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ESTIMATION OF INSTABILITY FLAW LENGTHS FOR TANK 6 (U)

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1.0 SUMMARY

Instability flaw lengths were estimated for high level waste Tank 6 at its current fill height of 244 inches with an average specific gravity of 1.1.[1] The instability flaw lengths were obtained by interpolation of the results from previous stress and fracture analyses for Type I high level waste tanks. The instability flaw lengths under normal operation are 111 and 63 inches, respectively, at the mid-girth weld and the bottom girth weld. In the case of seismic loading, the instability flaw lengths are respectively 64 and 33 inches in those locations. If a flaw grew beyond the instability length, a rapid unzipping or rupture of the tank would be predicted. The expected maximum flaw length in Tank 6 is six inches and the actual lengths are most likely one to two inches. Therefore there is a margin of at least five on length against flaw instability for postulated flaws in the highest stress regions (bottom girth weld) in Tank 6.

2.0 INTRODUCTION

Several flaw leak sites have been recently found in high level waste Tank 6. To demonstrate the structural stability of the current Tank 6 configuration, instability flaw lengths were calculated in two strategic locations: the mid-girth and the bottom girth welds. If the instability flaw length under the current fill height (FH = 244 inches) with an average specific gravity (SG) of 1.1 for the waste content is greater than the actual flaw, the tank is structurally safe. This report documents the details of an engineering approach to estimate the instability flaw lengths using the results from previous stress and fracture analyses [1,2], and the lower bound fracture properties determined through mechanical testing [3,4].

Instability flaw lengths for Type I waste tanks at various stress levels have been previously reported [1]. In that report, the most accurate instability flaw length was directly obtained with J-integral analysis using the finite element method with actual stress-strain tensile data of the material (A285 Grade B carbon steel). Several approximate fracture methodologies, including the J-integral estimation scheme [5,6] and the failure assessment diagram (FAD) approach [7], were shown to render results close to the results from the finite element analysis, especially when the applied stress is less than one-half of the yield stress [1]. The instability flaw lengths for Tank 6 under its current fill height were estimated from the finite-element-based J-integral analysis, with the stresses calculated for Type I tank [2] scaled with respect to the specific gravity.

Both normal operation and seismic loading cases were considered in the previous stress analysis [2]. In the present flaw stability analysis, flaws were assumed to be located, separately, at the mid-girth (about 129 inches above the tank bottom) and the bottom girth welds (about 24 inches above the tank bottom). The load combination showed that

[1] Subsequent to the final draft of this report, the fill height in Tank 6 was reduced from 244 inches to 227 inches. Therefore, the instability lengths in this report are conservative with respect to the Tank 6 condition as of March 31, 2001. Figure 2 shows the relative effect of fill height on instability crack length.

the stress in the hoop direction dominates. Therefore, for a simplified but conservative estimation, the instability flaw length is obtained by placing an axial flaw in a cylindrical structure subjected to a internal pressure which yields a uniform hoop stress equivalent to the local stress calculated in Reference 2.

The lower bound fracture properties were selected from the test database of A285 Grade B carbon steels [3,4]. The results from fracture testing of A285 steel near the lower limits for tank operating temperature (70 °F) show that considerable stable crack growth occurs in the material [3,4]. This tearing capacity was taken into consideration in the case of the normal operating conditions. No credit for tearing capacity was taken for seismic (dynamic) loading of the material due to the limited availability of test data to date.

Section 3 of the report lists the steps in estimating the instability flaw lengths. The results are summarized in Section 4. A discussion of the results is provided in Section 5.

3.0 FLAW SIZE ESTIMATION SCHEME

The stress analysis, fracture property inputs, and fracture mechanics analysis are the three fundamental parts of a flaw stability analysis. The present flaw length estimation is based previous analyses and interpolation and/or extrapolation of the results must be used. The general procedure is

Step 1. Scale the stresses calculated in Reference 2 with respect to the current specific gravity of Tank 6 (SG = 1.1), for two fill height cases (268 and 204 inches) that bracket the current Tank 6 fill height (244 inches).

Step 2. Interpolate/extrapolate the instability flaw length at the two J-integral values used in Reference 1 (i.e., 3567 and 1093 in-lb/in^2, the fracture toughness test results for a specific heat of A285 steel at normal loading and seismic loading conditions, respectively) for the two fill heights selected in Step 1.

Step 3. Interpolate the instability flaw lengths with respect to the fill height to obtain the flaw length for fill height at 244 inches of the current Tank 6, at the two J-integral values in Reference 1.

Step 4. Interpolate the instability flaw lengths in Step 3 with respect to the desired J-integral values (i.e., 2638 in-lb/in^2 and 1093 in-lb/in^2, the lower bound toughness properties for normal loading and seismic loading conditions, respectively).

Section 3.1 describes the stress combination using the existing stress results [2]. The details of the instability flaw lengths estimation are presented in Section 3.2.

3.1 Stress Combination

The stress analysis for Type 1 waste tanks was previously issued for the following load cases[2]:

Load Case No.	Description
1	Steel Tank Dead Weight
2	Steel Tank Annulus Pressure (8” water gage)
3	Temperature Differential (Δt = 130 °F)
4	Hydrostatic Pressure Loads (FH = 276”, SG = 1.4)
5	Hydrostatic Pressure Loads (FH = 268”, SG = 1.5)
6	Hydrostatic Pressure Loads (FH = 204”, SG = 2.0)
7	Hydrostatic Pressure Loads (FH = 138”, SG = 2.0)
8	Hydrostatic Pressure Loads (FH = 69”, SG = 2.0)
9	Seismic and Hydrodynamic Pressure Loads (FH = 276”, SG = 1.4)
10	Seismic and Hydrodynamic Pressure Loads (FH = 268”, SG = 1.5)
11	Seismic and Hydrodynamic Pressure Loads (FH = 204”, SG = 2.0)
12	Seismic and Hydrodynamic Pressure Loads (FH = 138”, SG = 2.0)
13	Seismic and Hydrodynamic Pressure Loads (FH = 69”, SG = 2.0)

The Load Cases 5, 6,10, and 11 (live loads) were used in the instability flaw length estimation for Tank 6. These load cases bracket the current fill height (244 inches) so interpolation can be performed. The Load Cases 1, 2, and 3 (dead loads) were always added to the live loads. Note that in the case of Tank 6 current condition, the specific gravity of the waste content is 1.1. Assuming linearity, the live loads were scaled with respect to the specific gravity. For example, to obtain the normal operation stresses for a fill height at 268 inches with specific gravity 1.1, the results of the Load Case No. 5 will be multiplied by (1.1/1.5).

In the stress analysis [2], the finite element node numbers 37 and 51 coincide, respectively, with the mid-girth weld (about 129 inches above the tank bottom) and the bottom girth weld (about 24 inches above the tank bottom). The stresses at those two finite element nodes were selected for load combination.

Both the membrane (σ_m) and the bending stresses (σ_b) were reported [2]. The maximum tensile stress in the tank can be obtained by $\sigma_m + |\sigma_b|$. The results show that the stress in the hoop direction of the tank is much greater than that in the axial direction. Therefore, only the hoop stress acting on an axial crack was considered in the fracture analysis.

The stresses in the walls of the tank are position dependent. For the simplicity in the fracture analysis and conservatism in flaw size estimation, the <u>local</u> maximum tensile stress in the hoop direction was regarded as a <u>global</u> uniform hoop stress acting in the cylindrical body of the tank. It is equivalent to a Type 1 tank loaded with an internal pressure of $\frac{t}{R}\sigma$ [8], where σ is the hoop stress, t is the thickness of the tank wall (0.5 inches), and R is the average radius of the tank (450 inches).

The final hoop stresses scaled from the results in Reference 2 and used in the fracture analysis (Section 3.2) are listed in Table 1.

Table 1. Stress Levels at Mid-Girth and Bottom Girth Locations
(based on T-CLC-H-00483)

Fill Height (SG=1.1.)	Stress (Normal Operation)		Stress (Seismic Condition)	
	Mid-Girth	Bottom Girth	Mid-Girth	Bottom Girth
204 inch.	2.9 ksi	8.7 ksi	5.0 ksi	11.9 ksi
268 inch.	5.2 ksi	11.2 ksi	8.5 ksi	15.4 ksi

3.2 Instability Flaw Length

The steps in the estimation of the instability flaw lengths for Tank 6 are listed in Section 3.0. This section illustrates the specific process of obtaining the instability flaw length for Tank 6. One of the cases, the bottom girth weld with a lower bound material toughness of 2638 in-lb/in^2, is used as an example. The results are shown in Figures 1 to 3.

Table 2 contains the instability flaw lengths (for two J-integral values) calculated in Reference 1 with the finite element method using the actual stress-strain data for applied stress range from 6 to 24 ksi. Figure 1 is plotted with the data in Table 2, along with the interpolations for the bottom girth weld using the stresses for fill heights at 204 and 268 inches. Repeating this process for the other stress levels, the results are shown in Table 3.

Table 2. Instability Flaw Lengths at Various Stress Levels
(from WSRC-TR-2000-00478)

Applied Stress Level (ksi)	Instability Flaw Length (inch.)	
	J = 1093 in-lb/in^2	J = 3567 in-lb/in^2
6	71	114
12	38	57
18	25	37
24	17	24

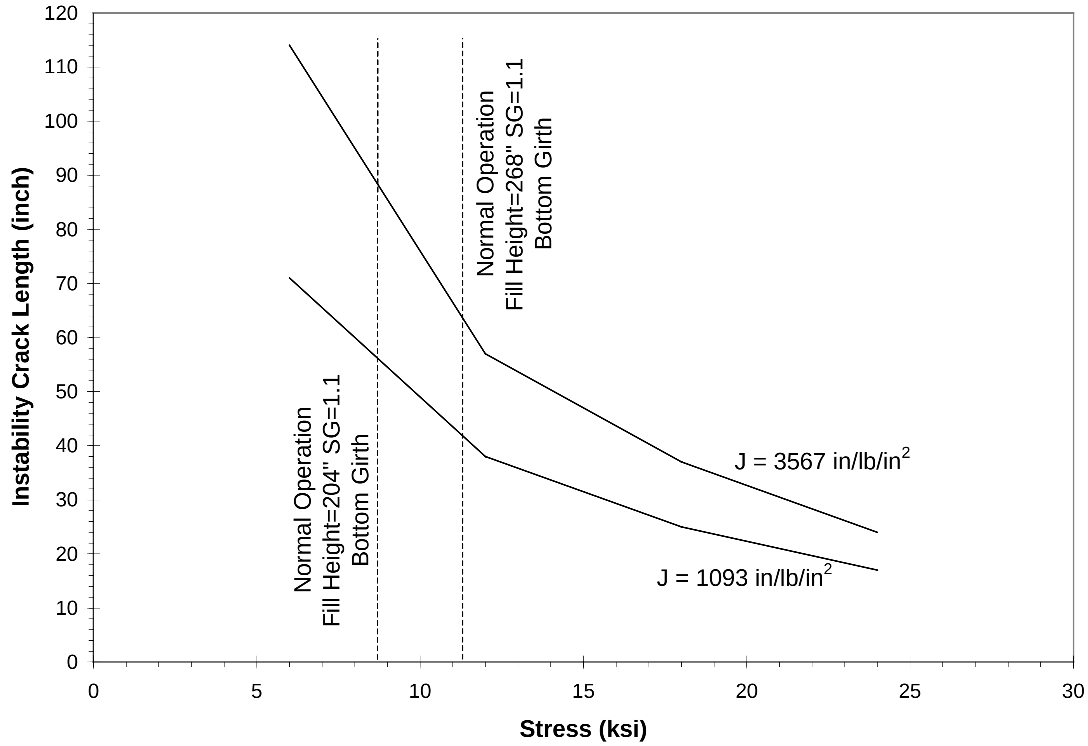

Figure 1. Instability Flaw Length vs. Applied Stress

Table 3. Interpolated Instability Flaw Lengths at Girth Weld Locations for Two Fill Heights Calculated in T-CLC-H-00483

		Instability Flaw Length (inch.)			
		Normal Operation		Seismic Condition	
Fill Height (SG=1.1)	J-integral (in-lb/in^2)	Mid-Girth	Bottom Girth	Mid-Girth	Bottom Girth
204 inch.	1093	88	56	76	39
	3567	143	89	123	58
268 inch.	1093	75	42	57	30
	3567	121	64	90	45

The data in Table 3 can be used to plot the instability flaw length versus fill height at two J-integral values (Fig.2). This allows interpolation with respect to the fill height. Therefore, the instability flaw lengths for the fill height at 244 inches can be obtained. The results can be seen in Table 4.

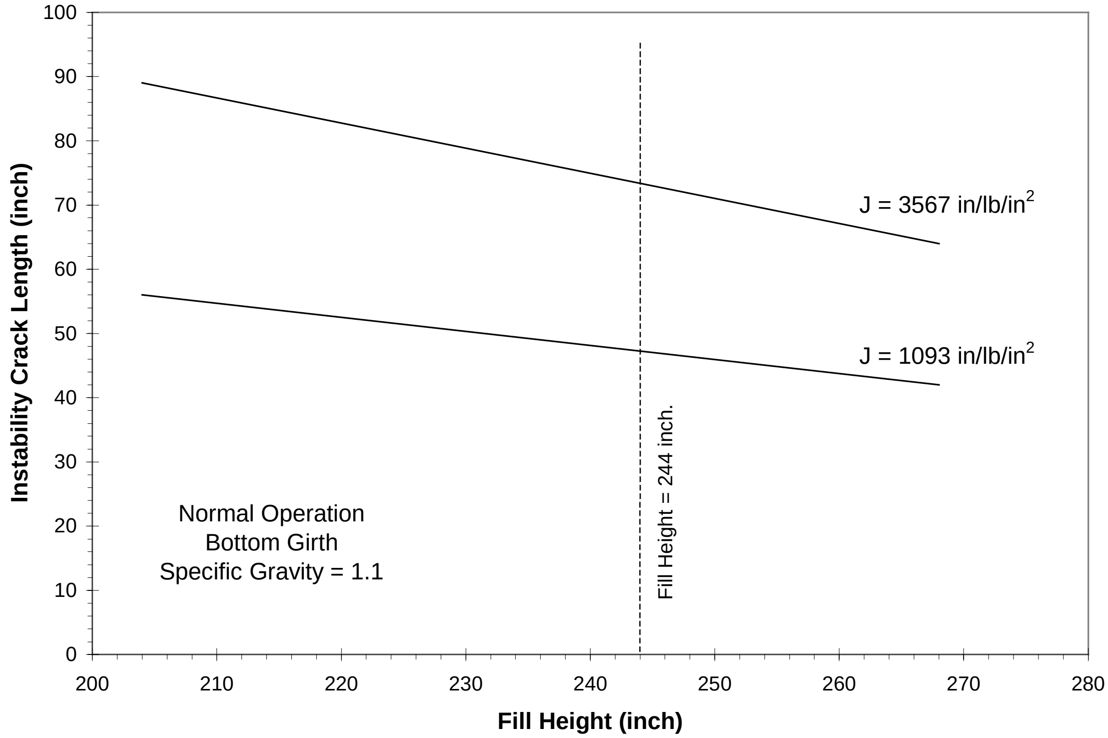

Figure 2. Instability Flaw Length vs. Fill Height at Two J-integral Levels for Stress at Bottom Girth Weld under Normal Operation and SG = 1.1

Table 4. Interpolated Instability Flaw Lengths for Current Tank 6 Loading at two J-integral Levels Calculated in WSRC-TR-2000-00478

	Instability Flaw Length (for Fill Height = 244 in. and SG = 1.1)			
	Normal Operation		Seismic Condition	
J-integral	Mid-Girth	Bottom Girth	Mid-Girth	Bottom Girth
1093 in-lb/in^2	80 inch.	47 inch.	64 inch.	33 inch.
3567 in-lb/in^2	129 inch.	73 inch.	102 inch.	50 inch.

The data in Table 4 allow the construction of Figure 3, which in this case, is for the bottom girth weld under normal operation. Figure 3 shows the instability flaw lengths in the bottom girth weld at two J-integral values used in Reference 1. For the present case of Tank 6, a lower bound J-integral value (2638 in-lb/in^2) [3] was used for normal operating condition. This lower bound J-integral (fracture toughness) was obtained by testing A285 carbon steel E400 heat L-T orientation specimens, and one-sided 90/90 tolerance interval minimum. The capability of the material in stable tearing has been taken into consideration. Figure 3 shows that the instability flaw length of 63 inches is determined.

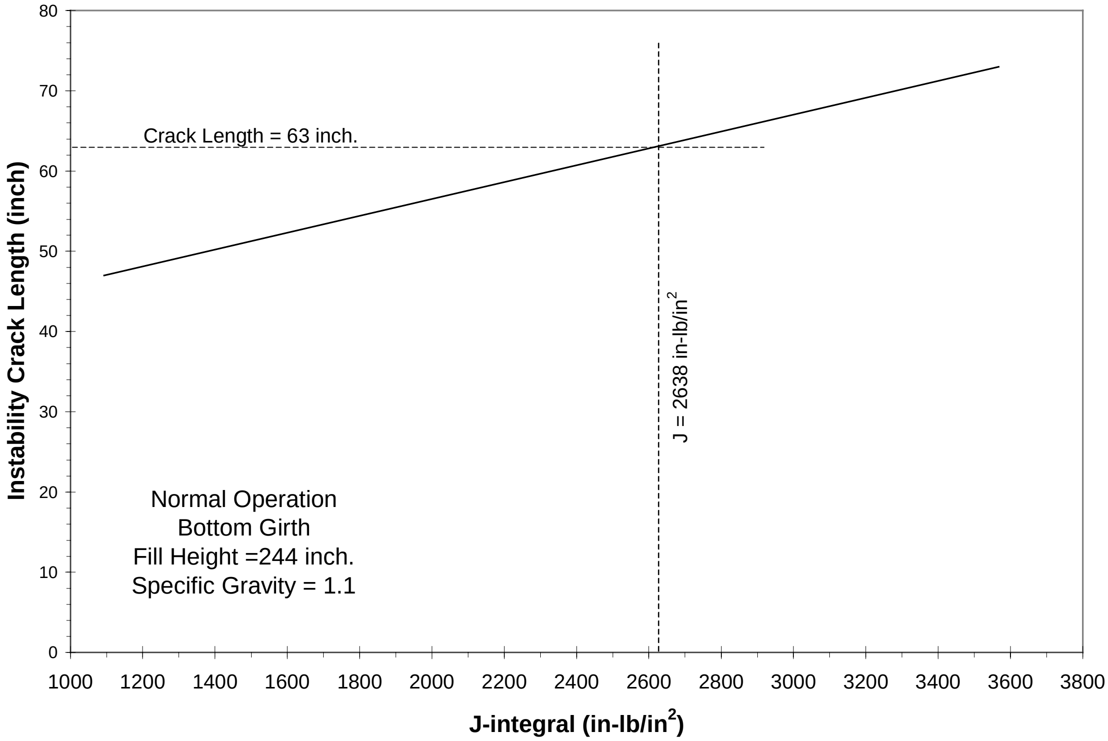

Figure 3. Instability Flaw Length vs. J-integral for Stress at Bottom Girth Weld under Normal Operation when Fill Height = 244 in. and SG = 1.1

A J-integral corresponding to crack initiation (1093 in-lb/in^2) is used in the seismic loading condition. Therefore, no interpolation on the J-integral results from the previous analysis is needed in this case. The instability flaw lengths at the mid-girth and bottom girth welds of Tank 6 with fill height at 244 inches and specific gravity 1.1 under normal operating and seismic loading conditions are summarized in Table 5.

Table 5. Instability Flaw Lengths for Current Tank 6 Loading at Lower Bound J-integral Levels

Instability Flaw Length (for Fill Height = 244 in. and SG = 1.1)			
Normal Operation J = 2638 in-lb/in^2		Seismic Condition J = 1093 in-lb/in^2	
Mid-Girth	Bottom Girth	Mid-Girth	Bottom Girth
111 inch.	63 inch.	64 inch.	33 inch.

4.0 RESULTS

Based on the normal operating loads [2] and a lower bound J-integral value of 2638 in-lb/in^2 (462 kJ/m^2) [3], the fracture analysis results [1] were used to estimate the instability flaw lengths. These instability flaw lengths are, respectively, 111 and 63 inches at the mid-girth weld (about 129 inches above the tank bottom) and the bottom girth weld (about 24 inches above the tank bottom). In the case of seismic loading condition, the lower bound J-integral was determined to be 1093 in-lb/in^2 (191 kJ/m^2) [4]. the resulting instability flaw sizes are 64 and 33 inches at the mid-girth weld and the bottom girth weld, respectively. The results are summarized in Table 5.

5.0 DISCUSSIONS AND REMARKS

Since the instability flaw lengths are long with respect to the tank sidewall, a check of the instability length results using a limit load method is performed. It should be noted that the high level waste tanks are mainly loaded with the hydrostatic pressure from the waste content. Under normal circumstances, the hoop stress due to the hydrostatic pressure varies linearly from zero at the top of the fill height to a maximum near the bottom weld location. It seems unlikely this type of loading would cause an entire section yielding, even a flaw is present. Nevertheless, the limit load solution for an axial throughwall flaw in a pressurized pipe can be calculated [9] according to an empirical formula which gives accurate predictions for the ductile pipe rupture tests:

$$\sigma_{\mathrm{lim}} = \sigma_{\mathrm{f}} / \mathrm{M}$$

where

$$M = (1 + 1.2987\,\lambda^2 - 0.026905\,\lambda^4 + 5.3549\mathrm{x}10^{-4}\,\lambda^6)^{0.5}$$

$$\lambda = c/(Rt)^{0.5}$$

σ_{lim} is the hoop stress corresponding to the limit pressure, σ_f is a reference flow stress and is taken as the average of the material yield (36.1 ksi) and ultimate stresses (60.2 ksi), and c is the half crack length. It can be shown that, for the longest flaw lengths (at the mid-girth weld) are 111 (normal operation) and 64 (seismic loading) inches, the limit hoop stresses (σ_{lim}) are, respectively, 12 and 19 ksi. From Table 1, it can be seen these limit stresses are higher than the maximum local stresses at the bottom girth weld, respectively for the normal operating and seismic loading conditions when Tank 6 is filled to 268 inches (current fill height is 244 inches). In other words, even the longest flaw (111 inches for normal condition or 64 inches for the seismic loading) is subject to an internal pressure that could have rendered a hoop stress that is equal to the high local stress at the bottom girth weld, the plastic collapse of the tank would not occur. In fact, the limit load calculation for the seismic case is unnecessary, since the seismic loading is not a sustained load and the plasticity could not be developed over the entire uncracked ligament of the waste tank during the short transient.

The use of J-integral value at crack initiation (J_{IC}), 1093 in-lb/in^2, in the seismic loading case implies that the cleavage fracture would be possible in the fast loading case. Reference 8 also provides a stress intensity factor (K_I) solution for an axial throughwall crack:

$$K_I = \sigma_h (\pi c)^{0.5} F$$

where

$$F = 1 + 7.2449 \times 10^{-2} \lambda + 0.64856 \lambda^2 - 0.2327 \lambda^3 + 3.8154 \times 10^{-2} \lambda^4 - 2.3487\times10^{-3} \lambda^5$$

and σ_h is the hoop stress generated by an internal pressure. By converting J_{IC} to K_{IC} (plane strain fracture toughness) and substituting K_I in the above equation, the instability flaw length can be solved with a given σ_h which has been listed in Table 1. Following the similar interpolation scheme, the instability flaw lengths for the current Tank 6 fill height (244 inches) and specific gravity (1.1) under seismic loading condition are 69 and 38 inches, respectively at the mid-girth and bottom girth welds. These flaw lengths are bounded by those tabulated in Table 5. Therefore, it can be concluded that, under the present condition, Tank 6 will not fail if the flaw length in the mid-girth weld and the bottom girth weld, respectively, does not exceed 111 and 63 inches for normal operation. Under the seismic loading condition, the instability flaw length would be reduced to 64 and 33 inches, respectively, for the mid-girth weld and the bottom girth weld.

The residual stress near the weld and in the heat affected zone was not considered in this analysis, since the lengths are long with respect to the extent of the residual stress region [10].

The maximum allowable fill heights for Type 1 tanks is 276 inches [11]. The stresses for specific gravity 1.4 in Reference 1 can be used directly to estimate the instability flaw lengths using the fracture analysis results in Reference 1. Following the same procedure described in Sections 3.0 to 3.2, the instability flaw lengths can be obtained for a Type 1 tank with maximum allowable fill height (276 inches) and an averaged specific gravity of 1.4. The results are shown in Table 6:

Table 6. Instability Flaw Lengths for Type 1 Tanks at Maximum Allowable Fill Height

Instability Flaw Length (for Fill Height = 276 in. and SG = 1.4)			
Normal Operation $J = 2638$ in-lb/in^2		Seismic Condition $J = 1093$ in-lb/in^2	
Mid-Girth	Bottom Girth	Mid-Girth	Bottom Girth
61 inch.	40 inch.	42 inch.	22 inch.

Table 6 shows that the instability flaw lengths remain long for Type 1 tanks even at the maximum allowable fill height.

It is expected that the throughwall length of the flaws caused by stress corrosion cracking (SCC) be bounded by six inches [12]. Based on the size of the salt deposits on the walls of Tank 6, the actual flaw lengths were estimated to be at most one to two inches [12].

Therefore, a margin against flaw instability causing structural failure of at least a factor of five (or 33” instability length for the seismic condition at lower girth weld ÷ 6” maximum flaw size from SCC at girth weld) exists for bounding location in Tank 6.

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