Industrial quench tanks are continuously cooled by recirculating water from cooling towers. These cooling effects must be taken into account. Figure 1 shows austenitic manganese steel loads consisting of hammers and an experimental wedge block (4 to 8 in., 10 to 20 cm thick), quenched at severities of \( H = 2 \) and 3 per inch. The cooling rate of the quench tank attributable to the cooling water \( \dot{T} \) is given by:

\[
\dot{T} = \frac{m}{M_W} (T - T_{CW}) \quad \text{Eq. 1}
\]

where \( m \) is the cooling water flow rate, \( M_W \) is the mass of quench water, \( T_{CW} \) is the cooling water temperature as it enters the tank, and \( T \) is the tank temperature. The cooling water flow rate is usually known, but if not, it can be estimated from the data. At the end of a quench, when the castings are sufficiently cool, their contribution to heating the tank could be neglected and the tank temperature is solely affected by the cooling water. In Fig. 1, 30 minutes after the quench, the tank cooling rate was 0.136°C/min, the tank temperature was 23.4°C, the cooling water temperature could be taken to be the tank temperature prior to the quench, 20°C. The 17 x 12 x 13 ft quench tank contained 75,100 kg water. Using this information in Eq. 1 yields a cooling water flow rate of 3000 kg/min. This figure is probably more reliable than a nominal design value and could be used to double-check for any system blockages.

The “adjusted water temperature” curve thus obtained represents the water temperature in the absence of any cooling (see Fig. 1, both graphs). The quench times can now be found by a similar construction as in Fig. 4 of Part I.

Charpy specimens were taken from the wedge blocks such that the notches were from quarter-thick locations. Table 1 shows the quench time, chemical composition, and impact toughness of the wedge blocks. Both quenches were sufficiently fast \( (t_{90\%} < 10 \text{ min}) \) that few thick carbide films were observed in either block. Only the presence of phosphide eutectic at triple grain boundaries caused some intergranular weakening.

Figure 2 shows another quench where both the quench water and the incoming cooling water temperatures were measured. It will be noticed that the tank temperature never reaches the cooling water temperature because of the ambient heating in hot summer conditions. Thus, while the cooling water tries to cool the tank, the surroundings contribute to its warming. The combined effect of these on tank cooling can be expressed by the following heat balance:

\[
\dot{T} = \frac{m}{M_W} \left( T - T_{CW} \right) - \frac{hA(T_{amb} - T)}{M_W C_W(T_{amb} - T)} \quad \text{Eq. 3}
\]

where \( h \) is the overall heat transfer coefficient of quench tank for ambient effects, \( A \) is the effective area of the tank, \( T_{amb} \) is the ambient temperature (34°C in this example). Prior to quench, the tank temperature did not change, but a temperature differential was maintained between the tank temperature and the cooling water temperature, where the cooling effect of the cooling water equaled the ambient heating of the tank. This allows an expression to be obtained for the ambient heat transfer coefficient:

\[
\frac{m C_W (T_{CW,0} - T_{CW,i})}{M_W} = \frac{hA}{M_W} \left( T_{amb} - T_{i} \right)
\]

The “adjusted water temperature” curve thus obtained represents the water temperature in the absence of any cooling (see Fig. 1, both graphs). The quench times can now be found by a similar construction as in Fig. 4 of Part I.
where subscript “nought” indicates the initial conditions at time zero. Therefore, the differential temperatures that must be added to the tank temperature to eliminate the effects of cooling water and the ambient heating are given by:

$$\Delta T = \frac{m}{M_w} \left[ (T - T_{cw,0}) - (T_{amb} - T_{0}) \right] \Delta t$$

Eq. 5

Figure 2 shows the adjusted temperature curve thus obtained. From a similar construction as before, the 80% quench time was determined to be 9 minutes. This was judged to be a slow quench and corrective action was taken to increase the agitation in the tank.

**Major Cost Benefit**

In the analysis of the first industrial quench, the incoming water temperature was assumed to be equal to the initial temperature of the quench tank. The measured cooling water temperatures in Fig. 2 show that this can be significantly different. It is best to take numerous temperature measurements in the quench tank to get an estimate of the degree of mixing and an average tank temperature, the cooling water temperature as it enters the tank, and the ambient temperature, to improve the precision of the analysis.

The great advantage of quench time analysis using quench water temperatures versus thermocouples attached to castings is the lower cost of implementation. The thermocouples can be permanently installed at the tank locations and will provide measurements for many years without servicing. Another advantage is the consistency of measurement. The measured water temperatures are related to the average load temperature, whereas temperatures from an embedded thermocouple in a casting will strongly depend on its location in the section.

**Heisler charts:** The analysis focused on determining a quench time from experimental data. Further details on temperature distribution in the casting can be established using Heisler charts with dimensionless variables of time (Fourier number), temperature, and average heat transfer coefficient (Biot number). Figure 3 illustrates one such derived distribution for the wedge-block casting quenched at a severity level of 3 per inch. At 90% quench, the casting interior is still too hot and the casting should be left in the tank.

As an example of application in process control, in summer months the quench water became too warm to satisfactorily quench thick sections. The hypothetical diagram in Fig. 4 shows how quench time analysis can be used to obtain an operating domain for a given quenching operation with respect to section thickness and water temperatures.

Additionally, quench time analysis can provide an independent verifica-
is of the order of 10 minutes. For austenitic manganese steels, the critical quench time is when the detrimental thick carbides start forming at the grain boundaries. For the plain section thickness can be obtained. For austenitic water temperature at a given water circulation intensity. By choosing a critical quench time, the maximum water temperature for a given section thickness, quench time, and quench intensity. The estimation of quench times by analyzing the quench water temperature measurements has been shown to be an inexpensive, yet powerful, process control tool. The estimated time directly relates to how long a casting spends at high temperatures or in a given temperature range. In industrial conditions, factors such as the cooling water and ambient effects have been taken into account by deriving an “adjusted” water temperature, from which a quench time has been estimated reliably. The single-valued quench time parameter provides a basis for comparing and ranking different quench operations. The analysis also allows the calculation of other details in the quenching process, such as cooling rates and temperature distributions with time.

### Table 1 — Composition, wt%, and impact properties of wedge blocks in Fig. 1

<table>
<thead>
<tr>
<th>Block</th>
<th>Quench severity, H, in.</th>
<th>Quench time, ( t_{90%} ), min</th>
<th>Near cope</th>
<th>Near drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>9.1</td>
<td>162</td>
<td>136</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6.3</td>
<td>163</td>
<td>128</td>
</tr>
</tbody>
</table>

**Charpy V-notch impact energy, J**

![Fig. 4 — Hypothetical relationship between section thickness, quench time, and quench water temperature at a given water circulation intensity. By choosing a critical quench time, the maximum water temperature for a given section thickness can be obtained. For austenitic manganese steels, the critical quench time is when the detrimental thick carbides start forming at the grain boundaries. For the plain section thickness, quench time is of the order of 10 minutes.](image)

**Application Summary**

The estimation of quench times by analyzing the quench water temperature measurements has been shown to be an inexpensive, yet powerful, process control tool. The estimated time directly relates to how long a casting spends at high temperatures or in a given temperature range. In industrial conditions, factors such as the cooling water and ambient effects have been taken into account by deriving an “adjusted” water temperature, from which a quench time has been estimated reliably. The single-valued quench time parameter provides a basis for comparing and ranking different quench operations. The analysis also allows the calculation of other details in the quenching process, such as cooling rates and temperature distributions with time.

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**Selected References**

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