5. TUBE EXPANSION PROCESS AND TEST/ANALYSIS SUPPORT

5.1 Overview

Since the TSPs do not undergo any displacement relative to indications developed within the TSPs during normal operation, tube burst at these locations is prevented by the TSP. Thus, the burst capability requirement of 3 times the normal operating differential pressure is obviated by the presence of the TSP, and the RG 1.121 requirement relative to $3\Delta P_{NO}$ is inherently met. If the TSPs did not undergo displacements during a postulated SLB event, the same would be true of the RG 1.121 requirement relative to $1.43\Delta P_{SLB}$. However, the TSPs are subjected to out-of-plane loads during a SLB, and TSP displacements are predicted to occur at local areas on the TSPs thus exposing cracks presumed to exist in the tube within the span of the TSP.

The principal requirement of the tube expansions is to restrict TSP deflection to a value such that the probability of burst (POB) during a postulated SLB event is essentially negligible. It can be shown that the burst probability for the STP- 2 SGs under peak bounding SLB loading is negligible even without tube expansion; however, 16 hot leg tubes will be expanded at plates C, F and J (see Figure 3..2 of WCAP 15163, Rev 1) to provide added margin for the probability of burst. The modification design to accomplish this consists of expanding the tube, with an internal sleeve installed, into an hourglass shape at the elevation of the TSPs, such that the TSP is captured by the tube/sleeve combination (Figure 5-1). Expanded tubes will be plugged.

Interaction of the expanded tube region with the TSP will effectively cause the expanded tube assembly to act similar to a stayrod, to significantly restrict the potential out-of-plane motion of the TSPs. To increase the load capacity of the expanded joint and to prevent the potential for tube-to-tube interaction in the unlikely event that an expanded tube experiences a circumferential separation in the expanded region, a surrogate sleeve is used. The expanded tube OD will be larger than the nominal tube OD by approximately [ ] ^{a,b,c} and larger than the TSP tube hole diameter by approximately [ ]. ^{a,c} A description of the design and testing of the expansion process is provided in this section.

An implicit requirement of the tube expansion modification is that the integrity of the expansions must be such that they perform their intended function for long periods of exposure to the secondary side environment. For South Texas Unit 2, the period of performance is one cycle, approximately 18 months operation, since the SGs are scheduled to be replaced during the 2002 outage.

5.2 Review of Prior Applications

The tube expansion process has been previously applied at the Byron 1 and Braidwood 1 plants. The process to be applied at South Texas 2 differs from the Byron/Braidwood processes only in that the expansion diameter is slightly smaller than used at Byron/Braidwood and that standard thickness laser welded sleeves will be used instead of thinned sleeves at the TSP expansions.

5.3 Tube Expansion Process Requirements

The overall requirements for the application of tube expansion are summarized in Section 6 of this report. If TSP motion is restricted to less than or equal to 0.30" during a postulated SLB, the probability of burst will be less than 10^{-5} under the assumption that all tubes have throughwall indications at all of the hot leg intersections (Plates C through R included). If TSP displacement during a SLB is restricted to less than or equal to 0.20", the probability of burst is estimated to be much less than 10^{-5}. For TSP displacement <0.20", the leakage from cracked tubes is bounded by the leak rates for Indications Restricted from Burst (IRB) (see WCAP –15163, Rev 1, section 8)

The following design requirements were established for the tube expansions. The actual performance of the tube expansions exceeds the design requirements as discussed below.

1) The tube expansion at the TSP shall provide resistance to TSP motion of at least [ ]. a,b,c The associated stiffness of the expansion relative to plate motion shall be [ ] a,b,c when averaged over the initial 0.05 inch of TSP displacement as determined by TSP pull force versus displacement test on expanded joints.

2) The expansion shall be performed above and below the TSP by a hydraulic expansion process. A sleeve stabilizer shall be installed to extend above and below the parent tube expansion.

3) The expansion process shall be designed to achieve a maximum expanded tube diameter increase of approximately [ ] a,b,c when applied over the range of material properties (tubes and TSPs) and over the range of tube/TSP intersection dimensions. The limit on the expansion diameter is a design goal to limit residual stresses in the expanded tube; larger expansions are acceptable to meet the expanded tube stiffness and load requirements.

5.4 Tube Support Plate Expansion Process Description

Figure 5-1 illustrates the TSP expansion configuration. The tube expansion is performed using hydraulic expansion equipment for Westinghouse ¾" diameter tube sleeving and a modified sleeve delivery mandrel. The expansion is generated by supplying high-pressure water to an expansion mandrel/bladder system. The same length bladder [ ][a,c] used for sleeve expansion in the laser welded sleeving system is used for the tube expansion process.

For development purposes, the tubes, sleeves, and TSP simulants were manually positioned. The sleeve sections used for the TSP expansions were actual TSP laser welded sleeves cut to an overall length of [ ]. [a,c] Although the field applications of this process at Byron 1 and Braidwood 1 used sleeves thinned in the expansion region to accommodate tooling limitations, these limitations have been eliminated, and non-thinned sleeves are used for the South Texas 2 application. The test samples used to determine the resistive load characteristics of the expanded assembly were configured with the sleeve centered at the axial center of the TSP simulant, and with varying levels of axial misposition.

Field application is performed using the ROSA based sleeving system, which includes the Search and Locate End Effector (SALEE), SALEE expansion mandrel, ROSA control computer, and standard sleeving system hydraulic expansion pressure unit. The mandrel has an integral eddy current coil that senses the center of the TSP and enables the tool to automatically stroke into the install/expansion position. The sleeve delivery mandrel has been modified to properly position the center of the sleeve, and consequently the center of the expansion bladder, adjacent to the center of the TSP. The expansion process is computer controlled for consistency and repeatability.

During the expansion process, the sleeve initially yields and contacts the tube. After the yielded sleeve contacts the tube, the computer compares the applied pressure to deflection slope between successive data collection points (100 points/second minimum sample rate). When tube/sleeve yielding occurs, evidenced by a change in the slope of the pressure-time trace, the computer continues to supply a constant volumetric rate of fluid injection for a specified time period. When the prescribed time period has been achieved, the pressure input is terminated and the system is depressurized.

5.5 Tube Expansion Process Test and Analysis Results

5.5.1 Tube Support Plate Expansion Testing

Test specimens were prepared at various expansion pressures to establish a relationship between expansion pressure and projected tube OD and also to establish a relationship between tube OD and resistive load capability at varying TSP deflection levels.

Test specimens were made using [12” long, Alloy 600 mill annealed, 0.750” OD x 0.043” nominal wall thickness tube sections and 6“ long, Alloy 690 thermally treated, 0.640” OD x 0.038" nominal wall thickness sleeve sections. TSP simulants, Figure 5-2, were made from 405 SS plate material to ASME specification SA-240, which is the same as the South Texas 2 TSP material specification. The TSP simulants were ¾” thick, approximately 2.4” square sections with a center tube hole surrounded by 4 tube holes and 4 flow holes, with hole diameters, hole-to-hole pitches, and chamfers consistent with the SG manufacturing drawings. The ligament thickness at the edges of the TSP simulant was designed to be approximately half of the nominal ligament thickness. These simulants conservatively represented the in-plane stiffness of the TSPs since only a small portion of the plate pattern was used. It is expected that the use of a TSP simulant that represented a larger portion of the plate would yield higher resistive load capabilities. The tube yield strength, 48 ksi and sleeve yield strength, 45 ksi, used for the test samples represent lower bound limits. The manufacturing records for the South Texas 2 SGs indicate the actual minimum yield strength of the TSPs was 54.9 ksi. For test purposes, 405 SS plate with yield strength of 43 ksi was used. Sleeves were centered axially at the center of the TSP simulant, which was centered over the 12” tube length.] a,c,e

Samples were produced with a nominal fitup condition, that is, with the sleeve axially centered on the TSP, and with varying levels of sleeve/expansion mandrel axial misposition relative to the center of the TSP. Samples were tested at room temperature by tensile loading in a Satec® 120,000 lb capacity tensile loading machine. The load testing setup is shown in Figure 5-3. One end of the sample was attached to the movable crosshead using self-adjusting tube OD gripper jaws. A fixture was bolted to the stationary base of the machine. This fixture is a stiff, box-like structure that restrains the TSP simulant while the movable crosshead essentially extrudes the expanded tube/sleeve assembly through the TSP simulant hole. Plate bending effects encountered during an actual SLB event, which would act to pinch the tube and further increase the resistive load capacity of the expansion, were not modeled into the test setup. Machine speed was set at 0.25 ips. Previous testing, discussed in Reference 1, indicated that, at these speeds, the load response is independent of pull rate. The motion of the tube relative to the TSP simulant was accurately isolated by use of a deflectometer, a precision testing device designed for such purposes, attached to the tube and the TSP simulant. Use of the deflectometer eliminated the effects of potential gripper jaw slip and specimen elastic stretch during loading from influencing the load vs. displacement curve.

Resistive load vs. TSP displacement curves were produced for each specimen. A sample of these curves is given in Figure 5-4. At normal operating temperatures, the material properties of the tubes, sleeves, and TSPs would be reduced by approximately 8% compared to room temperature conditions, and therefore, would be expected to result in a slight reduction in the resistive load capacity compared to the room temperature results. However, further evaluation of the operating performance characteristics of the expanded joint indicates that the room temperature data are conservative for application at operating conditions for the following reasons:

1) Out-of-plane bending of the plate during a postulated SLB would cause a bending lockup (cam-lock) condition between the tube/sleeve and TSP, and would act to significantly increase resistive loads, compared to the room temperature tests that utilized flat plates to simulate the TSPs.

2) Interaction between the TSP and the tube OD results in a more severe galling condition at operating temperature than at room temperature. Previous testing related to structural integrity of hybrid expansion joint (HEJ) sleeve assemblies indicates that the extent of galling of Alloy 600 tubing and therefore, the galling forces, significantly increase at 600˚ F compared to room temperature. Because the geometry of an HEJ assembly and the TSP expansion assembly are similar; this result applies to the TSP expansions as well.

3) Crevice packing would limit the expanded diameter of the tube/sleeve assembly within the TSP, increasing the diameter difference between the expanded tube/sleeve assembly immediately above/below the TSP, and thereby increasing resistive load. The interaction angle between the tube OD and TSP hole diameter would become rotated towards the horizontal (plane of TSP), and this interaction angle would act to load the tube in shear as well as create resistive load by the extrusion action. Preliminary testing using [”] [a,b,c] long bladder assemblies indicates that the resistive load capability is dramatically increased over equal sized (Δd) expansion using the [”] [a,b,c] bladder, due primarily to the interaction angle between the tube OD and TSP. In this testing, the [”] [a,b,c] expansion was located so that 1/8” of the bladder overlapped the edge of the TSP. At the tube to TSP interface, a more shallow tube angle with reference to the horizontal is created, and a portion of the tube inside the TSP is not expanded. The expansion profile is symmetric about the axial center of the expansion. Using the [”] [a,b,c] bladder, the tube and sleeve are expanded to contact with the TSP, and a steeper angle with reference to the horizontal is created at the tube to TSP interface compared to the [ ] [a,b,c] bladder expansion profile. Open crevices were used in the tests performed. The interaction angle of the tube OD with the TSP is more shallow with reference to the horizontal compared to the interaction angle developed when a packed crevice limits the tube/sleeve expansion diameter.

4) Thermal expansion effects would act to create a tighter joint at operating temperatures since the sleeve expands more than the tube due to the differences in thermal expansion coefficients between the tube and sleeve materials. The tube/sleeve assembly would also act to create a tighter fitup condition with the TSP assembly, as the thermal expansion coefficients of both Alloy 600 and Alloy 690 are greater than the expansion coefficient of the 405 SS TSP material. This would result in higher radial preloading between the tube/sleeve and TSP at operating and faulted conditions. This thermal expansion effect was not provided by the room temperature testing, and therefore, will add to the resistive load capacity of the expanded TSP joint at operating conditions.

5) Material properties of the TSP simulant dramatically affect the resistive load capabilities of the expanded assemblies. The yield strength of the test TSP simulants was 43 ksi at room temperature, whereas the actual material test reports for the South Texas 2 TSPs indicate a minimum yield of 54.9 ksi at room temperature. The higher actual material properties of the South Texas 2 TSPs will more than compensate for any decreases in resistive load capability based on tube material property reduction at operating temperature.

6) The combined data sets of 2/17/98 and 1/30/98 (see Figure 5-5) are used to develop the minimum acceptable bulge size. In the 1/30/98 testing, the testing fixture was determined to have been set up in a manner that resulted in deflection of the test fixture being included in the overall measured TSP displacement value, which artificially reduced the apparent joint stiffness. In the 2/17/98 testing the test fixture was installed so that the fixture deflection was limited, with the result that the observed joint stiffness was considerably larger than that from the 1/30/98 data set for equal sized expansions (see Figure 5-5). For conservatism, the entire TSP data set including the 1/30/98 data was used for establishing the minimum acceptable bulge size.

It is concluded that it is reasonable and conservative to apply the room temperature joint stiffness values to SLB event conditions without adjustment for decreased material properties at elevated temperatures.

The expansion assembly stiffness was determined by calculating the stiffness coefficient over the first 50 mils of TSP displacement. A lower bound on the test population of joint stiffness was then used as input to the TSP dynamic analysis for determination of TSP displacements during a postulated SLB event. Figure 5-6 plots the resistive loads of the samples vs. bulge size at 50 mils of TSP displacement. The stiffness of the samples is obtained by dividing the load at 50 mils of displacement by the displacement (0.05") to obtain the stiffness in lb/in. The average stiffness of all samples (including axially mispositioned samples) was [ ] a,b,c lb/in, which significantly exceeds the minimum stiffness of [ ] a,b,c lb/in assumed in the preliminary displacement analysis.

Only one data point exhibited a stiffness of less than [ ] a,b,c lb/in. This sample, which had a [ ] a,b,c" diametral expansion, exhibited a load at [ ] a,b,c, resulting in a stiffness of [ ] a,b,c lb/in, significantly less than those of the remainder of the test population. The low measured force at [ ] a,b,c mils of TSP displacement was due to an improperly installed test fixture, which resulted in indicated displacement with no resultant resistive load increase. At 100, 150, 200, and 250 mils of TSP displacement, the resistive load values of this specimen fit much better with the remainder of the population. In addition, the peak load fit well with the total population.

Several other samples from the 1/30/98 data set exhibited similar displacements with no load increase at the start of the loading. The distortion of the load curve for these samples is most likely attributable to free travel in the fixture and not to the sample, as all samples were observed to be axially locked prior to the load testing. All samples were checked for axial and rotational fixity prior to tensile loading. In all cases, the TSP simulant could not be rotated or axially displaced (by hand check) prior to testing. As the sample was axially (and rotationally) locked, it is not reasonable to believe that the TSP simulant could be displaced with no resistive load increase during the load tests. The source of the errors was attributed to the manner of attachment of the specimen to the test fixture, which resulted in excessive flexibility and free travel of the test fixture.

A second set of samples was tested with bulge sizes the same as for the first set, with the same tube and sleeve material heats, and with the same TSP simulant dimensions. This set is labeled "2/17/98 Data" in Figure 5-6. In these tests, the flexibility issues related to the test fixture were corrected. As seen in Figure 5-6, the second set of data results in significantly higher resistive loads, and comparison of the linear regression lines for each set of data indicates that the lines are parallel. For conservatism, the data sets of 1/30/98 and 2/17/98 were combined to form one data set. From this data set, the average stiffness over the first [ ] a,b,c. This data set can be further divided into nominal fitup samples, offset samples, samples with bulges [ ] a,b,c and samples with bulges [] a,b,c. In all cases, the stiffness over the first [ ] a,b,c mils never varied by more than 10% from the average value for the entire data set. If only the 2/17/98 data are used, the error about the regression is dramatically reduced, and the minimum acceptable bulge size is reduced by 10 mils compared to the minimum value indicated by the combined data.

The load vs. displacement testing indicates that the [TSP material properties have a significant effect upon the resistive load developed as the TSP is pulled over the bulge. Comparison of data from thinned sleeve assemblies, with bulge sizes comparable to the Reference 1 Addendum 1 data, indicates that use of the 42.76 ksi TSP simulants increases resistive load by greater than a factor of 2. A linear regression line for the 1995 data indicates an expected load of [ ] a,b,c of TSP displacement. In those tests, SA-285 Grade C hot rolled plate with a yield of 33 to 36 ksi was used. The geometry of the TSP simulants was the same for both the 1995 data (Reference 1) and the current data. For the 1998 data, using 42.76 ksi yield 405 SS TSP simulants, a linear regression fit of the data indicates that the expected resistive load at [ ] a,c,e, more than twice the value for comparable sized specimens in the prior (1995) tests. Since the actual South Texas 2 TSPs are manufactured from SA-240 (405 SS) plate with a minimum yield of 54.9 ksi, use of the 1998 data will provide a substantial level of conservatism relative to the actual expected pull-out forces.

5.5.2 Considerations for Re-expansion of Undersized Expansions

The expanded tubes will be inspected following application of the process to verify that the expansion (proper bulge size) has been achieved. If the minimum acceptable bulge size has not been achieved, an additional tube must be selected for expansion. Due to the design of the expansion bladder, re-expansion of under-expanded joints is not feasible, since the increased sleeve to bladder gaps may cause bladder failure prior to complete expansion. Re-expansion should be attempted only if both expansions (above and below the TSP) are below the minimum acceptable value. This would be the case if a premature bladder failure occurred during the expansion process. The under-expanded tube will provide added margin against TSP deflection during a postulated SLB event.

5.6 TSP Stresses Produced By the Expansion

A finite element analysis of the expansion effects for application of the process at Byron/Braidwood was performed and documented in Reference 1. This evaluation concluded that the TSP ligaments would not be yielded by the expansion process, even for an off-nominal ligament thickness of 0.075", which is substantially less than the nominal ligament of 0.11". The assumed TSP material yield strength used in the Reference 1 analysis was the ASME Code minimum value of 30 ksi for SA-285 Grade C hot rolled plate. Material records for South Texas 2 indicate the TSPs have a minimum yield strength of 54.9 ksi. Therefore, the greater than 80% increase in TSP yield strength, compared to the Reference 1 results, is more than adequate to accommodate the approximately 5% higher expansion pressure required for use of a non-thinned sleeve to achieve the same bulge size. Due primarily to TSP material properties, smaller bulges are required for South Texas 2 than for Byron/Braidwood for equivalent expansion assembly stiffness. The smaller bulge requirement therefore results in reduced peak expansion pressures and reduced stresses in the TSP due to the expansion process.

5.7 NDE Support for Tube Expansion

5.7.1 Determination of Expansion OD from ID Measurement

Post-expansion diameter verification of the expansions is required to ensure that the minimum stiffness requirements are met. Field measurements are made by NDE to define the ID of the actual bulge. The expansion joint load test basis is in terms of tube OD bulge. Due to the required IDs and non-expanded sleeve ID, mechanical measurement devices could not be inserted into the samples to determine the ID corresponding to the test OD. Therefore, a set of calculations was developed to predict IDs based on measured ODs, and ODs based on measured IDs. Fitup drawings, References 2 and 3, will be included in the field procedure and design change specification, which define the range of acceptable tube IDs, based on these calculations.

To verify the adequacy of the OD to ID transfer calculation, several specimens were sectioned after expansion. The tube and sleeve pre-expansion dimensions were recorded, the specimens were assembled as TSP expansion samples, the expanded ODs were measured, and the specimens were sectioned at the maximum OD diameter of the bulges. The bulge IDs were measured with "Intrimiks" (special micrometers used for inspection of inside diameters) at the location of the maximum OD bulge diameter. Table 5-1 provides a summary of the calculated ID values and mechanically measured ID values for the sectioned samples. Although the sectioned samples used 7/8" tubes and sleeves, the calculation method is based on the measured sleeve wall thickness, assumed tube ID and wall thickness, and eddy current measured ID, which is used to calculate applied strains, and therefore, the amount of wall thinning due to the expansion process. The calculation method is independent of tube/sleeve size and can be applied equally to 7/8" and ¾" diameter tubes. The predicted IDs were nominally within 1 mil of the measured values. Similar results are obtained when the OD is predicted based on an ID measurement.

As part of the justification of eddy current ID measurement in the expansion region provided in Reference 1, 7 samples using ¾" tubes and sleeves were prepared for verification of efficacy of the process. Following assembly of the test samples, the maximum OD bulge sizes were measured. The IDs in the expansion region were then calculated and compared to the values determined using eddy current methods.. The average variance for the 7 samples (14 expansions) was -0.0008", with a standard deviation of 0.0018". The variance is defined as the eddy current measured diameter minus the calculated value. To verify these results, one of these samples was sectioned. The physically measured IDs were ["] a,b,c. The eddy current measured IDs were [ ] a,b,c, respectively, while the calculated IDs were [ ] a,b,c.

The required expansion ID dimensions will be established for each field expansion. Based on the excellent correlation between calculated and mechanically measured expansion IDs, a similar calculation can be performed to establish the resultant tube OD. Comparison of calculated and mechanically measured specimen IDs showed that in most cases the difference between the two values was less than 0.001". An accurate calculation of the expansion OD achieved can be performed, based on the known dimensions of the sleeve being used to calculate the sleeve hoop strain and the measured tube ID from the eddy current trace and an assumed tube wall thickness of 0.043".

5.7.2 Bobbin Profilometry for Expansion Diameter Measurements

In the field, a standard bobbin profilometry probe will be used to determine the mean diameter of the expansion maxima (above and below the TSP). If the minimum bulge diameter requirements are not achieved, additional tubes must be expanded. A detailed discussion of bobbin coil profilometry was presented in Reference 1. A summary is provided below.

The technique involves the use of a bobbin coil probe excited in differential and absolute modes at multiple frequencies, typically ranging form 10 kHz to 630 kHz. The lowest frequency penetrates outside of the sleeved tube and is used for steam generator landmark detection. The highest frequency has a very shallow depth of penetration and is used for the measurement of the diameter of the expansion. The bobbin probe integrates the signal response about the circumference of the tube and yields a mean diameter measurement at a given axial location.

A standard, with expansions of known diameter, is used to construct a calibration table that relates the diameter of the tube to the voltage of the eddy current response. The calibration standard for the process will include expansions bulge diameters that are close to the expected range of expansion process result in order to achieve the most accurate measurement possible.

Section 10.4 of Reference 1 shows the results of the evaluation of the expansions for both 7/8 and ¾ inch diameter tubing along with the calculated bulge I.D.s based on the O.D. measurements and the expansion strain. These tables show that the eddy current measurement of the inner diameter, on the average, meets the expected value within ±0.002" [ ] a,b,c. This uncertainty on the bobbin profilometry results is acceptable and no adjustments are necessary to the bobbin data for field process applications. This shows that the tube I.D. can be reliably measured using eddy current methods. This measurement coupled with the knowledge of the strain experienced during the expansion process can be used to verify that the O.D. of the bulge falls within the desired process range.

5.8 Tube Stabilization with an Expanded Sleeve

Adequate restraint is provided by the sleeve if circumferential cracking is postulated to occur in the original tube. For a crack that is postulated to form at the top edge of the TSP, the interaction between the tube and sleeve in the expanded area provides for a rigid link between the tube sections. Expanded specimens cut apart in the expansion region indicate intimate contact between the tube and sleeve. The expanded sleeve provides a relatively rigid structure with the tube even if it is assumed that the tube is separated at the upper edge of the bulge. The tube at this point still acts as though it were fixed due to the stiffness of the sleeve and the interaction of the tube and sleeve with the TSP.

The potential for fluidelastic vibration of the tube is negligible. If the tube is postulated to separate at the upper edge of the expansion, the tube end is effectively restrained by the sleeve expansion above the bulged region. At the intersection between the tube and sleeve, the gap is zero and progresses to a maximum of [ ] a,b,c inch in the unexpanded area. Lateral motion of the tube end is limited to the size of the gap, and the stiffness of the sleeve is sufficient to restrain further lateral motion of the tube, such that contact with adjacent tubes is precluded. The bending stiffness of the sleeve is sufficiently large that any operational loading due to flow effects is negated by the sleeve stiffness, and tube-to-tube contact will not occur. With the limited range of motion of the tube end, the end conditions are similar to a pinned connection when contact with the sleeve occurs. As long as some boundary condition fixity is provided, the potential for fluidelastic excitation is minimal.

In summary, the sleeve provides effective tube stabilization under the assumption that the parent tube is separated in the region of the expansion. The sleeve functions to essentially eliminate the likelihood of fluidelastic vibration of a separated parent tube and provides lateral restraint to prevent the assumed separated tube end from contacting adjacent tubes.

5.9 Potential for Circumferential Cracking In Expanded and Plugged Tubes

5.9.1 TSP Region

5.9.1.1 Operating Experience for Circumferential Cracking

After one cycle of operation, all TSP expansions at Braidwood were inspected using the +Point coil. No indications were detected. The OD bulge diameters inspected at Braidwood included a maximum of 0.108", and 31 bulges greater than 90 mils, of which 5 were greater than 0.100". Since the target expansion for South Texas 2 is [ ] a,c, compared to the target for Braidwood of [ ] a,c, and process improvements have been made to reduce the potential of axial misposition which, in turn, determines bulge variance and the potential for large bulges , the potential for having bulges greater than [ ] a,b,c is greatly reduced. Therefore, the likelihood of experiencing a circumferential crack in the parent tube at the TSP expansions is reduced for South Texas 2 compared to Braidwood. Since no circumferential indications were detected in the TSP expansions at Braidwood after one cycle, and smaller bulges will be made at South Texas 2, circumferential cracking is not an issue for the single cycle of operation planned for South Texas.

No cracking has been found in the hydraulic expansions at TSP intersections in the preheater region of South Texas Units 1 and 2. Similarly, no cracking at the expansions has been identified in the Model D4 SGs that include these expansions, which include expansions up to about 41 mils Δd in more than 10 years of plant operation.

5.9.1.2 Potential for Circumferential Cracking

The potential for circumferential cracking in the hydraulically expanded and plugged tubes was evaluated in Reference 1. The operating temperature of the expansions in the plugged tube condition is between 522^{o} F and 540^{o} F, as determined by the secondary coolant temperature. Operating and laboratory experience for hydraulic expansions are reviewed in Reference 1. It was concluded that the low temperatures in plugged tubes with hydraulic expansions having [ ] a,c lead to a low likelihood of circumferential cracking. The South Texas 2 TSP tube expansions will have bulge [ ] a,b,c; thus the likelihood of circumferential cracking is even further reduced.

5.9.2 Tubesheet Expansion Region

5.9.2.1 Operating Experience

After one operating cycle, circumferential indications were detected at the top of tubesheet region at Braidwood. The tube to tubesheet expansion process at Braidwood 1 was hard rolling. The EOC 6 inspection (first inspection after implementation of the 3V ARC) was the first use of the +Point probe at Braidwood 1; prior TTS inspections were performed with the RPC probe. The results of the Braidwood-1 1997 inspection were discussed in a meeting between Commonwealth Edison (ComEd) and the NRC on 4/29/1997 (Reference 4).

ComEd concluded that the top of tubesheet circumferential indications were likely undetected indications from the prior inspection that had grown to +Point detectable levels at EOC6. The signals of the circumferential indications were the same as circumferential indication signals in non-expanded tubes; thus, the indications in the expanded tubes did not represent a new degradation mechanism, but were, in fact, ODSCC at the roll transition.

Subsequent evaluation indicated that the incidence of circumferential indications among the population of expanded tubes was independent of the number of expansions performed in a single tube.

5.9.2.2 Potential for Circumferential Cracking

South Texas Unit 2 Manufacturing and Operating Experience

The South Texas Unit 2 SG tubes were hydraulically expanded in the tubesheet. The industry operating experience with hydraulically expanded tubes has demonstrated that hydraulic expansions are significantly less susceptible to circumferential cracking than are the hardrolled expansions.

During the prior +Point inspections at STP-2, no circumferential (or axial) cracking has been detected at the tube expansions. Consequently, compared to Braidwood 1, circumferential cracking at the transitions of the expanded tubes at STP-2 would be extremely unlikely since:

1) No evidence of cracking at the top of tubesheet expansion transition has been observed to date during multiple cycles of inspections, nor during destructive examination of tube pulls from STP Unit 2 in support of the licensed 1-Volt ARC, whereas circumferential cracking had been previously observed at Braidwood
2) The detection capability of the +Point probe is significantly better than that of the RPC probe utilized at Braidwood EOC5. The potential undetected indications at STP are insignificant compared to those at Braidwood where the +Point probe had not been used prior to tube expansions. .

Expansion Joint Design

The design of the TSP locking expansion was modified for STP-2 based on the Braidwood operating experience. The objective was to reduce the residual stress in the tube due to expansion by reducing the required bulge diameter by 0.010-0.020”. To compensate the expected loss of load carrying capability, a full wall thickness sleeve was utilized for the STP-2 process instead of the undercut sleeve utilized at Braidwood. The reduced expansion diameter reduces the residual stress in the tubes; thus the potential for circumferential cracking is reduced.

Summary

Circumferential cracking at the TTS tube expansions in the locked tubes at South Texas Unit 2 is not considered a significant issue for the following reasons:

1. Operation of the STP-2 SGs with locked tubes will be limited to one cycle, followed by replacement of the SGs.
2. The STP-2 SGs utilize hydraulic tube expansions. +Point inspections have been performed at the TTS transition region at STP-2 in prior cycles (at least 3 inspections). No circumferential (or axial) cracking has been observed in the transition region of the STP-2 SGs.
3. The design of the locking expansion was modified for STP 2 application to reduce the residual axial stress in the expanded tube. Compared to Braidwood 1, the potential for circumferential cracking at the TTS transitions in the locked tubes is essentially negligible because of the use of hydraulic tube expansions and because of the prior absence of observed TTS degradation.

5.10 Requirements on Limiting Tube Denting for TSP Integrity

In severely dented SGs, tube support plates have been observed to be cracked, and this raises a potential concern regarding the ability of the TSP to support the axial loads applied by the tube expansion process and by postulated SLB loading. Implementation of ARCs and tube expansion would not be considered for very heavily dented tube support plates, but would be appropriate for TSPs with light to moderate denting. South Texas 2 has stainless steel TSPs. Consequently, corrosion induced denting is not expected and has not been found in TSP intersections using stainless steel TSP material. Therefore, no requirements are necessary to limit denting for TSP integrity.

5.11 Conclusions

The process for tube expansion at the TSPs for South Texas Unit 2 is essentially the same process that was applied for the prior implementation of 3V ARC at Byron and Braidwood.

A target expansion size of [ ] ^{a,b,c} was selected for the TSP expansion. The computer controlled expansion program will produce expansions of [ ] ^{a,b,c} in low yield strength tubing and expansions of [ ] ^{a,b,c} in high yield strength tubing. Expansions of this size will result in axial stiffness exceeding the minimum required stiffness of [ ] ^{a,b,c} at the TSPs. Based upon the load displacement data developed for the TSP expansions, a regression curve (Figure 5-6a) plotted through the data indicates that for low yield tubing (48 ksi yield), expansions produced at the target value of [ ] ^{a,b,c}

would provide approximately [ ] a,b,c resistive load, resulting in an axial stiffness of approximately [ ] a,b,c of TSP displacement.

At the lower 90% prediction interval, a minimum expansion of [ ] a,b,c (Figure 5-6a) in low yield strength tubing would provide a resistive load of [ ] a,b,c lb, resulting in the minimum stiffness requirement of [ ] a,b,c lb/in. It is important to note that this minimum acceptable value was conservatively developed using the entire TSP resistive load data set, which includes the 1/31/98 data set in which the test fixture was installed such that the indicated deflection included fixture deflection. If only the 2/17/98 data set is used (Figure 5-6b), at the 90% prediction interval a minimum acceptable bulge size of [ ] a,b,c is supported. An artificial data point at 20 mils tube OD bulge and 0 lb resistive load was added to the data set, because for an open crevice, the tube OD bulge must exceed the crevice gap ([ ] a,b,c diametral) for the expansion to create a resistive load. The 90% prediction interval curve, when evaluated for engineering principle, shows its conservatism. The lower 90% prediction interval curve for all data (Figure 5-6a) indicates a minimum [ ] a,b,c diametral bulge in order to develop a resistive load greater than 0 lb. This is physically illogical, since any bulge greater than the crevice gap will create a resistive load greater than 0.

As the tube to TSP interaction angle (with reference to the vertical axis) gets larger - for example, if the crevices are packed- the resistive loads increase. In the testing program the crevices were all open, resulting in smaller tube to TSP interaction angles. This causes the tube to more easily pulled through the TSP as the angle decreases. Figures 5-6a and 5-6b provide the indicated regression curves, along with the 90% confidence intervals, and 90% prediction intervals for the combined data set and the corrected data set. The regressions were selected based on the compatibility of the data set with the physical phenomena in the Δd range tested (up to about 0.100") in these, and prior tests. A strictly mathematical “best fit” may not logically represent the physical interaction of the expansion. For example, the best fit solution for the combined TSP data set results in large predicted loads at small expansions. Therefore, the chosen fit was selected based on the expected dynamic interaction between the expanded tube and TSP.

A minimum bulge size of [ ] a,b,c would not be expected to result in the TSP being “locked” to the tube with a high degree of confidence. That is, the springback of the material would permit a small amount of axial play between the tube and TSP in the expanded condition. The TSP displacement analysis (Section 4) assumes the TSP is locked to the tube. If axial play were present, the stiffness assumptions applied to the dynamic analysis would not remain valid. Therefore, an additional requirement was imposed which requires the minimum bulge size to support axial locking of the tube to the TSP. All samples were checked for axial and rotational locking, and it was found that expansions greater than or equal to [ ] a,b,c resulted in the TSP being both axially and rotationally locked to the tube. Therefore, a minimum bulge size of [ ] a,b,c is defined for both high and low yield tubing. It should be further noted that the amount of axial play in samples with approximately [”] a,b,c of diametral bulge is approximately [ ] a,b,c. Previous testing indicates that the load difference between low (50 ksi) and high yield tubing (73 ksi) in the range of [ ] a,b,c expansion bulges ranges from [ ] a,b,c lb, respectively. Therefore, equal sized expansions in high yield tubing will result in greater stiffnesses. The determination of high yield strength can be based upon the tube heat records for South Texas 2, which identify the yield strength values for individual tubes. The expansion process therefore can be adjusted for the individual tube being expanded to optimize the expansion production.

In summary, the expansion process will be targeted toward obtaining approximately [ ] a,b,c bulges in low yield strength tubing and approximately [ ] a,b,c bulges in high yield strength tubing. For TSP expansions, minimum bulge diametral increase is 45 mils independent of material yield strength. Acceptance criteria for the TTS field expansions will utilize the yield strengths from the tube heat records. For high yield (73 ksi) tubing, the minimum acceptable bulge diametral increase is 46 mils. For low yield (48 ksi) tubing, the minimum acceptable bulge size is [ ] a,b,c. These data can be interpolated for other tube yield strengths. These bulge sizes provide the minimum joint stiffness requirements of [ ] a,b,c for the expansions at TSP intersection.

5.12 References

1. WCAP-14273; Technical Support for Alternate Plugging Criteria with Tube Expansion at Tube Support Plate Intersections for Braidwood-1 and Byron-1 Model D4 Steam Generators; W-NSD, February 1995.
2. W-NSD Drawing 1B80238 , "South Texas Unit #2 (THX) Support Plate Expansion Sleeve Installation Fitup".
3. W-NSD Drawing 1B80237 , "South Texas Unit #2 (THX) Top of Tubesheet Tube Expansion 3V ARC Sleeve Installation".
4. Westinghouse Internal Memo NSD-RFK-97-017; "Com-Ed NRC Meeting on Braidwood 1 Inspection Results", 5/2/1997.

Table 5-1
Comparison of Calculated vs. Mechanically Measured IDs of Sectioned Samples
Calculated ID is based on Mechanical Measurement of Maximum Expansion Bulge Size

Sample	Mech. Meas. ID 1	Mech. Meas. ID 2	Calc. ID 1	Calc. ID 2	ID 1 Var. (Meas - Calc.)	ID 2 Var. (Meas. - Calc.)
D	0.7680	0.7646	0.7684	0.7659	-0.0004	-0.0013
E	0.7796	0.7802	0.7796	0.7822	0.0000	-0.0020
F	0.7776	0.7826	0.7793	0.7837	-0.0003	-0.0011
G	0.7776	0.7792	0.7781	0.7792	-0.0005	0.0000
H	0.8058	N/A	0.8060	N/A	0.0002	N/A
I	0.7862	N/A	0.7870	N/A	-0.0008	N/A

Figure 5-1
Tube Support Plate Expansion

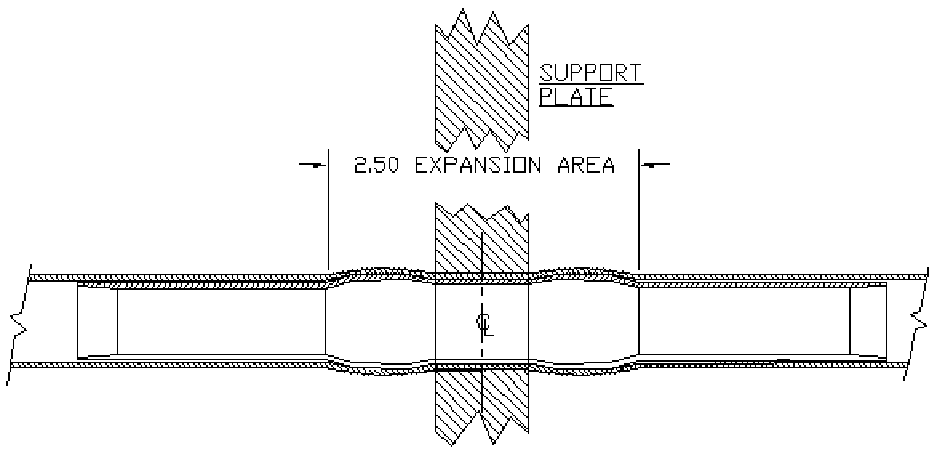

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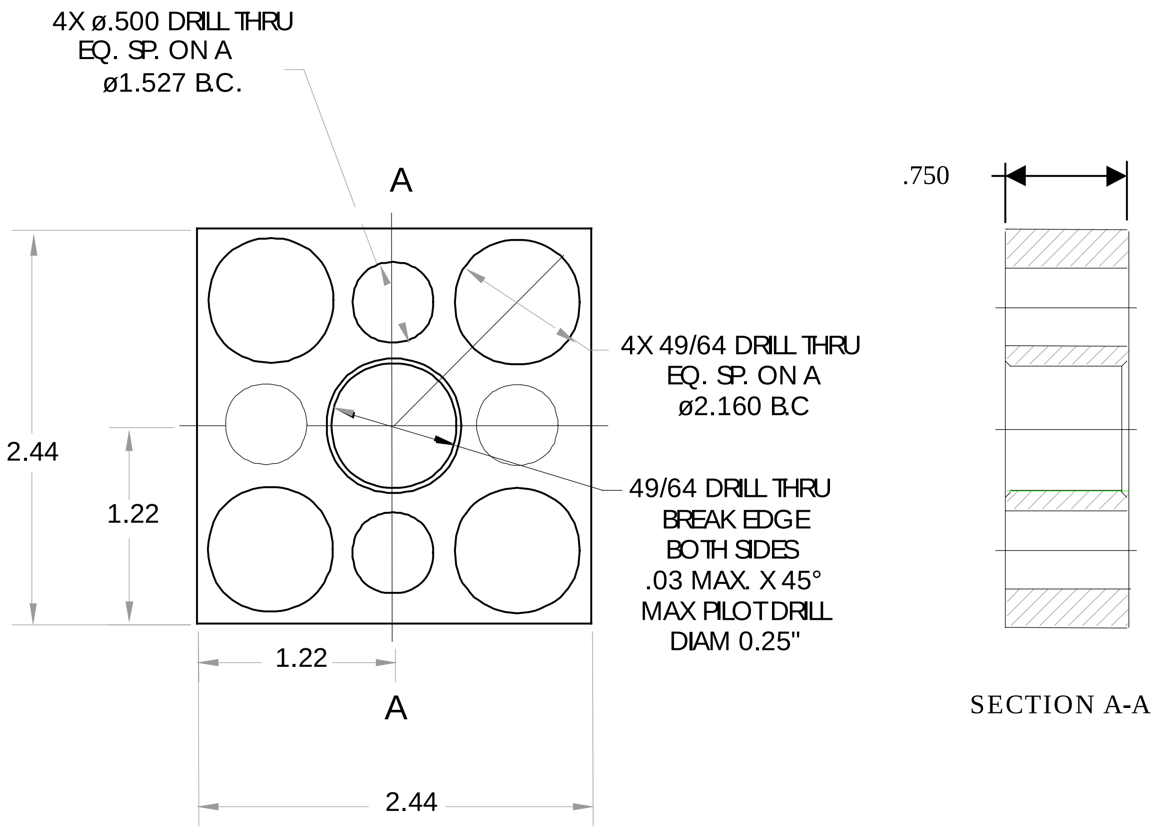
Figure 5-2
Tube Support Plate Simulant for Expansion Load Testing



Material: ASME SA-240 405 Stainless Steel Plate

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Figure 5-3
Expansion Joint Load Test Setup

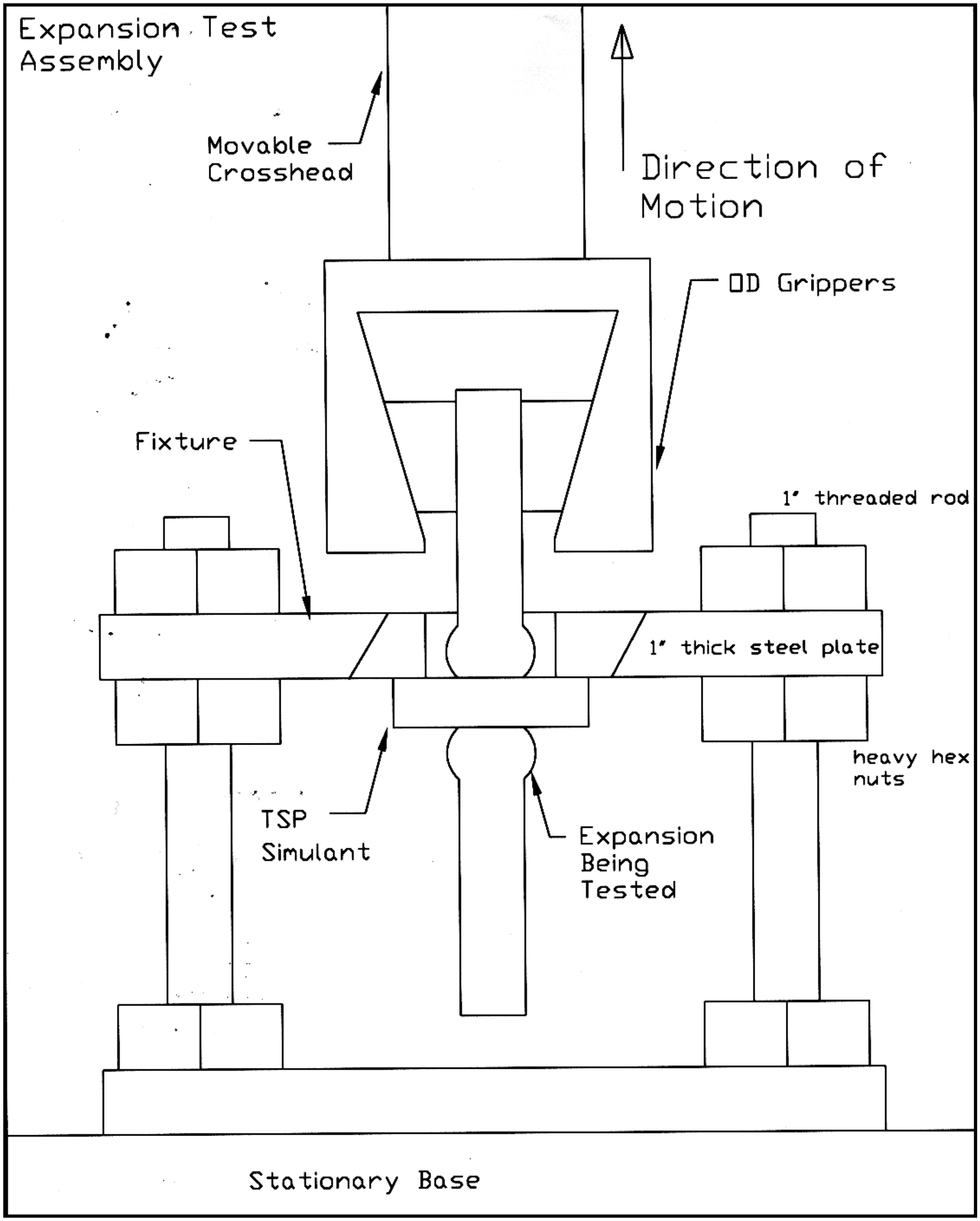

Figure 5-4
Typical Resistive Load vs. Bulge Size Tensile Loading Curve: TSP Specimen

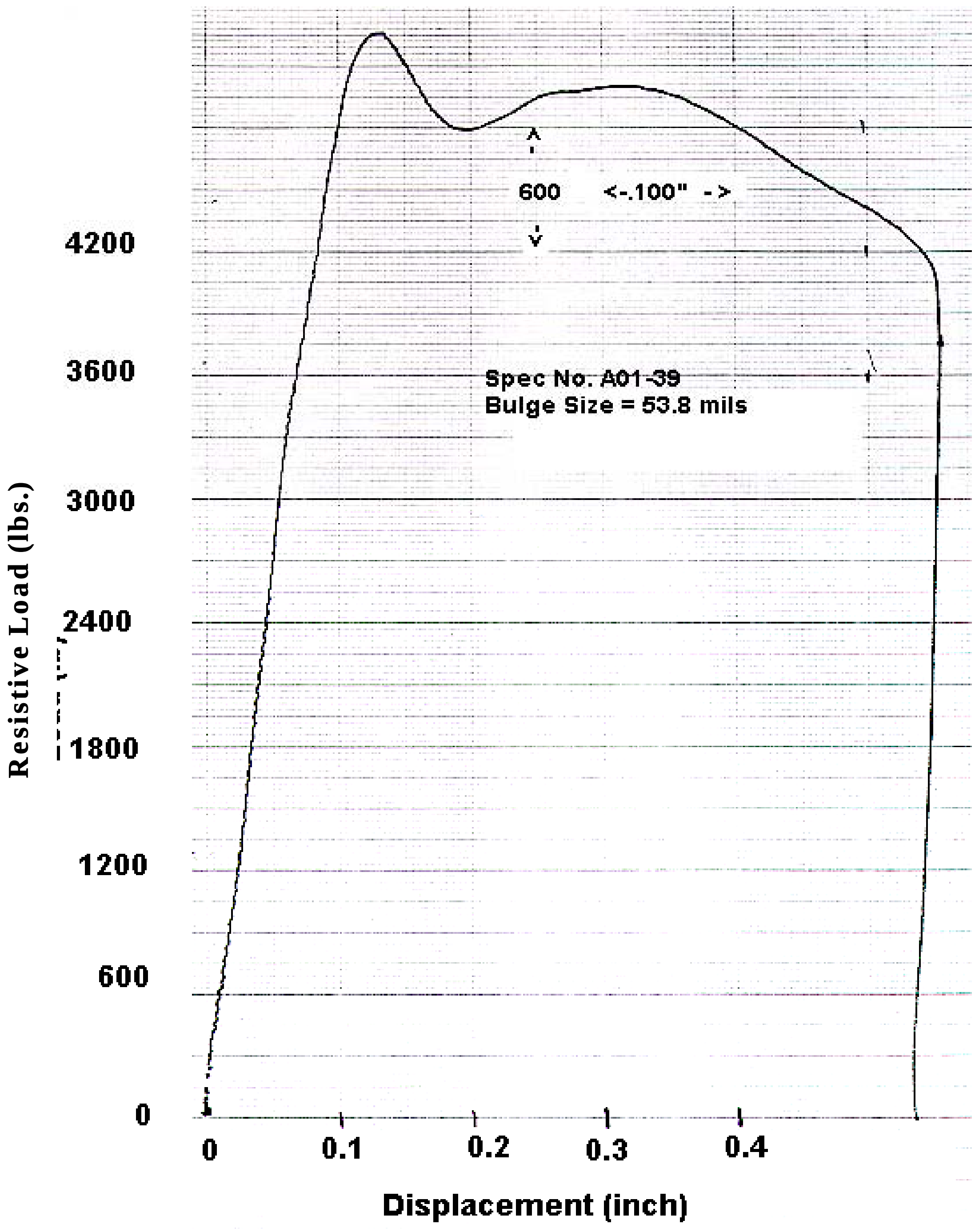

Figure 5-5
Comparison of Resistive Loads at 50 mils TSP Displacement:
1/30/98 Data Set, 2/17/98 Data Set, and Combined Data Set

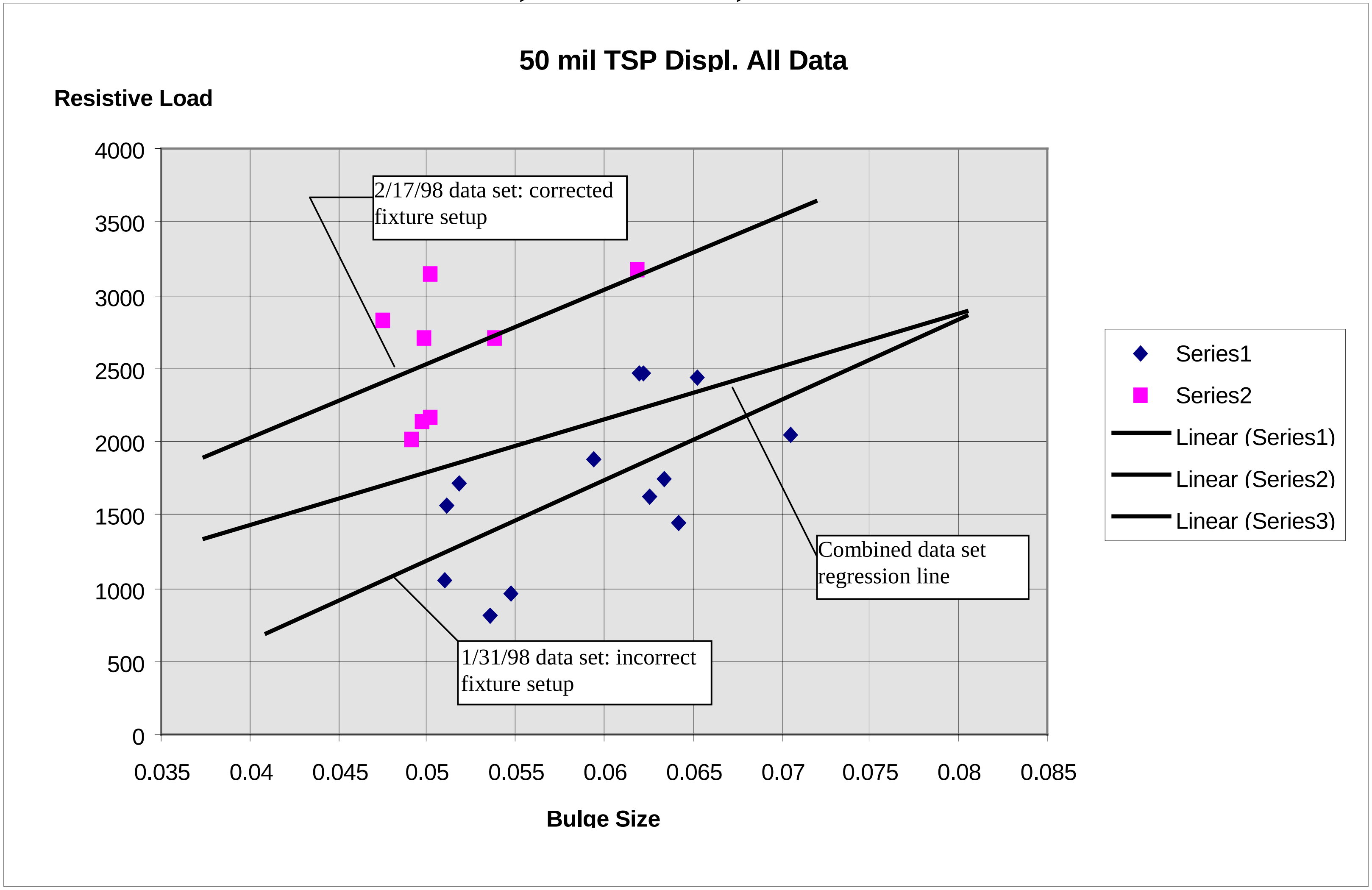

Figure 5-6a
Resistive Loads at 50 mils TSP Displacement: TSP Sample Combined Data Set
Determination of Minimum Bulge Size
Normal Regression, 90% Confidence and Prediction Intervals

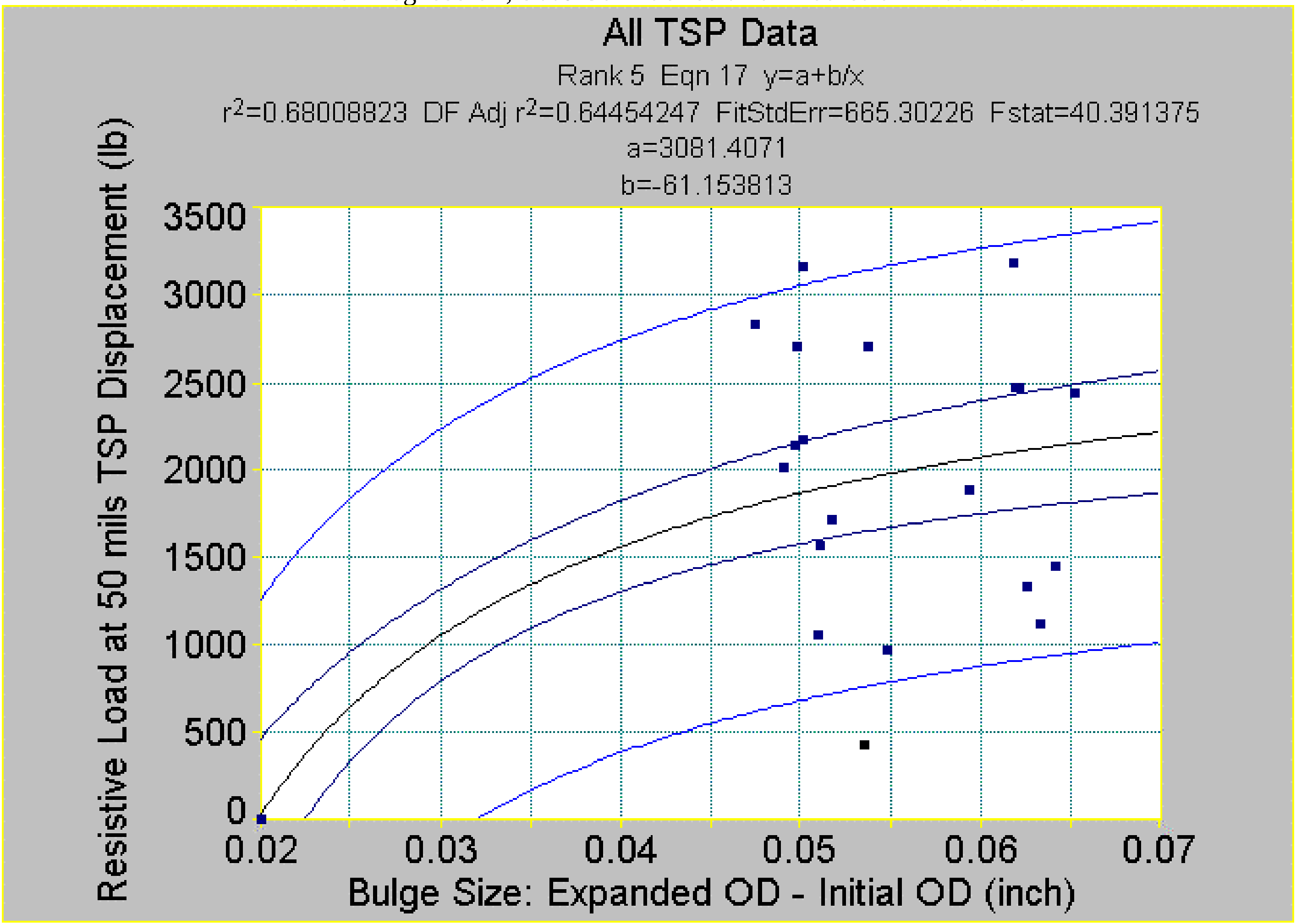

Figure 5-6b
Resistive Loads at 50 mils TSP Displacement: 2/17/98 TSP Sample Data Set
Determination of Minimum Bulge Size: Normal Regression, 90% Confidence and Prediction Intervals