

RHIC Dipole Beam Tube-to-End Flange Weld Evaluation

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RHIC PROJECT
Brookhaven National Laboratory

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Abstract

The Beam Tube-to-End Flange weld in the RHIC Dipole Magnet is an autogenous weld, melting a small land machined into the End Flange. Warm-up studies of the RHIC Dipole Magnet revealed excessive stresses in the Beam Tube-to-End Flange weld for the maximum acceptable warm-up time. A test sample was manufactured using the existing RHIC Dipole weld procedure. The test sample was sectioned radially and inspected microscopically. The observed dimensions were analyzed using Finite Element techniques, which revealed inadequate weld geometry. The test specimen also exhibited evidence of melting through the thickness of the beam tube. Additional analysis found an acceptable weld can be produced by modifying the weld preparation and using filler metal.

Background

The RHIC Collider Ring Division conducted analyses of the effects of cool-down and warm-up on the RHIC magnets. Part of the analysis focused on the effects on the beam tube¹. The thermal gradient created during cool-down will only impact the first magnet in each sextant. However, each magnet contains electrical heaters to accelerate warm-up. These heaters are located at the outer periphery of the magnet coldmass, thus the coldmass shells will warm and expand at a greater rate than the center of the coldmass where the beam tube is located. The beam tube forms the inner boundary of the coldmass pressure vessel, and is sealed with a weld to the coldmass end volume end flange at each end of the magnet. The proposed Warm-Up scenario, using a differential temperature of 50°K, produced a weld stress of 28,504 psi. Further analysis shows the stresses in this weld will exceed the 1992 ASME Boiler & Pressure Vessel Code allowable stresses for Type 304L stainless steel at the maximum allowable working pressure with a temperature differential of just 15°K. This analysis assumed a fillet weld of acceptable geometry.

Inspection of the Beam Tube-to-End Flange weld on the RHIC Full Cell #2 Dipole magnets DRE-011 and DRE-012 found at least half of the 0.090 inch deep weld land remained intact after welding. The weld also exhibited distinctive concavity, but it was not possible to measure the concavity due to the small size of the weld. This discovery cast further doubt on the weld design.

Procedure

A test specimen was prepared using a 10 inch diameter, 1.50 inch thick Type 304L plate. A hole in the center of the plate was prepared for a beam tube in accordance with RHIC Drawing

beam tube received for RHIC. This tube did not require preparation. The specimen was assembled for welding, and back-purged with 99.99% pure Argon at a rate of 30 cubic feet per hour (CFH) for a minimum of five minutes. Gas Tungsten Arc Welding (GTAW) was performed using a 3/32 inch, 2% thoriated tungsten electrode and 300 to 50 amperes of DC current. Shield gas was 99.99% pure Argon flowing at a rate of 15 CFH through a Number 4 gas cup. Back-purging was maintained for a minimum of five minutes after welding was completed.

The beam tube of the test specimen was cutoff 0.25 inches from the weld, and the test specimen was sectioned into four equal quadrants to facilitate handling. Smaller sections were then cut along the radial for the specimen. Four opposing surfaces were cut for metallographic examination. Each specimen was ground by hand on silicon carbide (SiC) papers, beginning with 240 grit, and followed by 320 grit, 400 grit, and ending with 600 grit. A mixture of kerosene and paraffin was used as a lubricant. The specimens were cleaned after each step with ethanol in an ultrasonic cleaner. The specimens were then polished in two steps using a 6 μ diamond paste followed by a 1 μ diamond paste. Both steps were performed using a nylon cloth on an 203mm (8") rotating wheel with Buehler's metadi fluid, which is a solution of water and polypropylene glycol, as a lubricant. Again, the specimens were cleaned with ethanol in an ultrasonic cleaner after each step. Finally, the specimens were electrolytically etched using a 10% solution of oxalic acid and distilled water and a stainless steel cathode. A ten volt electrical potential was applied for approximately 15 seconds.

Results and Discussion

The specimens were examined and photographed under an ocular microscope at 16x. The beam tube thickness was measured using a ball-end micrometer, and this dimension was used to verify perpendicularity of the section specimens. The weld dimensions, defined in Figure 1, are provided in Table 1.

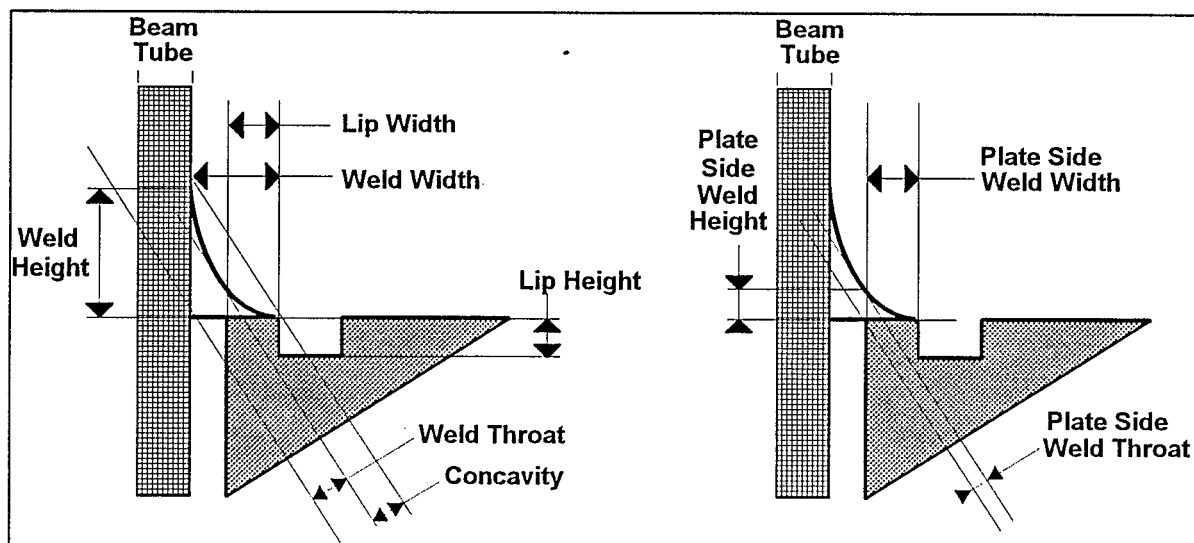


Figure 1. Weld Dimensions

Table 1
End Plate-to-Beam Tube Weld Dimensions

Dimension	Specimen B	Specimen L	Specimen RR	Specimen T	Worst Case
Beam Tube	0.075"	0.0785"	0.0785"	0.0785"	0.0785"
Lip Width	0.0625"	0.063"	0.062"	0.062"	0.062"
Lip Height	0.034/0.038"	0.024/0.033"	0.0325/0.035"	0.072"	0.072"
Weld Width	0.060"	0.056"	0.086"	0.148"	0.056"
Weld Height	0.085"	0.115"	0.119"	0.051"	0.051"
Weld Throat	0.041"	0.044"	0.041"	0.028/0.033"	0.028/0.033"
Concavity	0.023"	0.0045"	0.015"	0.011"	0.023"
Plate Side Weld Width	0.060"	0.053"	0.064"	0.130"	0.053"
Plate Side Weld Height	0.084"	0.104"	0.062"	0.064"	0.062"
Plate Side Weld Throat	0.0425"	0.044"	0.039"	0.051"	0.039"

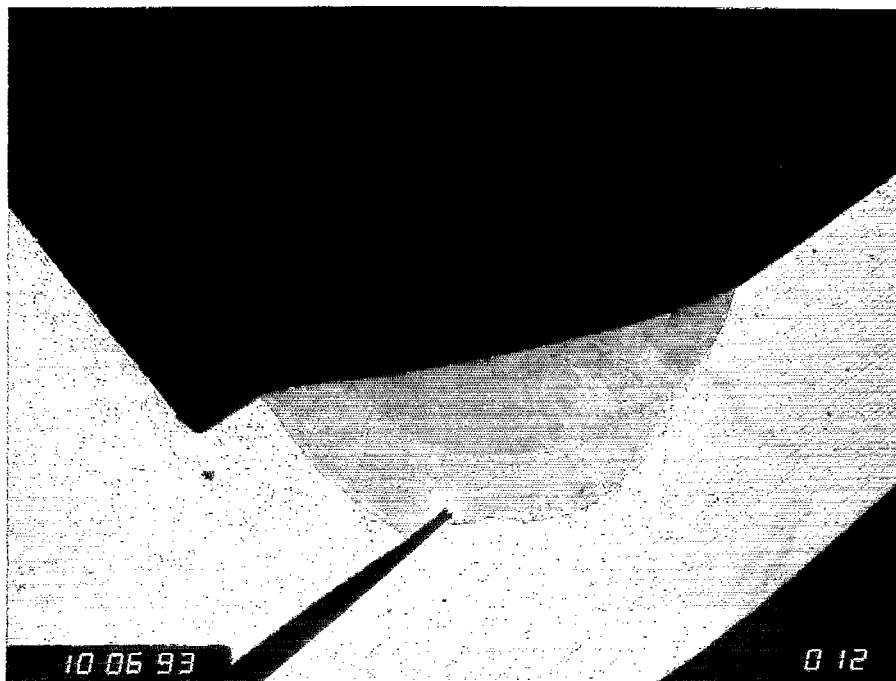
To evaluate the suitability of the weld and evaluate possible corrective action, five cases were analyzed using finite element analysis. The five cases are described in Table 2.

Table 2
Finite Element Case Description

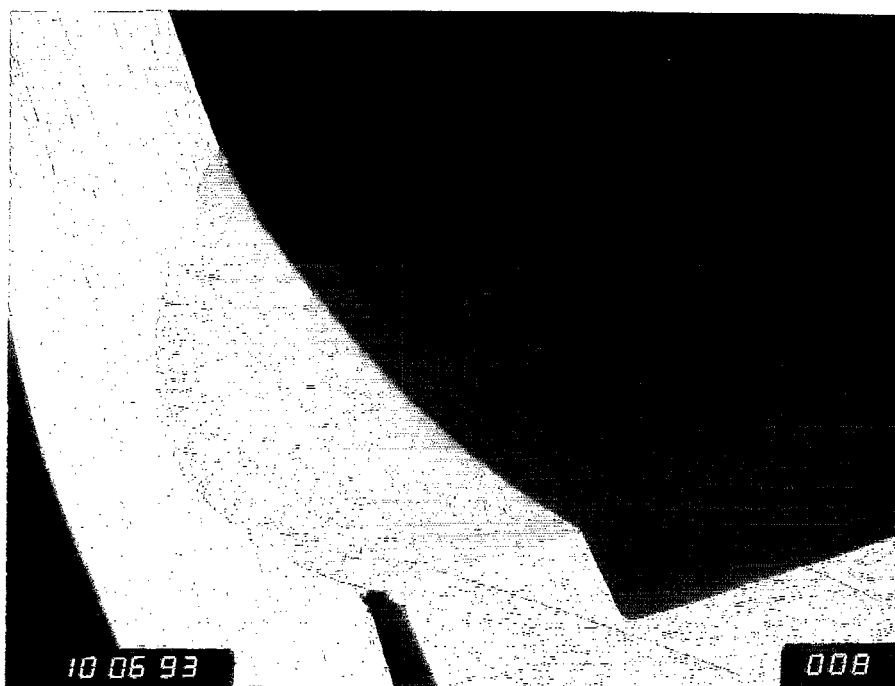
Case	Weld		
	Dimension	Preparation	Composition
1	0.080" x 0.125"	0.060" x 0.090" weld lip	filler metal
2	0.080" x 0.125"	0.060" x 0.090" weld lip	autogenous
3	0.140" x 0.125"	0.120" x 0.090" weld lip	filler metal
4	0.140" x 0.125"	0.120" x 0.090" weld lip	autogenous
5	0.140" x 0.125"	No weld lip	filler metal

The five cases considered a 0.020" gap between the beam tube and end plate, therefore the weld leg is extended from the 0.125" nominal weld leg to the beam tube, yielding 0.140". The autogenously welded cases assumed the weld preparation lip was melted to the root of the preparation. The linear-elastic analysis uses 2-D axisymmetric elements and a spring element ($K=1.51 \times 10^4$ #/in./rad) to simulate the spring stiffness of the beam tube. Ten layers of axisymmetric elements across the 0.078 inch beam tube thickness were used to simulate bending. Relevant material properties are:

- Modulus of Elasticity, $E = 28 \times 10^6$ psi
- Poisson's Ratio, $\nu = 0.3$
- Yield Point (Table UHA-23²) = 25 ksi for Type 304L, 30 ksi for Type 316LN
- Allowable Stress, $S_{All} = 16.3$ ksi for Type 304L, 18.8 ksi for Type 316LN



Photograph 1 - Specimen L, 16x



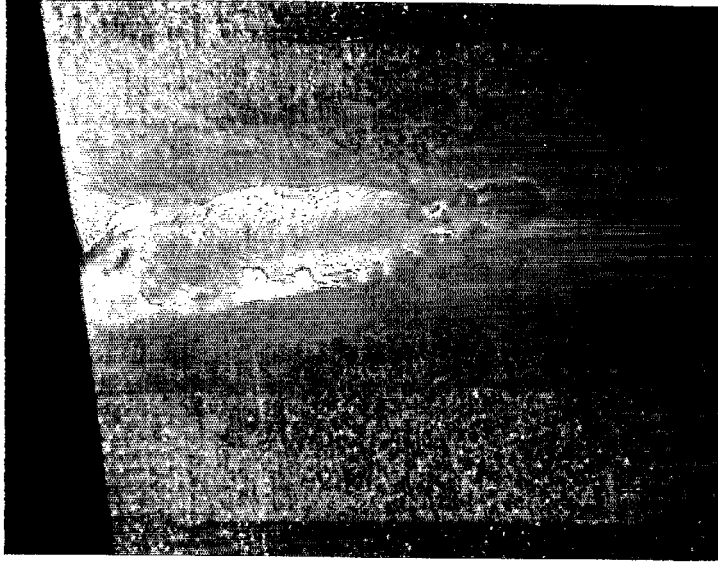
Photograph 2 - Specimen T, 16x



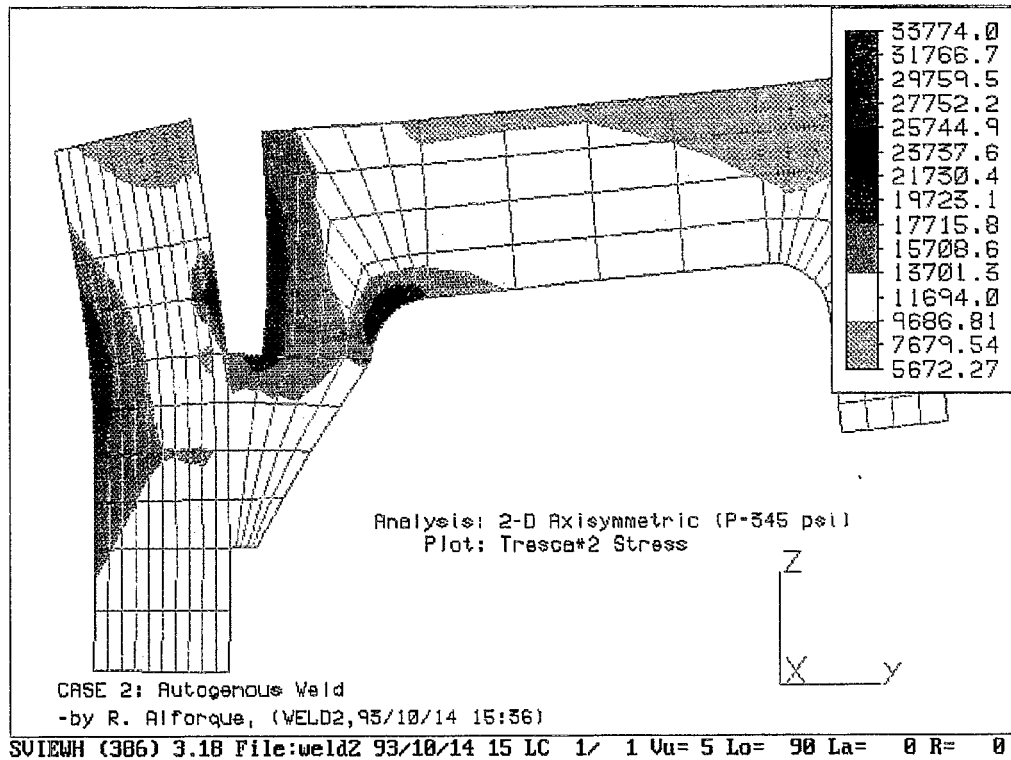
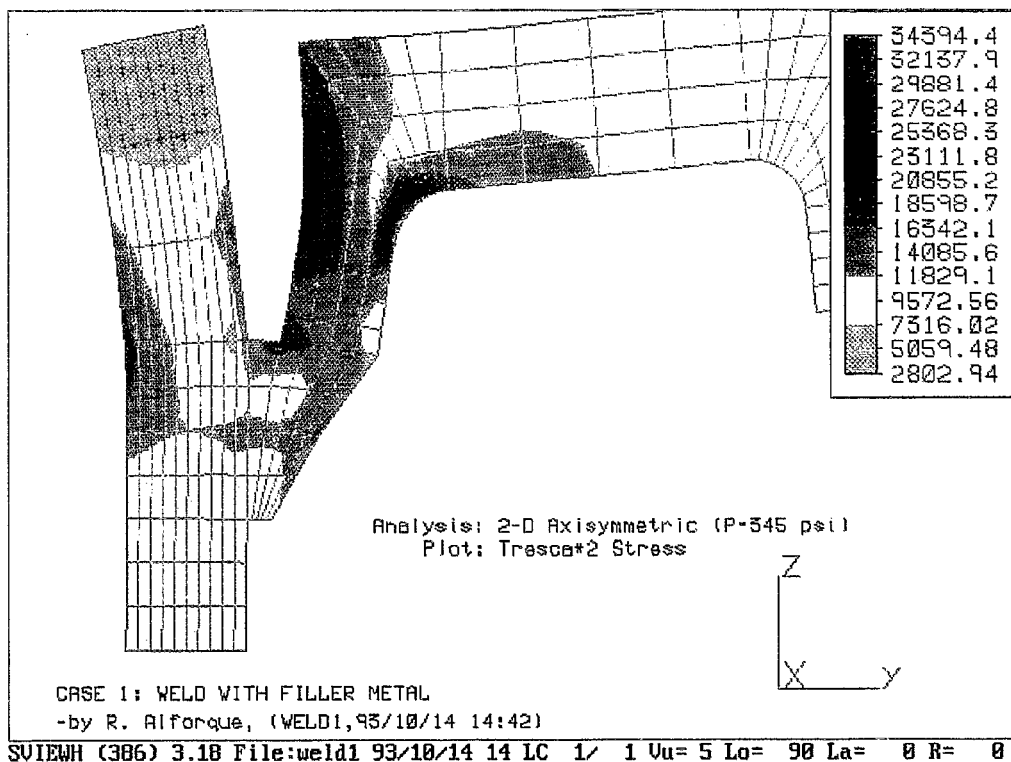
Photograph 3 - Specimen RR, 16x



Photograph 4 - Specimen B, 16x



Photograph 5 - Weld Melt Through, Inside of Beam Tube, 10x



Stress intensities for the test pressure of 345 psi are shown in the appended 2-D Axisymmetric Tresca*2 color plots, and are summarized in Table 3. The joint does not meet ASME Boiler & Pressure Vessel Code, Section VIII, Division 1 rules, thus Division 2³ rules were used. Stresses at the design operating pressure were acceptable. However, Section AD-151.2³ requires that the maximum stress intensity be less than 80% of the yield strength at the test temperature. The minimum specified yield strength for 316LN is 30 ksi, and for 304L is 25 ksi. This means stress intensities may not exceed 24 ksi for 316LN and 20 ksi for 304L. Only Cases 4 and 5 are acceptable using this criterion. Case 5 is preferred because of the cost savings from elimination of the machining, and Case 5 does not present a problem for welding.

Table 3
Maximum Stress Intensity at Specified Locations
(Pressure=345 psi)

Case Number	Beam Tube (316LN)	End Plate (304L)	Weld
1	18.7 ksi	31.1 ksi	19.5 ksi
2	22.3 ksi	23.4 ksi	21.3 ksi
3	20.7 ksi	21.8 ksi	17.4 ksi
4	20.8 ksi	18.1 ksi	18.1 ksi
5	21.8 ksi	19.1 ksi	19.1 ksi

Section QW-184 of the ASME Boiler & Pressure Vessel Code⁴ specifies criteria for fillet weld qualification. This section requires weld concavity not to exceed 1/16 inch (0.063 inch). The concavity for these test specimens falls within this range, but this same section also specifies the difference in the length of the fillet welds shall not exceed 1/8 inch (0.13 inch). This difference is larger than the weld under investigation, and the concavity requirement may have been developed for larger welds, making it inapplicable for this case. However, ASME uses the largest triangle fitting inside the weld to determine weld dimensions, hence weld concavity is addressed indirectly. The test specimen welds were found inadequate using this method of measurement. Using filler metal will minimize weld concavity.

Using filler metal also will aid in heat control. Heat control is important in this case because of the significant differences in material thickness. The beam tube was melted through its thickness at one point on the test specimen. See Photograph Specimen 'B' and Photograph 5. The use of the back purging also worked to prevent melt-through of the beam tube. Inert purge gas is recommended⁵ for root bead welding of austenitic stainless steels using the gas tungsten arc process. Back purging provides oxidation protection to the weld root and adjacent base metal surfaces. The oxidation protection also increases the surface tension of the weld pool, providing complete weld root fusion, and good weld contour and surface uniformity. This eliminates the rough interior surface of a butt welded pipe or tube, decreases the tendency for the weld pool to drop through the joint during welding, and decreases the tendency for root bead cracking. In this case, the welding probably would have melted through the beam tube had back purging not been used. The consequences would be significant additional cost to rework the magnet coldmass.

Conclusions

Only Cases 4 and 5 meet the requirements of the ASME Boiler & Pressure Vessel Code. Case 5 is preferred because of the cost savings from elimination of the machining, and Case 5 does not present a problem for welding.

The use of back purging during welding operations involving the beam tube will eliminate the potential for interior surface oxidation, melt-through, and root bead cracking.

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- ¹ J. Koehler Memorandum; Beam Tube Stress During Cooling or Warming a Magnet (Revised), June 9, 1993
 - ² ASME Boiler & Pressure Vessel Code, Section VIII, Rules for Construction of Pressure Vessels, Division 1; July 1989
 - ³ ASME Boiler & Pressure Vessel Code, Section VIII, Rules for Construction of Pressure Vessels, Division 2 - Alternative Rules; July 1989, with 1991 Addenda, December 1991.
 - ⁴ ASME Boiler & Pressure Vessel Code, Section IX, Welding and Brazing Qualification, July 1991, with Addenda, December 1992
 - ⁵ AWS D10.4-86, Recommended Practices for Welding Austenitic Chromium-Nickel Stainless Steel Piping and Tubing

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Appendix

2-D AXISYMMETRIC TRESCA*2 COLOR PLOTS

