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Title: Views on Fracture Toughness

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Views on Fracture Toughness

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Background – Our Challenge

- **GTS reservoir design involves a multidisciplinary approach and understanding of several complex processes for systems needed years ahead of FPU**
- **Designs are conservative to mitigate against possible failure and provides margin against incomplete understanding of:**
  - Hydrogen/structural material interactions
  - Non-uniform forging properties
  - Welding effects
  - Diffusion properties
  - Failure mechanisms
  - Unknowns
- **Given this, we must design and manufacture reservoirs that are safe and reliable when handled for assembly and during storage/functioning**

Background – Our Approach

- **Heavy reliance on past experience and robust surveillance program**
  - Past 50 years of storage of reservoirs in tritium for past 50 years
  - Hundreds of successful function tests and favorable metallographic/burst tests provide high confidence that our product is safe and reliable

Looking Forward

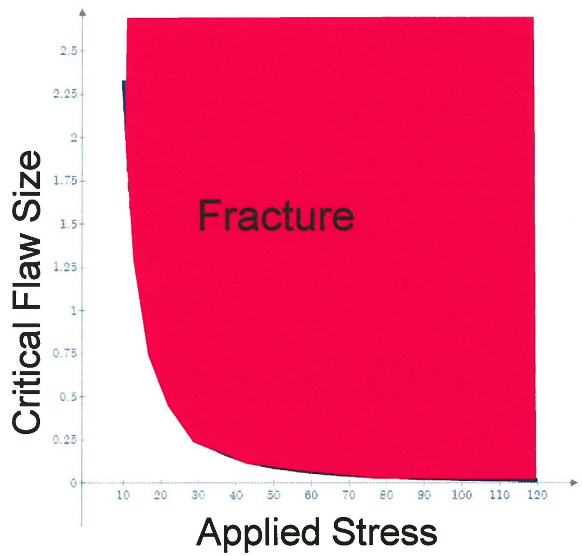
- We will need flexible designs capable of meeting increasingly challenging requirements
- Decreasing safety factor for lighter designs by increasing knowledge and predictive capabilities to maintain confidence
- Maintaining cutting edge research programs directly tied to current and future stockpile systems

Elastic Fracture Toughness

- **Originally developed to predict failure of brittle materials due to sudden propagation of an existing flaw**
- **Simple equation can predict fracture in a component as a function of applied stress given a flaw size or vice-versa**

$$K_{1C} = C \cdot \sigma \cdot \sqrt{\pi \cdot a_{crit}}$$

- K is fracture toughness
- C is constant based on geometry and loading
- σ is applied stress
- a is flaw size

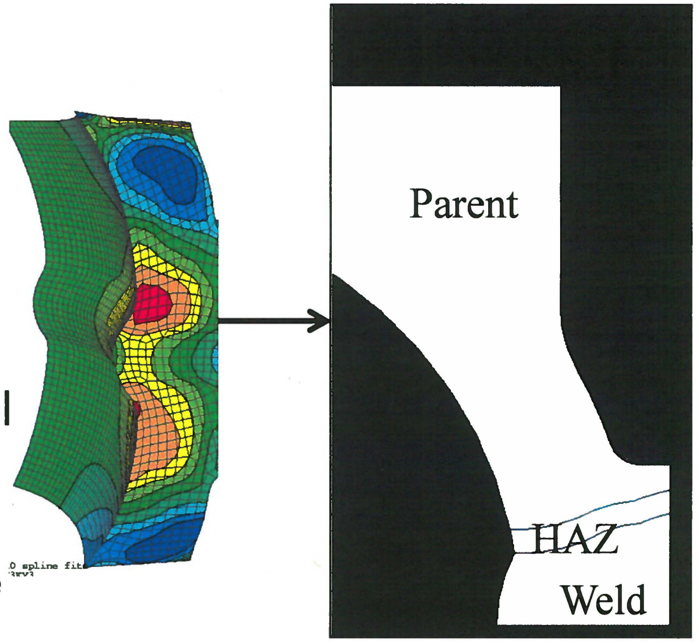


Fracture Toughness

- **GTS reservoir materials are chosen and designed to have ductile failures**
  - 55-75 ksi yield
  - > 85 ksi ultimate
  - Grain flow and size
- **However, some effects are not fully understood:**
  - Welding residual stresses
  - Hydrogen effect on properties
  - Helium effect on properties
  - Small composition changes
- **Nevertheless, testing shows that our design methodology is sufficient to meet current requirements**

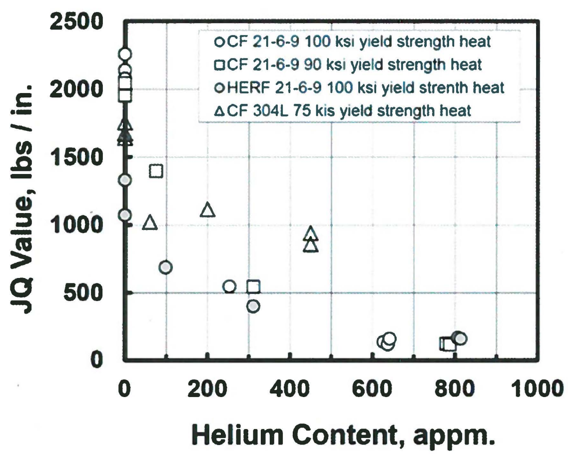
Residual Stresses (Steinzig et al)

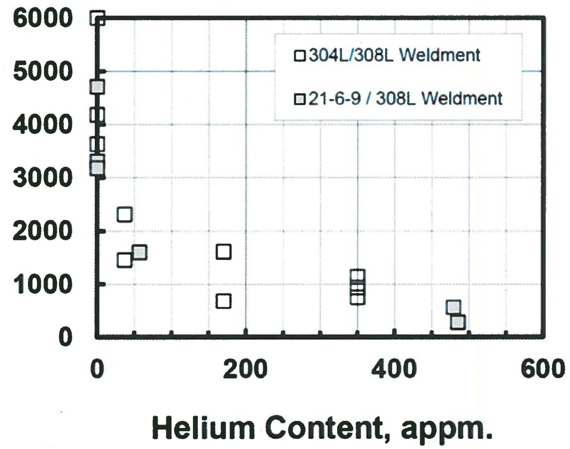
- **Three measurement methods on "worst case" component**
  - Hole drilling and contour agree fairly well - ~40 ksi residual stress
  - Neutron provides 3D state, but requires delicate tuning and "unstressed region" for calibration
- **Modeling approach has been to measure the properties in three resulting materials and model as such**
  - Introduces false gradients and requires piecemeal approach and passing data among variably compatible software
- **Not predictive or suited to process design**
  - Matched to measurements as opposed to predicting measurements



Tritium / Helium-3 Effects (Morgan et al 2013)

- **Charge samples to appm levels consistent with reservoirs and test**
  - Conventional Forged vs High Energy Rate Forged
  - 304L vs 21-6-9
  - Weld vs base

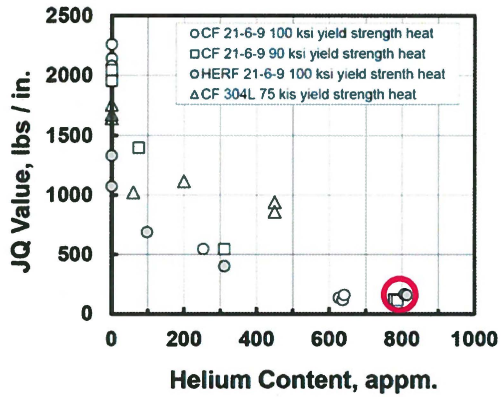


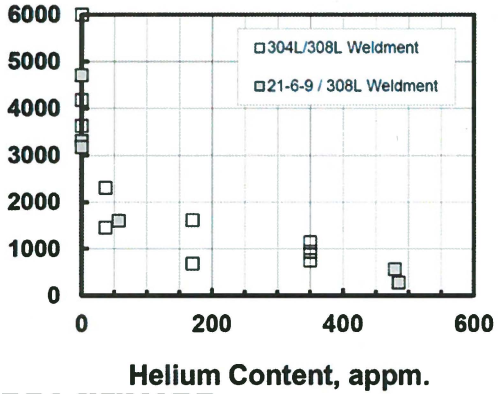


  - **Data shows significant toughness decrease with increasing helium and strong dependence on material and forging process**

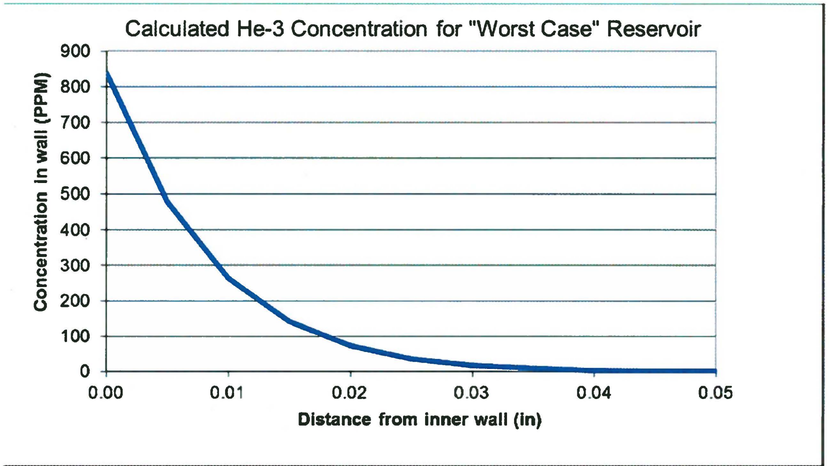
How Fracture Resistant are We?

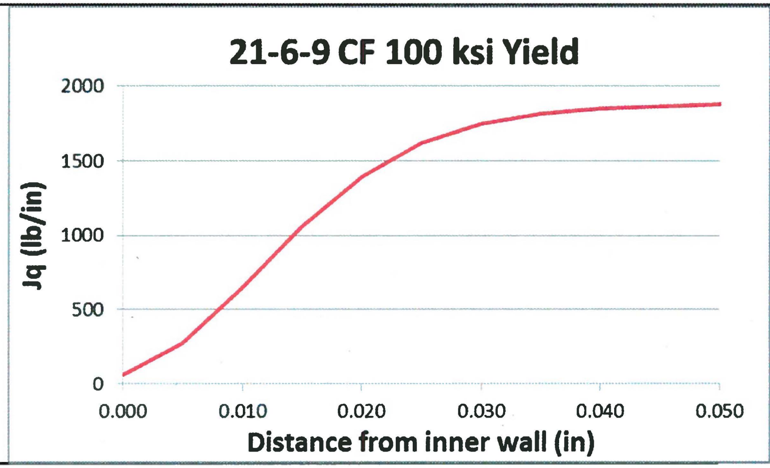
- **Due to years of surveillance data, science-based testing, and calculations, we can get a good idea**





Conventionally forged 21-6-9 is worst case for Fracture Toughness and is used for "worst case" analysis



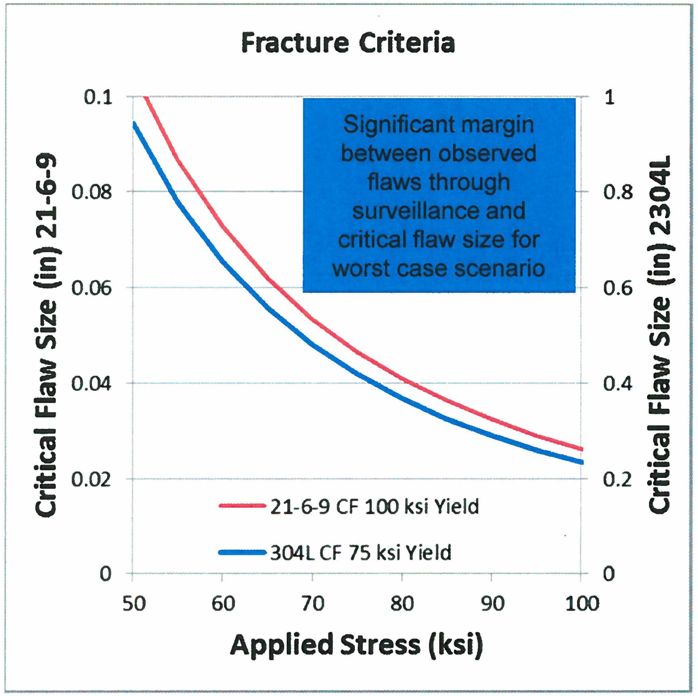


How Fracture Resistant are We? VERY RESISTANT

- **Based on the following assumptions:**
  - Lowest bulk fracture toughness measured by Morgan et al
  - Bulk applied forces as shown
  - Geometry factor of 2

$$K_{1C} = C \cdot \sigma \cdot \sqrt{\pi \cdot a_{crit}}$$

Material	Critical Flaw Size (in)		
	55 ksi	75 ksi	100 ksi
21-6-9 HERF 100 ksi yield	0.136	0.073	0.041
21-6-9 CF 100 ksi yield	0.087	0.047	0.026
21-6-9 CF 90 ksi yield	0.092	0.050	0.028
21-6-9 Weld	0.217	0.117	0.066
304L Weld	0.650	0.350	0.197
304L CF 75 ksi yield	0.784	0.422	0.237



Modeling Work (Schembri 2006)

- **Solubility/Diffusivity**
  - Model was run with both the Caskey versions and the San Marchi et. al. versions

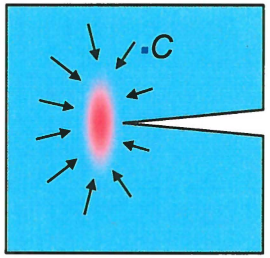
Caskey	San Marchi el. al.
$S = 402e^{-\frac{906.45}{T}} \frac{appm}{\sqrt{psi}} = 19.2 \frac{appm}{\sqrt{psi}}$ @25C	$S^* = 259e^{-\frac{709.6}{T}} \frac{appm}{\sqrt{psi}} = 23.9 \frac{appm}{\sqrt{psi}}$ @25C
$D = 37.5e^{-\frac{6370.34}{T}} \frac{in^2}{day} = 1.95E-8 \frac{in^2}{day}$ @25C	$D = 72.3e^{-\frac{6483}{T}} \frac{in^2}{day} = 2.58E-8 \frac{in^2}{day}$ @25C

▪Note: *S** is used with *fugacity* to calculate concentration, while *S* is used

▪with *pressure* to calculate concentration – surface concentrations differ by ~20%

Model details (Schembri 2006)

- **Stress/diffusion coupling:**
  - The flux of tritium is proportional to the gradient in the pressure stress (negative of hydrostatic stress):



$$-\nabla \mathbf{J} - \alpha C = \frac{dC}{dt}$$ (conservation of mass)

$$\mathbf{J} = -\mathbf{D} \bullet \left[\nabla C - \frac{\kappa_p}{3} \nabla(\mathbf{tr}(\mathbf{T})) \right]$$ (constitutive equation: "Fick's Law")

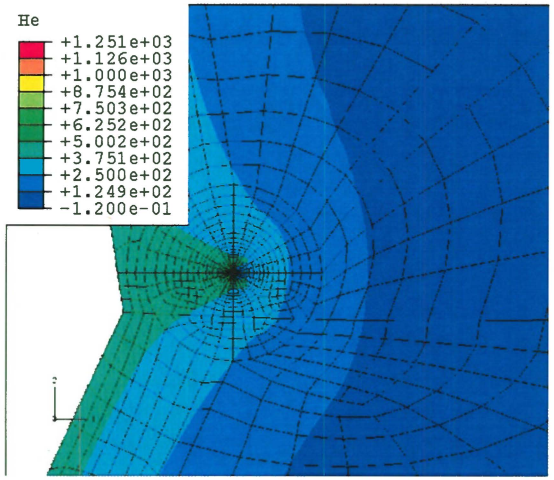
  - κ_p is derived from a chemical potential that describes the interaction between the stress field and the volumetric strain caused by the tritium atoms in the lattice (Sofronis & McMeeking, 1988). It turns out to be:

$$\kappa_p = \frac{V_H C}{RTS}$$

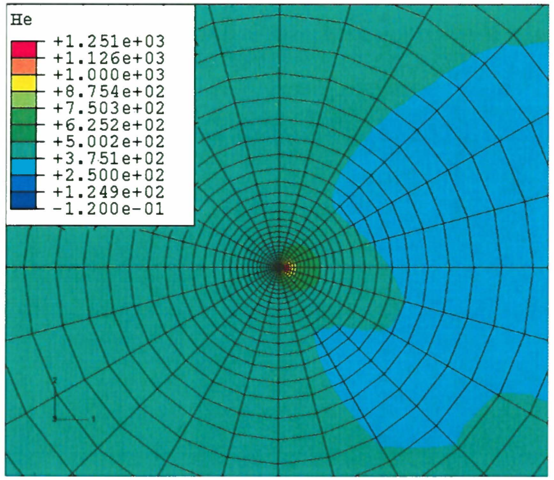
Where V_H is (roughly) the partial molar volume of hydrogen in iron (~2.0E-6m^3/mol)

Model details (Schembri 2006)

- **Modeling of He-3 content after three cycles with 0.005" crack present shows highly localized increased concentration, but fairly uniform bulk properties consistent with testing**



Bulk geometry



Near crack tip

- **Based on this modeling, fracture toughness would need to be on the order of gray cast iron for crack to propogate**

Conclusion

- **Due to years of work in research and surveillance, LANL has high confidence that our GTS are designed and manufactured to be fracture resistant to the point that it will not primarily drive designs going forward**
- **This will allow for more work focused on fundamental understandings of the effect of manufacturing processes and hydrogen interactions**
- **Ultimate goal is a multistage capable physically-based predictive model capable of aiding reservoir designs from the ground up**
  - Model needs to capture physics-based history variable evolution through manufacturing steps and predict failure including hydrogen effects
  - More discussion in later talk