ENCLOSURE 3

NINE MILE POINT UNIT 1 CORE SHROUD CRACKING EVALUATION

Nine Mile Point Unit 1

Core Shroud Cracking Evaluation

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Vertical Welds V-9 and V-10

Background

Visual inspection of the core shroud at Nine Mile Point Unit 1 (NMP-1) during refueling outage number 14 (RFO14). Extensive cracking was identified in the weld heat affected zones of certain vertical welds of the core shroud shell courses. Since the integrity of these welds is needed to support the structural requirements for tie rod repairs that were implemented in March 1995 (RFO13), a thorough investigation was undertaken to understand the observations and validate the integrity of the core shroud. An independent evaluation conducted to investigate the extensive cracking identified adjacent to the V-9 and V-10 vertical welds in order to support the overall assessment of core shroud integrity. The results of this evaluation are presented in the following report. Technical information, developed by MPM Technologies and referenced in this evaluation, is included in summary form as an attachment to the overall NMP-1 report.

General Information

Nine Mile Point Unit 1 is a BWR 2 having five external recirculation pump loops. The core shroud is an internal component designed as a stacked cylindrical structure that channels coolant water flow through the reactor core. The uppermost cylinder in the shroud geometry is slightly larger than the lower cylinders in order to accommodate the core spray spargers. Shroud cylinders are constructed of regular grade Type 304 (ASTM A-240) stainless steel plate material. Three heavy ring sections (also constructed of regular grade Type 304 stainless steel material) are welded to the ends of some of the cylinders and provide the support structures for the separator head, the top guide and the core plate. G. O. Carlson supplied the materials. A review of the CMTRs did not reveal any unusual chemistry or mechanical property differences among the plates. The shroud was fabricated by P.F.Avery Corp., Billerica, MA during the period 1965-1967 using fabrication practices typical of that time period. The material was cold rolled and

processed then solution heat treated (SHT) 1850^{0}F to 2050^0 F and rapid quenched to a temperature below 700^{0}F. The degree of cold working was controlled by specifying a maximum surface hardness of R_B 90. Cold straightening and bending was permitted after SHT if a bending radius equal to or greater than 20T was maintained. A minimum ferrite content in the weld deposit was specified at 5% to minimize the potential for hot cracking during welding. It was subsequently discovered that the minimum ferrite requirement was also beneficial to develop resistance to IGSCC. The minimum ferrite level required for resistance to IGSCC is a function of the carbon content, and typically exceeds 8% ferrite. Ferrite levels lower than 8% are beneficial but protection from cracking cannot be assured. A submerged arc welding process was used for most shroud cylinder welds, although it is clear from visual inspection records that the closure weld (H4) was a manual process likely performed in the 2G orientation and had about 5 to 6 passes on the weld crown. Vertical welds joint configurations were designed as double-vee (22½^0) geometries. Typical fluence levels near the H4 and H5 welds were estimated by General Electric Nuclear Energy to be about 3.5 x 10^{20}n/cm^2 for the shell course containing the V-9 and V-10 welds. Shop records indicate that the H5 weld was intermittently undersized at the 200 degree azimuth, and was repaired by adding additional weld metal. This was the only deviation report available for fabrication of the core shroud.

Visual Examination of the Inspection Tapes

The following observations were noted during a visual inspection of the inspection tapes. The overall evaluation of welds V-9 and V-10 is approached from an assumption that physical cracking observations accurately reflect, and are direct evidence of the physical and chemical conditions that govern core shroud degradation. The observations are listed for convenience.

1. Apparent continuous cracking of the vertical welds is found in the 90 inch tall shell course located between horizontal welds H4 and H5
2. Cracking is extensive on vertical welds V9 and V10 which form the shell between two plates.

- Dominant cracking pattern on these vertical welds is effectively concentrated within the weld HAZ and predominately originating from the outer surface.
- The cracking pattern is confined to the weld HAZ, and overall, is predominantly parallel to the weld. From a detailed perspective the cracking orientations are highly mixed within the HAZ having both axial and circumferential features. In many cases cracking patterns are observed that encircle small areas within the weld HAZ. The cracking characteristics reflect the complex residual stress patterns near the surface and associated with the weld HAZ. Cracking patterns with these same general features are similar to IGSCC patterns observed in degraded core shrouds at other plants.
- Cracking from the OD surface at V-9 and V-10 was measured using ultrasonic sizing techniques. The through-wall crack depth dimensions were greater near the H-4 horizontal weld (top) as compared to locations near the H-5 horizontal weld (bottom). A maximum through-wall dimension was observed at approximately 60 to 80% through-wall dimension. The thruwall cracking dimension was measured to be approximately 50% more shallow at the bottom than at the top. No cracking depth could be measured within 8 inches of the bottom of the V-9 weld (adjoining H-5) using state-of-the-art ultrasonic sizing techniques.
- OD axial cracking is seen in both plates making up the subject cylinder; however, most of the cracking associated with the vertical welds is concentrated in one plate (located between azimuths from 190^0 to 10^0) of the two plate cylinder construction. The cylinder is 90 inches tall and 174 1/16 inch ID. Plate thickness is 1.5 inches. This doesn't imply that the second plate is immune to cracking, because OD cracking adjacent to vertical welds is observed in both plates. The extent of cracking is significantly less in the second plate compared to the first plate. Cracking is seen in both of these plates associated with both horizontal welds (H-4 and H-5) on the top and bottom of the cylinder. It appears that the degree of sensitization (material susceptibility) may be slightly greater in the plate for which cracking is more pronounced. These differences are likely related to differences in the rates of quenching from solution heat treating temperatures, or in the maximum

temperatures achieved during solution heat treatment as opposed to specific plate chemistry differences.

- Axial cracks in the subject vertical welds were much easier to see during visual inspection than for cracks at other locations. The improved visibility may be to be due to a larger crack mouth opening at the surface. It is believed that these cracks are easier to see than core shroud cracks seen elsewhere where cracks are driven solely by the action of localized residual stresses.
- The absence of axial cracking on the inner surfaces of weld HAZs of V9 & 10 is significant since these ID surfaces are at the same azimuths and elevations that are cracked extensively on the outer surfaces. A complicating factor is that the environment is more oxidizing and the material at a slightly higher fluence (more susceptible) on the inside than on the outer surfaces where the cracks originated. A minimal number of short circumferential cracks were observed on the inner surfaces of both vertical welds. These circumferential cracks remained largely within the weld HAZ and did not progress along a direction parallel to the length of the weld. The greatest concentration of these short circumferential defects was seen on the more sensitive plate side of weld V-10. There were a total of 18 locations in which circumferential cracks were found visually on one side of the weld, and 4 locations on the other side of the same weld over a total weld length of 90 inches. Therefore these indications represent only a very small portion of the cylinder height because the dimension across each crack opening is only a few mils. The orientation of the ultrasonic search units during examination were such that small defects in the circumferential orientation would not be seen. On the inner surface of weld V-9 similar visual observations were seen at 4 locations on one side of the weld, and 6 locations on the other side of the weld. Ultrasonic examination saw none of these indicating very little, if any, axial dimension.
- Edges of the outer surface of weld preps on V9 and V10 were visually observed to be ground on both sides. Such grinding is typical of methods that would have been used to smooth any geometrical anomalies across the weld. This may indicate some difficulty with

fitup while fabricating the shell course. It is very difficult to produce a uniformly smooth circle with a large diameter welded structure. The source of the difficulty is the process of bending the shell plates to a circular configuration and the localized distortion attendant to welding the ends of the rolled shell plates. This configuration and the additional strength of the weld metal over the base plate material lead to a local increase in stiffness at the weld.

Cracking Scenario

Understanding the reason or reasons for the extensive number of outer surface cracks in the longitudinal welds V9 and V10 is important to understanding the core shroud degradation. Other utilities have not seen the same extent of nearly continuous cracking in vertical welds. Only minor circumferential cracking is seen on the ID of these welds. A plausible mechanism is suggested that explains the patterns of intergranular stress corrosion cracking (IGSCC) observed in these welds.

Required Parameters for Cracking

Three coincident parameters are required for IGSCC; namely a susceptible material, an environment that supports cracking, and the presence of a tensile stress to help initiate and drive cracking. The details of specific influences on each of these parameters is extensively documented in the literature, and the observations of IGSCC in stainless steel recirculation loop piping and susceptible in-vessel components of BWRs are well known. In particular, cracking has been seen in many BWR plants in the weld heat affected zones (HAZs) of Type 304 stainless steel (both high and low carbon containing materials). Core shroud weld HAZs have been particularly susceptible. All of the requisite parameters for IGSCC are present in the core shroud, and the presence of IGSCC is expected. In fact a preemptive tie rod repair was implemented in March 1995 during refueling outage (RFO13) based upon this knowledge.

The combined actions of the neutron and gamma fluxes will alter each of the three parameters required for IGSCC. The phenomena are all time dependent factors. First, the material is made more vulnerable (enhanced degree of sensitization, DOS). This influence is seen at NMP-1 as an enhancement of existing levels of sensitization produced thermally during welding or original plate heat treatment. The enhancement process is normally seen for irradiation fluence levels approaching 10^{19} neutrons/cm^2. Second, the oxidizing power of the environment is increased by radiolysis of the water passing near and around the core. Radiolysis takes place as the water flows in proximity of the reactor core. The recombination of oxidizing species produced by radiolysis is time dependent and continues to occur around the coolant circuit. The corrosive power of the coolant is greatest at inner surface locations of the upper portion of the core shroud. At some locations the radiolysis and recombination processes occur simultaneously. The purity of the demineralized water making up the environment also influences the environmental parameter, and in particular the quality of the water depends upon the presence or absence of harmful specific anions such as chlorides or sulfides. Third, the influence of irradiation on the levels of residual tensile stress is related to time dependent stress relaxation processes (creep). The effect will be seen as a reduction in the magnitude of residual tensile stresses at fluences as low as 2 or 3 x 10^{20}neutrons/cm^2. Finally, Irradiation Assisted Stress Corrosion (IASCC) has been identified to characterize a special case of IGSCC in which prior thermal sensitization of the material is not required, and the stress driving force is generated internally. The appearance of IASCC will be similar to the IGSCC found in the core shroud except that crack mouth opening is always very tight, and crack faces will be heavily oxidized. IASCC is not restricted to locations previously sensitized by thermal processes such as welding. The fluence levels necessary to trigger IASCC are believed to exceed 5 x 10^{20}neutrons/cm^2. The maximum fluence for the vertical weld of this evaluation is about 4 x 10^{20} neutrons/cm^2, and thus the IASCC threshold has not yet been reached for these welds. Therefore, the irradiation influence on the core shroud V-9 and V-10 welds is one of enhanced material sensitization, increased oxidizing power of the environment, and potentially reduced magnitudes of residual stress particularly in the latter stages of growth. The

time dependency of these effects always must be considered when evaluating the timing of their influence.

Sources of Stress

The core shroud functions to direct the flow of coolant water through the reactor core during operation. During postulated emergency accident conditions, it also serves to maintain core and control rod alignment. It is not a pressure boundary component and the applied stresses are extremely low at all shroud welds. Therefore the driving forces for IGSCC are short range residual stresses. Typical sources include welding, machining and grinding, and longer range locked in stresses from fabrication and installation (fit-up). IGSCC driven by residual stresses has a distinctive surface appearance (tight with very irregular paths (wandering in and around the weld HAZ). The cracking characteristics observed in the NMP-1 core shroud exhibit an appearance typical of what has been seen in other BWRs. The principal differences in the patterns of cracking observed at NMP-1 lies in the extent or severity of cracking in the shell course containing longitudinal welds V-9 and V-10. The importance of these new observations is in the extent of the cracking and the relationship of that cracking extent to the design of the preemptive tie rod repair that already has been installed.

As stated above, localized residual stresses and locked-in fabrication stresses make up the primary driving force for core shroud IGSCC. The localized residual stress patterns will vary with location, but generally are tensile as a result of processes used in the fabrication of core shrouds. The residual stress patterns developed while welding of austenitic stainless steel (single phase) materials are reasonably well established by measurement and are predicted successfully using finite element modeling.

The extensive cracking seen in vertical welds V-9 and V-10 have not been reported in the industry; however in many cases the inspection of vertical welds has been limited to locations near

the intersections with horizontal girth welds. Although cracking was known to be possible along vertical welds, it was felt that the extent of any cracking along vertical welds likely would be less than the extent of cracking along horizontal welds, because lower residual stresses should result from the high degree of flexibility that exists in individual shroud cylinders. Unfortunately, extensive cracking patterns have been identified with the V-9 and V-10 welds, and these cracks are observed predominantly on the outer surface. It should be pointed out that ID cracking was also observed on other vertical welds, but the two welds of this evaluation are in the shell course that surrounds the reactor core, the cracking associated with these welds is nearly continuous, and the cracking locations are primarily on one side and that side is opposite to what would be expected from environmental and materials considerations. Therefore, a mechanism is needed to explain the residual stress patterns (or other conditions) required to explain the observations.

A detailed view of fitup stresses, locked in while assembling shell courses to make the shroud geometry, provides insight useful to explain the observed cracking patterns. The individual shell courses of the core shroud are fabricated into right cylinders. Two plates are rolled to shape, end weld prepped, plates fitted end-to-end, and tack welded to form a cylindrical shape. Next, these cylinders are positioned on their side to provide a horizontal groove in which to apply the submerged arc welding process (SAW). Welds are first applied from the inner surface, then back chipped and welded from the outer surface. Welding parameter differences (within the range of the qualified procedure) are predicted to result in different residual stress patterns and magnitudes. Recent predictive modeling at MPM Technologies suggests that the residual stress patterns near the inner surface of the core shroud will be lower in magnitude from those near the outer surface when the welding heat input is on the low end of the qualified procedure for NMP-1 core shroud fabrication. Maximum stresses are predicted to be tensile on both surfaces, but the tensile stress on inner surface will be at a lower magnitudes than those produced on the outer surface. As the welding heat input is increased to the upper end of the qualified welding procedure, the magnitudes of the tensile residual stress patterns tend to become the same.

Next the fitup effect is superimposed on the residual stress patterns developed when welding two unconstrained plates into the in the shroud cylinders. If the shell plates resulting from rolling are not perfect half circles, some degree of adjustment will be required to fit the plates into a round cylinder. Typically, adjustable internal structure(s), known as spider(s), are fitted into the assembly to provide both adjustment and support. Temporary welds are used to secure the spider(s) to the shell plates. [Note: evidence of a removed spider was seen near the top of one of the vertical welds during visual examination.] The shell structure is very flexible because of the large diameter (174 inches) and the thin wall (1.5 inches) geometry. In addition, the subject shell section between horizontal welds H-4 and H-5 is 90 inches in length. Calculations indicate the shell resting on its side would deform 2 inches from its own weight. The spiders resist this effect and typically two or more are used on a shell of this size. The flexibility of the shell is demonstrated and a 2 inch to 6 inch adjustment is reasonable. Calculations by MPM Technologies that consider the superimposed effects of both welding residual stresses, and the changes in those stresses attendant to fitup adjustments of 2 inches deflection (at the weld azimuth), predict that the residual stress pattern for the low heat input weld will be characterized by an ID axial tensile stress that is below the threshold (or marginal) required for crack initiation. The OD axial stress was higher than that produced by welding alone. This is precisely the type of residual stress pattern suggested by the cracking pattern seen on the shroud vertical welds. A 2 inch adjustment (deflection) is reasonable to expect for a shell of this size. Larger fitup adjustments produced very little change from these patterns. The effects on weld residual stress patterns produced at higher heat inputs were not altered sufficiently to suppress inner surface cracking.

Discussion of Cracking Patterns

A careful examination of cracking patterns and locations suggests that built-in fabrication residual stresses are dominated by large tensile stresses near the outer surface of the H-4/H-5 shell course, and stresses exist near the inner surface are below those required to initiate cracking on the inner surface. Modeling studies suggest that the highest surface stresses are oriented axially, and these

are the stresses that initiate IGSCC. As the cracking progresses into the wall thickness, the tensile component of the axial stress rapidly drops and becomes compressive. A compressive stress field would arrest a growing crack, except that the hoop stress remains tensile and will tend to produce a combined stress (principle stress) that turns the cracking direction to axial and growth continues. The hoop stress (circumferential) has been predicted to be lower than the axial stress on the surface, but once a crack is initiated, the hoop stress can support a crack propagating along the axial direction. The axial stress is reduced as the circumferential flaw extends away from the weld, and the material degree of sensitization decreases. Eventually the conditions for crack growth will not be supported. Thus the crack remains tensile for significant through thickness dimensions. Therefore, cracks will tend to initiate in the hoop direction, then turn to grow in the axial direction under the action of the hoop stresses. This pattern is followed on both ID and OD. The residual stress predictions developed by MPM Technologies suggest that the growth of an axial crack from the shroud OD surface will become very slow at depths about 1 inch into the plate, because the stress intensity falls to very low tensile levels (approximately 5 ksi-in$^{1/2}$).

Some degree of inner surface axial stresses are suggested from the few circumferentially oriented cracks seen visually on the ID. The presence of circumferential cracks indicates that axial stresses exceed a crack initiation threshold. However, the hoop stresses near the ID apparently are of insufficient magnitude to turn the cracks and cause them to propagate into the thickness. An evaluation of the cracking patterns observed in the V-9 and V-10 welds appear to be supported by the modeling results that combine the shell fabrication processes of welding at a low heat input and having to deflect the shell for fitup.

The fitup of multiple shell courses will introduce additional changes to the residual stress patterns around certain weld locations. The vertical weld patterns described above will be altered for a distance of about 10 to 12 inches from the intersection of the horizontal weld being fitted. The weld residual stress pattern for the horizontal weld will be altered if adjustments to mitigate ovality are required to fitup the mating shell courses. This manipulation is likely to be highly

variable according to the degree to which the shell section must be adjusted for fitup. If the shell long seam is pulled inward then released after tacking, the horizontal shell weld will be placed into residual tension on the OD, and residual compression on the ID. Similarly if the shell is pushed outward 90^0 from the welds, the material on the outer surface will be placed into compression at the weld, then will reverse to tension OD and compression ID upon release of the adjusting deflection. Both of these scenarios will produce the locked in stress fields that are likely to vary around the circumference, based upon the jacking required to move individual locations into alignment. Cracking patterns can be highly variable and are difficult to predict apriori.

The question remains "Why don't all the longitudinal seams exhibit the same cracking behavior?". This is believed to be due to individual circumstances related to manufacturing the shell courses. No two shell courses will be fabricated (formed and welded) exactly the same, they will not require the same out-of-roundness adjustment for fitup to form the shell, nor will they necessarily be symmetrical. Fitting one shell to another also requires adjustment, and will influence the stress state in the shell course for locations up to 10 to 15 inches remote from the horizontal girth welds. When the shells are relatively short, the zone of influence on the residual stresses developed during the fabrication of individual shells will be altered over a substantial portion of the shell. An example of a short cylinder is the shell course between the H-3 and H-4 horizontal welds. This cylinder is 18 inches tall and the residual stress patterns for entire cylinder will potentially be influenced by the H-3 and H-4 welds. This is especially true for those cylinders welded to stiff heavy walled rings. In these cases the most of the deflections required for fitup will be taken up on the thinner cylinder side, and residual stress patterns will be influenced accordingly. Taller cylinders such as the 90 inch cylinder fabricated with the subject vertical welds V-9 and V-10 will be influenced over a much smaller portion of the vertical weld.

Finally, the reactor flux will result in a higher fluence at the upper portions of the V-9 and V-10 welds than will be present at the lower elevations of the same welds. Since an increased fluence will produce enhanced material sensitization, the crack growth may have propagated faster near

the top of the subject shell course than at the lower sections of the shell course. This would help explain the differences in crack depth along the subject vertical welds.

Conclusions

The cracking observations made on the vertical welds of the shell course between horizontal welds H-4 and H-5 have been evaluated as evidence describing the requirements for IGSCC. The cracking pattern in the vertical welds V-9 and V-10 is unusual compared to reported observations from most BWR utilities. Generally, a greater preponderance of cracking would be expected on the inner surfaces, because typical residual stress patterns would be similar on OD and ID, and the fluence effects on environment and material would tend to produce conditions more likely to experience IGSCC on the inner surface. Cracking patterns were just the opposite. A detailed evaluation of fabrication related residual stress patterns explains the cracking pattern differences seen in the core shroud at NMP-1. The cracking pattern differences within the first ten inches of the intersections between the vertical and horizontal welds are possibly related to fabrication steps joining the multiple shell courses. The differences in the depths of cracking between the top and bottom portions of the vertical welds are explained by the effects of fluence to enhance material sensitization and thus crack growth rates for a given stress intensity.

The nature of IGSCC at NMP-1 is similar to cracks seen in other BWRs. The specific conditions for the particular cracking patterns can be explained by normal fabrication practices used in manufacturing the core shroud.