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**Factors Affecting the Failure of
Copper Connectors Brazed to
Copper Bus Bar Segments on a
615-MVA Hydroelectric Generator
at Grand Coulee Dam**

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SUMMARY

On March 21, 1986, the United States Bureau of Reclamation experienced a ground fault in the main parallel ring assembly of Unit G19--a 615-MVA hydroelectric generator--at Grand Coulee Dam, Washington. Inspection of the unit revealed that the ground fault had been induced by fracture of one or more of the copper connectors used to join adjacent segments of one of the bus bars in the north half of the assembly.

Various experimental techniques were used to detect and determine the presence of cracks, crack morphology, corrosion products, and material microstructure and/or embrittlement. Visual and radiographic inspection were carried out at the site at Grand Coulee Dam. All other experimental techniques, including additional radiography, were performed at the Hanford Site by Pacific Northwest Laboratory^(a) or at the Hanford Engineering Development Laboratory.

(a) Operated for U.S. Department of Energy by Battelle Memorial Institute.

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INTRODUCTION

On March 21, 1986, the United States Bureau of Reclamation (USBR) experienced a ground fault in the main parallel ring assembly of Unit G19--a 615-MVA hydroelectric generator--at Grand Coulee Dam, Washington (Figure 1). Inspection of the unit revealed that the ground fault had been induced by fracture of one or more of the copper connectors used to join adjacent segments of one of the bus bars in the north half of the assembly.

The parallel ring assembly is a group of bus bars that carry current from ten equally spaced stator connections to the main generator leads exiting the

FIGURE 1. View of 615-MVA Generator Unit G19 Showing Location of Main Parallel Ring Assembly

unit. The assembly consists of two half-sections extending in opposite directions from the main leads around the upper perimeter of the stator frame (Figure 1). Each section consists of two banks (vertical columns) of bus bars, supported and separated from one another by support cleats located at approximately 4-ft intervals along the assembly (Figure 2).

The individual bus bars comprising the assembly are made from 3/8-in.-thick by 5-in.-wide by 12-ft-long tough pitch copper (TPC) that has been bar-edge rolled to a 65-ft diameter and connected by brazed joints. Overall lengths vary from approximately 10 to 100 ft, depending on the location of the respective stator connections. Bar length increases with depth in the assembly.

Each brazed joint is made up of four connectors, two brazed to the top and two to the bottom of adjacent segment ends. The connectors are 3/16-in.-thick by 2-1/2-in.-wide TPC strip and are arranged in two configurations for the parallel assembly joints:

1. A flat configuration is used when segments are at the same elevation (Figure 2).
2. A "Z" joint configuration is used when the segments are at different elevations (Figure 3). Each bus bar is held at a constant elevation until just before the main lead connection where its elevation is then changed to line up with the main lead connections. All bus bars on a given side of the generator change elevation between the same set of supports, as shown in Figure 3; also, the vertical offset between bus bar ends increases from the bottom to the top of the assembly. The ground fault initiated in the outer bank of bus bars at the second from the bottom Z-shaped joint.

Connectors were brazed to the bus bars by combined convective/resistive brazing. High-conductivity TPC cannot be resistively heated to brazing temperature by passing current through the braze interfaces. Additional external heat, generated by graphite brazing electrodes, is also needed to bring the joint area

FIGURE 2. Bus-Bar Section Showing Connection to Main Generator Lead and Support Cleats

up to brazing temperature. Thus, the brazing current heats the electrodes as well as the copper interface components, with the graphite electrodes producing the majority of heat needed for brazing.

Both half-width top and bottom copper braze connectors on one side of the Z joint were brazed simultaneously. (It was found during prefabrication brazing studies that satisfactory brazes could not be made if a full-width connector was used.) Sheet-braze alloy 0.01 in. thick was placed in the joint area before brazing.

The braze material used was a copper-silver-phosphorus material called Sil-Fos (74%Cu-20%Ag-5%P). The melting range for copper-silver-phosphorus braze alloys is 1300 to 1500°F; a catalog lists the specific

FIGURE 3. Inner Bank of Insulated Z Connectors

alloy as having a melting point of 1185°F and a flow temperature of 1300°F (ASM 1983b). Copper has a melting point of 1981°F (ASM 1983a). The phosphorus reduces copper oxide and eliminates the need for external fluxes.

Brazing control was manual; the power supply was set to a preselected level and turned on. The operator visually judged the progress of the braze and turned the power supply off and on to control temperature. Additions of Sil-Fos rod alloy were made during brazing at the operator's discretion.

EXPERIMENTAL OBSERVATIONS

Various experimental techniques were used to detect and determine the presence of cracks, crack morphology, corrosion products, and material microstructure and/or embrittlement. Visual and radiographic inspection were carried out at the site at Grand Coulee Dam. All other experimental techniques discussed below, along with additional radiography, were performed at the Hanford Site at Pacific Northwest Laboratory (PNL)^(a) or at the Hanford Engineering Development Laboratory (HEDL).

The USBR developed a bus-bar identification scheme that will be used throughout this report. Bars were divided into two groups. The set closest to the rotor was designated "inner"; the set furthest from the rotor was called "outer." Bars in a given set were lettered consecutively from top (A-layer) to bottom (F-layer). Azimuthal positions of each set were noted in the set records.

VISUAL OBSERVATIONS

During the site inspection trip by PNL and HEDL personnel, it was noted that a ground fault had melted the outer E-layer Z connector and that the resulting fire had discolored insulation wrappings on several surrounding Z joints (Figure 4). The USBR personnel were in the process of removing insulation from the Z joints around the failed strip; substantial cracking was visible in several other Z-joint half-sections. It was subsequently decided to remove all Z joints on the generator side where the fault occurred. Three lower-level Zs were cut off and sent to PNL for detailed examination. A small number of flat joints were cut during Z removal, and half of each of two of these joints were also sent to PNL.

The PNL labs received the Z joints F-inner, E-outer, and D-outer, along with flat joints A-inner and A-outer. Visual inspection of the two lower Z joints revealed severe cracking in several of the half-width Z strips. Figure 5 illustrates the two positions where the major cracks were observed. One

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

FIGURE 4. Damage at Outer E-Layer; Layers A-D Removed

position was at the edge of the brazed joint in the transition region from bus bar to strip (bus bar F-inner). The other position was in the Z-bend radius (bus bar E-outer). Note the relatively well-shaped Z bends in E-outer compared to those in F-inner. Figure 6 is another view of E-outer and F-inner. The F-inner photograph illustrates that both types of cracking can occur in the same strip.

Visual inspection of F-inner indicated that two out of the four strips were completely cracked and one of the remaining strips was substantially cracked (Figures 5 and 6). The two strips that contained the major fractures separated completely when the Z strip was sectioned for metallography. Figure 7a presents the fracture faces that were visually observed. The top and bottom strip failure occurred in the material near the braze area. The crack appears to be intercrystalline rather than transcrystalline, as it exhibits a

FIGURE 5. Cracked Z-Joints, Showing Crack Types; E-Outer (Above) Illustrating Bus-Bar Edge Cracking, F-Inner (Below) Illustrating Z-Bend Cracking

ragged-edge appearance. Some portions of the fracture surfaces have a heavy corrosion product on them; other regions are lightly corroded. It is assumed that the darker the corrosion product, the longer the cracked surface has been exposed to the atmosphere.

A closeup view of the Z-bend failure in E-outer is shown in Figure 7b. The fracture surface has essentially the same appearance as F-inner even though the break is at a different region. Note that there appears to be a line down the middle of the fracture surface, denoting the intersection of two cracks growing in slightly different directions. This indicates that cracks were growing from both sides of the strip surface. This phenomenon can be detected on the F-inner surface-fracture faces but is harder to observe.

The D-outer Z exhibited no visible cracks (Figure 8). Note by comparison of the three different Z-layer joints, Figures 5 and 8, that the vertical section of the Z increases from the bottom layer toward the top, as noted earlier in Figure 3.

FIGURE 6. Cracked Z-Joints F-Inner (Above) and E-Outer (Below)
Illustrating Jagged Crack Front

(a)

(b)

FIGURE 7. Fracture Surfaces from Joint F-Inner; Fracture in Strip Near Bus Bar (7a), Fracture in Z Bend (b)

FIGURE 8. D-Outer Z Joint

RADIOGRAPHY

Radiography was performed on several Z and flat brazed joints. Various joints were inspected with the original insulation around them. Others were inspected after the insulation was removed. High-resolution x-ray machine radiography was used on joints that were removed from the generator and could be inspected without the physical restraints on source and film placement of in-situ examinations. Lower-resolution, radioactive isotope x-ray (gamma) radiography was used for in-situ inspection.

X-Ray Machine Radiography

X-ray machine radiography was initially used to determine whether this inspection technique could be used to detect the presence of cracks in the strips. Several Z joints that exhibited visual cracks were removed from the generator and radiographed on site. The results showed that machine radiography not only detected metal separation and cracks visually observable, but detected cracks that were not visible.

X-ray inspection and interpretation is sometimes difficult because the image seen on exposed film is a projection of everything between the x-ray source and the film surface, graded in shades of light to dark depending on the depth and density of the material being irradiated. This means that one

exposure is used to highlight defects in thick sections of a given part and another exposure must be used to highlight defects in the thin sections.

This problem is exaggerated in a part such as the Z-bend, as there are three different regions to inspect and the x-ray source is essentially perpendicular to the bus-bar surface. One region is the brazed section where a thick bus bar is sandwiched between two thin strips, with a much thinner brazed layer between the strips and the bus bar. The second region is the flat portion of the Z where the gap between the two thin copper strips is packed with an insulating material. The third region is the vertical legs of the Z where the two thin strips are side by side but the shot is down their length, thus creating an effective "thickness" of copper material much greater than even the brazed area.

Visual inspection indicated that cracks could be expected in the flat regions close to the braze or in the Z-bend regions. Therefore, x-ray exposures and film placement were selected to optimize defect resolution in these areas. High-resolution machine radiography readily detected through-thickness cracks in the F-inner flat strip area and also in the insulation material between the strips, as in Figure 9. Two sets of slightly offset large cracks running across the right-hand strips appear in this radiograph. The position of one crack is offset from the other and the density of one set is less than the other because one is in the top strip and the other in the bottom. A series of cracks running parallel to the length of the strips (perpendicular to the strip cracks) can be seen; these are associated with the insulation packing between strips. The radiograph in Figure 9 also exhibits partial-penetration cracks in the left-hand strips. One set of partial-penetration cracks are in the Z-bend area while another is near the braze area. The radiograph indicates that these latter cracks penetrated back toward or into the braze area.

Another radiograph was taken that highlighted the braze-joint area (Figure 10), illustrating that the partial-penetration crack front in the strip did run past the edge of the bus bar but that the region it runs into is an unbrazed area. The dark gray regions in the light-colored area at the bottom of Figure 10 are unbrazed areas. This radiograph indicates that there was considerable unbrazed area near the front side of the joint at one of the

FIGURE 9. X-Ray Machine Radiograph of F-Outer Joint Maximizing Cracking Contrast

FIGURE 10. X-Ray Machine Radiograph of F-Outer Joint Maximizing Detection of UnbraZed Area

strips. The unbraZed areas appear darker because they contain less material; the smaller the amount of material through which x-rays must travel, the greater the exposure to the film.

The radiograph in Figure 11 illustrates detection of the E-outer Z-bend cracks. Not only are the cracks themselves readily detectable, but the radiographs indicate that the crack front progressed by an intergranular, jagged path.

Radioactive Isotope X-Ray Radiography

Radioactive isotope radiography was investigated for in-situ inspection as it was possible to place the isotope x-ray-emitting source between individual joint layers, thus allowing radiographic inspection of individual joints. However, compared to classical x-ray machine radiography, this inspection technique was less sensitive in detecting cracks.

The in-situ geometry created physical limitations in using the radioactive source over the source-to-joint and source-to-film distances. In addition, in-situ joints were wrapped with insulation and the gaps between strips were filled with an insulating material that was itself fractured. These factors decreased detection resolution and complicated film reading. However, resolution was found to be sufficient to allow ready detection of through-wall cracks (Figure 12) and partial-penetration cracks (bottom left-hand side of Figure 13) in Z joints that have had the insulation removed.

Unexpected problems arose in onsite inspection of in-situ Z joints when indications that were originally interpreted as cracks in the strips turned out, upon removal of the insulation, to be cracks in the insulation between strips. The problem arose because the cracks in the insulation ran perpendicular to the length of the strips, the same direction as cracks in the strips. All previously observed cracks in the insulation, such as seen in Figure 9, ran parallel to the strips. It was therefore assumed that any cracks running perpendicular to the strips were in the strips themselves. This is not, however, an insurmountable inspection problem. It simply means that extra radiographs highlighting the difference between cracking in insulation and in strips will need to be taken when in-situ cracking is detected.

FIGURE 11. X-Ray Machine Radiograph of E-Outer Joint
Illustrating Detection of Z-Bend Crack

FIGURE 12. Isotope Radiograph of F-Outer Joint Illustrating Detection of Through-Thickness Crack

FIGURE 13. Isotope Radiograph of F-Outer Joint Illustrating Detection of Partial-Penetration Crack

METALLOGRAPHY

Metallography was performed on three brazed joints. Two of these were Z joints and the third was a flat joint. One Z joint was from the F layer while the other was from the D layer, two levels above the F layer. The flat joint was from the A layer. There were visible cracks in the F-layer joint but none in the D- or A-layer joints. Radiography revealed the visible cracks as well as multiple nonvisible cracks in the F-layer joint. No cracks were detected by radiography in the D- or A-layer joints.

A full joint characterization was done on the F-layer Z-bend. This included material from the unaffected bus-bar region, the complete braze area, the strip region near the braze area, and the strip region near the bend area. The various F-layer specimens were chosen so that they lay in a line parallel to the bus-bar edge. The line was selected so that it cut a region where visual and x-ray observations indicated that there were partial-penetration cracks present near the braze area and in the Z-bend area (Figure 14). Neither the D-layer Z nor the A-layer flat exhibited visual or x-ray-detectable cracks. Random cuts were therefore made in approximately the same region where the F-layer cuts were made.

Specimens were observed in both the as-polished and the polished-and-etched conditions. Observation of as polished metallographically mounted specimens allows ready characterization of small cracks. Observation of polished and etched specimens allows study of brazing effects on grain structure and relation of crack-growth morphology to the microstructure.

OBSERVATIONS ON AS-POLISHED SPECIMENS

An overview composite picture of the F-layer Z joint (Figure 15) indicates that no cracking was present on the bus-bar side of the braze or in the brazed area but that considerable cracking occurred in the Z-joint material. Cracking had initiated in the unbrazed area, along the flat section of strip between the braze and the Z bend, as well as in the bend. The few deep cracks most likely developed from one of the many small surface cracks.

FIGURE 14. Schematic of Metallographic Specimen Placements for F-Outer Layer Z Joint

Small cracks are relatively evenly spaced along the surface from the brazed area to beyond the Z-bend area, while deep cracks are either near the brazed region or are in the Z bend. Higher magnification reveals that essentially all cracks initiate at surface pits, as shown in Figure 16. Note the speckled appearance of the as-polished surfaces in Figure 16 in contrast with the braze porosity of Figure 15. The speckles in Figure 16 are copper oxide particles, which are always present in TPC.

Surface pits were found on the bus-bar surface as well as along the complete length of the brazing strips. Thus, it is assumed that surface-pit formation is to be expected in TPC bar or strip and is not solely associated with the brazing operation. Pits are present along the vertical length of the Z even though no cracks are emanating from them (Figure 15).

Cross sections of the D-layer Z covered the regions from one braze area, around both Z bends, and into the other braze area (Figure 17). Multiple small

FIGURE 15. Unetched Metallographic Characterization of F-Outer Joint from Bus Bar to One-Half of Z

FIGURE 16. Cracks in F-Outer Connector Z-Bend Area

cracks emanate from surface pits but no deep cracks can be seen (Figure 18). Pits but no cracks are found in the A-layer flat joint (Figure 19).

Unbraze areas were found in all braze joints. The F-layer joint exhibited the highest degree of unbraze area, particularly near the edge of the bus

FIGURE 17. Unetched Metallographic Characterization of D-Outer Joint

FIGURE 18. Cracks Present in D-Outer Connector Strip

bar, as well as small voids all along the complete length of the braze (Figure 15). The D-layer joint exhibited braze voids along its length but complete wetting and filling of the bus bar, at least at this section (Figure 17). The A-layer flat joint exhibited complete wetting along the bus-bar length but exhibited unbrazed areas, as well. Braze material was even found on the top of the flat joint (Figure 8).

FIGURE 19. Unetched Metallographic Characterization of A-Outer Joint

OBSERVATIONS ON POLISHED AND ETCHED SPECIMENS

Observations of polished and etched F-layer specimens indicate that the cracks are intergranular in nature, both deep cracks near the braze and near the Z bend as well as the small cracks (Figures 20 and 21). This suggests that all these cracks propagated by the same mechanism. Cracks in the D-layer joint exhibited the same characteristics (Figures 22 and 23).

FIGURE 20. Etched Metallographic Characterization of F-Outer Joint

FIGURE 21. Illustration of Intergranular Nature of Crack Propagation in F-Outer Strip

Comparison of the microstructures in the vicinity of the braze, as shown in Figures 20, 22, and 24, indicates that the temperatures as well as the amount of additional braze material varied greatly between brazes. The F-layer braze exhibited the least amount of heat and the least amount of added braze

FIGURE 22. Etched Metallographic Characterization of D-Outer Joint

FIGURE 23. Illustration of Intergranular Nature of Crack Propagation in D-Outer Strip

material. Both the amount of heat applied and the amount of braze material added appear to increase from the bottom layers to the top layers.

The differences in grain structure near the various braze areas yield general information about the brazing time/temperature conditions. Well-annealed material only exhibits grain growth as it is heated to high temperature or held

FIGURE 24. Etched Metallographic Characterization of A-Outer Joint

at intermediate temperature for long time. Material that has been cold-worked and then heated first recrystallizes to a smaller grain size and then exhibits grain growth if held at elevated temperature. The greater the amount of cold work, the faster the grain-refining recrystallization process proceeds. This change in microstructure is illustrated as a function of time at temperatures, cold work, and room-temperature yield strength in Figure 25 (AMAX 1974). Yield strength increases with amount of cold work and decreases as recrystallization and grain growth proceed.

FIGURE 25. A Survey of Property of ANP-OFHC Band Copper

Observations of the various grain structures present in the braze areas indicate that both the bus-bar material and the strip material contained enough cold work to promote grain refinement before grain growth began. This can readily be seen in the bus-bar case if one compares the grain sizes present outside, shown in Figure 20, with the grain structure present in the various braze areas. The grain structure away from the braze is relatively uniform in size across the complete cross section. The grain structure in the braze region in the F-layer braze (Figure 20) exhibits a refined structure near the braze and a structure similar to that found away from the braze in the middle region of the bus bar.

The D-layer bus bar in Figure 22 exhibits intermediate grain growth close to the braze and a refined grain structure in the middle of the bus bar. The A-layer bus bar in Figure 24, exhibits large grain growth near the braze and intermediate grain growth in the middle of the bar. These results indicate that the F-layer braze was cooler than the D-layer braze, which in turn was cooler than the A-layer braze. This is because the grain-size change sequence upon heating would be: 1) no change, 2) refined grain size, 3) intermediate grain size, 4) large grain size. The qualitative ranking of the heat input into these brazes determined by grain-structure analysis agrees with the ranking presented earlier on the basis of braze-metal fill.

The result of an analysis of the strip grain structure is a little more complex as there was no real as-received microstructure well away from the braze zone for classifying typical as-received grain structure. However, the general trends in changes of strip microstructure agree well with those of the bus bar.

Although the above observations are made from only one cross section in each of the many brazes and coverage by nondestructive inspection techniques was limited, the results apply to the failed region, at least. If other joints were made in the same way and subjected to the same nominal operating times and stresses, they are likely to be microcracked or worse.

OXYGEN ANALYSIS

Oxygen-analysis specimens were taken from various sections of the bus bar and brazing strips to determine whether oxygen uptake during brazing or service could be a contributing factor in the component failure. It was hypothesized that oxygen could be picked up during a very high-temperature braze or possibly during operation if a corona was present between the copper and the insulation. Oxygen specimens were taken from the D-layer Z joint and from the A-layer flat joint.

The oxygen analysis results are presented in Figure 26 and indicate essentially no change in oxygen content due to brazing or subsequent service. In fact, if there is any change at all, the oxygen content appears to decrease near the braze area. It also appears that the oxygen content of both bar and strip are approximately the same and well within the expected range of TPC oxygen content of 200 to 800 ppm.

CORROSION-PRODUCT ANALYSIS

An olive-green corrosion/oxidation product was present on the surfaces of the majority of through-thickness cracks. A corrosion-product analysis revealed that the following crystalline phases were present:

- copper chloride
- copper oxide
- hydrated calcium sulfate.

The phases are listed in order of relative amounts. Copper chloride and copper oxide are expected corrosion/oxidation products of copper. Calcium sulfate was probably leached out of the mica insulation. Neither the chloride nor oxide exhibits a green color, according to the Handbook of Chemistry and Physics (Weast, 1984-1985), but a complex copper oxide/chloride does. Thus, it is postulated that the olive-green color comes from a noncrystalline copper-oxygen-chloride complex.

FIGURE 26. Oxygen Content for Various Positions Along Z and Flat Joints

DISCUSSION

The x-ray inspection capabilities and the failure mode of the brazing strip are discussed in this section.

ASSESSMENT OF X-RAY INSPECTION CAPABILITIES

A comparison of the x-ray radiographs and the metallography results allows an estimation of the expected crack-detection sensitivity of in-situ radiographic inspection. Radiographic inspection can readily detect component failures when through-thickness cracks run the length of a brazing strip (Figures 9 and 15). However, radiographic inspection cannot detect the very fine, short cracks (less than 5% of the strip thickness) that are also present in the F-layer Z joint (Figure 16). The expected detection limit of in-situ isotope radiography in the specific instance of Z-strip inspection lies somewhere between these two extremes.

A determination of the capability of radiography to detect defects requires a knowledge of the type of defect present as well as the sensitivity of the x-ray technique. Metallography illustrates that the cracks in the strips were propagating in an intercrystalline manner. This means that x-ray inspection of these cracks would be less sensitive than a comparable inspection for typical high-cycle, fatigue-induced cracks, which are transcrystalline and usually straighter, because x-rays travel in a straight line and x-ray defect detection depends on depth variations in the traversed material.

The above discussion indicates that actual inspection records must be used to determine inspection sensitivity in cases such as the strip failures. A careful comparison of radiographs and metallography leads to the expectation that intercrystalline cracks one-half the thickness of the strips can be detected. Examples of inadequate crack detectability are the small cracks, that were not detected by radiography; these cracks are less than half-way through the Z-bend of layer D in Figure 18. Examples of positive detectability are the cracks that are nominally halfway-through near the braze region and in the bend region in the F-layer Z (Figure 15). The radiographs illustrating detection of these defects appear in Figures 9, 10, and 11.

ASSESSMENT OF BRAZING STRIP FAILURE MODE

This investigation has documented that the brazed Z-formed strips failed prematurely by a predominantly intercrystalline mode. It appears that these intergranular cracks initiate from pits in the as-received copper-strip surface, that cracks initiate on both sides of the strips, and that they propagate from both sides towards the center. The change in corrosion-product color and apparent thickness as a function of strip thickness indicates that the cracks are slowly propagating in a fatigue-induced manner.

Failures characterized during this study occurred in two distinct locations. One was in the strip at the end of the braze, and the other was in the Z-bend radius; failures were not exclusively associated with the braze area. Both failure locations are stress-concentration regions. Flexing or axial stress is concentrated in strip material near the braze due to the change in restraint, i.e., from the thick bus bar to the thin strip. Stress is concentrated in the bend region because of flexing loads or displacements, plus possible residual stresses due to bending experienced after brazing. Thus, it is not very surprising to observe that cracks form at either the brazed end of the strip or in the Z bend.

A simple residual stress field plus axial expansion/contraction strains would be expected to result in localized bending stresses in only one dominant loading direction. The fact that apparent fatigue-induced cracks propagate from both sides of the strip indicates that the strips are seeing a complete stress reversal cycle. It is likely, however, that the loads/strains associated with this fatigue cycle were augmented by residual and thermally induced strains.

An initial resonance vibration analysis conducted by the generator manufacturer at the time of installation indicated that there should be no resonance problems when the generator was operated near 120 Hz. However, further analysis of these early results indicated that they were only applicable for the segments which did not contain Z joints.

A recent analysis of the left- and right-hand segments that contain Z joints indicates that the left-hand segment, where the failure occurred,

should experience a resonance around 120 Hz while the right-hand side, where no failures were found, should not. The difference in resonance response was attributable to different distances between left- and right-hand segment-support members.

It was visually observed that there was considerable separation between failed surfaces in joints where fewer than all four connectors failed. This indicates that the failed joint was under considerable tensile residual stress, which would be expected to add to the service-induced loads. In addition, it is expected that this highly stressed member probably carried more than its expected quarter of the service-induced load due to its eccentric geometry. It is assumed that the final contact between connectors and bus bar before brazing was achieved by clamping force instead of by adjustments in connector configuration. This would account for the high residual relaxation strain exhibited in Z joints with failed connectors. Thus, it is expected that connectors in a given Z joint would fail in a serial sequence, which would be dictated by individual connector geometry, and that connector-failure rate would increase with time.

In a phenomenon characteristic of material embrittlement, both failure regions exhibited intercrystalline cracking without any apparent localized necking. The fact that cracks in both regions failed similarly indicates that metallurgical changes induced during brazing, such as accelerated grain growth, were not the controlling factor. Therefore, other embrittling failure mechanisms must be considered. A major analysis problem is associated with the type of cracking mode exhibited by the failures.

Copper structural members can fail prematurely in a number of ways. These include:

1. general corrosion
2. galvanic corrosion
3. pitting
4. intercrystalline corrosion

5. stress-corrosion cracking
6. corrosion fatigue
7. high-cycle fatigue
8. creep
9. hydrogen embrittlement.

The first 4 failure modes require a corrosive atmosphere; numbers 7 and 8 require the action of stress; 5 and 6 require the presence of both a corrosive media and stress activity; and number 9 requires the presence of hydrogen at high temperatures plus stress action at low temperatures.

General and galvanic corrosion are ruled out as the mechanism because they result in a general thinning of the material and the strip failures exhibited extremely localized penetration, not general attack. Pitting is present on the bus bar and strip surfaces but is not the controlling fracture mechanism. Pitting, per se, does not penetrate very far into the thickness of the copper.

It is also possible that the pitting on the copper surface results from manufacturing processes and not from corrosion. Corrosion pits require an aqueous atmosphere accompanied by localized oxygen-concentration cells. It is not obvious that either the aqueous atmosphere and/or the concentration cells are present on the copper surface under the insulation. It is postulated that pits may be formed in the rolling operation and are actually places where copper oxide particles resided during rolling, but have been torn or expelled from the copper surface during handling or heating. The resultant defect would then be accentuated by further reduction in thickness. Whether the pits were formed chemically or mechanically, it is obvious that the majority of cracks detected in the strip emanate from the bottom of pits.

Intercrystalline corrosion preferentially attacks grain boundaries, as is seen in the strip failures, but multiple surface grains are attacked instead of the attack propagating into the thickness along a single crack front, as seen in the strips. Stress-corrosion cracking does propagate in an intercrystalline manner but is not the expected failure mechanism in this particular case because copper is very resistant to such attack, except in the presence of ammonia or ammonium compounds.

High-cycle fatigue and corrosion fatigue both yield transcrystalline cracking and are thus ruled out, as the strip cracks are intercrystalline in nature. Creep is not expected at the low temperatures experienced by the bus-bar system [estimated to be less than 100°C (212°F)] since low-temperature creep induces a transcrystalline failure. High-temperature creep on the other hand, induces intercrystalline failure.

This process of elimination leaves hydrogen embrittlement as the suspect failure mechanism responsible for the observed intergranular cracking. Hydrogen embrittlement induces intercrystalline failures and TPC is susceptible. It is, however, only susceptible under certain specific conditions. Hydrogen gas must be present and the copper must be heated above 374°C (705°F). If these conditions are met, the hydrogen diffuses into the TPC and reacts with copper oxide particles, reducing the copper oxide to free copper and releasing steam in the process. High-pressure steam is formed around the internal copper oxide particle and the associated high stresses create micro-fissures in the copper. This fissuring takes place preferentially on the grain boundaries because they are high-diffusion-rate paths for the hydrogen when it enters the copper. Thus, submicroscopic fissures are formed on the grain boundaries by high-temperature hydrogen embrittlement; these boundaries readily fracture under modest stresses at low temperature.

The high temperature required for steam formation implies that hydrogen ingress took place during brazing. The potential for hydrogen embrittlement of TPC during brazing in the presence of hydrogen is well documented. Was it possible for hydrogen to be present during the brazing of the Grand Coulee Dam generator bus-bar joints? Westinghouse investigated this question and determined that hydrogen embrittlement could occur if the braze was fluxed; they also determined that it was not expected to occur when brazing with fluxless Sil-Fos, as in the present application (Belkin and Nagata 1975).

The problem with the above conclusion appears to be that the Westinghouse study was done under controlled laboratory procedures and did not take into account the use of graphite electrodes, which were used in the onsite brazing. It is well known that graphite electrodes degrade by oxidation during use. For this reason, they are not recommended for use in continuous

production. It is postulated that the graphite electrodes oxidize at high temperatures by reacting with water vapor and oxygen in the air. The water vapor is reduced in this process and free hydrogen is released. This hydrogen in turn reacts with the copper to promote hydrogen embrittlement. Thus, the hot graphite electrodes create their own hydrogen atmosphere.

According to this scenario, the observed failures were induced by fatigue loading even though the fracture did not exhibit classical transgranular cracking morphology. It appears the the intergranular cracking morphology observed in this specific failure was controlled by a grain-boundary hydrogen-embrittlement mechanism.

The standard recommendation for eliminating the possibility of hydrogen embrittlement when using TPC is to replace it with oxygen-free copper (OFC). The literature indicates that industrial hydrogen embrittlement problems are only associated with coppers containing copper oxide particles (AMAX 1974). Oxygen-free copper is processed differently from TPC; this results in the elimination of copper oxide particles, thus eliminating the likelihood of hydrogen embrittlement.

In addition, a doubling of fatigue life can be expected by changing from TPC to OFC, as illustrated by Figure 27 (AMAX 1974). Thus, replacing the presently used TPC with OFC improves both resistance to hydrogen embrittlement and increases fatigue strength (AMAX 1974; Behnood and Evans 1983; Panousis, Wonsiewicz and Condia 1977).

FIGURE 27. Fatigue Strength of OFHC and TPC, Cold-Worked 70%

RECOMMENDATIONS

It is recommended that replacement connectors be fabricated from OFC instead of TPC and that the surface finish of the OFC be improved over that of the original TPC. It is also recommended that the Z-joint-containing segment-support spacing on the side of the generator where the failures occurred be changed so that a resonance phenomenon is not possible in the 120-Hz range.

Two other recommendations are that the radius of curvature of the Z joints be increased and that more care be taken to measure that all four connectors in a given Z joint are as uniform in configuration as possible. The increase in Z-joint radius will reduce the stress concentration in this area and, thus, is expected to increase the life of the component. Increased connector uniformity will allow equal load distribution to all connectors in a given joint. This is expected to increase the life of the joint over the joints originally installed, which exhibited considerable variation in connector geometry within a given joint.

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