Appendix D
Safety of Cryostat Closure Welds

Ultrasonic testing has shown the existance of incomplete penetration at the root of the cryostat closure welds. This subject was initially discussed in a report "Cryogenic Welding Metallurgy", January 7, 1982. Refer to this article for complete details and reference. Since that time much more accurate stress analysis has been performed. This appendix will summarize fracture toughness and fatigue crack growth rates based on these new values.

ANSYS stress analysis has demonstrated that the maximum radial tensile stress at the root of the weld is 24740 psi. This is the stress component which will cause a root crack to propagate.

The energy release rate G for a crack of length L in a plate of width W is given by

$$G = K^2/E = \sigma^2 W (1-\nu^2)/E \times \text{Tan} (\pi L/W)$$

W = 0.675" = plate thickness

L = 1/32"

σ = 24740 psi

K = fracture toughness

Crack depth L is based on the assumed maximum flow size. The landing in the closure weld is 1/16". It would be virtually impossible to TIG weld the root pass with less than 1/32" penetration. Then

$K = 7420 \text{ psi}\sqrt{\text{in}}$

Fracture would occur for the 1/32" flaw if the material had a fracture toughness less than 7420 psi$\sqrt{\text{in}}$. Unfortunately the weld shop did not provide the requested 316L rod for TIG welding the root pass on cryostat #1. A high ferrite 316L composition with a calculated ferrite number of FN = 12 was used instead. This material has a fracture toughness of ~ 82 Ksi$\sqrt{\text{in}}$. Alternately the critical flaw size is calculated to be 0.326" for a material with this toughness. Fracture toughness is more than adequate. In addition cryostat #2 root pass was TIG welded with a 3% to 6% ferrite 316L rod. Both welds were filled with 0% ferrite 316L SMAW which has a 4°K fracture toughness of 160 Ksi$\sqrt{\text{in}}$.

Crack growth rates:

The Paris equation is used to calculate the growth of a subcritical crack

$$da/dN = C(\Delta K)^n$$

where C and n are experimentially determined parameters, a is the flaw size, and N is the number of cycles.

Integrate this equation to determine the maximum number of cycles. Although 0.326" was the critical flaw size let's place an upper limit at 1/10 this value or 1/16".

$$N_f = \int_{a_i}^{a_f} da/C\Delta K^n$$

$\Delta K = K_{max}$ since $\Delta\sigma = \sigma_{max}$

The plane strain semi infinite plate model is chosen as an approximation to obtain a closed form solution.

$$\Delta K = [\pi\ \sigma^2\ a(1-\nu^2)]^{1/2}$$

Values for C and n do not appear in the literature for a high ferrite 316L GTAW. Use average values for 316L SMAW weld.

$C = 5.5 \times 10^{-13}$ meter/cycle
$N = 3.5$

Then

$\Delta K = 288\sqrt{a}$ MPa$\sqrt{m}$

and

$$N_f = \int_{7.9 \times 10^{-4}}^{1.59 \times 10^{-3}} \frac{da}{5.5 \times 10^{-13}\ 288^{3.5}\ a^{1.75}}$$

$N_f = 5.18 \times 10^5$

The problem can be simplified by using a constant value of da/dN ~ 10^{-6} mm/cycle for a stress intensity change of ~ 8 MPa$\sqrt{m}$. Then a 1/32" growth will take 7.9×10^5 cycles.

Conclusion:

Stress levels at the root of the closure weld are far below the critical stress intensity. Based on extrapolated data one-half million cycles would be required for a 1/32" crack to propagate to 1/16". Less than 1000 lifetime cycles are expected. No crack growth data can be found in this very low stress intensity range, but it is very likely that we are even below the threshold at which cracks can propagate. Weld root cracks are in general poor practice, but precaution in conductor and insulator damage must take precedence.