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Date: 9/12/02 5:55PM
Subject: Additional thoughts on D-B head crack testing

Debby et al:

I talked a little more to the guys here and I think that your concern over the temperature gradient through the thickness is a very second (maybe third order) effect from an applied strain concern. When we did our initial evaluation (report attached), we were concerned that our analysis had the cladding in a stress free condition at 605F. SIA had the cladding at a stress free condition at room temperature. The actual stress free temperature may have been around 1100F, which would be the stress-relief temperature of the RPV head after cladding was put on. When we looked at the strains imposed with the 500F or so temperature differences, the thermal strains were less than 0.1%. This was far less than the strains from the pressure-induced bulging at "failure", and we therefore neglected the 500F thermal strain. Strains with a 300F gradient would be even less, so with some calculations I believe you can show that any testing need not have to have that temperature gradient. You should do some good fluid/heat-transfer calculations to see with the gradient is through the thickness, and perhaps use a mean temperature in the test. On the otherhand, you may need water in the test pipe to be at 605F to provide the driving force (temperature controls the saturation pressure for the water decompression behavior) to create the opening area. Put high temperature heater tapes on the test pipe.

Also, as I noted, some fluid/heat transfer calculations could be done to determine what the metal temperature on the surface of the cavity might be. The water could be at 212F, but there would be some vapor region that acts as an insulator and the metal surface temperature is probably much higher. Also the external fluid in the cavity is probably really more of a boric acid with a little H2O in it, which might have a boiling temperature higher than 212F. Was there lots of boric acid in the cavity when they first uncovered it?

Zhili confirmed for me that the 6-wire cladding procedure would have the 6 wires effectively in one weld pool. If the weld wires were not making one weld pool, then the solidified flux from one weld wire would make inclusions in the weld pool from the following weld wire. Hence you should be able to see one row of cladding overlapping the next row in an etched metallographic section.

I remember that for the Midland head at Framatome-Lynchburg, that the inside surface of that head was ground smooth, i.e., there were no weld bead ripples on the inside surface. Even better, the photos of the section removed from D-B showed the inside surface was smooth (see attached picture).

The test could be as simple as shown in my attached sketch. We'd need to brace the test fixture for thrust loads if the cladding rapidly ruptures.

Regards,

K-2

Gery

p.s. Not sure I got all that were in the conference call in my distribution list.

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A: Analyses of Flawed Cladding (Davis Besse)

2. Estimate cladding strains induced from thru-thickness thermal gradients of 600 F to 250 F by performing finite element analyses of flat plates made of cladding material. Results of this analysis will be used to determine if the thru-thickness temperature gradient should be modeled in further tasks or included in any experiments.

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3. Estimate cladding residual strains induced from residual stresses assuming a stress-free temperature of 1100 F (the stress-relief temperature) and an operating temperature of 600 F. (Note: Steve Hunt told me the other day that at Dominion Engineering they do not think that stress relieving gets rid of all the residual stresses, hence they are now doing cladding weld simulation and using a creep law to assesss the residual stresses afeter the stress-relief. – Gery)

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4. Estimate the burst pressure for unflawed cladding flat plate, after including the clad residual stresses in item 2, and with or without the thru-thickness thermal-gradient in the clad plate (item 1). (Need to do a large strain analysis with sufficient number of ellemnts (integration points) through the thickness. - Gery

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5. Estimate crack driving forces as a function of flaw size and applied membrane stress in cladding by performing elastic-plastic finite element analyses of sharp surface breaking flaws in flat plates under biaxial tension. The flaw depths could from 5%, 25% and 50% of the clad thickness. The flaw lengths could vary from 3/8", 1" and 2". The applied stresses would be representative of the membrane stresses at the center of the wastage area cavity. Also, a flaw geometry simulating the actual DB flaw should be evaluated once this is determined. The J-integral calculated from these analyses could then be compared to appropriate JR curves for the cladding material. (Last sentence should read more like, "The applied crack driving force (J_{app}) from this analysis can be used in conjunction with the material J-R curves to calculate the pressure at crack initiation and perhaps maximum load." Note this implies that the appropriate stress-strain curve for the cladding material is used. See discussion in B-2 on strength gradient from carbon migration into the initial cladding layer. This strength gradient should be included in the most accurate modeling that you will do. We are also assuming that this analysis is for a constant thickness clad, whereas D-B crack appears to be in variable thickness area. Do you want to explore the effects of a variable thickness at all? For D-B case, have silicon mold made of the surface to see the irregularities, or use metallographic sectioning data

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Another aspect we recently thought of is the effect of thermal aging on the material properties. As Matt Mitchel noted at the Section XI meeting, there could be thermal aging issues for flange welds, and that might also apply to the cladding material. In that case the aging may increase strength lower ductility and lower toughness. I've seen some aging data for stainless steel welds on the effect of toughness (upper shelf CV energy going from 50 to 24 ft-lb), but we'd need to look into strength effects as well. If the flaws are relatively small, then we suspect you will have a limit-load driven problem, and the

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failure pressure may not be sensitive to toughness unless the toughness is very low. Hence, the aging effects on strength may actually increase the failure pressure. - Gery

6. Estimate the plastic collapse as a function of flaw size and applied membrane stress in cladding by performing elastic-plastic finite element analyses of a finite root tip (blunted) surface breaking flaws in flat plates under biaxial tension. The flaw depths could vary from 5%, 25% and 50% of the clad thickness. The flaw lengths could be varied from 3/8", 1" and 2". The applied stresses would be representative of the membrane stresses at the center of the wastage area cavity.

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Since Items 5 and 6 both need to be done with a large-strain analyses, the limit-load will naturally fall out of the FE analyses; hence Items 5 and 6 can be combined. (This would not occur with deformation plasticity FE analyses with a power-law hardening stress-strain curve, but we already know that large-strain FE analysis is needed for this problem.) - Gery

7. Similar to 4 except that instead of a flat plate geometry, the finite element model of the flaw could be driven by the submodel of the wastage area cavity which in turn will be driven by the global model of the full RPV head and closure flange. (I take it that ORNL has not doen this analysis yet. They needed more mesh refinement in the cladding last time I looked at their results. – Gery)

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8. Similar to 5 except that instead of a flat plate geometry, the finite element model of the flaw could be driven by the submodel of the wastage area cavity which in turn will be driven by the global model of the full RPV head and closure flange.

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9. Same as the Item 4, but including a thru-thickness temperature gradient is imposed. The internal surface would be roughly at 600F while the outer surface temperature would be 250F. The J-integral calculated from these analyses shall be compared to appropriate JR curves for the cladding material. (Again, you can calculate a failure pressure using the driving force and the material J-R curve, but you can't compare the two) Material stress strain curve is important, as well as appropriate J-R curve - Gery

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10. Same as the Item 5, but including a thru-thickness temperature gradient is imposed. The internal surface is would be roughly 600F while the outer surface temperature would be 250F.

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For Items 9 and 10, the proper heat-transfer boundary conditions should be applied to get the actual gradient through the thickness This will probably be a 2^{nd} order effect at failure pressure.

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B: Experiments of Flawed Cladding (similar to Davis Besse)

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The materials would come from either (1) mockups made to simulate the cladding from the Davis Besse RPV head and/or (2) other clad material taken from other vessels (i.e., with similar cladding process used, from among: Shoreham, River Bend II, Hope Creek II, PVRUF, Midland, etc.). Whatever cladding material is chosen should be fabricated using the tandem arc process.

should sample microstructure consistent with the DB cracking location; the other two locations could sample other regions of interest. The microhardness results could be used to determine sections for metallography. The metallography should characterize all pertinent unique microstructural features within the cladding, but should especially concentrate on those features near the DB cracking location. Also, microstructural and microhardness inhomogeneities could indicate possible locations for measuring tensile property anisotropy. Two disparate microstructures should be evaluated at a single temperature to be determined. Gleeble simulation may be required to reconstruct the microstructure within macroscopic tensile specimens.

As noted earlier, there will be migration of carbon to the cladding from the welding. This will be a gradient that will affect the strength, toughness and stress-corrosion cracking resistance. Ideally, some thin tensile specimens are done to try to capture some of this. (Kind of cringe at miniature disk bend tests, or those who run them, but sheet metal like thickness tensile specimens may be good enough. - Gery

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3. Triplicate fracture(J-r curve) toughness tests in the L-S orientation should be performed at 300F and 600F. These results could be utilized within the numerical predictions to simulate failure. Other mechanical tests as required by cladding material specifications should also be performed to ensure that the material meets minimum requirements.

For this problem you would need to do SEN(T) specimens in a fixed-grip condition to simulate surface crack constraint conditions. Below figures show how we did that in some past piping work. Blunt side-grooves were needed to get a straight crack front. We did it with a/t of 0.15, 0.25, and 0.50 in past piping work with 0.3" thick specimens. (Bend-bar specimens would not give similar constraint conditions to the surface crack in the cladding.) – Gery

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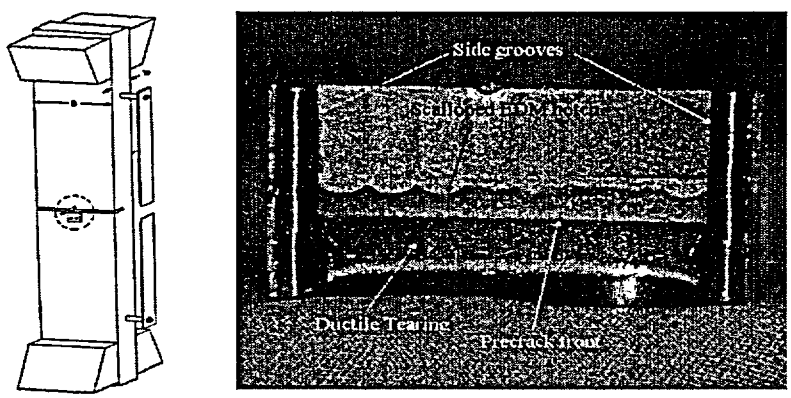

Figure 1 Fixed-grip SEN(T) specimen
(Photo shows typical 304 stainless steel specimen, sketch does not show side-grooves.)

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The cladding material shall be Type 308 or Type 308L stainless steel. Because the intent is to simulate the DB material as closely as possible, the DB cladding microstructure in the vicinity of the cracked and necked region should be determined. Also, the chemistry within this general vicinity should be evaluated to determine the cladding alloy. Crack depth should also be determined at the approximate center location (axially) of the crack and at each end. (Crack depth at end of flaws = 0. Maybe just say that the profile of the entire surface crack should be determined.) This profile will be utilized in both the subsequent experimental tests, but will also be modeled within the numerical failure predictions.

1. Burst Tests Burst tests should be performed on flawed and unflawed 0.25" thick cladding material to determine failure pressures. The surface area of the cladding test specimen should be approximately that of the wastage area of the Davis Besse RPV head. The tests should simulate as close as possible the loading, geometry, thermal, and material degradation** experienced by the DB head. As such, the burst tests should be biaxially loaded, either through a flat disk under pressure, a pipe-flanged arrangement, or spherical-arc shaped segment. The thermal gradient expected across the cladding should also be simulated as closely as possible (if determined necessary from the analyses???). The internal surface is expected to be roughly 600F while the outer surface temperature is app. 250F. Initial thermal feasibility tests shall ensure that this gradient can be maintained throughout the test. If it is not possible to maintain during the test, the thermal strains induced by this gradient should be measured and used to predict the thermal stresses induced in the cladding. The flaw geometries should be consistent with those utilized in the numerical study. The depths could vary from 5%, 25% and 50% of the clad thickness. The flaw lengths could be varied from 3/8", 1" and 2". Also, a flaw geometry simulating the actual DB flaw should be tested. Experiments could performed until complete failure. The failure strains would be monitored along with failure load and the crack opening displacement at failure (if appropriate). Three repeat tests per condition should be done.

   **Let's talk about the material degradation a little. The first cladding layer will absorb some of the carbon from the head material, and may end up being more like a high carbon stainless steel. The carbon will be a gradient, which gives a gradient of material properties, strength toughness, and stress-corrosion cracking resistance. In addition, there will be a thermal aging effect that also changes the material strength, ductility, and toughness (see earlier discussion). I believe we agreed before that the irradiation damage is negligible, but we are not experts on that. You may be able to simulate the carbon migration gradient in the experiments, but no the thermal aging. - Gery

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2. Macroscopic tensile tests could be machined from the cladding. These tests would be performed at 300 F, 450 F and 600 F. A minimum of 3 tests should be performed at each temperature. All tests should be done at quasi-static loading rates. Microhardness traverses could also be done both through the cladding thickness and perpendicular to the cladding axis. The perpendicular traverses should encompass three side-by-side cladding passes (one pass is 6 wires). One traverse should be at the carbon steel interface, one at the mid-cladding thickness, and one near the free surface. One through-thickness traverse