6 Numerical Examples

Once the additions to *Tmin* for the 2-D vertical piping span were completed, test cases were performed. The cases were performed to ensure that the correct shear and moment values were calculated before being used in the stress 2-D piping equations. Once the shear and moment values were verified, the *IF-THEN* statements within the *Tmin* computer code were verified for a specific case of where the maximum moment occurs. Within these *IF-THEN* statements, other *IF-THEN* checks were done to see where the elbows occurred in relation to the piping spans. When a moment passed through an elbow, the *SIF* value, which was determined by the type of elbow chosen, was multiplied against the moment [11].

When the end-user had chosen a valve in any section of the 2-D vertical piping span, a popup form prompts the user to choose a valve-connection type. This is seen in Chapter 5. The connection type of the valve also incorporated an *SIF* value [11]. However, because valves are of different lengths, which are dependant on the manufacturers, it was impossible to choose a standard valve length. As a result, the *SIF* value used for the valve would only multiply the moment at the exact center of the valve.

Because of these *SIF* values used within the computer program, the critical pipe-wall thickness location may not occur where the shear and or the maximum moment are at their largest values. The critical pipe-wall thickness is defined as the largest thickness value obtained after evaluation of all stress-states in the 2-D vertical piping span. As was seen from Figure 4-4 in Chapter 4, a spike occurs when the moment is multiplied by an *SIF* value. Therefore, the program may return a pipe-wall thickness location that may be more critical than a similar piping span with different connections and elbows. It should be understood that if the code returns a critical value of wall thickness at a valve, then the piping wall thickness at the connection points are the truly critical positions rather than the center of the valve.

In the following sections, two examples will be shown using a pre-determined 2-D piping system, with varying elbow and valve choices. The first example will not have any valves in any of the piping spans and is detailed in Section 6.1. The second example will show how shear may dominate the 2-D vertical piping span analysis by using an extremely short piping span in conjunction with a long span and is seen in Section 6.2. From each case, the resulting stress equations obtained from the differential stress elements, detailed in Chapter 4, will be used to determine a pipe-wall thickness. At each of critical sections where a valve, elbow, or the vertical span occurs, as well as the ends of the piping, and the maximum moment location, the pipe-wall thickness value will be compared to all others in the entire piping system. The largest of all the thicknesses is selected as the critical thickness with its corresponding critical section.

As shown in Chapter 5, the final critical piping section will be highlighted in red on the output screen. It should be noted that the critical section information is supplemented with a list of minimum thicknesses allow at various piping sections so that those can be checked, if the operations personnel suspect accelerated erosion or other situations that would cause excessive thinning of certain piping regions. This is also helpful where certain sections have been replaced under a preventative maintenance program. The older piping, in this case, will be thinner than the renewed piping so that those older sections will have to be checked even if they are not listed in the critical section dialogue box. Calculations were checked by hand by re-substitution of the variables used back into the equations for each section to ensure pipe-wall thickness calculation accuracy.

6.1 First Vertical Span Example—Basic Piping Configuration

The first 2-D vertical piping span to be analyzed is a basic configuration. This basic configuration does not include any valves and is seen in Figure 6-1. The input data used for this evaluation is seen in this figure as well and are the pipe span lengths, size, pressure, temperature, and specific gravity of the internal fluid. For the material used in this calculation, the allowable stress, S_a, was 17,900 psi and is used in all calculations. From the material used, and piping size, the total weight per length (W_{Tot}) of the span was found to be 5.88 lb/ft. The weight per length of the span was used in calculation of the shear diagram will be discussed later in this section.

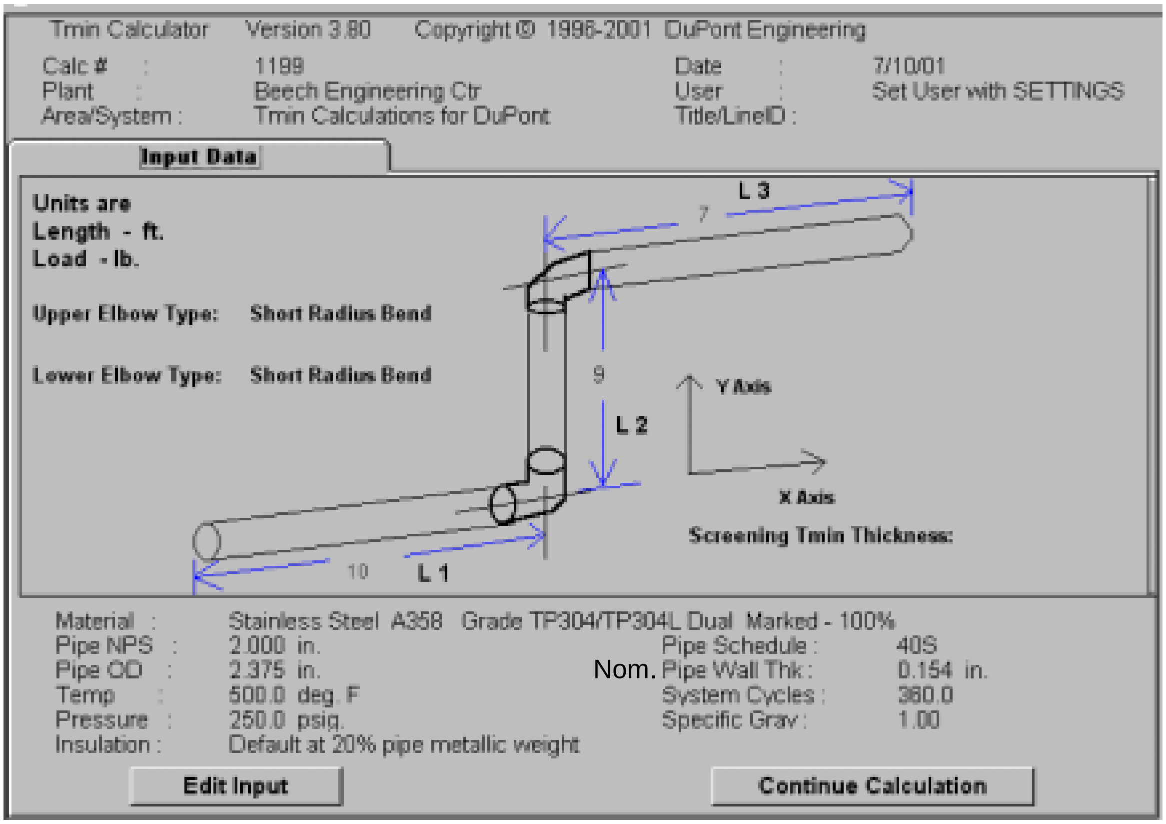

Figure 6-1. Example One. Piping Diagram used for the Basic Configuration Analysis

To begin analysis, the piping span dimensions and total weight of pipe per length were entered into a *Matlab* code to produce a visual diagram to follow for analysis. Using the shear and moment diagram seen in Figure 6-2, a step-by-step analysis will be followed. As seen in this figure, the shear values at the ends of the spans are seen as a maximum. However, in the center of the 2-D vertical piping span at the vertical section, the shear crosses the x-axis. When the shear crosses the *x*-axis, the moment is at a maximum; the moment is seen to be a maximum in the figure as well.

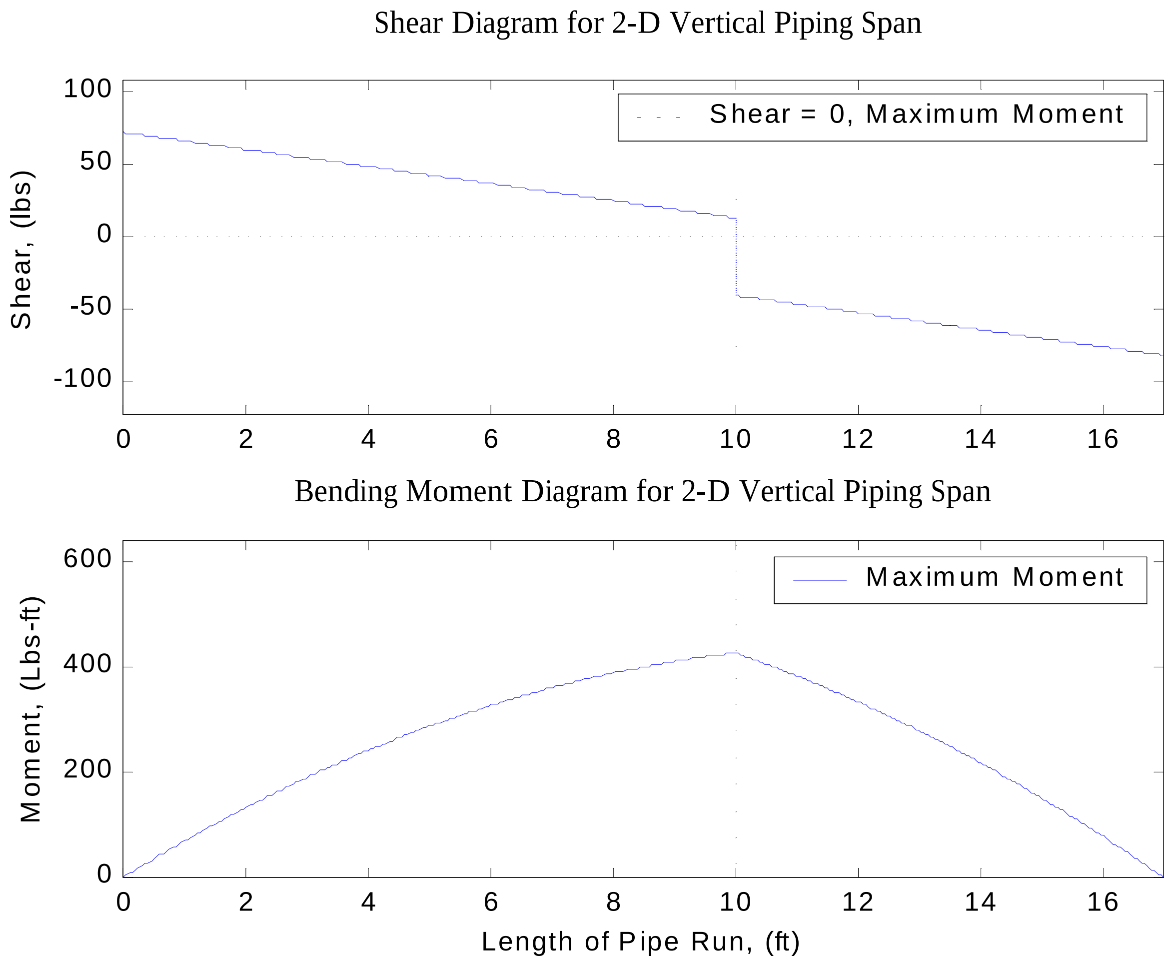

Figure 6-2. Shear and Bending Moment Diagrams for 2-D Vertical Piping Span for Figure 6 - 1

As stated in Chapter 4, because the moment diagram was created by taking the trapezoidal area under the shear diagram, sharp edges will be seen in the moment diagram. From the Figure 6-1, and looking at the shear diagram seen as Figure 6-2 (upper figure), the points where analyses will be completed in the 2-D vertical piping span are identified as V_1, V_2, V_3, and V_4. The shear at the bottom elbow connection is V_{eb} and at the top elbow the shear is V_{et}. At these shear locations, the shear values found are seen in Table 6-1. The moment values are identified as well in this table. All of these values seen in this table will be used throughout the analysis procedure of the piping span.

Table 6-1. Shear and Moment Values Obtained from Figure 6-2

Distance *Ft.*	Shear *V*	Shear *Lbs.*	Moment *lb-ft*
0	V_1	82.25	0
9.83	V_{eb}	25.13	407.22
10	V_2	23.40	417.27
10	V_3	-37.29	417.27
10.17	V_{et}	-38.45	409.96
19	V_4	-78.45	0

Left-End Span Analysis:

Starting at the left end of the piping span, the shear, V_1, is used the first analysis. The result of Mohr's circle stress analysis calculation results in Equation (6.1), which is then equated to the strength of the material at the temperature specified by the user. To emphasize the complexity of this equation, refer to Equation (6.2). It can be seen that by expanding Equation (6.1) in terms of *t*, that Equation (6.2) involves multiple powers of *t*. As seen by Equation (6.2) it is too complex to be solved by hand, thus the reason for the use of a root solving function (detailed in Chapter 4). As a result, the root-solver in *Tmin* was used for evaluation of the pipe-wall thickness for Equation (6.2). The shear stress, τ_{xy}, in Equation (6.1) is equal to $2V_1/Area$. This is the maximum shear stress at this piping section.

$$S_a = \sigma'_{MSST} = \left[\left(\frac{\sigma_H + \sigma_L}{2}\right) + \sqrt{\left(\frac{\sigma_H - \sigma_L}{2}\right)^2 + \left(\tau_{xy}\right)^2}\right] \tag{6.1}$$

$$0 = -S_a + \left[\left(\frac{\frac{P(D_o - 2t_{Min})}{2t_{Min}} + \frac{P(D_o - 2t_{Min})}{4t_{Min}}}{2}\right) + \sqrt{\left(\frac{\frac{P(D_o - 2t_{Min})}{2t_{Min}} + \frac{P(D_o - 2t_{Min})}{4t_{Min}}}{2}\right)^2 + \left(\frac{2V}{\frac{4}{\pi}\left(D_o^2 - (D_o - 2t_{Min})^2\right)}\right)^2}\right] \tag{6.2}$$

The equation is rearranged to equal zero and then is solved for the thickness that forces the equation to zero. This is done by the root-solver. The solver outputs the minimum pipe-wall thickness, t_{Min}.

Using the values input for this piping span (pressure, outside pipe diameter, etc.) and the shear values from the Table 6-1, the minimum pipe-wall thickness could be calculated. From the root-solver in *Tmin*, the pipe-wall thickness found to make this equation equal to zero was $3.26\text{x}10^{-2}$ inches. A calculation check was completed by hand using Equation (6.2) to verify the accuracy of the root-solver for this calculation. The solution calculated matched the allowable stress of 17,500 psi.

The pipe-wall thickness value obtained will be saved for later use for comparison in an array to find the largest *Tmin* value found. Moving along to the right of the shear diagram to the next location of interest: The connection of the elbow and the bottom span.

Elbow Connection at Bottom Span:

To begin analysis at this section, when the user chooses an elbow the exact length of the elbow is not known. This is because of the many types of elbows on the commercial market. To find this elbow connection distance to the lower piping span, the length of the lower piping span is used. This distance is found by Equation (6.3), which was incorporated into the previous version of *Tmin* [2]. This equation takes the distance from the start of the span and subtracts the *SIF* value found from this valve. Once this length was found, the weight of the elbow is next found by Equation (6.4).

$$\text{Length of Bottom Elbow} = 2*(\text{Length of Bottom Span} - \text{SIF for Bottom Elbow}) \quad (6.3)$$

$$\text{Weight of bottom Elbow} = 2*(\text{Length of Bottom Elbow}*W_{Tot}) \quad (6.4)$$

Once this connection distance is known the stresses at this location. The stresses are increased because of the *SIF* values from the elbow. To begin analysis of the 2-D vertical piping span, the *SIF* value of the elbow is calculated by an *IF-THEN* statement, which was found in the previous version of *Tmin* and placed there by DuPont [2]. In this *IF-THEN* statement the new *SIF* value will increase the elbows *SIF* value if the nominal pipe size (*NPS*) is greater than zero. In addition, if the *NPS* is less than zero, then the new *SIF* value is set equal to the outside diameter of the pipe.

Stress intensity factors for the elbow chosen depend on the type of elbow chosen by the user. These *SIF* values can be found in Chapter 4, Section 4.3. In this case a standard radius bend was chosen and its corresponding SIF value was one (1.0). The *SIF* values for the elbows can be seen in Chapter 4. As a result of the *IF-THEN* statement within Tmin, the SIF value was increased to a value of two (2.0).

The first equation found through 3-D Mohr's circle of the differential stress elements was the hoop stress Equation (4-6), found in Chapter 4. This equation could be solved directly for the minimum pipe-wall thickness as seen in Equation (6.5). This equation includes the *SIF* value from either the elbow or a valve, if one is present.

$$t_{Min} = \frac{P * D_o}{2(SIF * P + S_a)} \tag{6.5}$$

DuPont has followed ASME guidelines of Piping Standards B31.3, paragraph 304.1.2.a Equations 3a, 3c, 3d, & 3e [11]. This analysis of the hoop stress is detailed in Chapter 3. Through contact with DuPont they had used a substitution into Equation (6.5) to result in Equation (6.6) [30]. Using this equation, the minimum pipe wall thickness required for is easily solved and is AMSE standards compliant. In Equation (6.6) the temperature effect of the carrier fluid is observed, seen as a constant *Y*. This *Y* value is obtained from ASME standards and code Table 304.1.1 [28].

$$t_{Min} = \frac{P * D_o}{2\left(SE/Ibend + SIF * P * Y\right)} \tag{6.6}$$

This piping span is evaluated at 500 degrees Fahrenheit, resulting in a *Y* value of 0.4. In addition, *SE* is the allowable stress multiplied by a weld factor also detailed in ASME document B31.3, to result in a value of 17500 psi [28]. Finally, the *Ibend* is a numerical factor created by DuPont that is used when an elbow is present. Such as the case of the 2-D vertical piping span [2]. The value calculated for *Ibend* is *1.73* and is unitless.

The next equation found was the summation of the bending and longitudinal stresses, seen as Equation (4.8) in Chapter 4. The summation of these stresses is too complex to be solved by hand. The maximum moment is seen at the vertical section, the moment, *M*, used in this calculation is seen in Table 6-1. The maximum moment occurs when the shear is zero. As a result, Equation (6.7) presents the summation of the bending and longitudinal stresses without any shear present. The pressure, strength of the material, outside diameter of the pipe, and the moment are then passed through the root-solver to get a pipe-wall thickness, t_{Min}. This equation is then solved for the minimum thickness that forces it to zero.

$$0 = -S_a + \frac{P\left(D_o - 2t_{Min}\right)}{4t_{Min}} + \frac{M}{\pi/32\left(D_o^4 - \left(D_0 - 2t_{Min}\right)^4\right)} \tag{6.7}$$

The data used in the program were then passed through the root-solver of *Tmin* and the pipe-wall thickness is then solved for. The pipe-wall thickness calculated through Equation (6.6) was 2.82×10^{-2} inches, while for Equation (6.7) it was 2.77×10^{-2} inches. As a result, the largest pipe-wall thickness calculated was from Equation (6.6). This value will be saved for later comparison to other pipe-wall thickness values in the 2-D vertical piping span. The next section for evaluation is the vertical piping span.

Vertical Piping Span Analysis:

As seen on the shear diagram, a step function is seen at the vertical span location due to the weight of the vertical span, insulation, and elbows. Through analysis of Mohr's circle, it was found that there were 4 possible stress equations that are equal to the strength of the material at operating temperature. As noted in Chapter 4, analysis is completed at the bottom elbow top elbow when no valve is present in this span. When a valve is present in the vertical span, analysis will be completed there as well. The *SIF* value for the elbow depends on the type of elbow chosen. In this case the elbow was a short radius bend. For the type of elbow chosen, the *SIF* value is one (1.0) and using the IF-THEN statement described earlier, the resultant SIF value will be two (2.0).

Looking at the compression diagram in Figure 6-3 for the vertical analysis, the compressive loads are shown in Equations (6.8) through (6.10). As proved in Chapter 4 only compressive state equations will be used for analysis even when the piping span is in tension. As seen in Figure 6-3 the upper and lower section of the piping span will have a high compression. As a result these sections will be evaluated.

$$C_1 = V_2 = 23.46 \textit{ lbs.} \tag{6.8}$$

$$C_2 = -L_2/2*W_{Tot} + V_3 = -10.84 \textit{ lbs.} \tag{6.9}$$

$$C_3 = -V_3 \tag{6.10}$$

As a result of these additional compressive loads on the vertical span, Equations (6.11) and (6.12) are also used in the vertical span analysis. If the piping system experiences a tensile instead of compressive loads, these equations will work as well. Because of the complexity of these equations, the variables used in the 2-D vertical piping span analysis are passed through the root solver for pipe-wall thickness values. In each of these two equations, the moment *M* is used. Also seen in these equations is an *SIF* term. The *SIF* value is dependant on the presence of a valve or elbow and its corresponding numerical value.

$$0 = -S_a - \frac{32M*SIF}{\pi\left(D_o^4 - (D_o - 2t_{Min})^4\right)} + \frac{P*SIF(D_o - 2t_{Min})}{4t_{Min}} - \frac{4C*SIF}{\pi\left(D_o^2 - (D_o - 2t_{Min})^2\right)} \tag{6.11}$$

$$0 = -S_a + \frac{32M*SIF}{\pi\left(D_o^4 - (D_o - 2t_{Min})^4\right)} + \frac{P*SIF(D_o - 2t_{Min})}{4t_{Min}} - \frac{4C*SIF}{\pi\left(D_o^2 - (D_o - 2t_{Min})^2\right)} \tag{6.12}$$

Now that all the equations have been identified through the differential stress elements, Table 6-2 shows the resultant pipe-wall thickness values calculated for the vertical piping span.

Table 6-2. Pipe-Wall Thickness Values for Vertical Pipe Span

	Pipe Wall Thickness	
	Upper Vertical Span *inches*	**Lower Vertical Span** *inches*
Equation (6.6)	2.87x10-2	2.87x10-2
Equation (6.7)	4.41x10-2	3.58x10-2
Equation (6.11)	7.38x10-2	**7.40x10-2**
Equation (6.12)	6.86x10-2	4.51x10-2

As seen in this table, Equation (6.11) resulted in the largest pipe-wall thickness value for the entire vertical span. Therefore, this pipe-wall thickness will be compared to the rest of the pipe-wall thickness calculations for the rest of the 2-D vertical piping span. The next section to be evaluated is the elbow connection in the upper piping span.

Elbow Connection in Upper Piping Span:

At this location an SIF value is again used because of the elbow. 3-D Mohr's circle analysis was used for evaluation at this point to find the stresses. Since this location is similar to the previous elbow connection, the same stresses were found. Equations (6.6) and (6.7) were again used for calculation of the pipe-wall thickness. From Equation (6.6) the pipe-all thickness was 2.82×10^{-2} inches. While for Equation (6.7), the thickness value was 2.76×10^{-2} inches. Since Equation (6.6) gave the highest pipe-wall thickness it will be saved for later comparison. The final location to be evaluated is the right-end of the upper piping span.

Upper-Right Vertical Span Analysis:

Using Mohr's circle analysis revealed that this location is identical to the left end of the lower piping span, except that the shear, V_4, will be used. Using this shear value and the variables used throughout this piping span, the pipe-wall thickness found was 3.26×10^{-2} inches by using Equation (6.2). Through the analysis of this vertical piping span, it was found that the largest pipe-wall thickness value was at the bottom of the vertical span. The final pipe-wall thickness will be seen in Figure 6-3 as the minimum thickness needed to support structural integrity. As detailed in Chapter 2 the program then passes this value through a series of checks to determine the largest possible pipe-wall thickness. This final pipe-wall thickness is seen as the “Screening Tmin” in this figure.

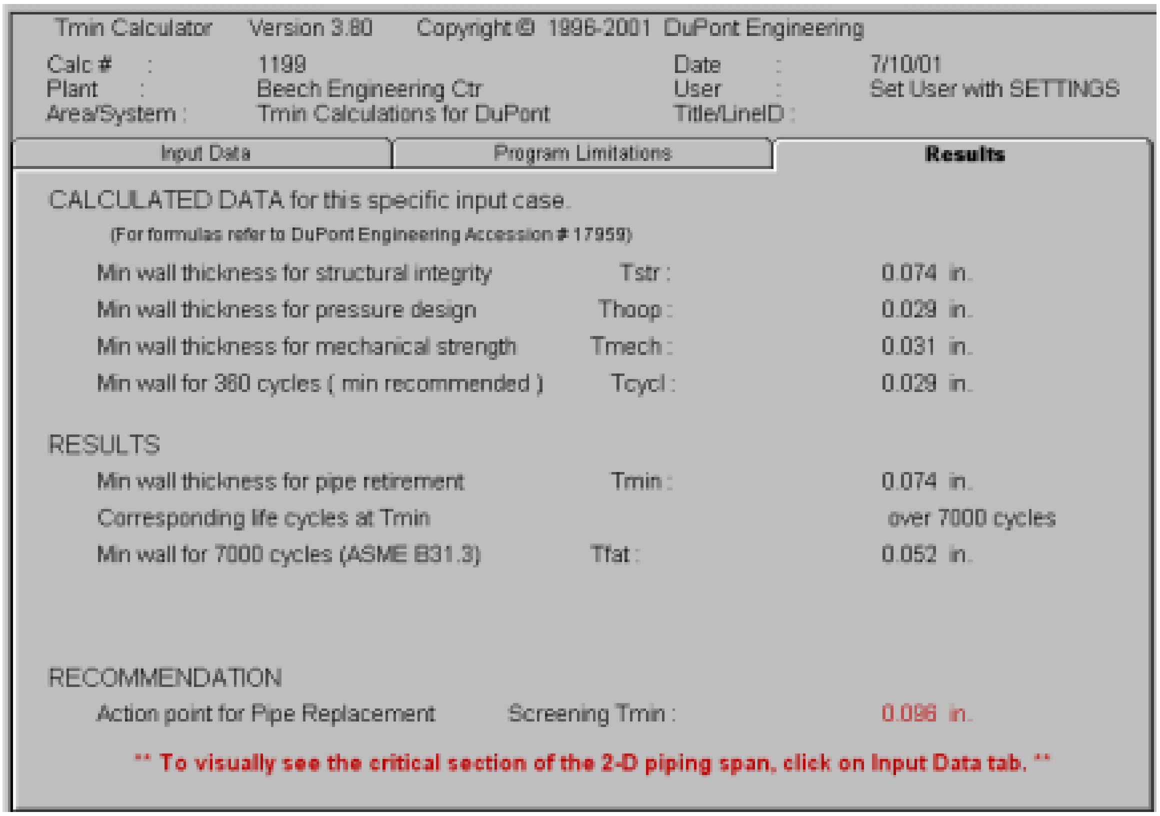

Figure 6-3. Example 1. Output tab for Final Pipe-Wall Thickness Values

At the bottom of this figure is a comment, “To visually see the critical section of the vertical piping span, click on the Input Data tab.” Figure 6-4 shows the Input tab results in which the highlighted critical piping section is seen in red. This is done to show the end user where to evaluate the pipe-wall thickness using testing machines. The next section will detail how shear may dominate the 2-D vertical piping span.

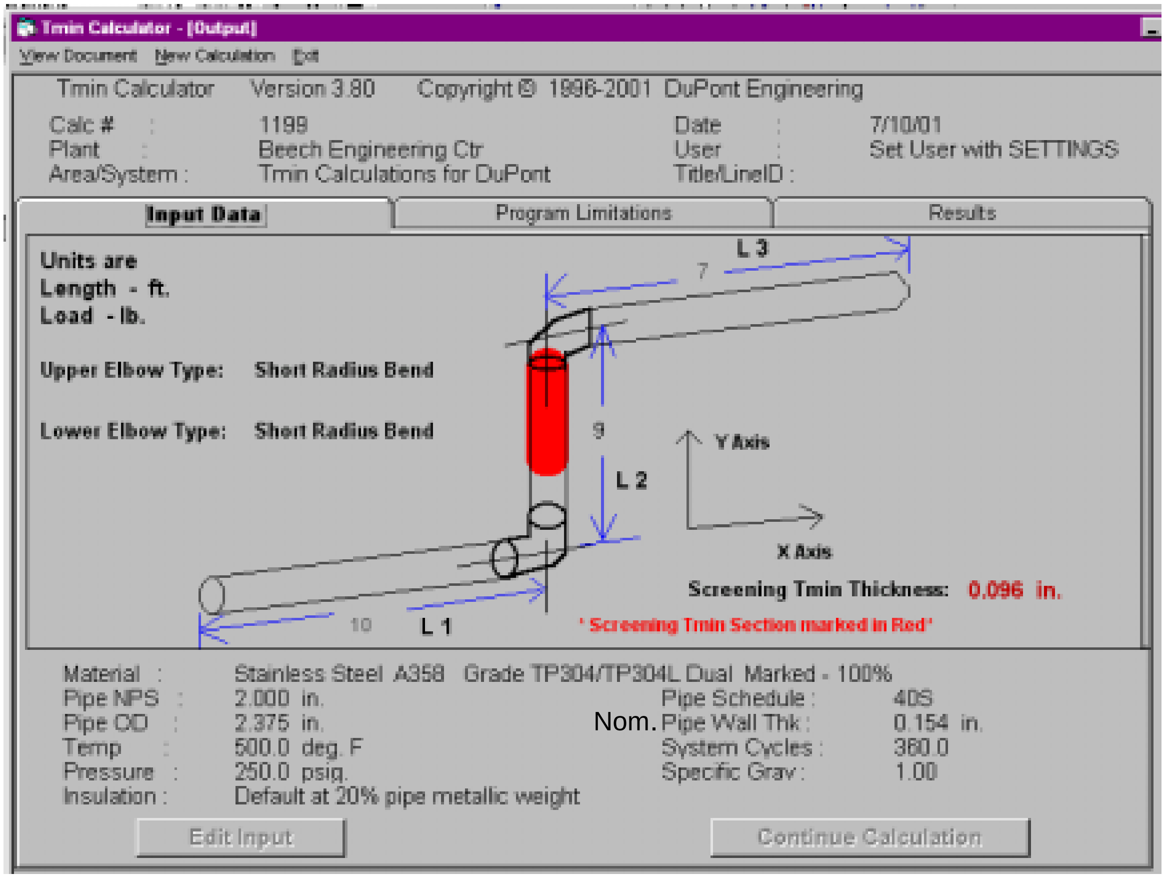

Figure 6-4. Example 1. Final Output Screen Showing Critical Piping Section

6.2 Second Piping Span Example—Shear Dominates

Figure 6-5 shows this test case. A short upper piping span will be used with a valve in the span. At the same time, a long lower piping span without a valve will be chosen. For this example, the elbows will be of the worst case, a *5D* bend, and is equivalent to a *SIF* value of 5.0 [11]. As discussed earlier the resultant *SIF* value will be passed through an *IF-THEN* statement will result in the new *SIF* value to be calculated. The new value calculated using a nominal pipe-wall thickness of 2 inches will result in the *SIF* = 20. The strength of carbon steel at a temperature of 500 degrees Fahrenheit that is used in this equation is 16,000 psi, the *Y* factor is 0.4, and the pressure is 300 psig.

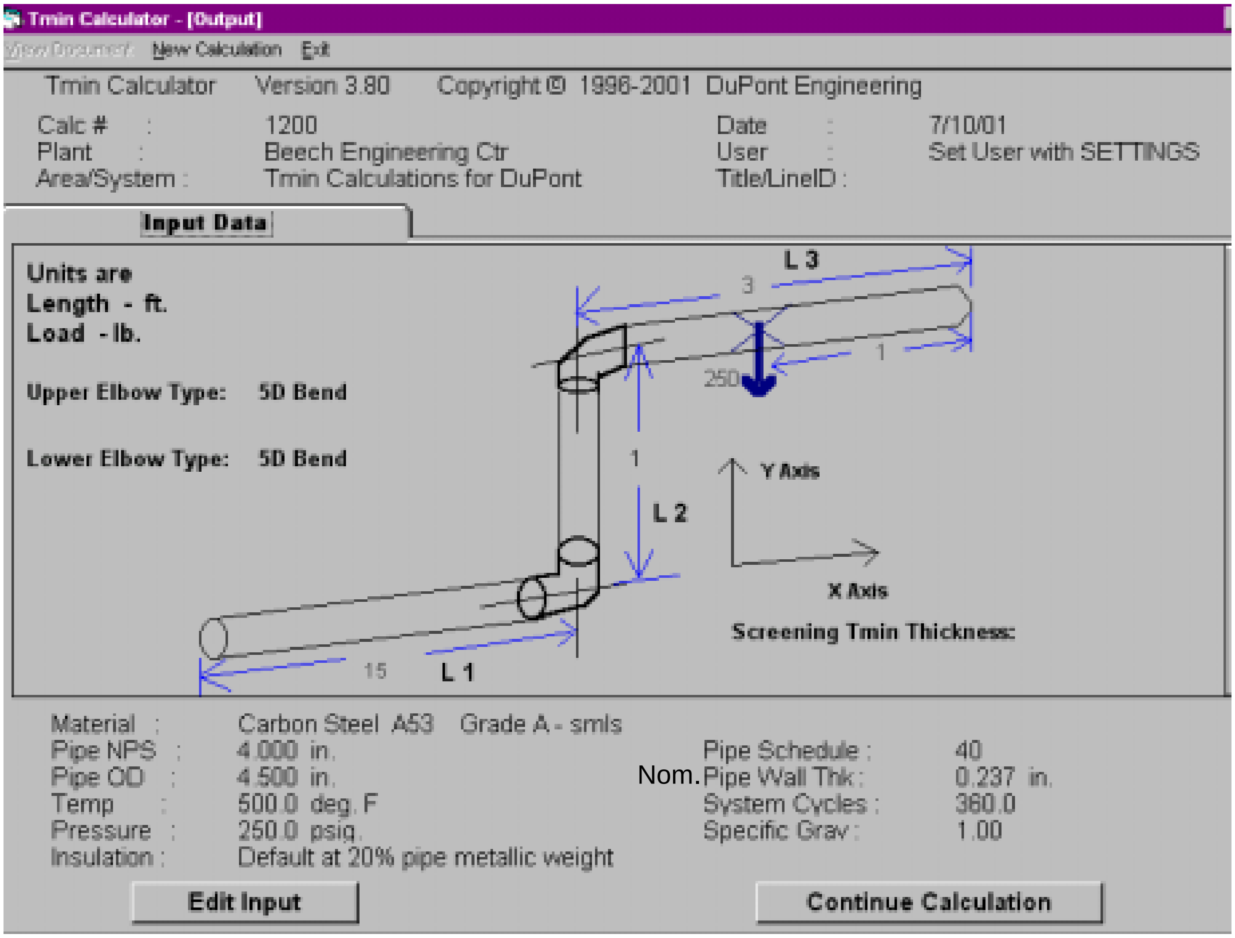

Figure 6-5. Example 2. Vertical Piping Span with Valve in Upper Span

From the piping material, schedule, insulation type, and outside diameter, the total weight per length (W_{Tot}) of the span including insulation and fluid loading can be calculated and is found to be 18.77 *lbs/foot*. In the following Table 6-3, the shear values for this case are shown. At the distance of 12.35 feet from the left end the shear is zero ($V=0$), the analysis of this section is discussed later in this section.

Table 6-3. Shear and Moment Values for Piping Example Two.

Distance Ft.	**Shear V**	**Shear Lbs.**	**Moment lb-ft**
0	V_1	231.81	0
12.35	V=0	0	17178.50
14.67	V_{eb}	-48.93	16478.66
15	V_2	-49.71	16301.37
15	V_3	-118.53	16301.37
15.33	V_{et}	-118.67	16124.08
17	V_4	-156.07	16005.69
17	V_5	-406.07	16005.69
18	V_6	-424.84	0

As seen in the table, the maximum moment occurs on the bottom-piping span because of the sign change between shear values. Because of this, one would assume that the lower span would be the dominating critical piping span. However, through analysis, it will be shown that large shear at the end of the upper-piping span generates the critical section. All of the calculation checks of pipe-wall thickness values obtained can be found in Appendix E.

Left-End Span Analysis:

The analysis will be done from left-to-right. The left end of the piping span will be checked first using Equation (6.2). Because of the complexity of this equation, the variables used for this piping section will be passed through the root solver. The resultant pipe-wall thickness value obtained for the left side of the 2-D vertical piping span is 6.82×10^{-2} inches. As stated earlier, the maximum moment is seen to occur in the lower span. Next the location of the maximum moment will be detailed.

Maximum Moment Location:

Through observation of the sign change in Table 6-3, it is seen that the moment occurs between the left end of the lower span and the vertical span. Figure 6-6 shows the point where the shear diagram crosses the x-axis and therefore, zero. To determine the location of the zero crossing, a simple slope equation can be used. The derivation for the distance can be seen in Equations (6-13) through (6-17) using Figure 6-5.

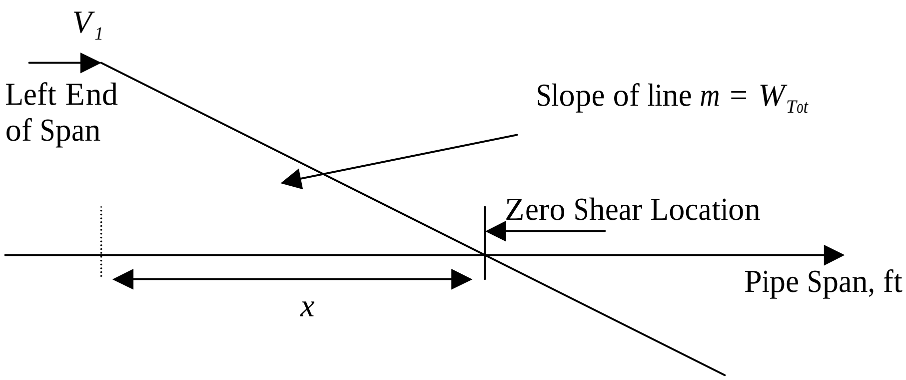

Figure 6-6. Close-Up of Zero Shear Crossing Point

$$y = mx + b \tag{6.13}$$

$$y = 0 \tag{6.14}$$

$$m = \text{Slope of line, } W_{Tot} \tag{6.15}$$

$$b = V_1 \tag{6.16}$$

$$x = \frac{V_1}{W_{Tot}} = 12.35\,\text{Feet} \tag{6.17}$$

The resulting crossing value is x = 12.35 feet from the left end of the lower span. Once this value is known, the program checks if the zero-shear location occurs in the elbow's length. If this occurs, the *SIF* value calculated for the elbow will be multiplied by the moment. Now that the crossing location, x, has been found, the pipe-wall thickness will be found by using Equation (6.6) in addition to Equation (6.7). For Equation (6.6) the pipe-wall thickness found was 6.84×10^{-2} inches. Next, using Equation (6.7), the pipe-wall thickness found from the root-solver was 3.40×10^{-2} inches. The pipe-wall thicknesses calculated by these equations at these locations will be compared and the largest is saved for later comparison against all other pipe-wall thickness values calculated. The next location is the connection at the elbow of the lower piping span.

Using Equation (6.3) the distance from the start of the span to the start of the elbow could be found. Once this length was found, the weight of the elbow was then found using Equation (6.4). Again, the elbows chosen were of a 5D design, and after passing through the *IF-THEN* statement described earlier, the final *SIF* value is 20.

The evaluations of the stresses observed at this location are identical to the previous section. Therefore, only Equations (6.6) and (6.7) will be used for pipe-wall thickness calculations. Equation (6.6) resulted in a pipe-wall thickness of 5.72x10-2 inches and for Equation (6.7) the thickness was 1.99x10-2 inches. The largest value obtained, from Equation (6.6), will be saved for later comparison of pipe-wall thickness values. The next section for evaluation is elbow connection of the lower piping span.

Elbow Connection at Bottom Span:

Using the same analysis for this piping section as detailed in the previous section the first equation is Equation (6.6). The second equation that was found was Equation (6.7). The pipe-wall thickness calculated through Equation (6.6) was 5.72×10^{-2} inches, while for Equation (6.7) it was 1.70×10^{-2} inches. As a result, the largest pipe-wall thickness calculated was from Equation (6.6). This value will be saved for later comparison to other pipe-wall thickness values in the 2-D vertical piping span. The next section for evaluation is the vertical piping span.

Vertical Pipe Span:

As seen in Table 6-3, at 12.35 feet the shear values changes. The different shear values indicate a step function in shear forces at the vertical span location. Upon evaluation of the differential stress elements on the vertical span, a compressive stress is observed. As stated in the previous section, the analysis of the vertical section will use Equations (6.6), (6.7), (6.11) and (6.12). First however, the compression values for the vertical span must be calculated. The compression values are as follows: C_1 = -71.41, C_2 = -109.15 lbs., C_3= -118.53 lbs. Table 6-4 shows the resultant pipe-wall thickness values after evaluation in the root-solver. In one are the pipe-wall thicknesses for the upper vertical section and in the second column the pipe-wall thickness value for the lower section of the vertical span.

Table 6-4. Comparison of Pipe-Wall Thickness Values for Vertical Pipe Span

	Pipe-Wall Thickness	
	Upper Vertical Span *Inches*	***Lower Vertical Span*** *Inches*
Equation (6.6)	5.72x10-2	5.72x10-2
Equation (6.7)	1.71x10-2	1.70x10-2
Equation (6.11)	2.69x10-2	2.71x10-2
Equation (6.12)	2.98x10-2	3.13x10-2

As seen in this table, Equation 6.6 resulted in the largest pipe-wall thickness value for the entire vertical span. Therefore, this pipe-wall thickness will be compared to the rest of the pipe-wall calculations in the rest of the 2-D vertical piping span. The next section to be evaluated is the elbow connection on the upper piping span.

Elbow Connection in Upper Piping Span:

Since analysis of this connection was detailed in the previous section gave Equations (6.6) and (6.7), they will be used again. The pipe-wall thickness found for Equation (6.6) was 5.72x10-2 inches, while for the second equation the pipe-wall thickness was 1.71x10-2 inches. The largest value obtained was from Equation (6.7) and will be saved for later comparison. The next location will be the valve location in the upper piping span.

Valve Location:

Looking at the differential stress element derivations in Chapter 4, it was found that Equations (6.6) and (6.7) (hoop, bending and longitudinal stresses) would be used for the valve location. Through the use of the root solver, it was found that the minimum pipe-wall thickness found was $1.98\text{x}10^{-2}$ inches for Equation (6.6). In addition, the thickness found through the use of the hoop stress was $5.72\text{x}10^{-2}$ inches. Once the pipe-wall thickness has been solved for through both equations, the larger of the two will be saved for later comparison. Moving to the right along the shear diagram from the vertical pipe span, the next location is the right-end of the upper piping span.

Right-End Span Analysis:

To begin the analysis of the right-end of the upper-piping span, Equation (6.2) will be used then passed through the root solver. The shear stress, τ_{xy}, in this case is equal to $2V_6/Area$, while the hoop and longitudinal stresses only require the pressure and outside pipe diameter. Using the outside diameter of 2.375 inches the program will then pass the data to the root solver. The resultant pipe-wall thickness value obtained for the right side of the span is $7.01\text{x}10^{-2}$ inches.

Upon analysis of this 2-D vertical piping span found that the largest pipe-wall thickness value was at the right-end of the upper piping span. What this means is that although the elbows had high *SIF* values, the end shear was the dominant factor in this 2-D vertical piping span. As a result, the *Tmin* program will display Figure 6-7 showing the minimum pipe-wall thickness found, as the minimum pipe-wall thickness need for structural integrity. As detailed in Chapter 2, the program then passes this value though a series of equations to find the largest possible pipe-wall thickness, which results in the "Screening Tmin" value.

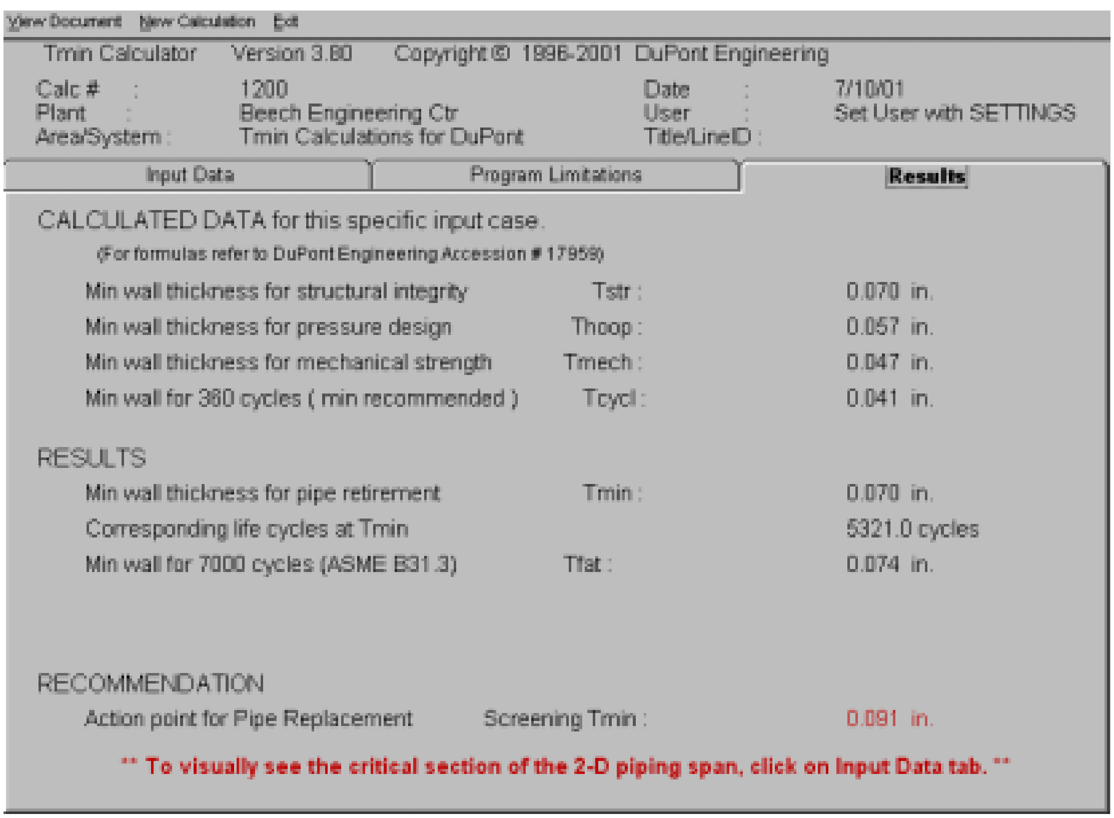

Figure 6-7. Second Example Output Tab for Final Pipe-Wall Thickness Values

As stated earlier, at the bottom of this figure is a comment, "To visually see the critical section of the vertical piping span, click on the Input Data tab." Upon clicking the Input tab results in the highlighted critical piping section seen in red seen in Figure 6-8.

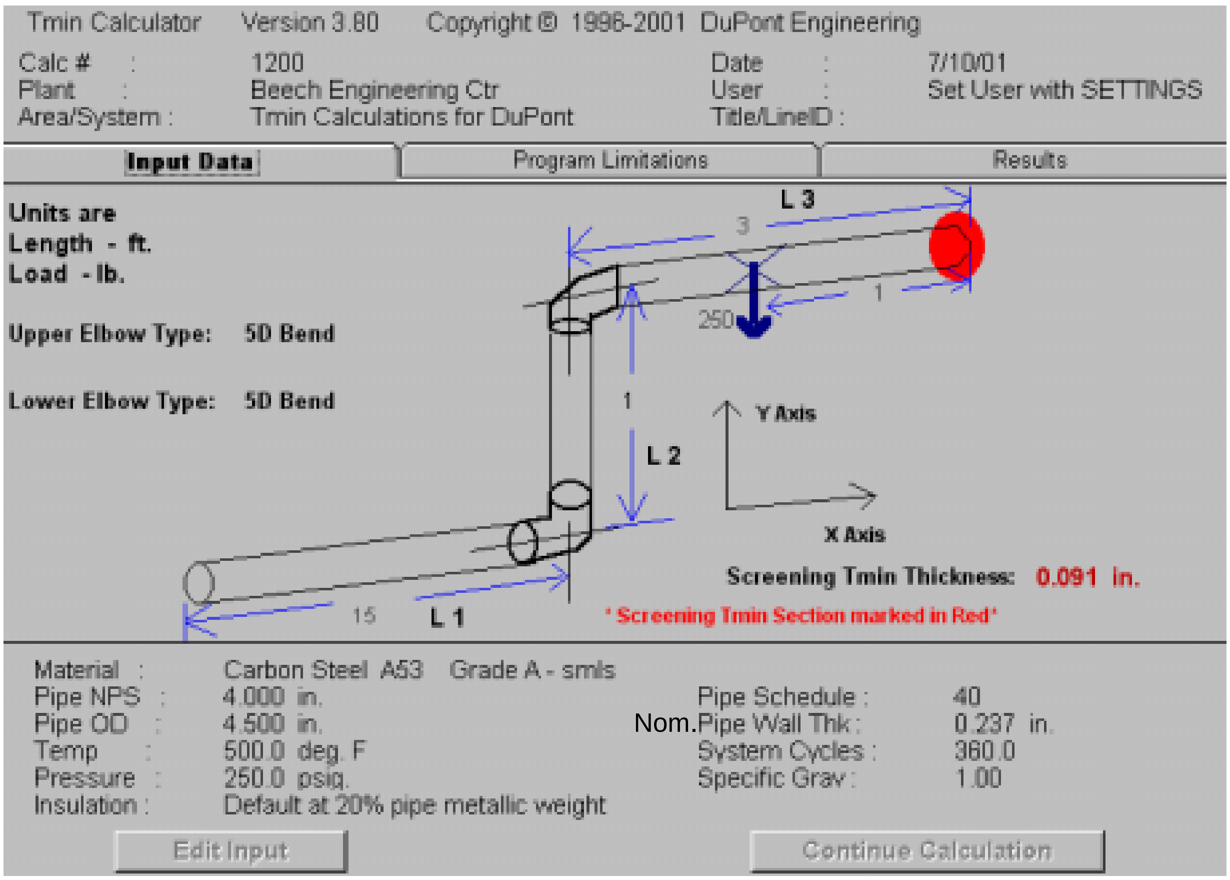

Figure 6-8. Second Example Output Screen for 2-D Vertical Piping Span Analysis

To verify that the additions made to Tmin did not affect the horizontal piping span calculations, several test cases were performed. These test cases were verified through comparison of the original code of *Tmin* 3.10 to the updated *Tmin* version. The values compared were the pipe-wall thickness values, all of which involved different pipe materials, pressures, temperatures, and horizontal piping span configurations.

Throughout this chapter, the differential stress elements detailed in Chapter 4 were instrumental in finding the critical section. Also, the root-solver solved the complex stress equations easily for pipe-wall thickness values. For a detailed analysis, the reader is encouraged to review Appendix A for other examples.