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REMAINING LIFE OF CONTAINMENT VESSELS FOR REPEATED EXPLOSIVE TESTING

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ABSTRACT

A methodology is developed for determining the remaining life of an 8-ft inside diameter (ID) spherical high explosive (HE) containment vessel. The methodology is based upon fatigue crack growth, and specifies the maximum number of HE tests that can be performed without any cracks growing to their critical crack size. An upper bound on crack growth for a single explosive test is determined in closed form by integrating the Paris Law assuming an infinite number of damped vibrations of the vessel with exponentially decreasing amplitude. The procedure is then to use this expression as a recursion relationship one test at a time, determining the new crack size and comparing it to the critical flaw size until the critical flaw size is reached, indicating the number of vessel tests permitted. Results are presented for a variety of initial postulated cracks in the parent vessel material. This method is also used for weld evaluation but is not reported in this paper.

INTRODUCTION

Cylindrical and spherical pressure vessels are used to contain the effects of high explosions. In some cases, the vessel is designed for one-time use only, efficiently utilizing the significant plastic energy absorption capability of ductile vessel materials [1]. Alternatively, the vessel can be designed for multiple use, in which case the material response is restricted to the elastic range [2]. For this multiple-use category, fatigue is a design consideration. The question arises as to the number of explosive tests that can be safely performed without vessel failure due to excessive fatigue crack growth [3]. Each explosive test results in repeated cycling of the vessel at progressively diminishing amplitudes as the vibrational response damps out.

A possible general approach to the fatigue analysis might involve using an S-N Curve for the material along with a method such as Miner’s Rule for combining cycles at different amplitudes. Unfortunately, however, the nature of the continuously diminishing amplitudes of vibration during a given explosive test makes Miner’s Rule difficult to apply. As a result, an alternate procedure, based on integration of the Paris Law for fatigue crack growth, was developed. By integrating the Paris Law for a given explosive test, assuming an infinite number of damped vibrations of the vessel, an upper bound on crack growth ***for that single explosive test*** is determined in closed form. The procedure is then to use this expression as a recursion relationship one test at a time, determining the new crack size and comparing it to the critical flaw size until the critical flaw size is reached, indicating the number of vessel tests permitted.

The procedure is illustrated for a 8-ft I.D. (2.4-m.) diameter HSLA-100 steel spherical vessel using a postulated initial partial through-wall crack. Results are also presented for three other initial postulated flaws, and the total number of explosive tests the vessel is capable of withstanding before fatigue failure is presented for each of the flaws.

The containment vessel is shown in Fig. 1, and consists of a minimum 2.5-in wall thickness HSLA-100 spherical shell with five ports. It is subjected to the transient pressure loading for a quantity of High Explosive, up to a maximum charge size of 62 lbs. equivalent TNT.

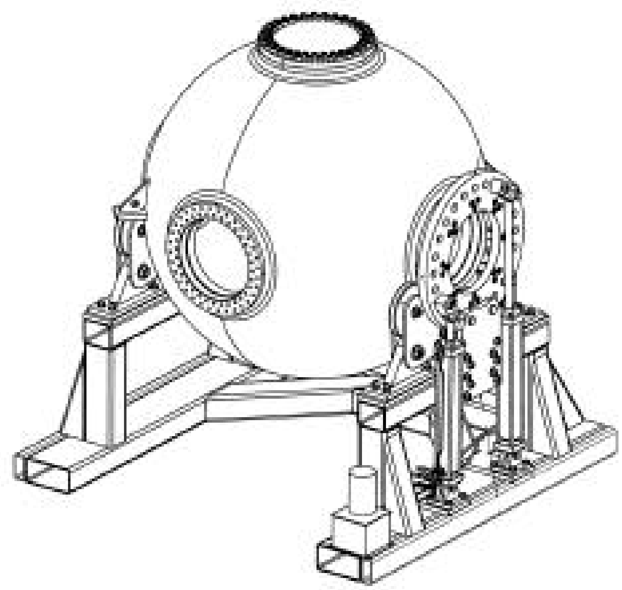

Figure 1 – LANL 8-ft. (2.4-m) confinement vessel.

Possible approaches to determining the remaining life of the vessel are addressed in Section 2. Implementation of the selected approach is developed in Section 3. The postulated partial through-wall crack is then investigated using the procedures developed in Section 4. Results (only) for three other postulated cracks investigated in this study are briefly discussed in Section 5. Results and Conclusions are presented in Section 6. Results indicate that the 8-ft. Containment Vessel can withstand greater than 20 high-explosive tests, at the maximum rated charge for the vessel, without failure by fatigue crack growth of initially acceptable flaws.

2. POSSIBLE APPROACHES

There appear to be two possible general approaches to the fatigue analysis and life prediction of the vessel. The first could be termed the S-N Curve approach (i.e., stress-cycles). In that case, vessel fatigue life is estimated using an S-N curve of the material, along with a method such as Miner's rule for combining cycles at different amplitudes. A total number of N cycles (at decreasing amplitudes) occur due to vessel vibrations during each explosive test. If M tests are performed, the total number of cycles over the life of the vessel at each amplitude is then known. Using the S-N curve and Miner's Rule, and incorporating a suitable factor of safety, results in a conservative life prediction for the vessel. The implication is that cracks nucleate and grow during the cyclic life of the material. A drawback is that with ultrasonic examination (UT) there is the possibility of an initial rogue crack present in the material just under the non-destructive evaluation (NDE) detectable depth, resulting in premature failure. A second drawback is that during NDE there could be a detected crack that meets the American Welding Society standard (AWS D1.1-92) acceptance criterion for the vessel (1/16 in. deep by 1.5 in. long). As the detected crack has effectively nucleated and grown to an extent before cycling of the vessel occurs, this would invalidate the S-N curve approach.

An alternate Fracture Mechanics approach for the determination of remaining life of a Containment Vessel is to integrate HSLA steel material data for crack extension as a function of alternating stress. One advantage of this method is that a crack flaw depth can conservatively be assumed, either at the lower limit of the NDE crack detection technology to be applied for the vessel inspection, or at the maximum crack size specified in the AWS D.1.-92-based vessel acceptance criterion (as used here). An additional advantage is that such da/dN vs. ΔK data are readily available for HSLA 100 steel. Further, Linear Elastic Fracture Mechanics (LEFM) approach is inherently conservative, and we further assume that the vessel is being operated near the transition temperature region. Vessel operation is actually well above this region in the elastic-plastic portion of the fracture toughness curve. Thus, fatigue life is underpredicted.

The purpose of this paper is to develop and demonstrate a fatigue-crack-growth assessment method that incorporates the decaying nature of the peak stress response for confinement vessels. API-579 (Recommended Practice for Fitness-For-Service) is not applicable to the present investigation primarily because of the nature of the impulsive pressure loading applied to the vessel. Therefore, the Failure Assessment Diagram (FAD) approach in API-579 has not been applied here.

3. IMPLEMENTATION OF THE APPROACH

The Fracture Mechanics approach is described in its simplest form in [4]. Data on the growth of a fatigue crack is fitted to the Paris law of the form

$$\frac{da}{dn} = C_1(\Delta K_I)^m \tag{1}$$

where a is the crack depth, n = Number of cycles, C_1 and m are fatigue crack growth material constants for HSLA-100, and typically the stress intensity factor range is

$$\Delta K_I = C_2 \sigma_r (\pi a)^{1/2} \tag{2}$$

where, σ_r is the stress range, and C_2 is a parameter associated with the specific crack geometry. Equation (1) becomes

$$\frac{da}{dn} = C_1\left[C_2 \sigma_r (\pi a)^{1/2}\right]^m \tag{3}$$

Separating variables and integrating, the growth of a known flaw of initial size a_o for N vibration cycles is given by

$$\int_{a_o}^{a_f} \frac{da}{a^{m/2}} = C_1 C_2^m \pi^{m/2} \int_0^N \sigma_r^m dn \tag{4}$$

where a_f = the final flaw size after N vibration cycles. It is assumed in Eqn. (4) that the crack geometry parameter, C_2, is a constant and does not change with crack growth. Variation of C_2 with crack depth are incorporated later in this paper as the postulated flaws are individually addressed.

First consider a single explosive vessel test. The vessel, following initial impulsive loading, undergoes vibrations in a variety of modes. The vibrations result in the opening and closing of the flaw, with corresponding crack growth following Eqn. (3). These vibrations damp out with time. It is assumed here that any negative stresses, leading to crack closing, do not cause crack extension. Therefore, only the positive stress range is taken as causing crack extension.

The design of the 8-ft. Containment Vessel is based upon in-plane vessel stresses through the thickness reaching, at most, the yield stress of the HSLA-100 material. Therefore, the peak stress at most reaches the yield stress, σ_o, i.e., the maximum stress range is $\sigma_r = \sigma_o$. The vibrational response of the vessel is extremely complex. However, due to various damping mechanisms, the vessel eventually ceases vibrating. Assuming viscous damping of the structural vibrations, and applying the logarithmic decrement [5] concept, the stress range, σ_r, is taken as the following:

$$\sigma_r = \sigma_o e^{-n\delta} \tag{5}$$

where δ is the logarithmic decrement. Combining Eqns. (4) and (5) results in

$$\int_{a_0}^{a_f} \frac{da}{a^{m/2}} = C_1 C_2^m \pi^{m/2} \sigma_o^m \int_o^\infty e^{-n\delta m} dn \qquad (6)$$

where the number of vibration cycles, N, has been replaced by ∞, at which point all vibrations have ceased for that particular explosive test. This is particularly convenient, as no assumption need be made as to the cycle number at which vibrations cease, nor at what cycle number the stress drops below the crack growth threshold. Use of an infinite number of vibration cycles for a given HE test is also conservative, as crack growth is assumed on every cycle, even for low cyclic stresses later in time. In reality, when the stress drops below the crack growth threshold, no further fatigue crack growth occurs.

Performing the integration, and evaluating the limits of integration, results in the following expression for the final crack depth for a given containment vessel test (using the maximum rated charge) in terms of the initial crack depth, material, and geometric constants:

$$a_f = a_o \left[1 + a_0^{\frac{m}{2}-1} \left(1 - \frac{m}{2}\right) \frac{C_1 C_2^m \pi^{m/2} \sigma_o^m}{m\delta} \right]^{\frac{2}{2-m}} \qquad (7)$$

The initial crack size for the first test would be the maximum crack size permitted by the acceptance criterion. The same Equation applies for subsequent tests, where a_o is equal to a_f from the previous test. Therefore, the procedure is to evaluate Eqn. (7) as a recurrence relationship one test at a time, determining the new crack size and comparing it to the critical flaw size, in the following sequence:

During vessel test No. 1, the initial crack size, a_o, extends to a_1:

$$a_1 = a_o \left[1 + a_0^{\frac{m}{2}-1} \left(1 - \frac{m}{2}\right) \frac{C_1 C_2^m \pi^{m/2} \sigma_o^m}{m\delta} \right]^{\frac{2}{2-m}} \qquad (8)$$

During vessel test No. 2, the crack size following test No. 1 extends to, a_2:

$$a_2 = a_1 \left[1 + a_1^{\frac{m}{2}-1} \left(1 - \frac{m}{2}\right) \frac{C_1 C_2^m \pi^{m/2} \sigma_o^m}{m\delta} \right]^{\frac{2}{2-m}} \qquad (9)$$

On the i+1st test, the crack size at the end of the ith test extends to a_{i+1}:

$$a_{i+1} = a_i \left[1 + a_i^{\frac{m}{2}-1} \left(1 - \frac{m}{2}\right) \frac{C_1 C_2^m \pi^{m/2} \sigma_o^m}{m\delta} \right]^{\frac{2}{2-m}} \qquad (10)$$

Crack growth during a given HE test is relatively small, permitting use of a constant value of the geometry parameter, C_2. This geometry parameter, which is typically a function of relative crack depth for a variety of crack geometries, is then updated, i.e., new values of C_2 are used in Eqn. (9), (10), etc., as described below. The above recurrence process is repeated until the critical flaw size is reached, as determined individually for the various flaws in the confinement vessel and the nozzle postulated in this study. Parameters required for evaluation of Eqn. (10) are presented next.

3.1 Logarithmic Decrement (Delta)

It is assumed that successive peak stresses monotonically decay in an exponential manner. The positive peak stresses are assumed of the form,

$$\sigma_n = \sigma_o e^{-n\delta} \qquad (11)$$

where n denotes the number of the oscillation cycle, and δ is the logarithmic decrement. A recent experiment was performed on an explosively loaded 6-ft. diameter vessel of similar design and materials to the present 8-ft Containment Vessel. Strain-time histories were recorded at various locations on the vessel. A typical surface strain-time history is shown in Fig. 2. Equation (11) is also fitted to the positive peaks of the strain-time history in Fig. 2. The fit results in a logarithmic decrement, δ, of 0.07. It is assumed that this value would be representative of damping in the 8-ft Containment Vessel due to similarities in material and design.

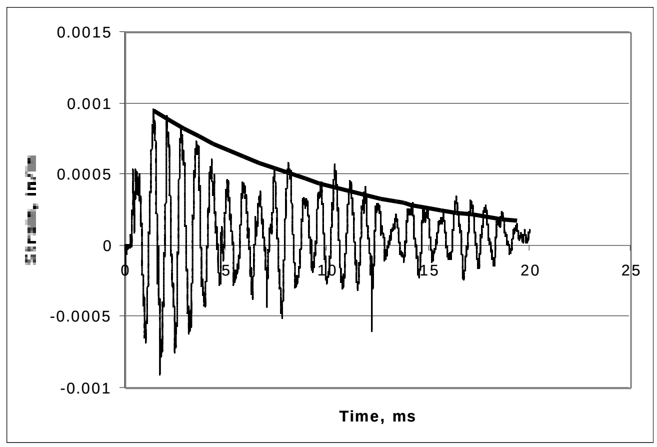

Figure 2. Determination of logarithmic decrement from vessel strain-time test data.

3.2 Constants C_1 and m for Paris Law -

Fatigue crack growth rate data are available from David Taylor Research Center (now called Naval Surface Warfare Center) for 1.5 in. thick HSLA-100 plate [6]. Figure 3 contains da/dN data and a Paris Law fit for the longitudinal (i.e., plate rolling) direction. Paris Law constants adopted for this study are therefore $C_1 = 1.56X10^{-9}$ and $m = 2.48$.

4. POSTULATED VESSEL FLAW NO. 1: PARTIAL THROUGH-WALL CRACK

The first flaw investigated is a 'Partial Through-Wall Crack' in the spherical vessel. The flaw is modeled as an edge crack existing partway through the spherical vessel wall. The vessel wall is modeled as a plate, as shown in Fig. 4, subjected to uniform tensile stress, σ. In this interpretation, b is the vessel wall thickness, and the crack grows in the through-wall direction. The double curvature of the spherical shell and the fact that the plate, shown in Fig. 4, is effectively wrapped into a spherical shape connected at left and right edges, both assure constraint against bending for the model in Fig. 4. The stress intensity for this crack configuration, as shown in Fig. 5, is a function of crack depth, i.e., a/b ratio [4]. In this very conservative model, the part through-wall crack extends in width over the entire circumference of the spherical vessel.

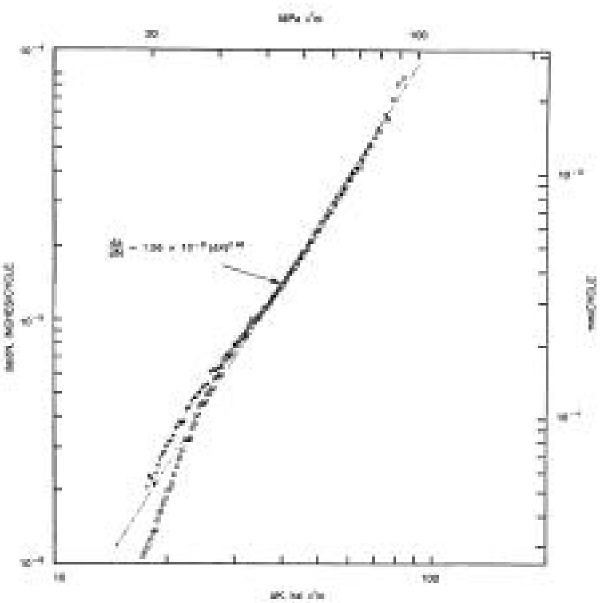

Figure 3. Fatigue crack growth data for HSLA-100 steel in rolling direction [6]

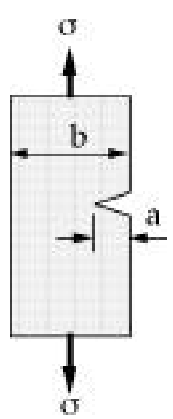

Figure 4. Partial through-wall crack in spherical vessel wall.

For small cracks, i.e., $a/b = 0$, the intercept in Fig. 5 is the classic value of C_2 = 1.12 for a single-edge-notched specimen [7]. Further, it is seen that a value, C_2, of 2.0 would provide an upper bound for the stress intensity factor, ΔK in Eqn. (2). This value of C_2 would be applicable to a crack that had grown almost entirely through the vessel wall. A more refined approach would be to update the value of C_2 following each iteration, i.e., each application of Eqn. (10). That is, the value of C_2 would be modified to account for the new crack depth following the vessel oscillations occurring in each high explosive test. A fit to C_2 along with a determination of critical crack size is presented in the following subsection.

4.1 Critical Crack Size, a_{cr} -

The critical flaw size is determined by setting the stress-intensity-factor range to the critical stress intensity factor for the HSLA-100 material, K_{Ic},

$$K_{Ic} = C_2 \sigma_r (\pi a_{cr})^{1/2} \qquad (12)$$

where as noted above, C_2 shown in Fig. 5 as solid black diamonds [4], is a function of crack depth and hence a_{cr}. The critical crack depth is then

$$a_{cr} = \frac{1}{\pi}\left[\frac{K_{Ic}}{C_2 \sigma_r}\right]^2 \qquad (13)$$

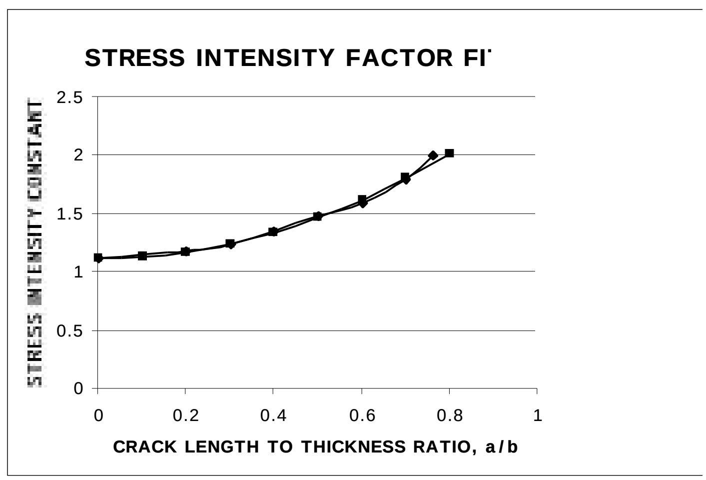

Figure 5 – Stress intensity factor fit to quadratic function.

A quadratic fit to the curve for the stress intensity constant is also shown in Fig. (5) (i.e., solid black squares) and presented for values of C_2 approaching an a/b ratio of 0.76 (corresponding to a value of C_2 of 2.0). The form of C_2 is taken from Barsom & Rolfe [7];

$$C_2 = 1.12 + 1.4\left(\frac{a}{b}\right)^2 \tag{14}$$

This is considered a good fit below an a/b ratio of 0.7. Equation (14) is combined with Eqn. (13) resulting in the following transcendental equation for critical crack size:

$$a_{cr} = \frac{1}{\pi}\left[\frac{K_{Ic}}{\sigma_r\left(1.12 + 1.4\left(\frac{a_{cr}}{b}\right)^2\right)}\right]^2 \tag{15}$$

Equation (15) was solved iteratively for the critical crack depth, using actual lower-bound K_{Ic} test data for HSLA-100 [6], a very conservative far-field alternating stress equal to half the dynamic yield strength of the material, and the vessel thickness:

$$K_{Ic} = 265\ ksi\sqrt{in}$$
$$\sigma_r = 100\ ksi$$
$$b = 2.5\text{ in.}$$

The resulting critical crack depth is a_{cr} = 1.13 inch, which corresponds to a full circumferential crack slightly less than halfway through the thickness of the 2.5-in. vessel wall.

4.2 Crack Growth Determination -

Two possibilities were investigated using the recurrence process described in Eqns. (8)-(10), the quadratic fit for C_2 in Eqn. (14), and the critical crack depth developed in the previous section: First, an initial 1/16 in. partial through-wall crack was assumed, and the recurrence process was continued until the critical flaw size was reached. Again, this initial crack size was selected for investigation because it is the maximum acceptable crack size for a new vessel per AWS D1.1-92. Resulting crack growth, up to the first 200 HE vessel tests, is shown in Fig. 6, where it is seen that the crack size only increases to above 0.1 in., well below the critical flaw size. A total of 840 HE tests would be required for the crack to grow to its critical length of 1.13 in.

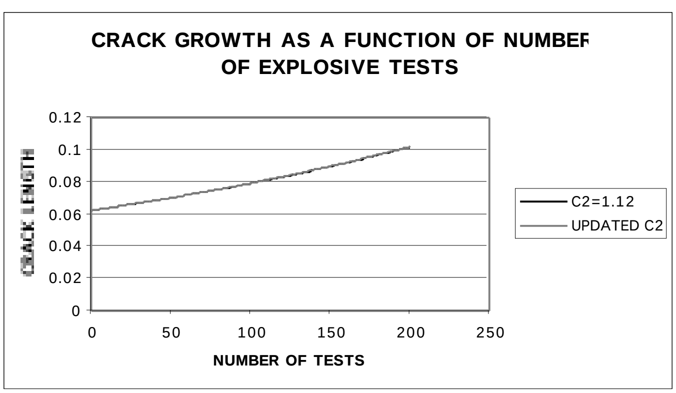

Figure 6 – Crack growth as a function of number of HE tests based on 1/16-in. flaw.

The second possibility is a crack induced from an HE-driven metal fragment impact. Impact of such fragments occur on the inner wall of the containment vessel, which are also being investigated but are not part of this paper. Observations on similar, though smaller vessels, are that these cracks have a depth of at most 0.4 inch on a given test. The question to be investigated is then,

> *"How many additional HE tests can be performed before a crack, caused by a fragment, must be repaired?"*

The incremental number of tests that can be performed for a given flaw size using the above theory is shown in Fig. 7. As can be seen in that figure, a flaw size of 0.6 in. would grow to the critical crack size in approximately 100 tests. However, the postulated flaw is an overly conservative model of fragment damage because of the localized damage inflicted by a fragment. A better model would be the thumbnail crack, discussed in the next section.

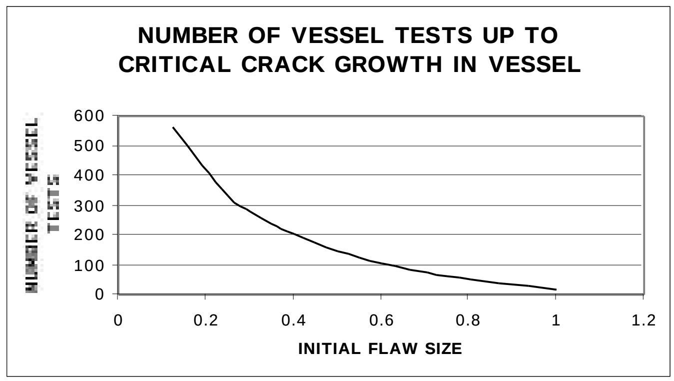

Figure 7 – Number of remaining tests based on observed flaw size.

5. OTHER FLAWS CONSIDERED

Three other initial flaws were postulated for the vessel and the procedure outlined in Section 3 was utilized to determine the remaining life, expressed as number of tests. These flaws were:

1. **A finite length, semi-eliptical, internal circumferential part-throughwall flaw [8,9]**. This flaw simulates a 'thumbnail' crack in the vessel shell wall due to the impact of a fragment. The stress intensity factor depends upon the parameter, $2c/a$, where $2c$ is the flaw width along the inner surface of the vessel and a is the maximum flaw depth of the crack.

2. **A part through-wall crack in a nozzle .** This crack represents a flaw in one of the five identical nozzles welded to the spherical containment vessel, as shown in Fig. 1. An edge-crack model similar to that presented in Section 4, but applied to a nozzle, was utilized.

3. **Corner crack at nozzle junction.** This crack represents a flaw at the junction of the spherical vessel and the cylindrical nozzle. Based on [10,11], the nozzle corner flaw is idealized as a through-thickness crack emanating from a hole in a flat plate, with the

radius of the hole in the plate representing the nozzle-vessel junction.

6. RESULTS AND CONCLUSIONS

Initial Flaws- Cracks up to 1/16" in length are acceptable during the initial full inspection of the vessel. The number of HE tests that can be performed before this crack grows to its respective critical size is a direct indication of the life of the vessel.

Results for the four postulated flaws investigated in this paper are summarized in Table 1, where the critical crack depth is presented, followed by the number of HE tests that could be performed in the vessel with an initial, maximum acceptable flaw of 1/16" crack length. It is readily seen that the nozzle corner flaw permits the minimum number of HE tests, although the limit of 66 tests indicated in Table 1 is considered very conservative because of the high alternating stress value used.

Applying a factor of safety of 3 on the number of tests, it is seen that the vessel is capable of withstanding in excess of 20 full HE tests before the postulated nozzle corner flaw would grow from the acceptable initial flaw length of 1/16" to the critical size.

TABLE 1
NUMBER OF HE TESTS FOR EACH POSTULATED FLAW

Postulated Flaw	Location	Critical Crack Size (in)	HE Tests to Critical Size
Full Circumference Internal Part-Throughwall Flaw	Spherical Vessel	1.13	840 Tests
Finite Length, Semi-Elliptical, Internal Circumferential Part-Throughwall Flaw	Spherical Vessel	1.95 (2c/a=3) 1.52 (2c/a=6) 1.31 (2c/a=9) 1.17 (2c/a=12)	1796 Tests 1281 Tests 1104 Tests 1005 Tests
Full Circumference Internal Part-Throughwall Flaw	Cylindrical Nozzle	1.44	926 Tests
Nozzle Corner Flaw	Nozzle & Vessel Intersection	0.31	66 Tests

Flaws Induced by Fragments - Flaws as a result of HE-generated fragments could be induced at any location in the spherical portion of the vessel. The vessel would be visually inspected for any significant fragment damage following each HE test (Cracks of 0.5 in. length or greater). The flaw induced by fragment impact is considered best modeled by the 'Thumb-Nail' crack (Section 5). If a fragment-induced flaw is observed on visual inspection, the procedure for estimating remaining life would be to measure the depth and width of the new crack. Based upon the width-to-depth ratio of the crack, the number of additional tests that could be performed in the vessel would be determined. The number of tests would then be divided by a safety factor of three. If the fragment-induced crack has a 2c/a ratio lying outside the range, $3 \leq 2c/a \leq 12$, then the crack could be conservatively modeled as a full circumferential part-through-wall crack. Using the crack depth, Fig. 7 would be used to determine the remaining life. Again, the number of HE tests indicated in Fig. 7 would be divided by three as a factor of safety. If the number of HE tests remaining is insufficient, an alternate procedure would be to repair the fragment-induced crack.

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