ENCLOSURE 2

MFN 13-073

Use of the Shumway T_{min} Correlation with Zircaloy for TRACG Analyses

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 [[ ]].

Introduction

A model for the *minimum stable film boiling temperature* (T_{min}) is implemented in TRACG[1]. There is much confusion in the literature about the nature of T_{min} because it is often taken to be equivalent to other temperatures such as the *Leidenfrost temperature* (T_{Leid}), *critical heat flux temperature* (T_{CHF}), or *quench temperature* (T_Q). Carbajo (1984)[2] carefully distinguishes the phenomenon associated with each temperature and describes flow and heat transfer conditions where the different temperatures become indistinguishable. It is likely that because of these special situations that the confusion persists. Carbajo defines the *minimum film boiling temperature* (T_{MFB}) which is equivalent to T_{min} as used in this work.

The recommended TRACG model for T_{min} is based on the Shumway correlation[3]. Shumway (1985) like Carbajo surveyed the correlations and data in the literature in an attempt to develop a better correlation that could be applied over a wider range. Shumway states a "new correlation was formulated which includes some effect of flow rate, pressure, void fraction, fluid properties and wall properties…" and continues to provide his correlation in Equation (19) of Reference [3]

$$T_Q = T_{sat} + 3.7\frac{\left(\rho_\ell + \rho_g\right)}{\Delta\rho}\frac{h_{fg}}{C_{p\ell}\,\mathrm{Pr}_\ell}\left[1+\left(1-\alpha\right)^2\right]\left(1+1.5\mathrm{E}\text{-}5\ \mathrm{Re}_\ell\right)^{0.15}(1-{P}/{P_{crit}})^{0.1}\beta$$

Shumway is correlating the *quench temperature* (T_Q) and has done so with the intention that his correlation be implemented in the boiling water reactor (BWR) version of TRAC (TRAC-B). Shumway makes the point that a computer code like TRAC-B does not need the so-called true T_{min} value corresponding to the location on the boiling curve where the heat flux is minimum (Q_{min}). Instead TRAC-B needs a higher T_{min} value consistent with how the heat flux for transition boiling is interpolated between a film boiling heat flux (Q_{FB}) and the critical heat flux (Q_{CHF}). Shumway's statement for TRAC-B applies also to TRACG. As implemented in TRACG, the value for T_{min} is used as a logical check to prevent transition to nucleate boiling when the calculated wall temperature T_w is above T_{min}. A lower value for T_{min} reduces the heat flux where transition boiling can occur and results in a higher and more conservative calculation of the cladding temperature.

The main point is that the computer code (TRACG) needs the temperature below which transition boiling can occur and the heat transfer coefficient will start increasing. Shumway defines the quench temperature (T_Q) to be the temperature of the surface at which significant deviations from film boiling are observed from a temperature versus time or distance curve. In other words, at T_Q there is an observable increase in the rate that the surface temperature is dropping that implies that the heat transfer coefficient is increasing. Carbajo equates the *quench temperature* with the *rewetting temperature* at which liquid can reestablish (and maintain) contact with the dry surface. By GEH's definition, this would be the *minimum stable film* *boiling temperature* (T_{min}) or the wall temperature below which stable film boiling can no longer be maintained.

As Shumway states, "the shape of the boiling curve is influenced by many phenomena which change in importance with the varying experimental conditions". The minimum heat flux (Q_{min}) and the temperature at which it occurs is not exclusively dependent on hydrodynamic or thermodynamic properties of the fluid. It varies with surface conditions such as roughness and surface thermodynamic properties. Factors such as velocity, pressure, subcooling, drop size, liquid contact angle, wetting agents, and even gravity influence the minimum heat flux. In fact, at higher mass fluxes the minimum conditions may not exist. The existence or nonexistence of a T_{min} point could be of little consequence provided the computer code implementation provides a reasonable heat transfer coefficient for modeling the transition between stable film boiling and nucleate boiling. In Shumway's words, "T_{min} is not a natural or physical property but is a consequence of many competing processes".

Establishment of Shumway T_{min} Correlation

Shumway's correlation was established exclusively from stainless steel (SS) data over a relative wide range of pressures and flow rates. The correlation is compared to the data used to establish it in Figure 1. The GEH evaluation of the correlation compared to the SS data is that on average it overestimates the 81 useable data points by 23 K with a standard deviation of 55 K when evaluated at α=1. For the 8 data points at and below 0.7 MPa, the correlation bias is -1.2 K. Relative to the 38 data points at 3.0 MPa and the 35 data points at 6.9 MPa, the correlation has a bias of 25.2 and 25.5 K, respectively. These small biases in the correlation are well within the scatter of the measured temperatures. These biases have been removed from the curves representing the SS application of the correlation that are plotted in Figure 1 and Figure 2.

Shumway adopted the material property dependence from others available in the literature but did not evaluate his correlation for any material other than SS nor was the correlation evaluated against other data that was not used in its development. Those two topics are addressed in this document because they are the two main objections to using the Shumway correlation.

Assessment of Shumway T_{min} Correlation Using Other Materials and Data

Like many correlations for T_{min}, the Shumway correlation accounts for the effect of the wall material properties via the non-dimensional β term.

$$\beta = \sqrt{\frac{\left(k\rho C_p\right)_\ell}{\left(k\rho C_p\right)_w}}$$

Henry (1985)[4] explains that β relates the invariant temperature that is achieved at the interface between two semi-infinite slabs of constant properties at different uniform temperatures when they are brought into intimate contact. The analytic solution for this heat conduction problem is attributed to Carslaw and Jaeger (1959)[5]. For very small values of β the initial wall temperature will be essentially equal to the interface temperature and the wall can be considered to be isothermal. When the liquid thermal properties are comparable to the wall thermal properties β has a value near unity. For this condition, the wall surface experiences significant thermal transients as the steam bubbles are produced at and depart from the wall. For substantially larger values of β the ability of the surface to sustain film boiling decreases so that the value of T_{min} increases. For a given pressure the thermal properties of saturated liquid water are determined so a change in β occurs only as a result of the thermal properties of the wall material. As seen from the Shumway correlation, an increase in β results in an increase in T_Q. Figure 2 shows how the higher values for β for zircaloy and zirconium dioxide (ZrO_2) relative to stainless steel are predicted by the Shumway correlation to produce a substantially higher value of T_Q even as the water pressure (and water thermal properties) are unchanged at 6.9 MPa.

The saturation temperature of water increases with increasing pressure. This effect alone can account for an increase in T_Q; however, this is not the only effect because other water properties such as the densities ρ_ℓ and ρ_g, h_{fg}, $C_{p\ell}$, and Pr_ℓ also change with the water pressure. Nevertheless, for a given water pressure these terms and T_{sat} are all determined so that differences in T_Q for different wall materials for a given water pressure is due entirely to how β is affected by the wall thermal properties $\left(k\rho C_p\right)_w$. These wall thermal properties are generally a function of the wall temperature T_w which changes in the same direction as T_Q; thus, it is necessary to evaluate the Shumway correlation at the correct wall temperature. It is a good approximation for purposes of determining the value of T_Q to assume that $T_w \approx T_Q$ at the point of interest where nucleate boiling can be re-established. That is the process used to evaluate the Shumway correlation for all the figures in this document and it also emulates the process of how the Shumway correlation is implemented in TRACG. Figure 3 shows how $\left(T_{\min} - T_{sat}\right) \equiv \left(T_Q - T_{sat}\right)$ evaluated from the Shumway correlation changes with water pressure. There is a maximum in the value of $T_{\min} - T_{sat}$ that is strongly affected by how the wall thermal properties affect the value of β.

The Shumway correlation, like many of the other correlations, includes contributions from T_{sat} and β; but, the use of these parameters varies widely from correlation to correlation. For example, compare the Shumway correlation to the correlation proposed by Henry[4] in his Equation (10). Henry plots how his correlation compares to different materials in water at atmospheric pressure in his Figure 9 in Reference [4]. Henry provides comparisons for both subcooled water at 80°F and saturated water at 212°F. The subcooling effect in Henry's correlation has been criticized in the literature as being too large. Furthermore, the Shumway correlation does not credit the increase in T_{min} due to fluid subcooling. For these two reasons, Henry's correlation and data for only saturated water are shown in Figure 4. Note that Figure 4 was designed to be similar to Henry's Figure 9 in Reference [4], thus it maintains the same axes in English units. Data reported by Henry for saturated water is denoted by "+" symbols in Figure 4 and is color-coded for different materials. Additional more recent data from other authors follows the same color coding and is denoted by the "x" symbols. The ten data points for 1018 carbon steel (CS), six data points for Zircaloy-4 (Zr) and three data points for zirconium dioxide (ZrO_2) are the low-pressure data points extracted from the paper by Peterson and Bajorek (2002)[6]. The cluster of four higher values for SS316 are also from Reference [6], but the cluster of five lower SS values are the low-pressure data attributed to Stewart and Groeneveld[7] from Figure 6-14 in Reference [**8**]. The solid symbols in Figure 4 were calculated from the Shumway correlation and follow the same color coding used for the other materials. Notice that Shumway's correlation predicts that the $T_{\min} - T_{sat}$ values for SS304, SS316, and Inconel are very similar due to the fact that the thermal properties, and hence β, for these materials are very similar. As expected from the higher value for β, the Shumway $T_{\min} - T_{sat}$ value for Zr is also higher. Notice how the Shumway prediction for these low pressures is in the middle of the Zr data from Peterson and Bajorek[6]. Overall the Shumway correlation matches very nicely the trend in both the data and the correlation from Henry over a wide range of material thermal properties. In the range of most interest for SS, Inconel and Zr, the Shumway correlation agrees with both Henry's correlation and the low pressure data within the estimated scatter of the data.

Shumway developed his correlation using most of the SS quench data available at the time with the specific objective of providing what was needed by a code such as TRAC-B. Shumway had the benefit of the earlier work by Stewart, Groeneveld, and Henry as well as the work and data from many other authors. The Shumway correlation used in TRACG and the Groeneveld-Stewart (G-S) correlation used in TRACE are shown together as a function of fluid pressure in Figure 5 so that they can be compared. The G-S correlation shown as the dashed green line was developed using only Inconel data and does not include any effect due to different material properties. The G-S correlation is a simple empirical fit versus only pressure. In the vicinity of the quench location TRACE uses the maximum of T_{min} from the G-S correlation and 725 K which is shown as dotted black line in Figure 5. The solid green curve in Figure 5 was obtained from Shumway's correlation using Inconel 600 material properties and the solid purple curve using SS316 material properties. Both evaluations of Shumway's correlation assume no credit for the void fraction term or the Reynolds term in the correlation. As expected, the Inconel and SS curves from Shumway are similar. The purple stars represent T_Q data for SS used by Shumway. The vertical scatter in the data reflects the range of Reynolds numbers for different flow rates as well as other factors such as differences in experimental techniques, geometry, and surface finish. All the open green symbols are for Inconel data extracted from Reference [**8**]. The solid green boxes with embedded purple "+" signs were determined from measured T_Q values for SS data in Oak Ridge National Laboratory Thermal-Hydraulic Test Facility (THTF) and Inconel data in Two-Loop Test Apparatus (TLTA) and Rig of Safety Assessment (ROSA)-III Loss-of-Coolant Accident (LOCA) integral system tests that were simulated as part of the TRACG qualification[9]. The data is widely scattered but it does appear overall that the Shumway correlation provides a better fit to the Inconel and SS data that the G-S correlation. The G-S correlation predicts a value that is too low (too conservative) relative to the bulk of the data.

Inconel data from Figure 5 is replicated by the open green symbols in Figure 6. That data associated with justification of the G-S correlation in Reference [**8**] tends to be lower because it is generally more consistent with the theoretical determination of the so-called true T_{min} values rather than with T_Q values that are needed for application in computer codes like TRACG. More importantly, an additional 894 Inconel data points in Figure 6 from the Rod Bundle Heat Transfer (RBHT) tests[10] are very well predicted by the Shumway correlation (solid green curve) as are the LOCA test data previously cited in Figure 5. That is due to the fact that the RBHT and LOCA integral system test data are T_Q data consistent with the type of correlation that Shumway developed.

Justification for Applying Shumway T_{min} Correlation for Zircaloy

Fuel rods in light water reactors (LWRs) are made of zircaloy. They are also cylindrical and vertically oriented which may present important geometric effects that are not captured by many experiments. The T_{min} and T_Q values for zircaloy are substantially higher than those for either Inconel or stainless steel. In terms of $T_{\min} - T_{sat}$ at 6.9 MPa, the Shumway correlation predicts a value that is 46% higher for zircaloy than for Inconel (see Figure 3). This difference is important for BWR anticipated transient without scram – instability (ATWSI) analyses. Note that this important credit for the material property is obtained even without considering the credit due to the void fraction term in the Shumway correlation. It has already been established in Figure 4 that the Shumway correlation does a good job of matching the material property dependence in the low-pressure data for SS, Inconel and zircaloy. Over the entire range of pressures necessary for BWR analyses, the Shumway correlation does a reasonable job of fitting the data for SS and Inconel as was shown in Figure 5. This section provides additional comparison of the Shumway correlation to zircaloy data.

Either T_{min} or T_Q data for zircaloy is more difficult to obtain. Reference [**6**] describes the problem very succinctly: "Few studies have reported data at elevated pressures or for zircaloy cladding material." This is probably due to several practical considerations: (1) zircaloy is more expensive than SS and Inconel; (2) zircaloy oxidizes readily at higher temperatures; (3) higher T_{min} and T_Q values for zircaloy require higher powers and temperatures; (4) the experiments to produce these higher powers and temperatures and maintain the experimental samples for reuse are more difficult to perform. Nevertheless, measured temperature traces for vertical, rod-like cylinders made from zircaloy do exist, from which quench temperature (T_Q) values can be extracted. T_Q values are as useful as T_{min} values because they experimentally justify the speedy return to a more favorable heat transfer mode for calculated values of $T_w \le T_Q$. As Shumway points out, computer codes like TRAC-B (and TRACG) need and use a T_{min} or T_Q criterion in the estimation of the boiling curve to preclude the transition to nucleate boiling for conditions where the wall cannot be rewetted because T_w is above the criterion. Thus, a lower value for the criterion is more conservative.

The ten open red triangles at 0.1 MPa in Figure 6 were extracted from 41 temperature traces shown in the figures in GEAP-13112[11]. Each temperature trace was evaluated to determine if it indicated an *obvious quench* as defined by a sudden downward change in temperature slope with time followed by a rapid temperature drop. More than half of the traces were not useful because there was no heatup, the thermocouple (TC) failed or was questionable, quench was not apparent because of precursory steam cooling, or there was a gap in the recording around the time where the quench would have occurred. The indication of quench was only obvious in 10 of the remaining 20 traces, and it is for these that the quench temperature was recorded and plotted in Figure 6.

A similar process was followed to extract 47 T_Q values from more than 85 temperature traces recorded by Hofmann et al.[12] Seven obvious quench temperatures (open red squares) were extracted from the 20 temperature traces with 0 µm of measured ZrO_2. For 100 µm of measured ZrO_2 there were 24 temperature traces, of which 16 (open red diamonds) exhibited an obvious quench, and for 300 µm of measured ZrO_2 24 (open red circles) of the 31 measured temperature traces indicated an obvious quench. All 47 values are plotted in Figure 6 with slight shifts in the experimental nominal pressure so that the different symbols for the different oxide thicknesses can be distinguished in the figure. There is insufficient data and fidelity in the Hofmann data to be able to discern how the varying oxide thicknesses influence the quench temperature.

The most representative zircaloy data for ATWSI conditions is that from the Halden experiments[13],[14]. This data was recorded for fluid pressures ranging from 6.5 to 6.9 MPa. The heat fluxes and flow oscillations that were experienced in the tests are representative of those calculated for BWR ATWSI conditions. The same process that was used to evaluate the GEAP-13112 and Hofmann temperature traces was applied to the recorded temperature traces from the Halden tests. [[

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The solid red curve obtained from the Shumway correlation using zircaloy material properties is substantially below the zircaloy T_Q values extracted from References [**11**], [**12**], [**13**], and [**14**] and thus it is conservative for the intended applications in the TRACG code. There are several plausible explanations for why the Shumway correlation is conservatively low. For the correlated curve, the Reynolds number was assumed to be zero because the experiments did not provide sufficient information to determine the experimental flow. The Shumway correlation (solid red curve) was also evaluated assuming that $\alpha = 1$ so no credit would be realized from the term $\left[1+(1-\alpha)^2\right]$ in the correlation. This term has been judged to have inadequate experimental support because in Shumway's words it is based on "a small amount of unpublished Semiscale void data" and the "accuracy of the void effect is untested". Especially for the cases of the Hofmann and Halden data the quench occurs for a much lower void fraction than 1.0 just based on how the liquid water was forced into the test section. It is also likely that a credit for liquid subcooling is observed in the data that is not represented in the Shumway correlation. As an upper bound on the temperature prediction from the Shumway correlation, a value of $\alpha = 0$ was assumed to obtain the dashed red curve in Figure 6. The dashed curve is in reasonable agreement with the quench temperature data; however, in applications of the Shumway correlation in TRACG analyses the term $\left[1+(1-\alpha)^2\right]$ is replaced by 1.0 because of the inadequate experimental support for this term.

The Hofmann data contained different amounts of measured oxide although there is so much scatter in the data that the effect on the experimental quench temperatures cannot be discerned. The fuel rods from the GEAP-13112 tests also ended up with a maximum ZrO_2 thickness stated as 1.8 mils considering the measurement uncertainty but unfortunately the amount of oxide was not measured and reported for each TC location. There is no indication in the Halden reports how much oxide accumulated during the tests, but based on the high temperatures and the sustained time at these temperatures, it is likely to not have been negligible. The key point is that the presence of zirconium oxide causes the quench temperatures to increase. Exactly how much the increase should be is debatable. As a basis for comparison, the Shumway prediction of the quench temperature for ZrO_2 is shown (without any credit due to void) by the solid black curve in Figure 6. This curve is also in reasonable agreement with the quench temperature data; nevertheless, TRACG analyses that utilize the Shumway correlation will conservatively not take credit for an increase in the predicted T_Q values due to ZrO_2. In other words, the Shumway correlation will be evaluated using properties for unoxidized zircaloy.

As a final justification for use of the Shumway correlation to conservatively predict the quench temperature for zircaloy, consider the comparison to the Zircaloy-4 data from Peterson and Bajorek[6]. There are 24 data points for "clean" unoxidized zircaloy for a range of pressures from 0.1 to 0.5 MPa that are plotted as the solid red circles in Figure 6. Note that many of the data points overlap so it is difficult to distinguish each one in the figure. Peterson and Bajorek processed the raw temperature data in much the same way as was used by Hochreiter, et al.[10] to process the RBHT data. Solving the inverse heat conduction problem allows one to more accurately determine the temperature T_{min} where the minimum film boiling heat flux occurs, and thus it provides values that are more consistent with the theoretical under pinning of the Shumway correlation. These T_{min} values are also expected to be lower than the raw T_Q values determined directly from the temperature traces. Note that the Shumway correlation evaluated using zircaloy properties (solid red curve) is essentially a best fit or is slightly under the unoxidized Zircaloy-4 data from Peterson and Bajorek (solid red circles).

Peterson and Bajorek also obtained data for oxidized Ziraloy-4 that showed how T_{min} increased substantially with additional surface roughness attributed to the presence of ZrO_2, but they did not isolate and directly quantify the effect of oxide thickness on T_{min}. All 37 of the T_{min} values for oxidized zircaloy are represented by the solid red diamonds with black outlines in Figure 6. These data cover three different values of surface roughness with the higher T_{min} values associated with higher roughness and more oxide. The key point is that T_{min} increases substantially as ZrO_2 increases so that with sustained time at an elevated temperature it becomes easier for zircaloy to rewet and quench. Neglecting this effect in the TRACG implementation of the Shumway correlation as applied to zircaloy is conservative.

Conclusion

Based on the zircaloy temperature data presented in Figure 6 one can conclude that using the Shumway correlation as implemented in TRACG to estimate T_{min} for zircaloy is justified because it provides a value of T_{min} that is lower than most of the data. Lower values of T_{min} are more conservative because they delay the return to nucleate boiling and thus result in higher and more conservative calculated values for the wall temperature (T_w).

Nomenclature

C_p	specific heat capacitance at constant pressure
h	fluid specific enthalpy
k	thermal conductivity
P	fluid pressure
Pr	Prandtl number
Q	heat flux
Re	Reynolds number
T	temperature

Greek Symbols

α	fluid void fraction
β	dimensionless material property ratio
ρ	density

Subscripts

CHF	critical heat flux
crit	critical point for water
f	saturated liquid water
FB	film boiling
fg	difference saturated water vapor and saturated liquid water
g	gas, steam
ℓ	liquid
Leid	Leidenfrost
MFB	minimum film boiling
min	minimum
Q	quench
sat	saturated
w	wall or fuel rod surface

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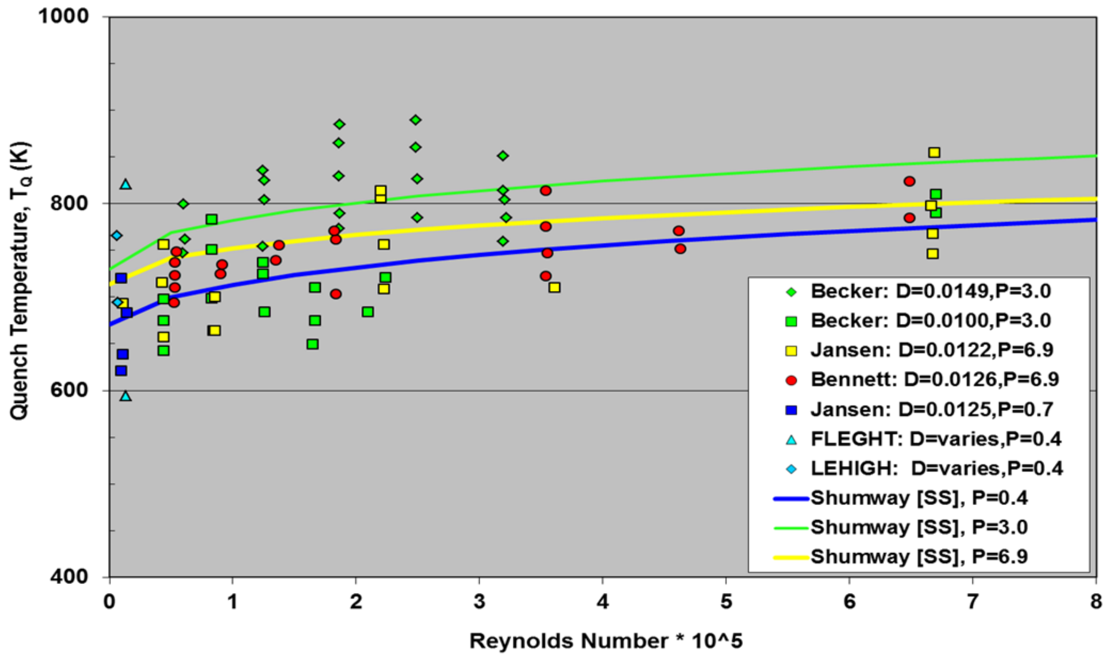

Figure 1 Shumway Correlation versus Stainless Steel Data

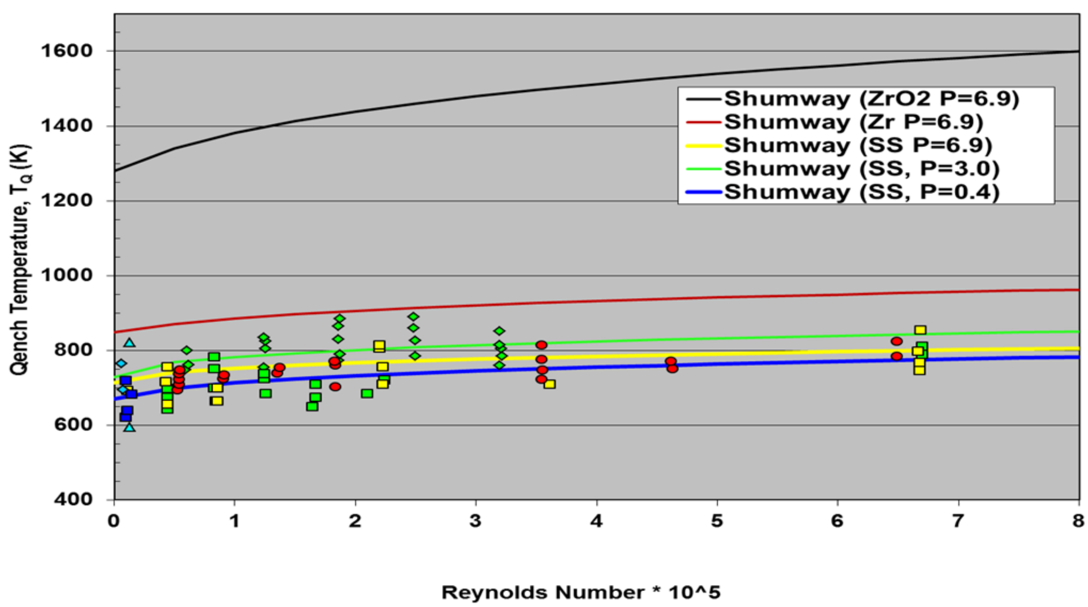

Figure 2 Shumway Correlation for Different Materials

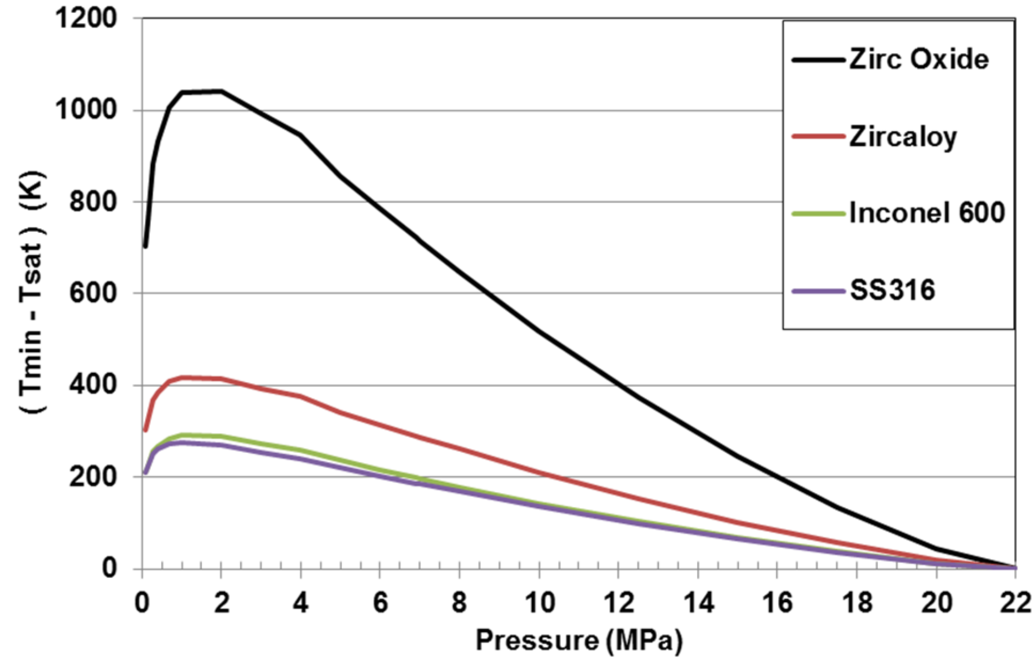

Figure 3 **Shumway Predicted T_{min}-T_{sat} versus Pressure for Different Materials**

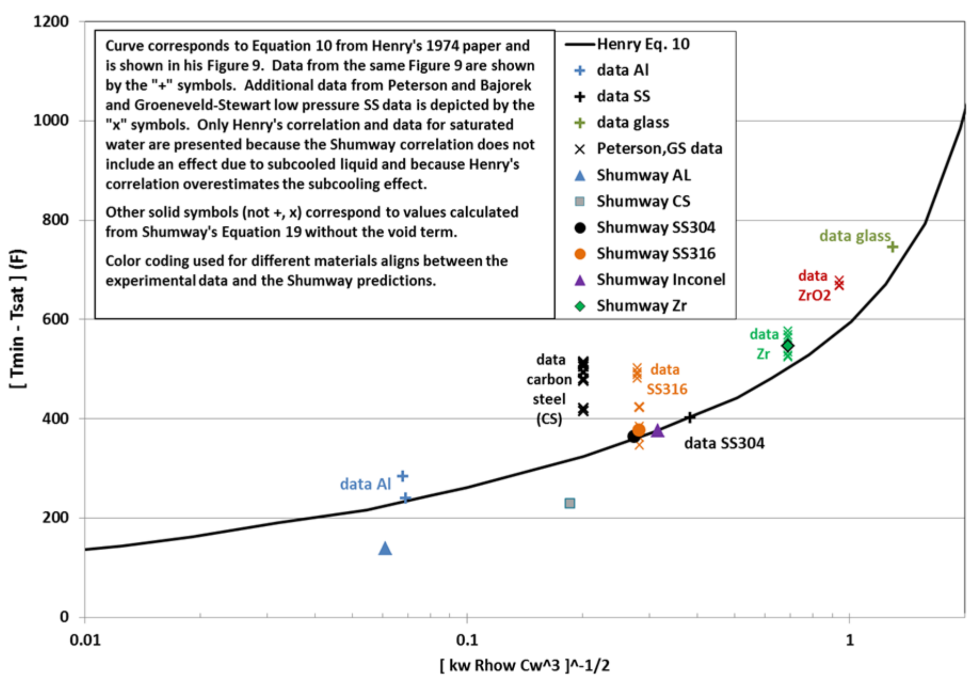

Figure 4 **Shumway Correlation Compared to Henry's Correlation for Different Materials**

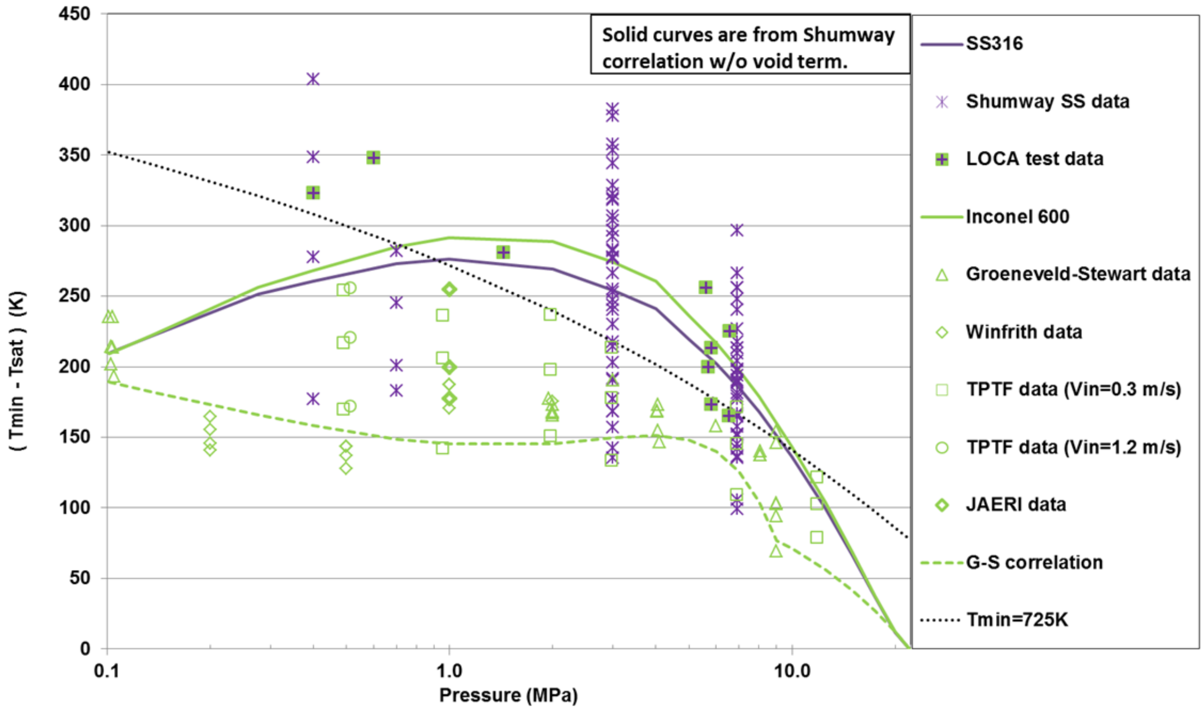

Figure 5 Shumway Correlation Compared to SS and Inconel Data versus Pressure

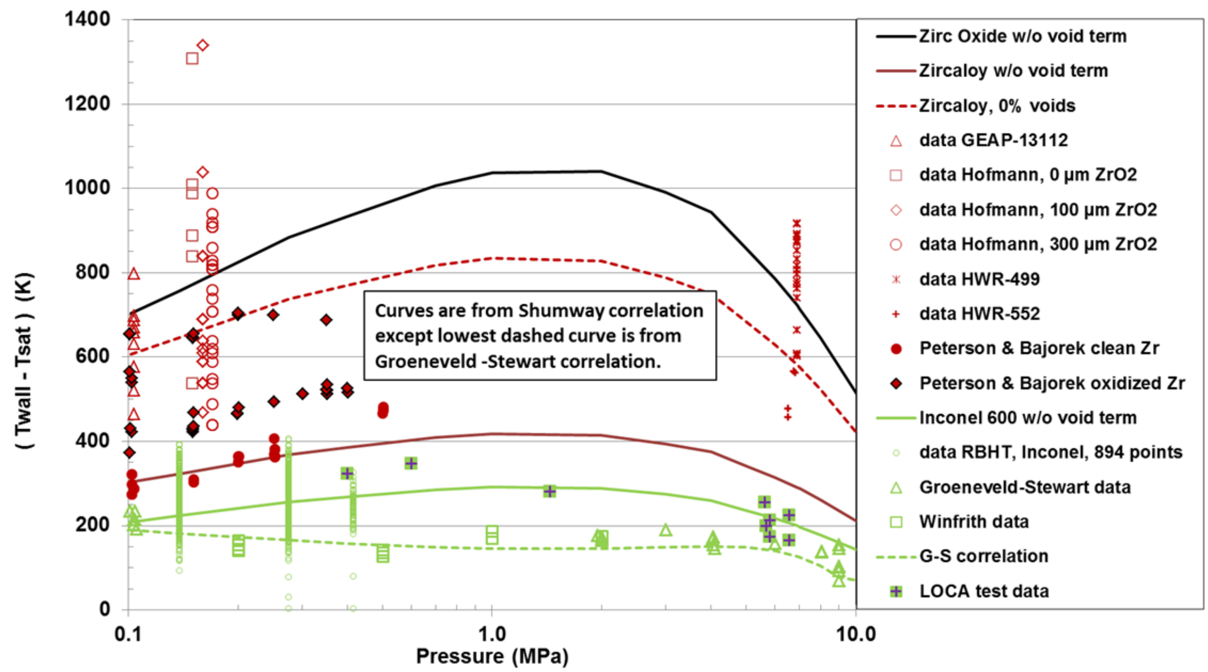

Figure 6 Shumway Correlation Compared to Inconel and Zircaloy Data versus Pressure