

## **Controlling the Heat Affected Zone (HAZ) in HF Pipe and Tube Welding**

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### **Introduction**

The High Frequency (HF) pipe and tube welding process was discovered in the late 1940's, developed into practical reality in the 1950's and became the predominant method for producing pipe and tube in the 1960's and 1970's. The advent of solid state welders in the early 1990's motivated an understanding of welding frequency, as these welders offered a significantly larger choice in welding frequency over the conventional vacuum tube welders of the time.

During the 60 year history of HF pipe and tube welding, those responsible for pipe and tube production have almost totally been guided by experimental knowledge and empiricism. Because one knows that "such and such" tube can be welded at "so many" feet per minute with "that many" kilowatts, it can be expected that another tube, close to this particular setup, can be run with a similar, logically scaled setup. And, if this setup doesn't perform properly, it is reasonable to assume that something "key to successful operation" has been lost. Successful, repeatable pipe and tube mill operation as we understand it today, involves having a good data base for previously produced, high quality pipe and tube, together with the discipline to reproduce a previously successful mill setup in a sufficiently short, viably productive change-over time.

A serious improvement to the pipe and tube manufacturing process would be the ability to predict and control at least some of the characteristics of the HF weld. This would help to more accurately extrapolate our empirical knowledge to new product requirements and to productivity improvements, such as achieving faster mill speeds. It would also make possible on-line production monitoring that could advise mill operators whether the current production run is meeting the customer's quality standard.

Heat Affected Zone (HAZ) Control is a revolutionary new development that enables these desirable improvements for HF welding. This new technology allows our empirical process knowledge (what we already know "works" and "doesn't work") to be combined with the results of mathematical physics so that standard mill products can be run in a more predictable process environment, and new mill products can be successfully run with shorter setup development times. This paper will present how HAZ Control Technology can improve the productivity of mill operation and the quality of the pipe and tube produced.

## What is the HAZ and How Does It Relate to Weld Quality?

Metallurgists define the Heat Affected Zone (HAZ) as “the area of base metal which has had its microstructure and properties altered by welding. The heat from the welding process and subsequent re-cooling causes this change in the area surrounding the weld.”<sup>1</sup> Differences in the microstructure of the HF seam weld and parent material determine how the results of Rockwell hardness or Charpy toughness testing, for example, will differ when these regions are subjected to material property measurements. The weld vee time-temperature distribution causes transformation of the metal’s microstructure and affects the “grain” size of the weld structure. Both have significant influence on material test results.

The time-temperature transformation of the metal’s microstructure leaves a signature that is visible to the human eye. It can be seen by looking at a cut and polished weld specimen under a microscope. This visible change in microstructure is the Heat Affected Zone and its geometry is the direct consequence of the weld’s heating profile. An example of a weld from an API line pipe sample is shown in Figure 1.

The metallurgist can often predict the changes in microstructure knowing the time-temperature history of the metallic specimen. For example, the microstructure of steels with different chemistries can be predicted from Time-Temperature Graphs. These curves can be produced by computer programs such as SteCal<sup>2</sup>. They show the time at temperature necessary to form the Ferrite, Pearlite, Martensite, etc. structures observable in the micrograph. Because of the rapid formation of the HF seam weld, the HAZ is created by the spatial temperature distribution at the weld vee apex, where material elements have reached their highest temperature, which determines the HAZ.

The tube mill setup factors that influence the HAZ include:

- The tube material, diameter and wall thickness.
- The mill speed and welder’s power level.
- Whether the weld is made by the induction or contact process, and the vee length of the weld area setup.
- The strip edge geometry when it passes through the weld area.
- The design of the weld box and the forge pressure it applies to the strip edges at the weld point.

While many mill setup parameters such as tube diameter, wall thickness and tube material are pre-established before the mill production run, there generally is some discretion over other setup parameters, such as weld power, welding

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<sup>1</sup> From the internet encyclopedia at [wikipedia.org/wiki/Heat-affected-zone](http://wikipedia.org/wiki/Heat-affected-zone), 2006.

<sup>2</sup> Tavin, P. and Perez, J., SteCal, ASM International Product Code 07482A, Universidad Politecnica de Madrid, ISBN-13: 978-0-87170-796-3, 2004.

frequency, vee length and mill speed. Through judicious selection of these “flexible” parameters, a weld HAZ, having the best material properties can be achieved for the pipe or tube’s end application.

It is important to understand that there is no “optimum Heat Affected Zone (HAZ)”. Having studied weld HAZs from a number of premium pipe and tube products, the author has concluded that the best HAZ weld depends of the final application for the pipe or tube. For example, it is easy to establish that manufacturers of API, Oil Country Goods Products strive for much wider and deeper HAZs than manufacturers of thin wall, coated tubes. Knowledge of what HAZ characteristics are necessary for the pipe or tube’s end application will always be necessary to produce the most cost effective pipe or tube with the highest quality.

### **What Affects The Characteristics of the HF Weld HAZ?**

So far, we have determined that many important material properties of the HF weld can be inferred from its Heat Affected Zone (HAZ), and that the HAZ results from the time-temperature changes that occur in the material while welding. Therefore, in order to study the characteristics of the HAZ, we need to know how the tube mill’s setup affects the time-temperature profile in the vee edge.

In the mid 1990’s several scientific papers were published, establishing for the first time, a mathematical basis for HF welding theory. One of the most significant results was the derivation of a mathematical theory<sup>3</sup> that accurately predicts the relationship between mill speed and weld power as a function of vee length, the strip’s material properties, and welding frequency. The theory has been successfully applied to determining speed-power relationships for HF welders, and has been used for several years at Thermatool Corp for weld rate prediction. It has been shown to predict weld power over a wide range of product sizes and mill speeds with reasonable accuracy.

The theory states that the temperature distribution in the weld vee is primarily due to the physical combination of the HF electrical current distribution which causes the vee to heat, and thermal conduction which determines how deeply this heat penetrates into the vee edge. The HF current distribution is characterized by the Electrical Reference Depth, and is a function of welding frequency. The thermal conduction process is characterized by the Thermal Reference Depth, and is a function of vee length and mill speed.

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<sup>3</sup> Scott, P.F. and Smith, W.; *A Study of the Key Parameters of High Frequency Welding*; Tube China '95 Conference, Beijing, China, November, 1995; Transactions of the International Tube Association, Warwickshire, UK, Pages 168-181. Available for internet download at [thermatool.com](http://thermatool.com).

In practical HF pipe and tube welding situations:

- The Electrical Reference Depth can be larger than the Thermal Reference Depth. This circumstance results in one kind of temperature distribution.
- The Thermal Reference Depth can be larger than the Electrical Reference Depth. This circumstance results in a second kind of temperature distribution.
- Both the Electrical and Thermal Reference Depths can be of the same size. This results in a transitional temperature distribution.

This topic is discussed more fully in the reference cited below.<sup>4</sup>

To summarize, the time-temperature profile in the weld vee creates the Heat Affected Zone (HAZ). The combined effects of HF electrical heating (described by Electrical Reference Depth) and diffusion of this heat into the vee edge by thermal conduction (Thermal Reference Depth) causes this temperature distribution. If the temperature distribution in the vee edge can be predicted from the Electrical and Thermal Reference Depths, and if these Reference Depths can be calculated from the principal mill setup parameters (tube diameter, wall thickness, weld power, welding frequency, vee length, and tube material properties), then a method can be crafted for predicting and controlling the Heat Affected Zone (HAZ) of an HF welded pipe or tube.

### **Is it Possible to Predict the HF Weld HAZ?**

In 1995, when mathematical results were first derived for determining the HF welding speed–power relationship, the author’s major disappointment was the inability to invert the Laplace Transform of weld vee temperature. Had this been accomplished, the result would have given the complete description of vee temperature. Instead, a mathematical approximation had to be made and only the vee apex temperature could be obtained.

Recently, a mathematical theorem was uncovered that allowed the complete inversion of this Laplace Transform. The new result gives a mathematical description of the complete weld vee temperature distribution. For the purpose of determining weld HAZ characteristics, the new equation can be evaluated at the vee apex. The results needed for HAZ prediction are given below:<sup>5</sup>

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<sup>4</sup> Scott, P.; The Effects of Frequency in High Frequency Welding; Tube Toronto 2000 Conference, Toronto, Ontario, Canada, June, 1996; Transactions of the International Tube Association, Warwickshire, UK, pages 11-14. Available for internet download at [thermatool.com](http://thermatool.com).

<sup>5</sup> Those with a masochistic nature may find the complete analysis, in all its painful glory, on the internet at [thermatool.com](http://thermatool.com).

1. The first result is a mathematical description for the shape of the temperature distribution that results in the weld's Heat Affected Zone (HAZ):

$$\frac{T(x)}{T(x=0)} = \frac{e^{-2\lambda\eta} [e^{\eta^2} - 1] + \frac{1}{2} e^{-2\lambda\eta} [e^{2\lambda\eta} \operatorname{erfc}(\lambda + \eta) - e^{-2\lambda\eta} \operatorname{erfc}(\lambda - \eta)] + \frac{2\eta}{\sqrt{\pi}} e^{-\lambda^2} - 2\lambda\eta \operatorname{erfc}(\lambda)}{e^{\eta^2} \operatorname{erfc}(\eta) + \frac{2}{\sqrt{\pi}} \eta - 1}$$

2. With the variable,  $x$ , defined as the distance measured from the vee apex into the vee edge (See Figure 2), the non-dimensional variables,

$$\lambda = \frac{\sqrt{\pi} x}{4 \gamma} \text{ and } \eta = \frac{4}{\sqrt{\pi}} \frac{\gamma}{\xi}$$

Result 1. The first number,  $\lambda$ , is the distance into the vee edge starting at its apex in units related to the Thermal Reference Depth,  $\gamma$ . The second number,  $\eta$ , is the size of the Thermal Reference Depth relative to the size of the Electrical Reference Depth,  $\xi$ .

3. The Thermal and Electrical Reference Depths can be calculated from the thermal and electrical properties of tube material, and principal mill setup parameters - vee length, mill speed and welding frequency:

$$\gamma = \sqrt{\frac{\pi \varepsilon y_o}{4 v}}$$

where  $\gamma$  is the Thermal Reference Depth,  
 $\varepsilon$  is the tube material's Thermal Diffusivity,  
 $y_o$  is the Vee Length of the welding setup,  
and  $v$  is the Mill Speed.

And:

$$\xi = \sqrt{\frac{\rho}{\pi f \mu}}$$

where  $\xi$  is the Electrical Reference Depth,  
 $\rho$  is the tube material's Electrical Resistivity,  
 $f$  is the Welding Frequency,  
and  $\mu$  is the tube material's Magnetic Permeability.

4. The second result provides the absolute reference value for the temperature distribution given in Result 1:

$$T(x=0) = \frac{\beta \xi}{4 K y_o d} P \left[ e^{\eta^2} \operatorname{erfc}(\eta) + \frac{2}{\sqrt{\pi}} \eta - 1 \right]$$

where  $P$  is the output power of the HF welder,

$\beta$  is the power transfer efficiency between the welder and the weld vee,

$K$  is the tube material's Thermal Conductivity,

and  $d$  is the tube material's thickness (tube wall thickness).

5. Finally, when physically characterizing a weld, it is sometimes more useful to solve the problem in terms of volumetric stored energy rather than temperature. In the theory of physics, temperature is the measure of the energy stored in a volume of material, so the two quantities really describe the same phenomena. In the linear theory, volumetric stored energy and temperature are related by the material's heat capacity and mass density. As there is no energy stored in a material (the stored energy is zero) when its temperature is at absolute zero, the relationship is given by:

$$\begin{aligned} \text{Stored Energy (Energy/Volume)} = \\ C_p (\text{Energy/Mass} \times \text{Absolute Temperature}) \times \rho_{\text{Mass}} (\text{Mass/Volume}) \\ \times T (\text{Absolute Temperature}) \end{aligned}$$

where  $C_p$  is the tube material's Heat Capacity,

$\rho_{\text{Mass}}$  is its Mass Density,

and  $T$  is its Absolute Temperature,

generally measured in degrees Kelvin or Rankine.

The advantage of using volumetric stored energy in welding problems is that it better accounts for the Heat of Fusion in the material. When an element of material is raised to its melting point, it stays at this temperature while continuing to absorb the energy needed to perform the phase change from solid to liquid. Likewise, if an element is cooled from the melting state, this gained energy must leave the element while it completely returns to the solid phase, before its temperature will begin to drop. Weld zones often experience temperatures that bring them into the solid-liquid phase change region. When the tube material is at or near the melting temperature, volumetric stored energy is the preferred description because it is a monotonically increasing, continuous function. The temperature in this region is single valued, and thus can be mathematically ambiguous.

For the equation in Result 2, we can convert temperature, when it is below the tube material's melting point, to stored energy per unit volume using:

$$E = C_p \rho_{Mass} T(x=0) = \frac{K}{\varepsilon} T(x=0) = \frac{\beta \xi}{4 \varepsilon y_o d} P \left[ e^{\eta^2} \operatorname{erfc}(\eta) + \frac{2}{\sqrt{\pi}} \eta - 1 \right]$$

Summarizing this section, the equation given in Result 1 accomplishes our fundamental objective in that it provides the ability to predict HAZ shape. Further, it shows that the shape of the HAZ can be described in terms of the Electrical and Thermal Reference Depths. Thus, the temperature distribution that creates the HAZ can be determined from basic mill setup parameters and the tube material's properties. Result 5 further extends this theory by applying the concept of volumetric stored energy. This gives a more useful description of the weld vee's properties, when the pipe or tube material is near its melting point.

### **Can the Weld HAZ be Controlled?**

If it is possible to predict the basic features of the Heat Affected Zone (HAZ), then it should be possible to control it. Work is currently underway to take the theory put forth in this paper and develop an open-loop HAZ monitoring and control system. If this should prove successful, some day closed-loop control of the weld HAZ may be possible.

The open-loop control concept is based on identifying the "best" HAZ for a particular pipe or tube application, and then measuring "how far away" the HAZ being produced by the tube mill is from this point. As previously pointed out, there is no "Optimum HAZ" so this needs to be determined through empirical study, and "trial and error". Values representing the actual HAZ during pipe or tube production can be calculated while the tube mill is in operation. This process uses data provided by the tube mill operator for the tube diameter, wall thickness and vee length, and data obtained in "real time" from the HF welder for weld power, welding frequency and mill speed. A control panel that displays the input data for an open-loop HAZ Control is shown in Figure 3.

The HAZ Control can be used to monitor production. The quantities above are all that is needed to evaluate the equations given in Results 1 and 5. Both the "best" HAZ and the HAZ from the actual production run are characterized by a shape or "HAZ Width" that is calculated from Result 1, and volumetric energy level or "Heat" determined from Result 5. These values are displayed to the operator as a two dimensional graph, using the coordinates of "HAZ Width" for the x-axis and "Heat" for the y-axis. The "HAZ Width and "Heat" for the given product's "best" HAZ are used to establish the center of the operator's display graph, and portrayed on this graph as a "target" (See Figure 4). A "cursor" is then used to indicate the position on the same graph of the actual HAZ values obtained while the tube mill is in production. The operator then watches the graph and adjusts the welder's power and welding frequency so that the "cursor"

is over the “target”, in the center of the graph. The inability of the operator to make acceptable pipe or tube and keep the “cursor” in the center of the “target” is an indication that an important mill parameter is no longer at its correct setting. This should signal the mill operator to investigate the cause of the problem. “Best” HAZ data that has proven to produce high quality pipe and tube with the HAZ Control can be stored in a library for recall at a later date. An operator screen for doing this is shown in Figure 5.

HAZ Control can also be used to find the best weld area setup for a new pipe or tube product, especially if “best” HAZ data is available from a similar product. The “best” HAZ data for a pipe or tube that is dimensionally close to the new product is loaded into the HAZ Control. The controller’s dimensional data is then adjusted to agree with that for the new product. If this data is not available, the HAZ Control can make its “best guess” as to these starting values. This fixes the starting position of the “target” for the new product. The weld power, welding frequency, vee length and mill speed are then adjusted while the tube mill is in operation to bring the “cursor” over the “target”. This has the effect of mapping the “best” HAZ from a known product or a “best guess” mill setup to a setup for the new product.

HAZ Control is an exciting “new frontier” for pipe and tube process development and many advanced products should be expected as this technology matures.

### **Conclusions:**

Historically, pipe and tube manufacturing has been driven by empirical knowledge and “cut and try” development. New process control methods, such as Heat Affected Zone (HAZ) Control, enable significant improvements for HF welding. This new technology allows our empirical process knowledge (what we already know “works” and “doesn’t work”) to be combined with the results of mathematical physics so that standard mill products can be run in a more predictable process environment, and new mill products can be successfully run with shorter mill setup development times.

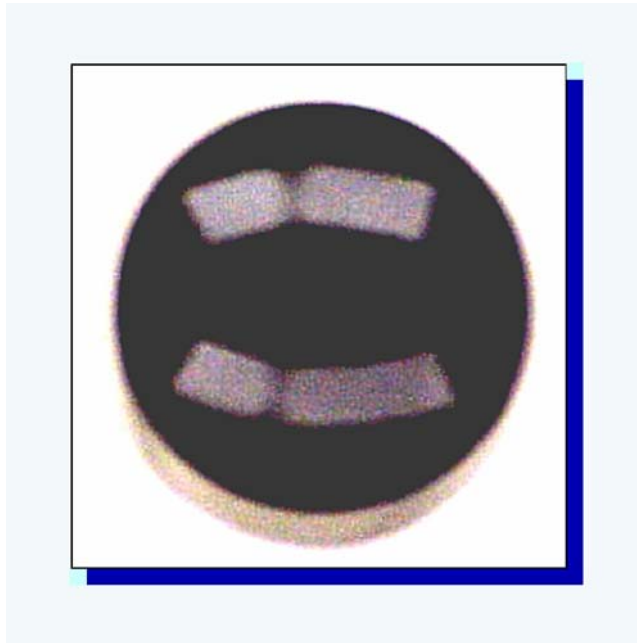
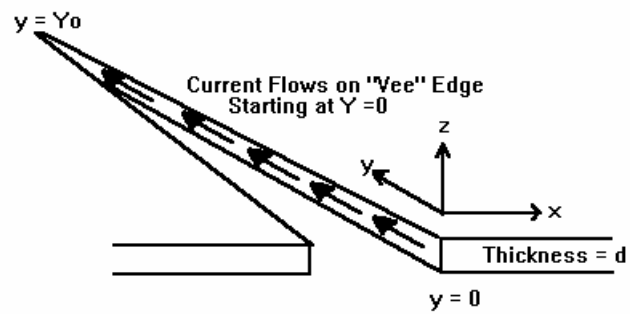


Figure 1 - Weld HAZ from API Line Pipe Product



TUBE GEOMETRY ANALYSED WITH THERMAL CONDUCTION MODEL

Figure 2 - Tube Geometry Used in Mathematical Model

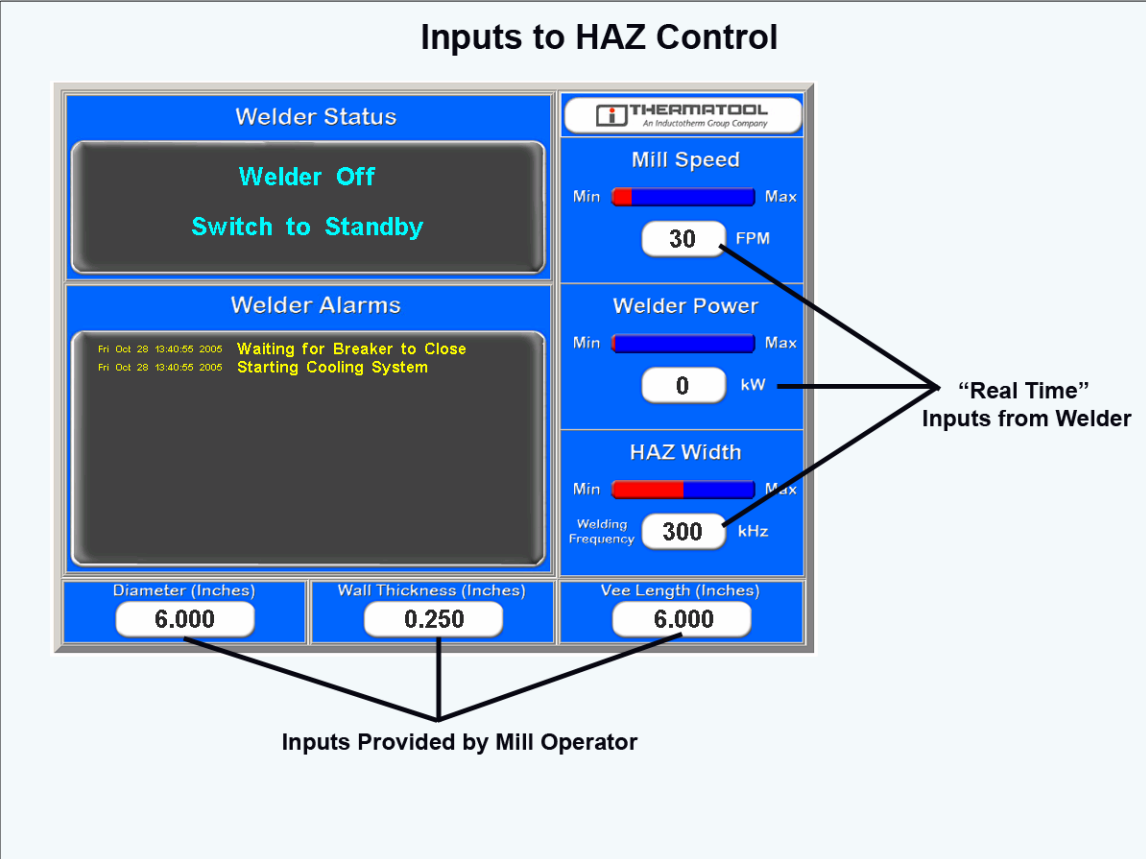


Figure 3 - HAZ Control Parameter Input Screen

### Mill Operator's HAZ Control Screen

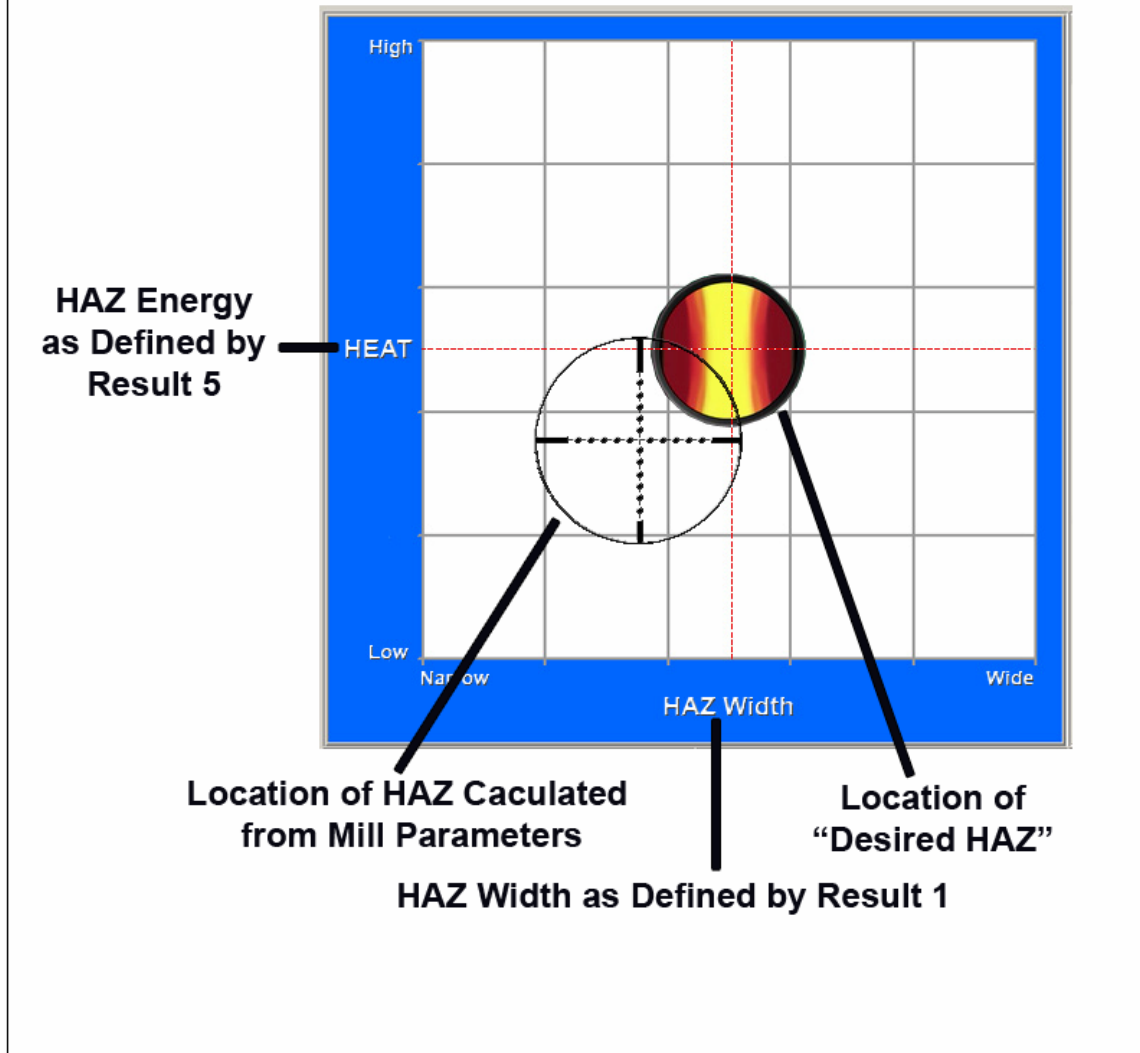


Figure 4 - HAZ Control Operator's Control Display

Job ID	Diameter (Inch)	Wall Thickness	Vec Length	Mill Speed (FPM)	Date & Time Captured
1	52	4.500	0.206	7.000	Fri Oct 28 14:29:04 2005
2	78	4.500	0.156	7.000	Fri Oct 28 14:31:21 2005
3	131	5.500	0.275	8.000	Fri Oct 28 14:33:19 2005
4	170	5.500	0.304	8.000	Fri Oct 28 14:34:26 2005
5	224	6.625	0.125	10.000	Fri Oct 28 14:35:04 2005
6	269	6.625	0.188	145	Fri Oct 28 14:37:42 2005
7	-	-	-	-	-
8	-	-	-	-	-
9	-	-	-	-	-
10	-	-	-	-	-
11	-	-	-	-	-
12	-	-	-	-	-
13	-	-	-	-	-
14	-	-	-	-	-
15	-	-	-	-	-
16	-	-	-	-	-
17	-	-	-	-	-
18	-	-	-	-	-
19	-	-	-	-	-
20	-	-	-	-	-
Job ID Number		Maximum Mill Speed (FPM)		Maximum Welder Power (kW)	
269		250		450	

Figure 5 - HAZ Control Data Storage Display