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**INGRANULAR STRESS CORROSION CRACKING: A
RATIONALIZATION OF APPARENT DIFFERENCES AMONG
STRESS CORROSION CRACKING TENDENCIES FOR SENSITIZED
REGIONS IN THE PROCESS WATER PIPING AND IN THE TANKS
OF SRS REACTORS (U)**

by

M. R. Louthan

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

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To: J. M. Stone, 773-41A

From: M. R. Louthan, Jr., 773-41A

Intergranular Stress Corrosion Cracking: A Rationalization of Apparent Differences Among Stress Corrosion Cracking Tendencies for Sensitized Regions in the Process Water Piping and in the Tanks of SRS Reactors(U)

1.0.0 Introduction and Summary

The frequency of stress corrosion cracking in the near weld regions of the SRS reactor tank walls is apparently lower than the cracking frequency near the pipe-to-pipe welds in the primary cooling water system. The difference in cracking tendency can be attributed to differences in the welding processes, fabrication schedules, near weld residual stresses, exposure conditions and other system variables. This memorandum discusses the technical issues that may account the differences in cracking tendencies based on a review of the fabrication and operating histories of the reactor systems and the accepted understanding of factors that control stress corrosion cracking in austenitic stainless steels.

Derivative Classifier

Intergranular stress corrosion cracks have developed in the Type 304 austenitic stainless steel piping for the primary cooling water systems of SRS reactors. These cracks have been detected because of moderator/coolant leakage (from through-wall cracks) and by ultrasonic inspection (1). The initiation and propagation of the cracks has generally been confined to sensitized regions of the pipe. The inspection has therefore focussed on known sensitized areas. Cracks in the piping system have been identified and sized by inspection of weld heat-affected-zones and of flame washed areas. Approximately 7% of the heat affected zones in the pipe-to-pipe welds on the large diameter process water piping have been found, by ultrasonic inspection, to contain indications of intergranular stress corrosion cracks. Similar ultrasonic inspections of a significant fraction of the heat affected zones of welds in the Type 304 stainless steel tanks of both P and K reactors have shown no indications of cracking (2).

The apparent lack of stress corrosion cracking near the austenitic stainless steel reactor tank welds is of interest when compared to the 7% frequency of cracking in the austenitic stainless steel pipe welds. The observed difference in the cracking tendencies of the steel in these two regions of the SRS reactor process water system may be attributed to a combination of factors, including:

- 1) irradiation induced relaxation of welding residual stresses in the tank steel,
- 2) the use of several low carbon steel plates for reactor tank construction,
- 3) the relief of weld residual stresses by the rolling operation used during tank fabrication (applies only to the center girth weld of each reactor tank),
- 4) the effect of plate size on the residual stress pattern in the weld heat affected zones in the bottom portion of the tank,
- 5) the effect of welding process on the resulting residual stress pattern in the tank welds, and

- 6) the possible effect of irradiation induced free radicals on the tendency of the in-tank moderator to initiate stress corrosion cracks.

Very limited experimental evidence to substantiate the apparent difference in cracking tendencies was provided in a early 1960's, in-reactor, corrosion test program using fixed displacement, surveillance type samples.

2.0.0 Discussion

The susceptibility of austenitic stainless steel to intergranular stress corrosion cracking (IGSCC) is dependent on synergistic effects among the applied and residual stresses acting on the steel, the metallurgical condition of the steel, and the environment to which the steel is exposed (3). The metallurgical condition of the steel plays a key role in determining its susceptibility to IGSCC because such susceptibility is dependent on the existence of a continuous chromium depleted region. This chromium depleted region is anodic, relative to the remainder of the steel, and forms a path that is sensitive (or susceptible) to localized corrosion. If heat treatments and/or welding procedures induce the precipitation of chromium carbides and if the carbon content of the steel is above a critical level, grain boundaries may provide a through wall corrosion sensitive path. The critical minimum carbon content for sensitization is generally thought to be in the range of 0.02 to 0.03 weight percent C (4).

Interactions among stress, environment and metallurgical condition will therefore determine the relative susceptibility of any given section of steel to intergranular stress corrosion cracking. Differences in cracking susceptibility among the various SRS reactors and differences among the various regions in any given reactor must be explainable in terms of differences in the stress, the environment and/or the metallurgical condition of the steel. Because of differences in fabrication procedures, neutron fluences and the carbon content of steels used for fabrication, the SRS reactor tanks might be expected to show differences in IGSCC susceptibility relative to the process water piping. These differences are outlined in subsequent sections of this memorandum.

2.1.0 Stress

The moderator/coolant water system for the SRS reactors operates at relatively low pressures. The low system pressure and the conservative system design cause the applied stresses acting on the reactor tank walls and on the process water piping to be very low, relative to the yield strength of the steel. Because of the low applied stresses, the stress component of the stress corrosion cracking mechanism in the process water system is attributed to the welding residual stresses and to the system fit-up stresses.

The observation that stress corrosion cracks in the heat affected zones of pipe-to-pipe welds tend to be parallel to the welds provide support for the importance of residual stresses in the cracking process. If applied stresses were important to crack development, each crack would be expected to have a significant axial component. Because this is not the case, the residual stresses must play a major role in determining the direction of crack growth. The conclusion that residual stresses are the important crack driving stresses is also supported by metallurgical analysis of stress corrosion cracks in flame washed areas of pipe elbows (5). The typically low values of crack length to crack depth ratios in heat affected zones of pipe-to-pipe welds suggest that crack growth rates are approximately equal in all directions, as would be anticipated if the cracking process was driven by residual stresses in the near weld regions. Cracking in flame washed regions of elbows and transition pieces may be attributed to fit-up stresses because of the difficulty in matching pipe positions across transition joints. This difficulty in position matching would have contributed to the need to use flame washing during construction of the piping system. The aspect ratio of cracks in these areas cannot be readily predicted; however, the random orientation of cracking in flame washed areas suggests that applied stresses did not play a major role in the cracking process (5).

The pipe-to-pipe welding process places the inner surface of the pipe in residual tension (6). These residual tensile stresses act parallel to the pipe axis and approach a maximum in the weld heat affected zone. Consequently, cracks driven by these residual stresses are parallel to the weld. These cracks are restricted to the heat affected zone because of the local nature of the sensitization that accompanied the welding process.

The residual stresses in welds on the reactor tank may differ significantly, in both magnitude and form, from those associated with the pipe-to-pipe welds because of the differences among the welding procedures used to construct the tanks and the welding procedures used to construct the piping system. Irradiation effects and tank fabrication techniques subsequent to welding may also contribute to differences among the residual stresses.

2.1.1 Tank Fabrication

The reactor tanks sidewalls were fabricated, by New York Ship, from one half inch thick plates of AISI Type 304 stainless steel. The welding technique used to join the plates was an inert gas, metal arc (Aircomatic Welding) process. A right circular cylinder portion of P, K, and L tanks (approximately sixteen feet in diameter, eleven feet high) was constructed by welding and roll forming flat sections of plate. This process is illustrated schematically in Figure 1. Four flat plates were welded to form two halves of the cylinder, as shown in the left hand portion of Figure 1. The two flat sections were roll formed into half cylinders after the welds were inspected. The two half cylinders were then welded to form the cylindrical tank section shown as the main portion of Figure 1. This cylindrical section was shipped to the Savannah River Site and field welded to the bottom tube sheet nozzle assembly. A sketch of the bottom tube sheet nozzle assembly is shown in Figure 2.

The roll forming operation, used to fabricate the half sections of the reactor tank, plastically deformed the welds that were made to join the two plate sections. This plastic deformation provided a mechanical stress relief to all but approximately four feet (the two offset "ends") of the mid plane weld in the reactor tanks. This mechanical stress relief significantly altered, and may have eliminated, the welding residual stresses that typically act as a driving force for intergranular stress corrosion cracking in the weld heat affected zones. Because of this reduction in the stress component of the driving force for IGSCC, the tendency for cracking would be less in the mid plane girth weld of the reactor tank than in welds that had not been mechanically deformed. Furthermore, irradiation effects may have provided a degree of stress relief even for tank welds where mechanical stress relief was not operative.

2.1.2 Radiation Effects

Neutron irradiation of weld heat affected zones in the reactor tank walls may have reduced the tendency of those zones to develop stress corrosion cracks. This reduction in cracking susceptibility is attributed to irradiation induced relaxation of the residual stresses in the weld heat affected zone.

The fast neutron fluence to the reactor tank walls increases the vacancy concentration, promotes dislocation climb, enhances creep and consequently causes the relaxation of displacement controlled stresses in the austenite lattice. Experimental measurements (7) have confirmed this irradiation induced stress relaxation in the SRS reactors and demonstrated measurable stress relaxation at fast fluences of approximately 10^{20} n/cm² (Figure 3).

Welding residual stresses are displacement controlled, thus, the irradiation induced motion of dislocations will decrease the magnitude of the welding residual stresses in the reactor tank. This decrease in residual stress should decrease the driving force for stress corrosion cracking in the reactor tank welds. The extent of stress relaxation increases with increasing neutron fluence and, because of the neutron flux distribution, should have been highest near the midplane of the reactor tank. Much of the irradiation induced relaxation of weld residual stresses would have taken place in the 1950's - 1960's, before the institution of neutron absorbing blanket assemblies that reduced the tank wall dose rate and more efficiently used the neutrons for production purposes.

Consideration of the effects of fast neutron fluence on residual stresses, therefore, provides a tentative basis to conclude that, by the mid 1960's, the residual stresses in the tank welds above the tank effluent nozzles had decreased because of irradiation induced stress relaxation. The magnitude of this decrease cannot be established; however, it is important to note that reactor operating histories indicate that the residual stresses in many of the reactor tank welds should have begun to decrease before the initiation of pD control of the reactor moderator.

The initiation of pD control is thought to have caused the release of chlorides from alumina films that are deposited on both the reactor tank walls and the process water piping (8). Furthermore, this chloride release has been associated with an apparent increase in the tendency for stress corrosion cracking in the process water system (8). The irradiation induced relaxation of residual stresses in the reactor tank weldments would have decreased the stress component of the driving force for IGSCC. It is possible that residual stresses in the heat affected zones of tank welds had relaxed to the point where the stress corrosion process was inhibited before pD control was initiated. The effectiveness of irradiation induced reductions in cracking tendency decreases with decreasing fluence (displacement damage). Thus, welds near the tank bottom which were exposed to much lower fluences than the welds higher on the tank wall, may not have experienced significant stress relief. Consideration of the accumulated fast (> 0.1 MeV) neutron fluence, Figure 4, suggests that virtually all welds in the cylindrical portion of the reactor tanks have experienced irradiation induced stress relaxation; however, the fluence to selected welds in the tank bottom nozzle assembly may not have been sufficient to cause relaxation of the residual welding stresses.

2.1.3 Tank Bottom Nozzle Assembly

The tank bottom nozzle assemblies (welded to the tank bottom tube sheet assembly) were also fabricated at New York Ship and transported to SRS. These assemblies (Figure 2) were field welded to the right circular cylinder section of the reactor (Figure 1) to form the reactor tank. This structural weld, in P, K and L reactors, has been exposed to a fast neutron fluence ($E > 0.1$ MeV) in excess of 2×10^{20} n/cm² and, thus, should have experienced some degree of irradiation induced stress relief. The magnitude of the fast neutron fluences to the walls of P and K reactors, Figure 4, suggests that the welds near the tank bottom were the only welds not exposed to fast neutron fluences in excess of 10^{20} n/cm². Irradiation induced stress relaxation of these lower welds, therefore, should not be anticipated.

The lack of irradiation induced stress relaxation in the lower portion of the SRS reactor tanks and the association of stress relaxation with a reduction in the driving force for stress corrosion is consistent with the

observation that IGSCC in the C-reactor tank was confined to knuckle region. This knuckle is unique to C-reactor and cracking observations in this hot formed, highly sensitized material should not be generalized to other reactors. However, the C-reactor tank did not contain known cracks remote from the knuckle and that observation is consistent with the lack of crack indications in the inspected portions of P and K reactor tanks.

2.1.4 Welding Processes

The pipe-to-pipe weldments in the SRS reactor process water system are multi-pass welds, that are initiated by making a root pass that joins the pipe inner surfaces. Subsequent welding passes add weld metal to the single V-groove joint; welding is completed when the V-groove is filled. The last pass of this full penetration weld is always on the outer surface of the pipe. Analytical and experimental evaluations have demonstrated that this welding procedure places the inner surface of the weld heat affected zone in residual tension.

Procedures for welding plate sections to form the reactor tank sidewall, the tank bottom nozzle assembly, and procedures for joining these two sections of the reactor tank, differ from the pipe-to-pipe welding processes. Welding is accomplished from both sides of the joint. For example, the T-weld that attaches the tank shell to the tank bottom and the weld that attaches the cylindrical portion of the tank to the tank bottom nozzle assembly are double V-welds which require welding from both the inside and outside of the reactor. This difference in weld configuration and procedures will alter the residual stress pattern and may significantly decrease the magnitude and/or distribution of tensile residual stresses at the inner surfaces of the SRS reactor tank weldments.

The level of residual stresses in the tank bottom nozzle assembly may also have been affected by the size of the plate sections used to form the assembly. The relative sizes of the plate sections in the bottom nozzle assembly and the tank wall are illustrated in Figure 5. The constraint on a weld joint is dependent on the dimensions and shape of the sections. Earlier SRL work with mild steel plates demonstrated that half inch thick material could be welded without susceptibility to residual stress driven, intergranular stress corrosion cracking if the minimum, in-plane plate dimension was less than two feet (9). This lack of stress corrosion

susceptibility in small, welded plate samples was attributed to the lack of sufficient residual stresses to cause crack propagation. If the effect of plate dimensions on residual stress is applicable to the SRS reactor tank, many of the welds in the tank bottom nozzle assembly will have low residual stresses because of the size of the plate section. This low level of residual stress may result in a lack of IGSCC in the heat affected zones of welds made on some of the small plate sections of the tank bottom nozzle assembly. However, the lack of constraint (and the associated residual stresses) depends on the welding sequence and some fraction of the small pieces may have been effectively constrained, depending on when welding was accomplished.

2.1.5 Summary of Consideration of Stresses

This discussion of the anticipated residual stresses in the reactor tank welds is consistent with the lack of UT indications of cracking in the inspected welds. The level of residual stresses in the heat affected zones of many of the welds may be significantly lower than the level of residual stresses in the heat affected zones of the typical pipe-to-pipe weld. The possibility of low residual stress levels may be attributed to the combination of irradiation induced stress relaxation, fabrication techniques, welding procedures and size of welded plate sections. Because stress corrosion cracking in low pressure systems, such as the SRS reactors, is typically driven by the residual stresses from welding, any factor that decreased the residual stress in the heat-affected-zones of reactor tank welds (as compared to the typical residual stress in the HAZ of pipe-to-pipe welds) should have decreased the susceptibility of the SRS reactor tank to IGSCC. Therefore, the anticipated lower residual stresses in the reactor tank welds is consistent with the apparent reduced susceptibility of those welds to stress corrosion.

2.2.0 Carbon Content

The susceptibility of welded austenitic stainless steels to intergranular stress corrosion cracking in high purity water (the moderator/coolant for the SRS reactors) generally decreases with decreasing carbon content in the base metal. This decrease in susceptibility has been related to the degree of sensitization that develops in the weld heat affected zone. Numerous studies have shown that austenitic steels having carbon

contents below approximately 0.02 to 0.03% are relatively immune to sensitization during standard welding practices. This decreased tendency for sensitization has promoted the extensive use of the low carbon stainless steels in nuclear applications and use of such steels has become "standard practice" to avoid IGSCC in the primary cooling systems of both BWR's and PWR's. The chemical analysis of the Type 304 stainless steel plates used in the construction of the SRS reactor tanks indicate that several of these plates had carbon contents low enough to qualify the steels as a low carbon, sensitization resistant, steel (Type 304 L).

The carbon contents of the plates of steel used to construct P, K and L reactors, Table 1, shows that low carbon steels were used in the construction of part of the tank wall of P reactor, the tank bottom of P reactor, part of the tank bottom of K reactor and a portion of the tank bottom nozzle assemble of P reactor. The use of low carbon steel plates for construction of these portions of the reactors would reduce the susceptibility to stress corrosion because of the reduced sensitization.

The combined effects of the low carbon content, irradiation and fabrication induced stress relaxation and the lack of constraint in a number of the reactor tank welds should significantly reduce the tendency of reactor tank welds to experience IGSCC, relative to the observed tendency for cracking in pipe-to-pipe welds. Because only about 7% of the pipe-to-pipe welds have been observed to undergo stress corrosion cracking, any significant reduction in the tendency for IGSCC would make the probability for cracking at any given location quite small. Known differences among the pipe-to-pipe welds and the reactor tank welds provide a basis to rationalize the apparent lack of IGSCC in many of the welds above the reactor tank bottom. The welds experiencing the greatest degree of stress relaxation are the welds that were inspected by the UT examination of the P and K reactors and includes the welds scheduled for inspection in L reactor. This rationalization therefore is consistent with the lack of UT indications of IGSCC in the SRS reactor tanks.

Welds, at and on the reactor tank bottoms, may have retained the welding residual stresses because of a lack of irradiation induced stress relaxation. Several of the steel plates used for construction of the tank bottoms and tank bottom nozzle assemblies also contain sufficient carbon

to allow sensitization during welding. Therefore, the rationalization applied to the reactor tank welds may not be applicable to welds below the effluent nozzles. The favorable reactor operation experience however, suggests a lack of significant cracking, even at welds on the reactor tank bottom.

2.3.0 Irradiation Induced Changes in Chemistry

The in-tank environment will alter the chemistry of the moderator/coolant by creating free radicals, peroxide and other species that would not be present in the absence of irradiation. The effect of these chemistry changes on the susceptibility of austenitic stainless steel to IGSCC has not been clearly established. The potential effects of irradiation induced changes in moderator chemistry must be considered in any complete evaluation of IGSCC in the reactor tanks. Additionally, the effect of the $\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$ (turbidity) deposits on the tank wall must also be considered. Unfortunately, the necessary data for this evaluation simply do not exist, although surveillance type studies at the Savannah River Site have provided limited evidence that in-reactor exposure of sensitized and stressed samples did not cause as extensive cracking as out of reactor exposures.

The SRS corrosion studies were conducted with fixed displacement stress corrosion test samples exposed to the moderator/coolant in corrosion test loop in the piping system of K-reactor and in thimble positions in the reactor tank (10). Cracking and failure were observed in sensitized samples exposed in the loop while no evidence of cracking was reported for the irradiated samples. The post irradiation examination of the test coupons was not extensive and the irradiation exposures may have caused the fixed displacement stresses to relax, thus, potential effects of irradiation on the moderator chemistry may not have been seen. However, regardless of the reason(s) for the apparent lack of cracking in the irradiated samples, the results of that very limited, experimental study from the 1960's are consistent with the lack of current lack of UT indications of cracking in the reactor tank weld heat affected zones.

3.0.0 Conclusion

The rationalization presented in this memorandum provides an explanation for the lack of UT indications of IGSCC in the SRS reactor tanks. The tank fabrication techniques, the welding procedures, the carbon content of selected plates of steel and the irradiation induced relaxation of residual stresses should combine to significantly reduce the tendency of the stress corrosion based on comparisons with pipe-to-pipe welds. This rationalization, however, does not preclude the possibility of IGSCC, particularly at locations in the reactor tank where the mitigation factors discussed in this memorandum were not operative.

The possibility for the discovery of, and/or the development of, IGSCC in the reactor tanks is real despite the differences between the reactor piping and the reactor tank wall. Therefore, programs for expanded in-tank inspections and for the development of reactor repair technologies are continuing. Modifications to the present inspection equipment will allow examination of areas where the action of the mitigation factors may have been limited (T-welds). These equipment modifications will provide for an expanded tank inspection program. The reactor repair program will provide the technologies required to weld repair cracks or leaks, should they develop or be discovered, in the reactor tanks.

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Table I

**Carbon Content of Type 304 Stainless Steel Plates
Used to Construct P, K and L Reactor Tanks**

REACTOR	% CARBON		
	Tank Wall	Tank Bottom	Nozzle Assembly
P	0.022 and 0.06	0.026 and 0.06	0.022
K	0.066 and 0.07	0.026 and 0.028	0.072
L	0.055 and 0.055	0.069 and 0.063	0.052

Figure 1. Schematic Illustration of Plate and Weld Positioning used in Construction of Right Circular Cylindrical Portion of SRS Reactor Tanks

Figure 2. Schematic Representation of Bottom Tube Sheet Nozzle Assembly for SRS Reactor Tanks

Figure 3 Effect of Neutron Fluence on Stress Relaxation of Austenitic Stainless Steel Samples Exposed to SRS Reactor Environments (after Reference 7)

Figure 4 Illustration of Position Dependence of Fast Neutron Fluence and Displacement Damage to P and K Reactor Tanks

Figure 5 Sketch Illustrating the Relative Plate Sizes in Various Portions of the SRS Reactor Tanks

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