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WCAP-13603
Addendum 1

RV Closure Head Penetration Alloy 600 PWSCC (Phase 2)

A Westinghouse Owners Group Program Report

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1.0 INTRODUCTION

Cracking was first found in reactor vessel head penetrations in the fall of 1991 during a hydrotest at Bugey Unit 3 in France. Further inspections led to the identification of other cracked penetrations in a number of European plants. These findings led to the studies whose results were originally reported in December of 1992. At that time the only observed cracks had been oriented axially with respect to the centerline of the penetrations, and the stress analyses and fracture studies supported the likelihood that the cracking would have this orientation.

Since that time, EDF has reported that destructive examination of the only head penetration known to have leaked revealed two circumferential orientated cracks, as shown in Figure 1. Both cracks were located at the outside surface of the penetration, one in the weld and one in the Alloy 600 base metal just above the weld. The crack in the weld is fabrication related while the crack in the penetration tube is primary water stress corrosion cracking. The presence of these cracks has raised the issue of their safety significance, since a circumferential flaw propagating entirely around the circumference could lead to severance of the penetration.

This addendum to the original report has been prepared to address that concern. The conclusions in the original report relative to the safety significance and propagation of axial flaws remain unchanged. The same stress analysis which served as a basis for the original work was used for this addendum.

2.0 GEOMETRY

The head penetration which had originally leaked was destructively examined by Electricité de France, and three additional flaws were found, as shown in Figure 1. These flaws were in addition to the through-wall axial flaws discovered by inspection in that same penetration.

The first of the three flaws shown in Figure 1 is the most important, because it has been verified to be the result of primary water stress corrosion cracking, and is oriented circumferentially. The second flaw is oriented axially, and therefore already treated by the axial flaw propagation studies reported earlier. The third flaw is also circumferential in nature, and is reported to be a "hot crack" resulting from the original welding process.

Therefore the crack number 1 in Figure 1 will be the subject of primary interest here. The flaw is oriented circumferentially, at an angle of about 30 degrees to the horizontal plane, as shown in the cutaway view in Figure 1. When viewed from the outside of the penetration, the flaw would appear as a horizontal line.

The flaw is located near the zero degree, or lower hillside location in the penetration, at the outside surface just above the weld. The flaw was reported to be 3 mm long and 2.25 mm deep.

The angular orientation of the flaw is such that it is propagating in a direction downward toward the centerline of the vessel. The plane of the flaw therefore includes only a very small portion of the circumference of the penetration which is above the weld. Therefore, even if the flaw were to extend around in this plane, the penetration would still be captured by the existing penetration to head weld. The evaluation discussed here has examined a number of possible paths of propagation, including continued propagation along the original plane.

3.0 STRESS ANALYSIS RESULTS

The three dimensional elastic-plastic stress analysis used as the basis for the original safety case has also been used for this evaluation. The stresses of interest here are primarily axial stresses, although the stresses projected transverse to a number of postulated crack planes were studied.

The steady-state operating stress was the loading of interest, and because plastic stresses are induced by the original welding process, the loading sequence is important. The loading sequence is listed below:

[ ]a,c

To investigate the possibility of extension of an existing or initiating circumferential crack, the stresses through the thickness of the penetration in the region above the weld were studied. A number of crack orientations were considered:

1. Crack parallel to the one at Bugey Unit 3, coincident with it
2. Crack parallel to the one at Bugey Unit 3, but above it
3. Crack parallel to the penetration – to head weld
4. Crack purely circumferential – perpendicular to the penetration center line.

Nine different locations around the circumference were considered, as shown schematically in Figure 2. Both the axial and hoop stresses are shown in each of these cuts in Figures 3 through 6. Note that the axial stress shows a peak value at the lower hillside location (cut 1), just above the weld, which is precisely where the crack was found in the Bugey Unit 3 penetration, as shown in Figure 1.

Another very important finding is that there is a large zone of deeply compressive stress which is located near the center of the penetration thickness. This zone forms a continuous core of compressive stress which continues around the entire circumference of the tube, above the weld region. This can be easily seen in the color contour plots of Figures 3 through 6.

Cuts were taken at each of four planes as listed previously considered for possible crack extension, and color contour plots of the stresses transverse to each plane are shown in Figures 7 through 10. [

]a,c

Crack coincident with the plane of Bugey 3 flaw. The color contour plot of this plane, which is oriented at a 30 degree angle to the horizontal, is shown in Figure 7. [

]a,c Clearly no potential exists for extension of such a flaw around the circumference, because of the compressive stresses.

Crack parallel to the one at Bugey 3, but above it. Figure 8 shows two possible planes of crack propagation at levels slightly above the Bugey 3 crack. These planes were chosen because propagation of a flaw in either plane would result in the potential for a relatively large portion of the penetration to be severed above the weld. [

]a,c This leads to consideration of the plane of the weld as a possible crack propagation path.

Crack parallel to the penetration-to-head weld. This plane is a very important one to consider, since a crack propagating along this path would eventually sever the penetration. The stress contours in this plane just above the weld are shown in Figure 9. Note that the axial stress at the outside surface peaks at precisely the location of the small flaw at Bugey Unit 3. [

]a,c

Crack purely circumferential. Figure 10 shows the color stress contours along a circumferential plane perpendicular to the centerline of the penetration, located at the same height as the Bugey flaw. [

]a,c

[

]a,c

4.0 CRACK GROWTH ASSESSMENTS

Although the likelihood of crack growth both through the wall of the penetration and around the circumference has already been discussed qualitatively with the stress results, this section will provide some quantitative calculations at the locations where crack growth would be most likely to occur.

The likelihood of crack propagation will be addressed by calculation of the driving force for the crack, called the stress intensity factor. The calculation of the stress intensity factor utilized the expression of Raju and Newman, and the expression has been presented and discussed in the original report, of which this is an addendum.

As with the stress analysis discussed earlier, a number of possible propagation planes were considered:

1. Parallel to the Bugey flaw, coplanar with it
2. Parallel to the Bugey flaw, in planes above it
3. Parallel to the weld
4. Purely circumferential

For each of these planes, the highest stress locations were chosen and K values calculated. The results are summarized in Table 1. Shown in the table are results for a number of cuts around the circumference for each of the planes. The cut locations are identified in Figure 2, and the angle in the table is that measured from the lower hillside location. The environment at the outer diameter of the penetration was assumed to be the same as at the inside of the penetration.

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]a,c

[

]a,c

5.0 SUMMARY AND CONCLUSIONS

Destructive examination of penetration number 54 from Bugey Unit 3 revealed the presence of a circumferential flaw initiating at the outside surface of the penetration. Fractography of the crack showed the mechanism to be primary water stress corrosion cracking, and it was concluded that the flaw initiated as a result of leakage into the annular region from a longitudinal flaw which had propagated through the wall.

[

]a,c

To further investigate the likelihood of crack propagation in the circumferential direction, a number of propagation paths were considered for postulated OD-initiated flaws. In addition to the plane of the existing Bugey flaw, planes parallel to it but above it were considered, as well as a horizontal plane and a plane which follows the top of the weld all around the penetrations.

A detailed crack growth evaluation has been performed to consider the effect of such a flaw on the structural integrity of Westinghouse plants, and it has been concluded that the likelihood of a detrimental impact on integrity is very low. [ ]a,c Therefore the conclusions reached in the original report relative to plant safety remain unchanged.

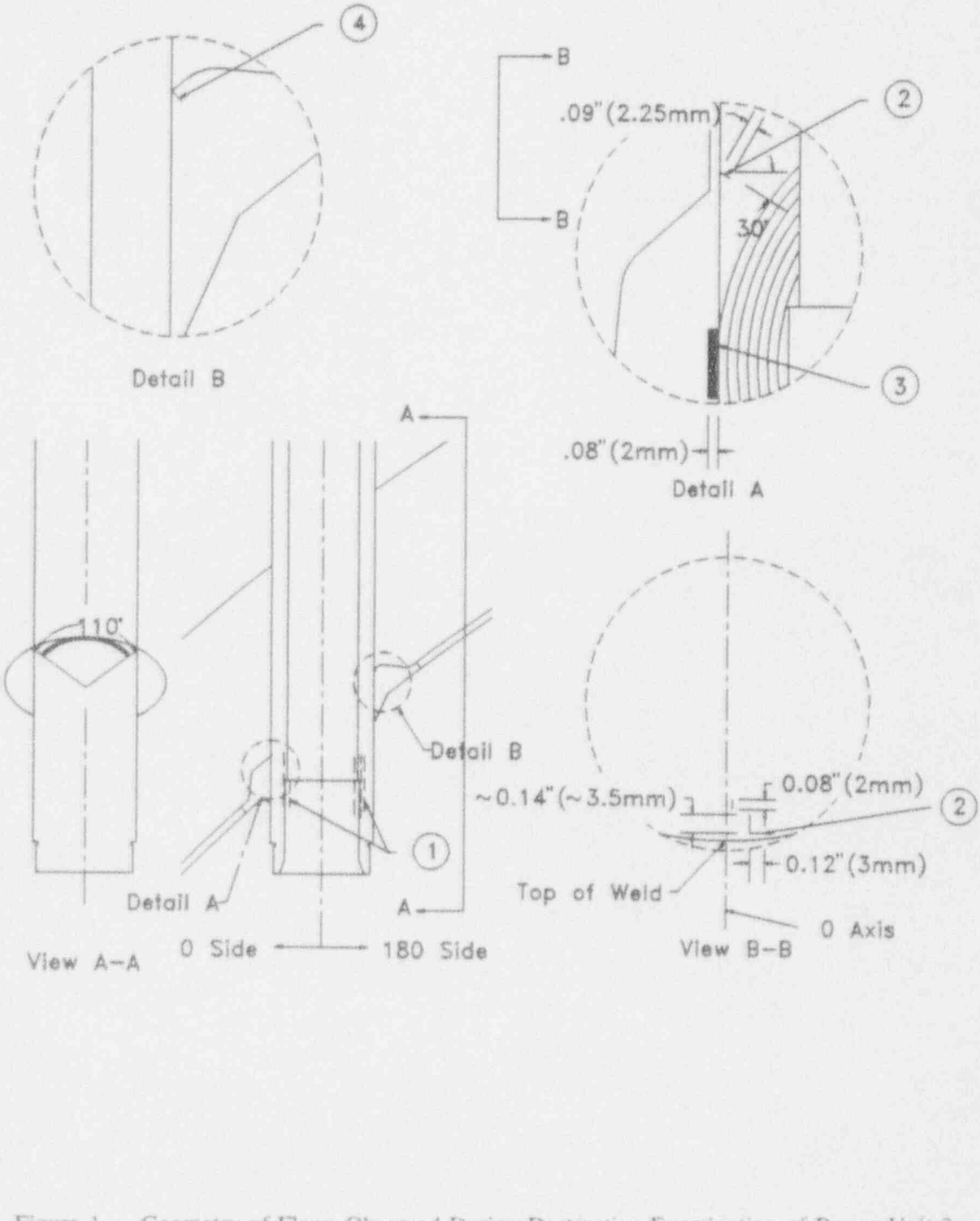

Figure 1. Geometry of Flaws Observed During Destructive Examination of Bugey Unit 3 Penetration 54

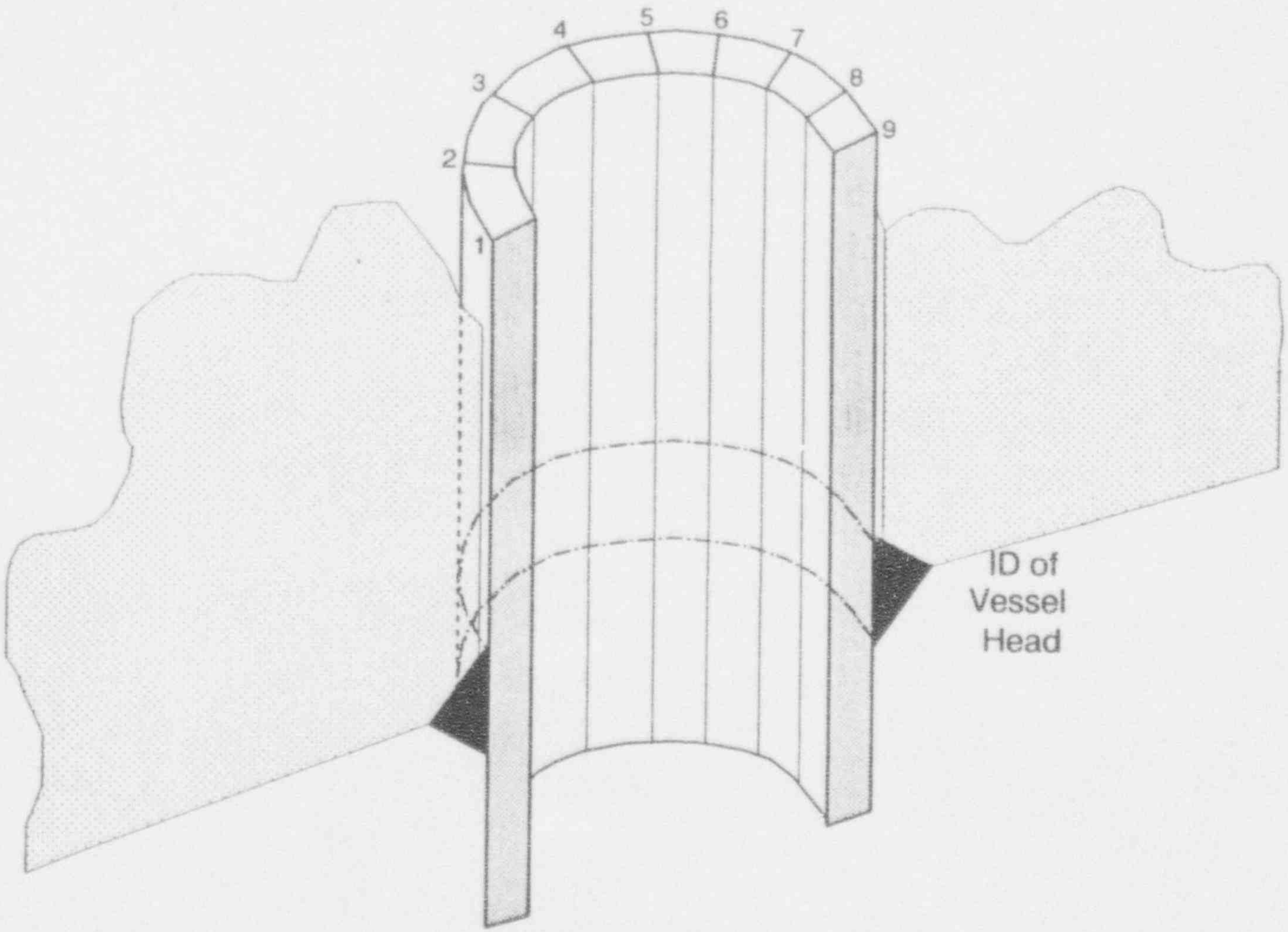

Figure 2. Schematic Showing the Stress Cuts Chosen to Display Both Axial and Hoop Stresses in the Penetration Near the Weld Region

a,c

Figure 3. Color Contour Plot Depicting Compressive Stress Zone in the Center of the Penetration Wall Just Above the Weld Zone

a,c

Figure 4. Color Contour Plot Depicting Compressive Stress Zone in the Center of the Penetration Wall Just Above the Weld Zone

a,c

Figure 5. Col›r Contour Plot Depicting Compressive Stress Zone in the Center of the Penetration Wall Just Above the Weld Zone

a,c

Figure 6. Color Contour Plot Depicting Compressive Stress Zone in the Center of the Penetration Wall Just Above the Weld Zone

a,c

Figure 7. Color Contour Plot of the Plane of the Flaw Found at Bugey Unit 3

a,c

Figure 8. Color Contour Plots of Two Planes Slightly Above the Plane of the Bugey Unit 3 Flaw, and Parallel to It

a,c

Figure 9. Color Contour Plot of a Plane Parallel to the Weld

a,c

Figure 10. Color Contour Plot of a Horizontal Plane Even With the Top of the Weld at the Lower Hillside

a,c

Figure 11.Crack Propagation Results for a Postulated Outside Surface Flaw in the Penetration Just Above the Weld

a,c

Figure 12. Crack Propagation Results for a Through-Wall Circumferential Flaw in the Penetration Just Above the Weld

a,c

Table 1
Summary of Crack Driving Force Results
