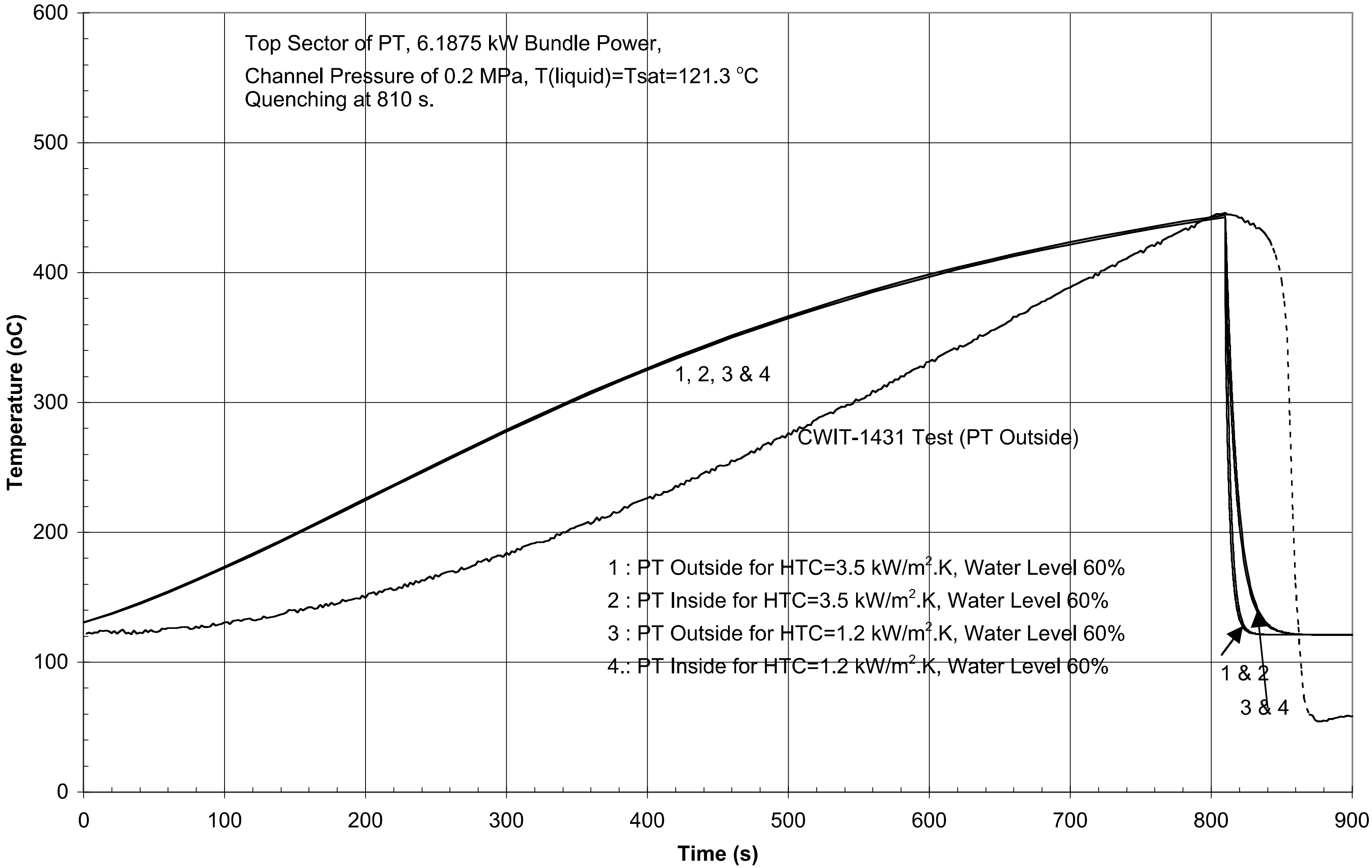

**Figure 3: MULTI-SMARTT PT Temperature Simulation of CWIT-1431 Test (Expanded Scale)**

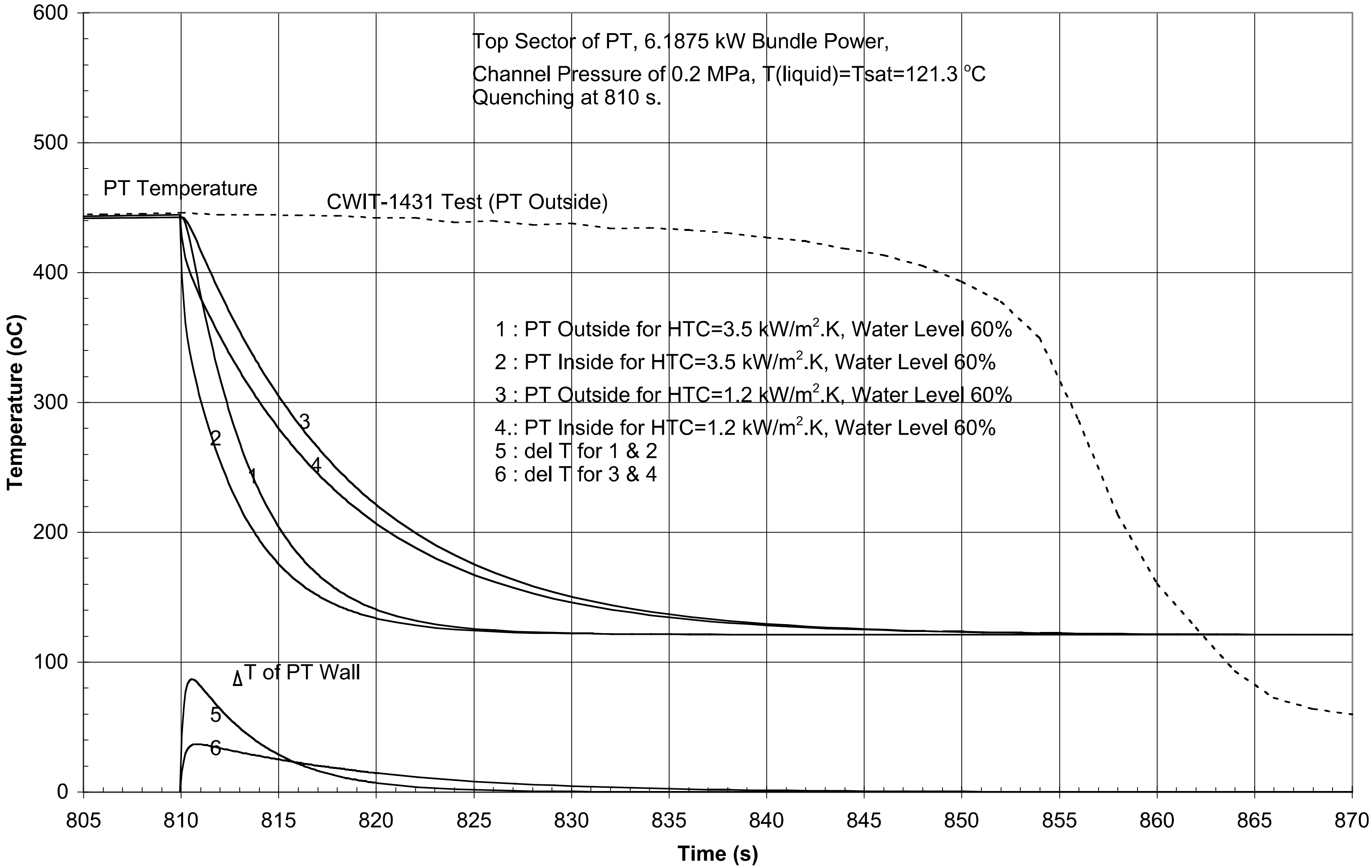

**Figure 4: MULTI-SMARTT PT Temperature Simulation of CWIT-1442 Test**

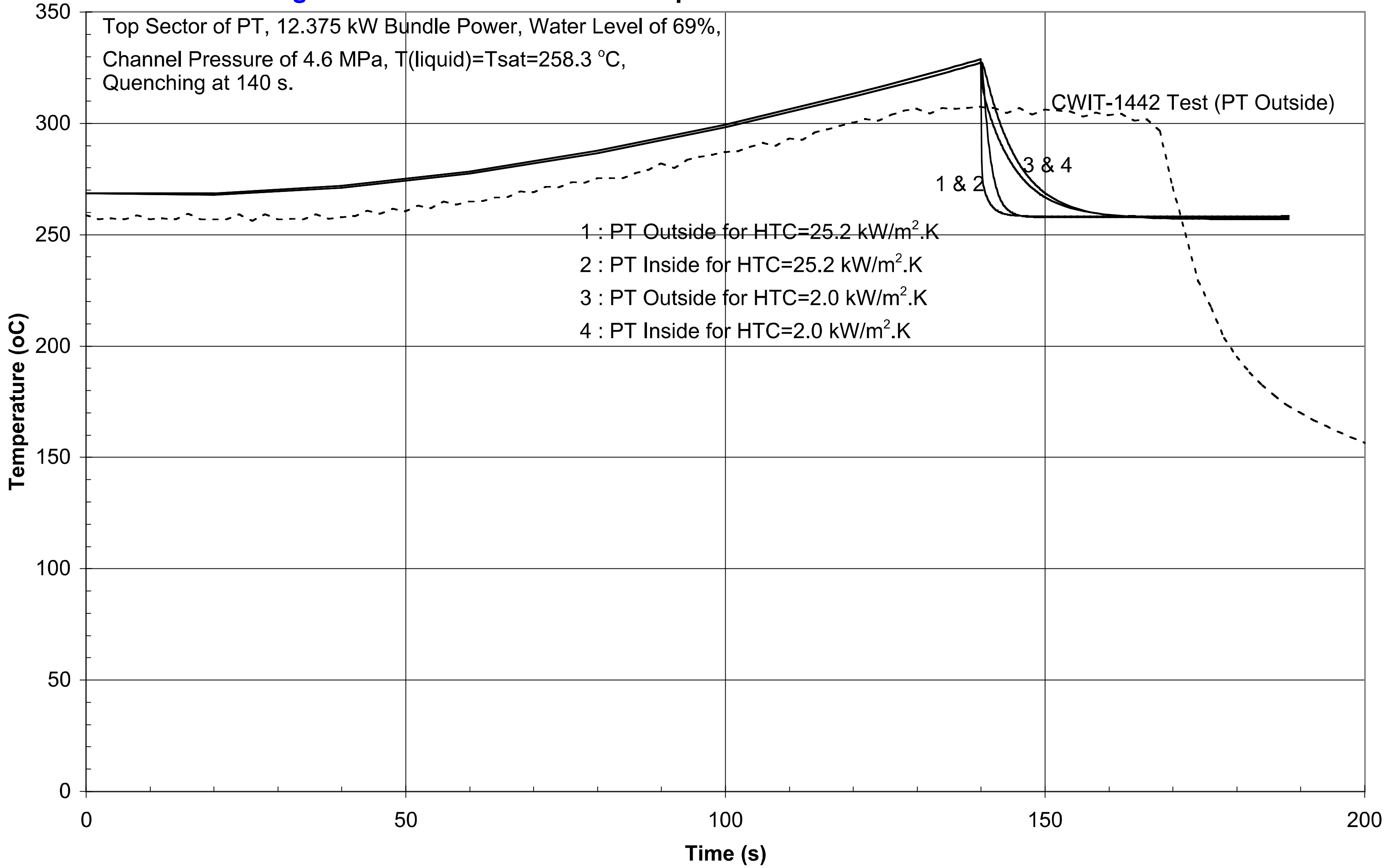

**Figure 5: MULTI-SMARTT PT Temperature Simulation of CWIT-1442 Test (Expanded Scale)**