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ERROR ANALYSIS OF THE TAI EQUATION

by

B. R. Cremer

October 23, 1961

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ERROR ANALYSIS OF THE TAI EQUATION

INTRODUCTION

There is a certain tolerance of error implicit in any calculation based upon measured physical data. Occasionally, the error is explicitly recognized by attaching a plus or minus variation to the calculated quantity. More often, however, the error is simply neglected.

The present analysis was performed to quantify the error implicit in a typical TAI (Trip-After-Instability) limit calculation. This error results from the precision of measurement of each of the parameters used in the calculation of the TAI limit.

Though not specifically considered, the results of this work could be used to establish the required minimum level of accuracy of the tube outlet temperature monitoring equipment. Further, some of the generalized equations could probably be programmed into the ROL (Reactor Operating Limits) to indicate how far each Panellit gauge could be "rolled" without exceeding a fixed minimum TAI limit. Since the examination of these other possibilities is beyond the scope of this report, they are left as suggestions for future work only.

SUMMARY AND CONCLUSIONS

The basic approach to evaluating the implicit error in TAI limit consisted of the following:

1. The defining TAI equation was written in total differential form.
2. Each of the component partial differentials were developed.
3. The equations were then evaluated at specific points, using base conditions typical of H reactor and not too dissimilar to the other B, D, F reactors.

The result of the mathematic manipulations is that a TAI temperature limit calculation will typically be in error by $\pm 1.3^{\circ}\text{C}$. This precision is, of course, dependent upon what value of header pressure, etc. that one chooses to typify the reactor. The following values were thought to be typical and were used in this work.

1. Front header pressure = 560 ± 20 psig

(The variance* is that which occurs from the end of the header to the center of the header.)

2. Rear header pressure = 80 ± 10 psig

(Again, the variance is that which occurs from the end of the header to the center of the header.)

* Rather than its usual rigorous statistical definition, variance is used here to denote simply the scatter of values one would expect when taking pressure measurements, etc.

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3. Low trip point⁽¹⁾ = 160 ± 5 psig

(The variance is that which is caused by the oscillations of the Panellit gauge.)

4. Effective range⁽¹⁾ = 50 ± 5 psig

(Again, the variance is that which is caused by the oscillations of the Panellit gauge.)

5. Inlet temperature = $10 \text{ C} \pm 0.5^\circ\text{C}$

(The variance reflects the precision of the inlet water thermocouple system.)

In addition to the obvious conclusion about the precision of the TAI temperature limit, the following general observations can be made:

1. Rear header pressure variations have about five times the effect on TAI temperature that the equivalent front header pressure variations have.
2. Decreasing the effective range by one psi (and therefore concomitantly increasing the low trip by one psi) has nearly five times the beneficial effect on the TAI limit that a one psi reduction in rear header pressure has.

DISCUSSION

The defining equation for the TAI limits is given in Process Standards⁽²⁾ as follows:

$$TAI = T_i + \left[\frac{(41.45)(F)^{0.709}}{\sqrt{F_H - P_{mrh}}} - T_i \right] \left[\frac{LT - P_{mrh}}{LT - P_{mrh} + ER} \right]^{1/2}$$

To simplify the subsequent algebraic operations, the following symbols are substituted for those used in the original defining equation:

Let $T = TAI$

$F = F_H$

$L = LT$

$t = t_i$

$R = P_{mrh}$

$E = ER$

Rewriting the equation,

$$T = t + \left[\frac{(41.45)(F)^{0.709}}{\sqrt{F - R}} - t \right] \left[\frac{L - R}{L - R + E} \right]^{1/2} \quad (1)$$

(1) These terms are rigorously defined in Process Standard A-020, HW-46000.

(2) HW-46000, A-020

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then utilizing the calculus to evaluate the errors in T, the following equation can be written,

$$dT = \left(\frac{\partial T}{\partial F} \right)_{R,t,L,E} dF + \left(\frac{\partial T}{\partial R} \right)_{F,t,L,E} dR + \left(\frac{\partial T}{\partial t} \right)_{F,R,L,E} dt + \left(\frac{\partial T}{\partial L} \right)_{F,R,t,E} dL + \left(\frac{\partial T}{\partial E} \right)_{F,R,t,L} dE \quad (2)$$

then, algebraically evaluating the partial differentials in the total differential equation (2) results in the following:

$$\left(\frac{\partial T}{\partial F} \right)_{R,t,L,E} = \left[\frac{(\sqrt{F-R})^{0.709} (41.45)(F)^{-0.291} - (41.45)(F)^{0.709} (\frac{1}{2})(F-R)^{-\frac{1}{2}}(1)}{(F-R)} \right] \left[\frac{L-R}{L-R+E} \right]^{\frac{1}{2}} \quad (3)$$

$$\begin{aligned} \left(\frac{\partial T}{\partial R} \right)_{F,t,L,E} = & \left[\left(\frac{L-R}{L-R+E} \right)^{\frac{1}{2}} \frac{(-\frac{1}{2})(41.45)(F)^{0.709}}{(F-R)^{\frac{1}{2}}} + \frac{(41.45)(F)^{0.709} (\frac{1}{2})(L-R)^{-\frac{1}{2}}}{(F-R)^{\frac{1}{2}} (L-R+E)} \left(\frac{[-L+R-E] - [-L+R]}{[L-R+E]^2} \right) \right] \\ & - t \left[\left(\frac{L-R}{L-R+E} \right)^{\frac{1}{2}} \frac{(-L+R-E) - (-L+R)}{(L-R+E)^2} \right] \quad (4) \end{aligned}$$

Factoring equation (4),

$$\begin{aligned} \left(\frac{\partial T}{\partial R} \right)_{F,t,L,E} = & \left[\frac{(41.45)(F)^{0.709}}{\sqrt{F-R}} \right] \left[\left(\frac{L-R}{L-R+E} \right)^{\frac{1}{2}} \left(\frac{1}{2F-2R} \right) + \left(\frac{1}{2\sqrt{\frac{L-R}{L-R+E}}} \right) \left(\frac{-E}{[L-R+E]^2} \right) \right] \\ & + \frac{t}{2} \left[\frac{E}{\left(\sqrt{\frac{L-R}{L-R+E}} \right) (L-R+E)^2} \right] \quad (5) \end{aligned}$$

$$\left(\frac{\partial T}{\partial t} \right)_{F,R,L,E} = 1 - \left[\frac{L-R}{L-R+E} \right]^{\frac{1}{2}} = 1 - \sqrt{\frac{L-R}{L-R+E}} \quad (6)$$

$$\left(\frac{\partial T}{\partial L} \right)_{F,R,t,E} = \left[\frac{(41.45)(F)^{0.709}}{\sqrt{F-R}} - t \right] \left[\left(\frac{1}{2} \right) \left(\frac{L-R}{L-R+E} \right)^{-\frac{1}{2}} \frac{(L-R+E) - (L-R)}{(L-R+E)^2} \right] \quad (7)$$

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Simplifying equation (7),

$$\left(\frac{\partial T}{\partial L}\right)_{F,R,t,E} = \left[\frac{(41.45 \times F)^{0.709}}{\sqrt{F-R}} - t \right] \left[\left(\frac{1}{2\sqrt{\frac{L-R}{L-R+E}}} \right) \frac{E}{(L-R+E)^2} \right] \quad (8)$$

and finally,

$$\left(\frac{\partial T}{\partial E}\right)_{F,R,t,L} = \left[\frac{(41.45 \times F)^{0.709}}{\sqrt{F-R}} - t \right] \left[\left(\frac{1}{2\sqrt{\frac{L-R}{L-R+E}}} \right) \frac{R-L}{(L-R+E)^2} \right] \quad (9)$$

Numerical evaluation of the partial differential equations (3,5,6,8, and 9, above) can be accomplished using the following base conditions:

$$t = 10 \qquad F = 560 \qquad R = 80 \qquad L = 160 \qquad E = 50$$

Substituting the base conditions in equation (3),

$$\begin{aligned} \left(\frac{\partial T}{\partial F}\right)_{R,t,L,E} &= \left[\frac{\sqrt{560-80} \times 0.709 \times (41.45 \times 560)^{-0.291} - (41.45 \times 560)^{0.709} \times (0.5 \times \sqrt{560-80})}{(560-80)} \right] \left[\sqrt{\frac{160-80}{160-80+50}} \right] \\ &= 0.031 \end{aligned} \quad (3a)$$

Substituting the base conditions in equation (5),

$$\begin{aligned} \left(\frac{\partial T}{\partial R}\right)_{F,t,L,E} &= \left[\frac{(41.45 \times 560)^{0.709}}{\sqrt{560-80}} \right] \left[\sqrt{\frac{160-80}{160-80+50}} \left(\frac{1}{1120-160} \right) - \left(2\sqrt{\frac{160-80}{160-80+50}} \right) \left(\frac{50}{160-80+50} \right)^2 \right] \\ &\quad + \frac{10}{2} \left[\frac{50}{\left(\sqrt{\frac{160-80}{160-80+50}} \right) (160-80+50)^2} \right] \\ &= -0.161 \end{aligned} \quad (5a)$$

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Substituting the base conditions in equation (6),

$$\left(\frac{\partial T}{\partial t}\right)_{F,R,L,E} = 1 - \sqrt{\frac{160-80}{160-80+50}} = 0.215 \quad (6a)$$

Substituting the base conditions in equation (8),

$$\begin{aligned} \left(\frac{\partial T}{\partial L}\right)_{F,R,t,E} &= \left[\frac{(41.45 \times 560)^{0.709}}{\sqrt{560-80}} - 10 \right] \left[\frac{1}{2\sqrt{\frac{160-80}{160-80+50}}} \left(\frac{50}{[160-80+50]^2} \right) \right] \\ &= 0.297 \end{aligned} \quad (8a)$$

Substituting the base conditions in equation (9),

$$\left(\frac{\partial T}{\partial E}\right)_{F,R,t,L} = \left[\frac{(41.45 \times 560)^{0.709}}{\sqrt{560-80}} - 10 \right] \left[\frac{1}{2\sqrt{\frac{160-80}{160-80+50}}} \left(\frac{80-160}{[160-80+50]^2} \right) \right] = -0.475 \quad (9a)$$

Now, substituting the slopes determined in equations (3a), (5a), (6a), (8a), and (9a) into the total differential equation (2), results in the following:

$$\begin{aligned} dT &= (0.031)(\pm 20) + (-0.161)(\pm 10) + (0.215)(\pm 0.5) + (0.297)(\pm 5) \\ &\quad + (-0.475)(\pm 5) = \pm 6.20^\circ\text{C} \end{aligned} \quad (2a)$$

From equation (2a) it can be seen that the TAI calculation can be in error by as much as 6.20°C. It is true that this error represents a worst case, since it is the total error which would result if none of the contributing errors were cancelling. This, of course, is not the general case in fact; however, it is impossible to say how often the errors may actually be non-cancelling, (i.e. additive).

Simply calculating a maximum error in TAI (due to measurement errors alone) does not give any indication of how frequently the maximum error will be seen. To estimate the frequency of occurrence of a six degree error, one must know the probability of each of the constituent errors being their maximum value. For example, assume the pressures and temperatures (intrinsic to the TAI calculation) vary in such a manner that, on the average, the maximum variations are experienced

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only 20 per cent of the time (i.e., 80 per cent of the time the temperature and pressure variations would be less than the maximum). In such a case the probability of experiencing the 6.20°C error in TAI calculation is 0.00032, or only three chances in 10,000. Thus, the relatively large possible error seems more acceptable if it has a low probability of occurrence.

Perhaps of greater interest is the size of the error one would expect 95 chances out of 100. In other words, what error would one expect with a 0.95 probability? To determine this, one must assess the maximum variation of the temperature and pressure parameters to be experienced, on the average, 98.98 per cent of the time (i.e., the fifth root of 0.95). Of necessity this assessment becomes rather arbitrary, relying more upon judgment and experience than academic knowledge. However, if the following values are assumed reasonable, the maximum error in TAI is $\pm 1.27^{\circ}\text{C}$ (calculated by the same procedure developed above).

1. Front header pressure = 560 ± 5 psig*
2. Rear header pressure = 80 ± 2 psig*
3. Low trip point = 160 ± 1 psig*
4. Effective range = 50 ± 1 psig*
5. Inlet temperature = $10 \pm 0.1^{\circ}\text{C}$ *

Thus it is evident that for practical purposes the TAI limit, calculated for a B, D, and F reactor, has a precision of about $\pm 1.3^{\circ}\text{C}$.

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Process Engineering

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* In this instance the variance shown is that value which, on the average, will be experienced 98.98 per cent of the time; only 1.02 per cent of the time will the variations reach their former value (shown on pages two and three).

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